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Editors

Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses

Proceedings of the 14th CIRP Conference on Life Cycle Engineering, Waseda University, Tokyo, Japan, June 11th–13th, 2007

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Preface

As has been proven in various ways, our industrial activities have already exceeded the capacity of the globe to safely perpetuate them. We need immediate action to change this critical situation to a sustainable one. This recognition has led to the establishment of life cycle engineering, whose aim is to enable a paradigm shift in the conventional concept of manufacturing, which has induced mass consumption and mass disposal and generated serious environmental problems. The mission of manufacturing should no longer be to produce with the greatest efficiency but, rather, to provide satisfaction to customers while having minimal environmental impact. To achieve this goal, a number of new concepts such as dematerialization, closed loop manufacturing, and product service systems have been proposed. Along with these concepts, various technologies have been studied. These technologies include those specific to a particular life cycle phases, such as DfE in the product development phase, MQL machining in the production phase, maintenance in the usage phase, and disassembly in the end-of-life phase. However, what characterizes life cycle engineering more significantly is its holistic approach to manufacturing, such as life cycle design and life cycle management. In life cycle design, a proper life cycle scenario should be created by selecting appropriate life cycle options, like maintenance, reuse and recycling, for example, and products and life cycle processes should be designed with this life cycle scenario in mind. Then the designed scenario should be realized and improved by means of life cycle management.

In the CIRP community, it was Prof. Leo Alting who first opened our eyes to the necessity of life cycle engineering with his paper "The life cycle concept as a basis for sustainable industrial production," presented at the CIRP General Assembly in 1993. He established the Life Cycle Working Group and also initiated the Life Cycle Engineering Conference in 1993. Since then, the CIRP conference on Life Cycle Engineering has continued to provide a valuable and prominent forum for discussing basic research, applications, and current practices, and has made great contributions to the development of life cycle engineering.

Many of the world's imminent environmental problems, however, have unfortunately not been solved. This situation does not mean that we do not have methods and technologies to cope with the problems at all. We have been discussing and studying life cycle engineering for more than a decade not only in the CIRP community but also in other research societies and in industry itself, and developed various solutions. What we need now is to accelerate the actual implementation of the concepts and technologies proposed in life cycle engineering. This brings a further challenge before us. We need to enhance the methods and technologies of life cycle engineering so as to create life cycle scenarios, which are sustainable ecologically, economically, and sociologically, and to implement them in the actual business world. For this purpose, we need more knowledge about products and customer behaviours as well as the environment, and more powerful tools to deal with complexity, because life cycle issues are quite complicated.

The 14th CIRP conference on Life Cycle Engineering takes place at the International Conference Centre of Waseda University in Tokyo from June 11th to 13th. It is co-organized by the Technical Committee for Life Cycle Engineering of the Japan Society for Precision Engineering and by the Waseda University Life Cycle Management Project Research Institute.

This compilation of the conference proceedings includes two keynote papers and 80 contributed papers. In the keynote papers, Itaru Yasui discusses the aim of life cycle engineering from the broad and long-term view of environmental issues in relation with human history, while Kiyoshi Sakai introduces various concrete measures taken in industry for achieving the long-term goals of life cycle engineering. The contributed papers, which cover various important topics in the field of life cycle engineering, are organized into three categories: life cycle design, sustainable manufacturing, and life cycle management. I believe that this volume provides valuable knowledge not only in terms of the latest version of the series of contributions of the CIRP conferences on life cycle engineering but also for advancing life cycle engineering for sustainable manufacturing businesses.

Finally, I would like to express my sincere appreciation to all contributors to this book. I also would like to extend my thanks to the members of the Organizing Committee and the International Scientific Committee for their devoted efforts to arranging the conference and to reviewing and compiling the papers in this book and making it available to the public. Last but not least I would like to express my sincere gratitude to the secretariat. Without its efforts this conference could not take place.

Shozo Takata
Chairman of the organizing committee
14th CIRP Conference on Life Cycle Engineering
Tokyo, Japan, June 2007

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Transition of Environmental Issues

--Fundamental Criteria for LC Engineering--

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1 INTRODUCTION

What are the real objectives of Design for Environment or other Life Cycle Assessment related tools? Of course the objectives are multi-dimensional, but the most urgent and important factor can be different in the situation of regions or countries, where environmental situation is different. It is therefore important to understand the concept of "Transition of Environmental Issues", if such tools become more effective in the countries as a target.

2 REDEFINITION OF ENVIRONMENTAL ISSUES

First of all, I would like to describe some experiences in Japan. In 1960s, the economical growth was so rapid and as one of side effects, very severe pollution issues such as Minamata Disease or Itai-Itai Disease came up. In the period of time, the most important endpoint of the issues was the adverse health effects, including death and disabilities. It was very lucky but such environmental issues were mostly solved in 1970s by the introduction of several environmental laws.

In late 80s, Japan had so-called "Bubble Economy" and as a result, increase in the amount of waste attracted attention of the society. In 90s, waste management issues continued and typical issues such as Dioxin Campaign or Endocrine Disrupting Compounds emerged and disappeared within several years. Everybody worried about his/her own health along with the health of children in the future.

Environmental issues such as loss of tropical forests can be understood different ways, but the endpoint of these issues is the loss of ecosystem, including extinction of species. It can be redefined it is a matter of life of natural species.

In 1992, World Summit for Sustainable Development was held in Rio, and we shared the importance of global environmental issues including global warming / climate change. These issues can affect the future of mankind by multiple effects, such as supply of food, loss of ecosystem services by the change of ecosystem itself, sea level rise and change in rain fall etc. The emission of Green House Gases is the reason to cause climate change, but it can be said that climate change is caused not by the real human activities but more simply by the very convenient characteristics of fossil fuel. Overuse of fossil fuel is the true reason to cause the issue.

Fossil fuels including oil, natural gas, coal and others will deplete within several hundred years. The human being in the year of 2300 will not be able to access fossil fuel. The current generation is in the midst of "Fossil Fuel Era", which stated in the year of 1770s by the invention of steam engines. We normally use the term of Industrial Revolution, but if we look the technology more closely, the real component of industrial revolution is fossil fuel.

History of human being, or Homo-sapience started some 180,000 years ago. The length of Fossil Fuel Era is just about 500 years or so. We have to understand our generation is only an exception with regard to the access to fossil fuel. The other generation of human being must use either renewable energies or nuclear energy.

This is the point of redefinition of environmental issues. As the first part of environmental issues, lives of human being and other natural species are the endpoint to be taken into account, but the latter part of environmental issues is how to create a new way of life without or less consumption of fossil fuel without having tragic decrease in global population due to insufficient supply of food, energy or materials.

The first issues in relevance to lives of human being etc. can be called by the term of "Local Risk Issues" and the second issue of fossil fuel can be called by the term of "Global Risk Issues". The transition in the relative importance in risks occurred in 1980s in Japan, shown as Fig.1.

Countries in transition or developing countries, the local risks will be still high enough and transition may well happen someday in the future. Important issues for those countries are how to overcome local risk issues.

Let us take a look at the history of local risk issues in some toxic materials.

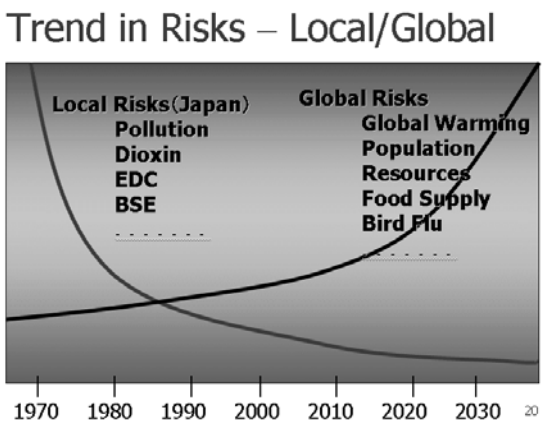

Figure 1 Transition from Local Risks to Global Risks. Local risks went into "Safe zone" in 1985 or so and at the same time Global risks exceeded the Local risk.

3 HOW TO REDUCE LOCAL RISKS – HISTORY IN ADVANCED COUNTRIES

As an example, I would like to consider the reduction of health risks due to the exposure to heavy metals, especially Pb.

Adverse health effects caused by Pb exposure are mainly to children less than 6 years old in the form of lower IQ. It is advised by WHO Pb concentration in the blood must be less than 10 μ g/dL, and it is necessary to keep the average value of Pb concentration less than 5.4 μ g/dL in order to minimize the number of children whose Pb levels exceed the upper limit. Taking the intake of Pb from food into account the concentration of Pb in the air must be kept less than 0.5 μ g/m^3. On the other hand, the regulation in USA is 1.5 μ g/m^3 in the air, though the way of discussion to determine the upper allowable value is almost same.

In the history of all advanced countries, Pb small particles were emitted to the atmosphere in the form of lead oxide because of the addition of an organic lead compound to gasoline as a knocking inhibitor. The use of Pb as an additive to gasoline started in 1920s and it is presumed more than 7 million tons of Pb were emitted into the air from automobiles in USA by the time when the addition of Pb compound drastically reduced after 1975.

Fig.2 shows the trend of average concentration of Pb in the blood of children in the USA. Just after the end of use Pb as gasoline additives, the concentration started to decrease linearly until it reached less than 3 μ g/dL.

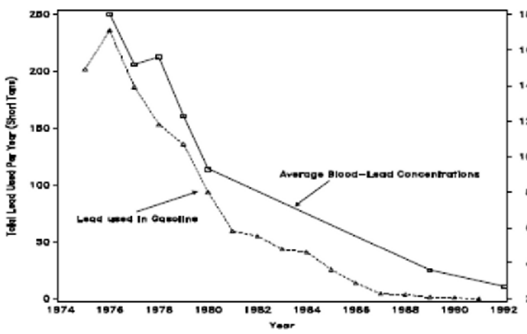

Fig. 2 Trends of Pb concentration in blood and correlation with the amount of lead used in gasoline in USA (by USEPA).

Fig.3 shows the usage of Pb in the USA. EU started RoHS (Restriction of Hazardous Substances) and it is now in effect since July 2006. Use of Pb was banned in electric and electronic apparatus along with some other toxic elements. Solder with Pb has been completely replaced by several kinds of non-Pb solders, but the reduction of risk due to the exposure to Pb in solder remains same because the route of exposure to Pb is through burning wastes with Pb. The amount of Pb for solders already decreased in 1980s and 1990s in USA and restriction only for solder will not be so effective in advanced countries, although Pb may cause health issues as a labor issue in recycling process of equipment containing Pb, which has been an important issue in East Asia.

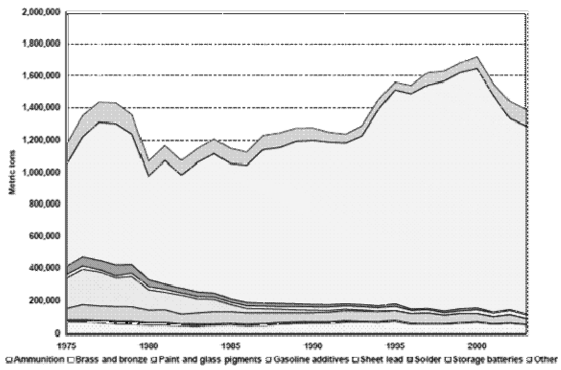

Fig.3 Usage of Lead in USA. Solder decreased in 80s and 90s.
http://minerals.usgs.gov/ds/2005/140/lead-use.pdf

Non-Pb solder needs to use Ag, In, Bi and other metals. Risks must be controlled with a holistic view of all possible risks including depletion of rare elements, health risk to human being and risk to ecosystems.

4 LONG TERM VIEW OF ENVIRONMENT WITH AND WITHOUT FOSSIL FUEL

Global warming became the most important environmental issue these days. To decrease CO2 emission alone is not so difficult as far as enough energy resource is available, because CCS(=Carbon Capture and Storage) is technologically possible to apply. Fossil fuel depletion is the other side of the same coin of global warming. Bio-fuel and bio-ethanol are candidates to decrease CO2 emission from transportation, but its limitation must be carefully examined because the use of some kinds of grain or edible parts will decrease supply of food on the Earth. The use of sugar cane will enhance the competition in land-use and may result in the decrease of forest in tropical region.

Human being started to use much fossil fuel from the year of 1800 or so. Fossil fuel will last only 500 years at most, and it is too short to be considered a gift from the heaven to the history of human beings. It must be considered fossil fuel era is rather special occasion and we have to consider what is the life of people without any fossil fuel. It is necessary to answer the question what is the maximum population to be survived on the Earth without the help of fossil fuel. It may be too early to consider the post fossil fuel era, but consideration of such situation will cause some kind of change in the mindset of people. It can be said at least it is not necessarily unhappy to live without fossil fuel.

Fig.4 shows some possible route to the years beyond 2300. One way is to choose to live with nuclear technologies and the other with only renewable energies. Which is more risky?

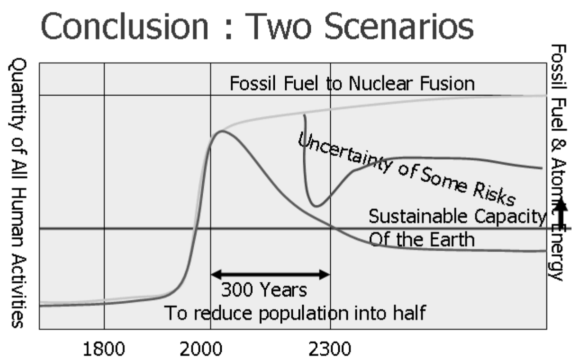

Fig.4 Two long-term scenarios with and without nuclear technologies.

5 CONCLUSION

How to minimize the total risk? This is the question we have to answer. The answer will provide an optimum solution to realize happy coexistence of human being and the Earth in the future. Long-term issues for the future such as how to survive in the year of 2500 may not be so important. Because everybody in the era will have much more intelligence to understand how to behave and how to enjoy each life, and the situation cannot be too bad.

Transient period, on the other hand, will be the worst, especially in the year of 2070 or so, after the human population reaches the maximum at around 7.8 billion in 2040 or 2050. People still have similar mindsets as the current generation, and will try to increase human activities in order to be more comfort, more convenient and much more speedy.

It is necessary to design things so as to keep the amount of consumption within carrying capacity of the Earth. But it is more important to design things to give satisfaction to all users by the quality or other values of products, and not by the quantity.

I would like to conclude this paper by my sincere expression of future expectation for the advancement of LC Engineering.

Ricoh's Approach to Product Life Cycle Management and Technology Development

Kiyoshi Sakai
Ricoh Company, Limited, Tokyo, Japan

Abstract
Ricoh aims sustainable environmental management that simultaneously realizes environmental impact reduction and profit creation. Toward such realization, we grasp impact quantity in each production process and establish development tasks by assessment of eco-balance and integrated environmental impact (IEI) throughout the whole product life cycle. As the target value, we draw a figure where the environmental impact is fitted into the allowable limit of the earth in 2050; and as its milestone, we have decided to have IEI reduced 20% by 2010. Thanks to the technical development, by 2005, we have increased sales revenue while decreasing IEI by 22%.

Keywords:
Sustainable environmental management; Product lifecycle management; Environmental technology

1 INTRODUCTION

Abnormal climate experienced in various parts of the earth recently is said largely caused by the fact that "the environmental impact created by human society exceeds the earth's capacity". It is concerned that such situation would be worsened by population increase or economic growth in the developing countries toward the future. In order to overcome such crisis and to transfer this irreplaceable earth to the next generation, it is necessary that not only central and local governments exert leadership but also business entities take initiative in reducing environmental impact. Such activity will only be meaningful by continuous implementation. Business entity's continuous activity can only be realized by its growth and development. For such purposes, new economic value needs to be created through environmental impact reduction activity.

Ricoh draws as the aimed figure the earth where environmental impact is controlled within the range of natural recovery capacity, promotes environmental impact reduction in the aim of its realization and at the same time pursuits economic value. Ricoh is gaining fruits. Concerning Ricoh's efforts, first, its idea of sustainable environmental management covering entire product lifecycle [1] will be explained. Next, example of environmental technology development [1] will be shown.

2 SUSTAINABLE ENVIRONMENTAL MANAGEMENT

2.1 Overall

In order to continuously strive for environmental impact reduction, standing on a long term viewpoint, it is necessary to promote "sustainable environmental management" that creates economic value through environmental conservation activity and to have such business entity survive and develop. Ricoh Group's efforts for the environment have developed from 3 viewpoints. Namely, they are "environmental correspondence", "environmental conservation" and "sustainable environmental management". In "environmental correspondence" of the initial stage of the efforts, it was passive activity to correspond to the external pressure such as regulation or customer demand. By having the viewpoint of "environmental conservation" added to it, efforts have been made with a sense of mission as an earth citizen; and measures for reducing environmental impact in business activity or product have voluntarily been taken. Nowadays, the viewpoint of "sustainable environmental management" is added; and we are actively reducing environmental impact of the business activity and at the same time pursuing creation of economic value as a business entity, in the aim of continuous environmental conservation.

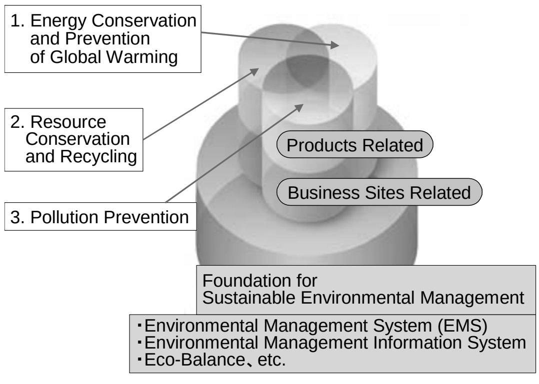

Figure 1: Ricoh Environmental Management Structure.

Overall picture of the sustainable environmental management promoted by Ricoh is shown in the Figure 1.

Promotion area of sustainable environmental management has the following 3 supports:

1. Energy conservation/Prevention of global warming
2. Resource conservation/Recycling
3. Pollution prevention

Each of them has the following 2 efforts:

- Product related efforts
- Business site related efforts

Further, as the basic tools for promotion of activity to cover all areas, we have EMS (ISO 14000 family), Environmental Management Information System to support it, Eco-Balance for grasping/analyzing environmental impact of the whole business activity, environmental education/enlightenment and environmental social contribution.

2.2 Product lifecycle management

When establishing medium/long term environmental action plan involving the whole business, environmental impact reduction should be effectively implemented, putting priority to the process with larger impact. And it should unifiably grasped as eco-balance to know how much environmental impact exists in what process through the whole product lifecycle not only in Ricoh, but also in the business activities at the supplier of materials/parts, use at the customer of the product or the final collection/recycle. For the assessment, EPS (Environmental Priority Strategies for Product Design) [2] of Swedish Environment Research Institute is used. EPS is a method, whereby damage quantity caused by CO_2 emission or chemical substance use and given to human health, ecological system, resource exhaustion and biodiversity is converted to the unified ELU (Environmental Load Unit). By EPS, effect of integrated environmental impact is grasped, instead of each single effect of CO_2 reduction or resource conservation.

Figure 2 shows the result of totalization by EPS of the environmental impacts given by each step of the product lifecycle, based on the eco-balance analysis of the whole business activity of Ricoh Group. The steps are divided to those originated from Ricoh and those originated from front and rear: namely, supplier and customer. Through such works, we grasp which steps of the product lifecycle give larger environmental impact, specify the subjects of environmental technology development and establish the tasks to be tackled with. Main products of Ricoh Group are copier and printer, which are used in the countries worldwide. According to the Figure 2, it is found that the impacts of inputted resources including chemical substances contained in products: namely, the upstream portion and the impacts by customers' paper use and electrical power use are large.

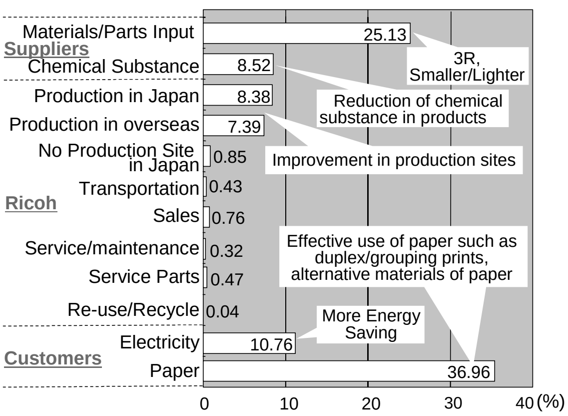

Figure 2: Integrated environmental impacts by each step pf product lifecycle.

2.3 Super long term vision

In determining reduction target of the whole business, we first image the aimed figure of the societies in the future (Figure 3). It depicts that the integrated environmental impact given by human being fits into the earth capacity and human being on the earth equally enjoy affluence. For such purpose, in the developing countries that anticipate large population increase and economic growth, the integrated environmental impact per head in 2050 must be of the same level as the developed countries. As the condition, assumption is made that the population already 40% in excess of the earth capacity is 9 billion (developed countries 1.2 billion and developing countries 7.8 billion) in 2050. On such basis, if calculating the integrated environmental impact per head in 2050 for controlling environmental impact within the earth capacity and making the society where both developed and developing countries equally enjoy affluence, it must be reduced to 1/8 of 2000 in the developed countries and kept 2 times of 2000 in developing countries.

As assumed conditions or ways of thinking themselves have many other study result/ opinion/forecast, it may be difficult to pursuit accuracy of numerical values. However, Ricoh's sustainable environmental management considers it important to hold up a clear super long term vision and to make a target setting. It considers that a rough super long term direction to proceed at present would be 1/8. Any change of the assumptions would have to be periodically checked.

Since the integrated environmental impact per head in the developed countries must be 1/8 in the society aimed in 2050, Ricoh considers that its target value should be in line with it. And also in consideration of growth of the company, we aim technical development that largely reduces the integrated environmental impact of the whole business activity by 2050. And we have established in 2004 the "long term environmental target for 2010" that reduces 20% by 2010.

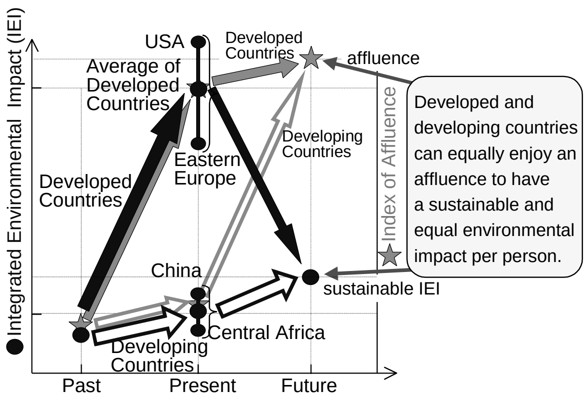

Figure 3: Figure of the society of super long term.

3 ENVIRONMENTAL TECHNOLOGY FOR ENVIRONMENTAL IMPACT REDUCTION

3.1 Environmental impact reduction in the production site

Environmental impact in the production process

For each step of the product lifecycle as shown in the Figure 2, example of environmental impact reduction will be shown. One of large environmental impacts in the production site is CO_2 emission through energy use of manufacturing equipment. Concerning CO_2 reduction, while Kyoto Protocol sets Japan's target at 6% reduction, Ricoh makes addition and targets 12% reduction from 1990 in 2010. While the performance in 2005 showed increase in these years due to production increase, the absolute quantity is reduced by 3.7% from 1990. In order to have a large CO_2 reduction in the production site, production process reform is needed, in addition to changing the equipment to energy conservation type with smaller warming coefficient

Cart pushing production

At Gotenba factory which is the main Japanese factory of copiers, the conveyor line is eliminated; instead, "cart pushing production" (new production method whereby the cart with the product on it is pushed by the air cylinder from its rear end) is developed. The copier is not put on the pallet on the conventional conveyor line, but is put on each cart. The space between each cart is flexibly connected and composes production line. The rear end cart is pushed by the air cylinder and the whole line slowly moves. Figure 4 shows how the "cart pushing production" looks like. Advantages of this method are as follows:

- By changing number of carts connected, it flexibly copes with the change of production quantity.
- Power consumption is kept the minimum.
- Space of production is minimized.

	Belt Conveyer	Push Cart	Savings
Electricity	90 Kwh/day	1 Kwh/day	99%
Space	1160 m^2	380 m^2	67%
Initial Investment	J. Yen 20.00M	J. Yen 0.28M	99%
Maintenance Cost	J. Yen 2.24M	0	100%
CO2	7.7 ton/year	0.1 ton/year	99%

Figure 4: Cart pushing production.

As the result, as shown in the Figure 4, when compared to the conventional conveyor line, in addition to the fact that power consumption is reduced by 99%, equipment investment and maintenance expenses are largely reduced. In terms of CO_2 emission reduction effect, annual emission quantity is reduced by 99%.

Super compact toner filler

In order to cope with the multiple model production in smaller lots of toner product, super compact toner filler is developed. In order to fill the toner produced into the toner bottle, we used to pour the toner into the bottle by rotating gigantic agitator and stirring the toner with nozzle like cork screw. Thus, in order to fill with a high speed, we used to need a large quantity of electric power.

Super compact toner filler simultaneously pours mixture of toner and air with the air pump; and enables smooth pouring as before. Technology to exhaust the air after filling also enables filling speed the same as before or more. As poured by air, large equipment has become unnecessary and installation space has become 1/40, power consumption per bottle 1/4 and CO_2 emission 1/4 (Figure 5).

As installation space is as small as 2 tatami mats, this toner filler is introduced for the purpose of production and delivery not only to the production site but also to logistics base or sales company, very near to the customer. Thanks to it, further effects are obtained, such as environmental impact reduction in transportation of the bottle in collecting from the market and in reusing, as well as shortening of delivery lead time. Currently, 56 units are in operation in 5 regions of Japan, Americas, Europe, Asia and China. As it fills when necessary and delivers to the user, it is called "on-demand filler" in-house.

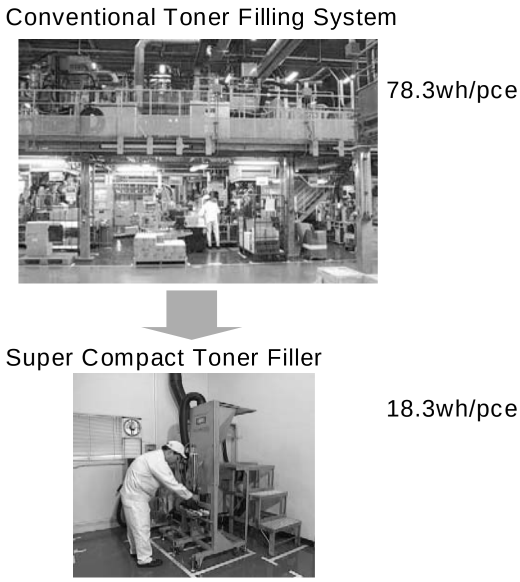

Figure 5: Super compact toner filler.

3.2 Reduction of user's environmental impact

HYBRID QSU

In addition to energy conservation in the business sites of our company, the product energy conservation contributes to reduction of energy at customer side. As copier has the system to melt toner with heat and fix it onto the paper, it is necessary to have the fixing device always heated so as to have the copier ready for use. On the other hand, the heat in the standby time when the copier is not in use remains for a long time; and it causes waste of energy. But if heat in standby time is of too low temperature, recovery time becomes long, causing disadvantage of bad usability.

Ricoh has shortened the recovery time from energy conservation mode from the conventional 30 sec. to 10 sec. or less in 2001; and further, in advance to other companies, it has accomplished compatibility of energy conservation and usability by developing QSU (Quick Start Up) technology whereby user can accomplish larger energy conservation. Later, “HYBRID QSU” is developed and installed into the high speed digital copier (the product with 100V power source introduced to Japan). “HYBRID QSU” is the technology that combines the QSU technology to shorten temperature rising time of fixing device and the capacitor to enable rapid charge and discharge (electricity accumulation device). By accumulating electricity in the capacitor, electricity consumed for remaining heat in standby is restrained; and by discharging at the time of recovery, the fixing device gets the temperature risen in a short time. With color copier, IH technology is installed as the color QSU, which shortens recovery time and accomplishes both energy conservation and usability.

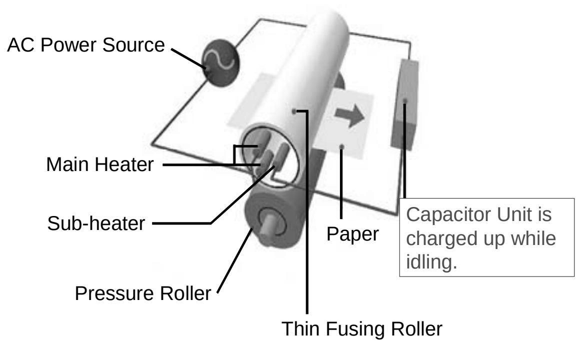

Figure 6: HYBRID QSU.

Rewritable sheet

For the purpose of reducing environmental impact of paper, we have adoption of recycled paper, improvement of usability/productivity of duplex/concentration function that effectively uses paper and further, direction toward alternatives of paper. As an example of the alternative, example of application in use of thermal rewritable technology will be explained.

Ricoh has developed IC tag sheet that installs IC tag onto the rewritable sheet in use of its unique thermal rewritable technology. Digital information recorded in the IC tag can be printed on the sheet by the exclusive printer. We assume utilization of the sheet in the process management in the factory and in the logistics management and consider worker’s visibility. Thus, we have developed A-4 size white sheet that is printed with high contrast black letter.

Thanks to the IC tag, utilization of digital management information is facilitated; and thanks to the rewritable sheet, worker can check by eyes the instruction contents in the IC tag. Such electronic management and checking by eyes are of great help to prevent human error in the production process in which workers intervene. As the sheet is rewritable 1,000 times, it contributes to a large reduction of paper. The user who utilizes the IC tag sheet as the shipping label anticipates about 80% CO_2 reduction as compared to paper.

3.3 Environmental impact reduction of the inputted resources

Direction of technical development

In order to reduce impact of inputted resources/parts in the upstream of the product lifecycle, there are various directions, such as compactness/lightness, reduction of inputted quantity by switching from single function product to composite product with more functions, switching to the materials with less environmental impact and reducing by promoting reusing.

Plant based plastic

Ricoh has introduced the copier that first installed the plant based plastic that draws attention recently as a low environmental impact material. Even if the plant based plastic is incinerated at the end of its useful life, CO_2 emitted is the one absorbed by photosynthesis in the course of the plant growth; therefore, theoretically the raw material does not increase CO_2 in the atmosphere. CO_2 emission from electricity use in the course of plastic production is 1250 Kg CO_2/ton, according to the LCA of poly-lactic acid, the base of the plastic developed this time [3]. It is less than half of general plastic.

While utilization of plant based plastic is studied by many companies, when considering installation into the copier, it was necessary to have a large improvement of physical properties such as shock resistance and flame resistance. In cooperation with plastic manufacturers, we have continuously improved the material and accumulated the know-how to mold the new material. As its result, we have succeeded in producing part from the new plastic material that has corn as raw material and has high combination ratio of plant based resin of 50% or more. In 2005, it has been adopted to a part of the main body of copier (Introduced in Japan). CO_2 emission in manufacturing the plastic parts combined with plant based plastic is anticipated to be reduced by 30%, as compared to the conventional plastic replaced.

Collection prediction

As the means to largely reduce new resource input, performance of the resource cyclic product is greatly expected, whereby used product is collected from the user, recovery treatment is implemented by exchanging/adjusting consumable parts and re-manufactured machine is inputted to the market again. In manufacturing the resource cyclic product, we need the used product collected from the user. In correspondence to the units collected, recovery plan/replacement part procurement plan/sale plan must be established. While Ricoh also implements recovery of copier, the timing of the end of use was up to the user; and appropriate prediction could not be made merely from the past data.

Then, in Japan, we have developed the technology to statistically predict the unit to be collected by extracting items useful for prediction such as employee scale or number of copies taken from the customer data of each copier and by analyzing/accumulating collection distribution for each item.

As the result, as shown in the Figure 7, collection quantity prediction can be made with almost no gap between prediction and actual performance. This technology is utilized since 2005. Because detailed collection prediction can be made, such as area, period (month, half term, full fiscal year) and number of copies for each model, we depend on the predicted values to establish highly efficient collection logistics/production plan of recovered machines.

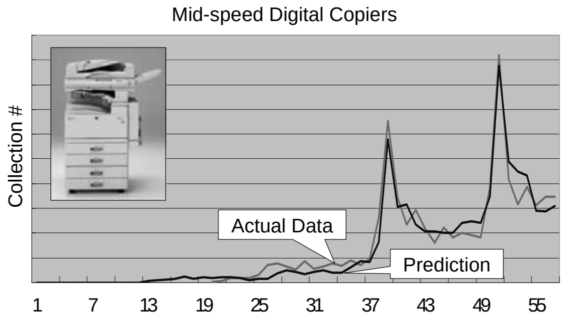

Figure 7: Prediction and performance of collection quantity.

Dry media cleaning

Ricoh's resource cyclic products also include toner cartridge for copier/laser printer. Flow of recovery treatment of toner cartridge includes disassembly, replacement of consumable part, assembly and inspection. As toner is attached inside of the cartridge, the toner has to be cleaned off the part after disassembly. The toner is attached to the plastic part by static electricity; therefore, mere air blow is not enough; and ultrasonic cleaning is done. This cleaning is the most time consuming process. By shortening this process, reduction of cost and environmental impact is expected.

Under the newly developed cleaning technology, the plastic sheets finely cut are rapidly blown up like confetti inside the device to be cleaned and wipe off the toner from the part. We call this device as "dry media cleaning". This "dry media cleaning" technology replaces the conventional ultrasonic cleaning process, resulting in large advantage such as largely shorter time, reduction of electric power in drying, unnecessary treatment of effluent of cleaning solution.

3.4 Result of reduction

In addition to the abovementioned environmental technology developments, in line with the environmental management, we are also conducting environmental impact reduction through improvement activities participated by everybody. They are the portion of the efforts concerning business sites shown in the Figure 1. Figure 8 shows the result of converting Ricoh Group's environmental impact reduced by two activities to the integrated environmental impact by EPS. Against the long term target to have the integrated environmental impact that is made 1 in 2000 reduced by 20% in 2010, 14% was reduced in 2003 and 22% in 2005. On the other hand, Ricoh Group's operating profit was 105 billion yen in 2000, 150 billion yen in 2003 and 152 billion yen in 2005. We are in the situation that the "sustainable environmental management" is realized, whereby environmental impact is reduced while earning profit.

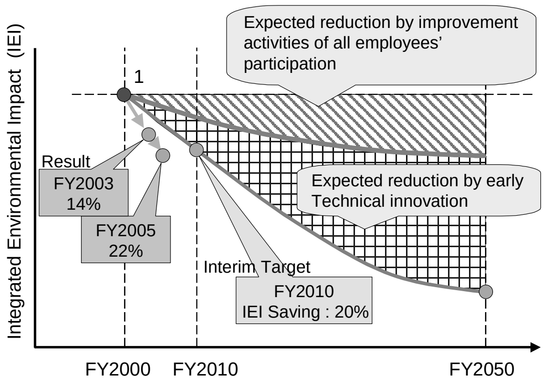

Figure 8: Reduction activity with a hard look at super long term.

4 CONCLUSIONS

I have shown environmental management that aims Ricoh's "Sustainable Environmental Management" and environmental technology that supports its realization. Summary of the concept will be as follow:

- Environmental technology development through the target setting with super long term viewpoint and integrated viewpoint over the product lifecycle.
- Reduction of integrated environmental impact in overall business activity through the environmental technology and improvement activity participated by everybody
- Promotion of environmental impact reduction by offering environmentally friendly product based on the environmental technology and by having more customers use such product.

As the result of promoting "Sustainable Environmental Management", we have won high evaluation, such as selection of 3 years in a low in 2005, 2006, and 2007 among the top 100 sustainable global corporations (Global 100) in the "World Economic Forum" (commonly called as Davos Meeting) held every year in Davos, Switzerland where executives of global corporation, prime ministers of countries, mass media and knowledgeable people gather.

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Module-Based Model Change Planning for Improving Reusability in Consideration of Customer Satisfaction

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Abstract
Enhancing reusability by extending a product's life and improving its functions by means of frequent model changes creates a contradictory issue in implementing reuse scenarios that reduce the environmental load in closed-loop manufacturing. This paper proposes a concept of module-based model change planning as a solution to this problem. In the paper, a method of identifying relationships between customer satisfaction and modules based on conjoint analysis and a QFD method is proposed first. Then a procedure for generating a module-based model change plan, which creates the minimum environmental load, is discussed. The proposed method is applied to copying machines as an illustrative example.

Keywords:
Model Change Planning, Module Reuse, Life Cycle Design

1 INTRODUCTION

To attain sustainable development, the manufacturing paradigm must be shifted from producing products efficiently to providing customer satisfaction using a minimum amount of production. Closed-loop manufacturing, which enables material circulation in terms of reuse and recycling, could be an effective means to achieve this goal [1]. In closed-loop manufacturing, the longer the life of a product model, the more effective reuse becomes. With many types of products, however, the product model is changed frequently because of changes in customer requirements and technological advancements. For implementing closed-loop manufacturing, it is necessary to resolve this contradiction.

To cope with this problem, we have proposed module-based model change, in which full model changes are not executed as in the ordinary model change strategy, but, instead, each module is improved at a different time, depending on the change in customer requirements [2].

In our previous paper, we proposed a method for identifying the relationship between customer satisfaction and modules, which is essential to realizing the change-planning concept. In this paper, we propose a procedure for generating a module-based model change plan, with which the environmental load is minimized while satisfying customer requirements.

In the following, the concept of module-based model change is described in chapter 2. The method for identifying the relationship between customer satisfactions and modules is summarized in chapter 3. Then, we discuss a procedure for module-based model change planning in chapter 4. The proposed procedure is applied to copying machines as an illustrative example.

2 CONCEPT OF MODULE-BASED MODEL CHANGE PLANNING

Modular design is widely adopted for various purposes such as manufacturability improvement and cost reduction by sharing the same modules among product families [3]. It is also effective for reuse, because it can improve disassemblability and increase demand for reclaimed modules if they are shared among a product family or product generations. For facilitating module reuse, it is effective to extend the period of production of each product, because demand for reclaimed modules can be secured longer and the marginal reuse rate can be increased as a result. However, extension of the production period impedes functional improvement of products, which is necessary for satisfying customer requirements. This means that there is a tradeoff between reusability and customer satisfaction.

As one possible solution to this issue, we have proposed module-based model changes, in which each module is improved at a different pace, depending on the change in customer requirements instead of executing a full product model change, as shown in Figure 1. If a module function is sensitive to the change of customer requirements, the model change of the module should be performed frequently. On the other hand, a module, whose function is insensitive to the change in the customer requirements, could be changed at longer intervals. In this way, we can strike a compromise between the reduction of the environmental load, which is enabled by the modules with longer model change intervals, and the satisfaction of customer requirements, which is made possible by the frequent model changes of the modules sensitive to the change in customer satisfaction.

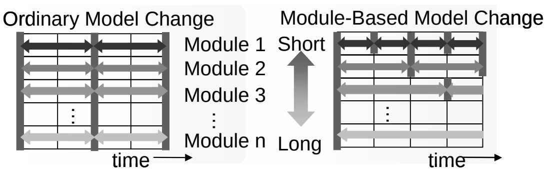


Figure 1: Concept of module-based model change.

3 IDENTIFICATION OF RELATIONSHIPS BETWEEN CUSTOMER SATISFACTION AND MODULES

3.1 Relationships between customer satisfaction and modules

If module-based model change is to be executed, the relations between product characteristics and module have to be identified. One difficulty we have to cope with here is the complexity of the relations between product characteristics and modules: there are no one-to-one correspondences among them.

We assume that customer satisfaction, CS, can be represented by satisfaction with product characteristics C_i, which correspond to major customer requirements, as shown in the upper part of Figure 2. These product characteristics do not correspond one-to-one with modules but, in contrast, are related to multiple modules, as shown in the lower part of Figure 2.

The identification of these relationships is performed in two steps. First, relationships between customer satisfaction and product characteristics are identified by means of conjoint analysis. Then, the relationships between product characteristics and modules are identified by using a QFD (Quality Function Deployment) methodology.

In the following, the methods are explained taking the example of copying machines. Regarding the product characteristics, the following 6 characteristics are selected in this study, considering items used in a survey on customer satisfaction with copying machines [4, 5]. They are image quality, power rate, noise level, warm-up time, usability, and paper jamming. With regard to modules, those which are regarded as basic to copying machines are selected. They are the scanning module, the image exposure module, the photoconductor dram module, the transfer and transport module, the fuser module, the delivery module, the paper feeding module, the driving module, the control module, the image development module, and the document-feeder module.

3.2 Identification of relationships between customer satisfaction and product characteristics by means of conjoint analysis

We assume that customer satisfaction, CS, and satisfaction with product characteristics, C_i, are evaluated in terms of utility, which expresses the degree of satisfaction numerically. Customer satisfaction with the product as a whole is represented by total utility U, and satisfaction with product characteristics is represented by part-worth utility u_i. The total utility is assumed to be calculated as the sum of part-worth utilities as shown in the following equation:

$$U = \sum_{i=1}^{m} u_i \ , \tag{1}$$

where m represents the number of characteristics. We also assume that the part-worth utility is determined by the value of the i-th product characteristic x_i with the coefficient of β_i.

$$u_i = \beta_i \cdot x_i \, . \tag{2}$$

To identify β_i, which represents the effects of changes in the product characteristics to the customer satisfaction, conjoint analysis is adopted. Conjoint analysis is widely used in the field of marketing research. It is effective to identify preferences of a group of customers with various needs [6], and it is used for estimating customer preference quantitatively by means of questionnaires. There are several methods for questioning user preference in conjoint analysis. In this study, pair-wise comparison is adopted because it is suitable when many characteristics are concerned. In pair-wise comparisons, the difference in the total utilities of two products which are different in two characteristics is evaluated in terms of the user preference grade. This grade is expressed as follows according to Equation (1):

$$\Delta U = U_L - U_R = \beta_a (x_{aL} - x_{aR}) + \beta_b (x_{bL} - x_{bR}) = -A. \tag{3}$$

Where as U_L and U_R denote the total utilities of the products presented to the respondent, ΔU expresses their difference, A expresses the user preference grade, and x_{aL}, x_{bL}, x_{aR}, and x_{bR} are the values of the two selected characteristics, C_a and C_b of the two products, L and R. For example, the case shown in Figure 3 gives the following equation:

$$\Delta U = \beta_{power} (2000 - 1000) + \beta_{noise} (60 - 70) = -1. \tag{4}$$

Questionnaires are filled out by 30 respondents, who use copying machines daily in their office. Each respondent compares ${}_6C_2$=15 combinations of products (6 corresponds to the number of copy machine characteristics used in this study). Equation (3) is formulated for each answer of the respondents. Then, β_i is calculated by means of multiple linear regression analysis. The results are shown in Figure 4, where the inclination of each line segment indicates β_i. In the figure, the inclination of warm-up time is negative, which is inconsistent with common sense. Since such a situation may occur when the value of the coefficient is small, the effect of warm-up time to customer satisfaction is omitted hereafter.

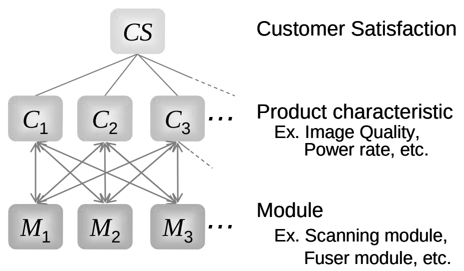


Figure 2: Relationships between customer satisfaction and modules.

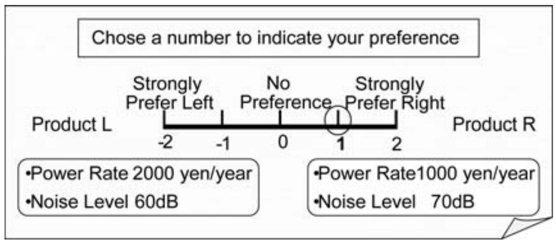


Figure 3: Sample conjoint analysis question.

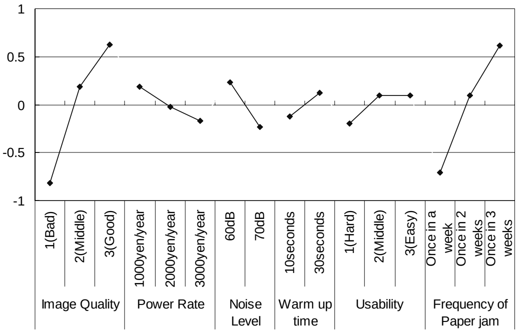


Figure 4: Part-worth utilities obtained by conjoint analysis.

3.3 Evaluation of relationships between characteristics and modules by means of QFD matrix

For evaluating the relationships between product characteristics and modules, a QFD matrix is used [7]. As pointed out already, there are no one-to-one correspondences between the product characteristics and the modules. In such a case, a single module cannot be assigned for improving a specific characteristic. A QFD matrix is suitable for identifying such complex relationships, and provides a guide for selecting candidates of modules to be changed. Before applying the QFD method, the characteristics C_i are further deployed into sub-characteristics C_{ik} to make the identification of the relationship between the characteristics and the modules easy. In the case of paper jamming, for example, the characteristic is subdivided into 3 sub-characteristics: frequency, ease of removal of jammed paper, and clearness of explanation of removal operations. As shown in Table 1, the strength of the relation of these sub-characteristics to the parent characteristics, h_{ik} is assigned in terms of 4 grades: 0, 1, 3, and 5. The strength of the relation between each pair of a sub-characteristic and a module, $f_{ikj,}$ is assigned also in terms of 4 grades, based on the opinions of a panel of experts. In terms of h_{ik} and f_{ikj}, the strength of the relations between modules and product sub-characteristics, α_{ikj} is represented in the following equation:

$$\alpha_{ikj} = \frac{h_{ik}\, f_{ikj}}{\sum_{k=1}^{l} h_{ik} \sum_{j=1}^{n} f_{ikj}}, \tag{5}$$

and the strength of the relations between j-th modules and i-th product characteristics, $\alpha_{ij,}$ is obtained in the following equation:

$$\alpha_{ij} = \sum_{k=1}^{l} \alpha_{ikj}\,. \tag{6}$$

Table 2 shows α_{ij} in the case of the copying machine.

4 METHODOLOGY OF MODULE-BASED MODEL CHANGE PLANNING

4.1 Outline of planning procedure

The purpose of module-based model change planning is to determine the model change timing of each module so as to maximize the reduction of environmental load by means of module reuse while satisfying customer requirements. The outline of the planning procedure is shown in Figure 5. This procedure is divided into two major steps. First, possible combinations of the model change timings of modules over a planning horizon are generated in order of the amount of reduction of environmental load, which can be achieved by module reuse. Then, the improvement of utilities realized by each plan is checked to determine whether it fulfils target values, which are set in advance. These steps are explained in 4.2 and 4.3, respectively, while an application example of the procedure to the copying machine is described in 4.4.

Table 1: Module weight as it relates to sub-characteristics.

			Strength of Relation: f_{ikj}												
Characteristic: C_i	Sub-characteristic: C_{ik}	Strength of Relation: h_{ik}	Scanning Module	Image Exposure Module	Photoconductor Dram Module	Transfer and Transport Module	Fuser Module	Delivery Module	Paper Feeding Module	Driving Module	Electric Equipment Module	Image Development Module	Document Feeder	Whole Product	total: Σf_{ikj}
Frequency of Paper Jam: $i=5$	Frequency of Paper Jam	5			3	3	3	5	1	5			3		23
	Easy to Remove Paper Jam	5			3	3	5	5	1	1			1	5	24
	Clearness of Explanation for Fixing Jammed Paper	3										5			5
	total: Σh_{ik}	13													
Weight of modules with the sub-characteristic: α_{ikj}					0.05	0.05	0.05	0.08	0.02	0.08			0.05		
					0.05	0.05	0.08	0.08	0.02	0.02			0.02	0.08	
												0.23			
Weight of modules with the characteristic: α_{ij}			0.00	0.00	0.10	0.10	0.13	0.16	0.03	0.10	0.00	0.23	0.07	0.08	

Table 2: Weight of modules with product characteristics: α_{ij}.

	Scanning Module	Image Exposure Module	Photoconductor Dram Module	Transfer and Transport Module	Fuser Module	Delivery Module	Paper Feeding Module	Driving Module	Electric Equipment Module	Image Development Module	Document Feeder	Whole of Product
Image Quality	0.08	0.08	0.22	0.13	0.08	0.00	0.00	0.00	0.29	0.13	0.00	0.00
Power Rates	0.01	0.06	0.00	0.00	0.49	0.00	0.08	0.02	0.23	0.11	0.00	0.00
Noise Level	0.07	0.11	0.07	0.07	0.16	0.07	0.08	0.07	0.13	0.12	0.07	0.00
Usability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.78	0.00	0.22	0.00
Frequency of Paper Jam	0.00	0.00	0.10	0.10	0.13	0.16	0.03	0.10	0.00	0.23	0.07	0.08

4.2 Generation of candidate combinations for module model change timings

The amount of the reduction of environmental load due to module reuse depends on the length of production period of each module model. Therefore, a module-base model change planner first generates possible combinations of production periods of module models, which are produced within a planning horizon. Let us consider a combination of production periods of models of the module M_j (j=1,...,n) covering the planning horizon of T years. This combination is denoted as

$$\Omega_{p\cdot j} = \{z_{j1}, z_{j2}, \cdots z_{jT}\} \quad \left(\sum_{y=1}^{T} z_{jy} y = T\right), \tag{7}$$

where z_{jy} indicates the number of models whose production period is y years. If $\Omega_{pj}=\{0,\ldots,0,1\}$, for example, no model change is executed for the module and the same model lasts for h years.

The total number of reused modules R_j, which are used for the production of the module throughout the planning horizon in the case of Ω_{pj}, can be calculated as follows:

$$R_j = \sum_{j=1}^{n}\sum_{y=1}^{T} r_{jy} \cdot z_{jy} \cdot y \cdot v, \tag{8}$$

where v is the average number of sales per year and r_{jy} is a ratio of reused modules used in the production of a particular module model whose production period is y years. For evaluating r_{jy}, life cycle simulation is adopted in this study. It can evaluate the amount of material flow of each phase of the product life cycle in closed-loop manufacturing, taking various factors into account, such as the term of guarantee of the product, collection volume of the discarded products, or the life span of the modules [8].

The amount of the reduction of environmental load due to module reuse in the case of Ω_{pj} can be calculated by multiplying R_j by L_j, where L_j represents the reduction of environmental load when one module is reused. L_j can be calculated by subtracting the environmental load for reusing the module from that for producing the module. Environmental load in each case is evaluated by means of the LCA (Life Cycle Assessment) technique. In this study, this load is evaluated in terms of emission of carbon.

The module-based model change planner first generates Ω_{pj} for each M_j in order of amount of reduction of environmental load. Then, by assigning the timing of model changes to Ω_{pj}, the possible model change plans of the product can be generated. The s-th model change plan Ω_s generated in this way is represented as follows:

$$\Omega_s = \{\Omega_{s\cdot 1}, \Omega_{s\cdot 2}, \cdots \Omega_{s\cdot n}\},$$
$$\Omega_{s\cdot j} = \{\delta_{s\cdot j1}, \delta_{s\cdot j2}, \cdots \delta_{s\cdot jT}\}, \tag{9}$$

where δ_{jt}=1 indicates that the model change of the module M_j is executed at the t-th year of the planning horizon, otherwise δ_{jt}=0. When generating Ω_s, the timing of model changes of the modules is to determine that they are distributed as uniformly as possible over the planning horizon in consideration of marketing strategy.

4.3 Checking the fulfilment of required improvements of utilities

In the latter half of the planning step, the improvements of the utilities achieved by the model change plan Ω_s are evaluated and compared with the requirements to see whether the plan satisfies them.

The effects of the module model changes, which are determined by the plan Ω_s, on the i-th product characteristics at t-th year of the planning horizon are represented in the following equation:

$$g_{it} = \sum_{j=1}^{n} \delta_{jt} \alpha_{ij}. \tag{10}$$

Figure 6 represents an example of the calculation of g_{it}. If all modules are changed, that is δ_{jt}=1 for all j, then g_{it}=1 according to the definition of the QFD matrix. Provided that the improvement of the product characteristics C_i in the case of ordinary model change, in which all modules are changed, is represented as ΔX_i, the improvement of the product characteristic at t-th year with the module-based model change is estimated as follows:

$$\Delta x_{it} = g_{it} \cdot \Delta X_i. \tag{11}$$

It is assumed that ΔX_i can be estimated from past experience. Then, the improvement of the part-worth utility due to the model change at the t-th year can be obtained using the coefficient β_i as follows:

$$u_i(t) = u_i(t-1) + \Delta x_{it} \beta_i. \tag{12}$$

Finally, the part-worth utilities corresponding to each product characteristics are checked to see if they satisfy the required value, u_{Gi} at each year during the planning horizon, as shown in Figure 7. u_{Gi} is estimated based on a survey of past products. If they could not fulfil the requirements, the next plan Ω_{s+1} is checked in the same way until a plan satisfying the requirements is obtained. In generating the next plan, the model change timing is changed first. Then, if the new timing is not successful, the combination of the production periods is changed as shown in Figure 5, because the change could increase environmental load.

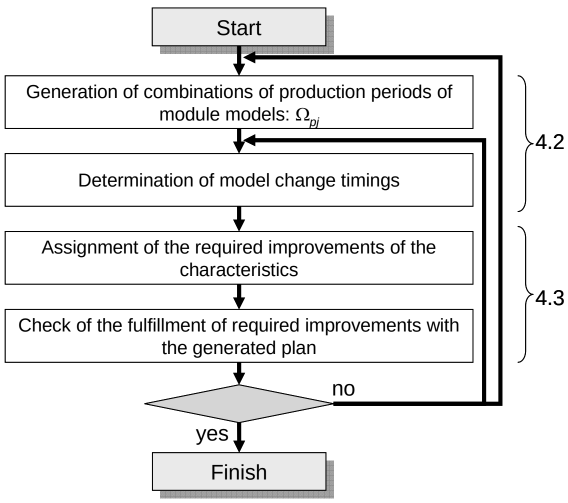


Figure 5: Procedure for module-based model change planning.

	M_1	M_2	M_3	
	1	0	1	$\leftarrow \delta_{jt}$
C_1	α_{11}	α_{21}	α_{31}	$g_{1t}=\alpha_{11}+\alpha_{31}$
C_2	α_{12}	α_{22}	α_{32}	$g_{2t}=\alpha_{12}+\alpha_{32}$

Figure 6: An example of the calculation of the effects of the model change of the modules on the improvement of the characteristics.

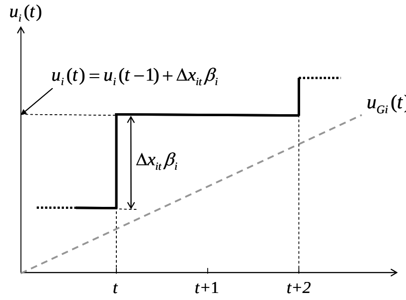


Figure 7: Check of the improvement of the utility against the requirement.

4.4 Application to copying machines

The above procedure was applied to the copying machine. The planning horizon is set to six years, in consideration of a long-term product planning horizon in the copy machine manufacture and the possibility of forecasting the technological trend. Since product characteristics such as image quality, usability, and paper jamming are so closely related to multiple modules that all associated modules must be changed to improve them significantly, the modules related to these characteristics are changed at least once within four years in the plan. Consequently, all modules are subjects to change within four years in this example.

To select the model change plan that can reduce the environmental load most, the reduction of environmental load when one module is reused, L_j, is evaluated for each module in terms of LCA. With regard to the inventory data for LCA, EcoLeaf data is used [9]. The EcoLeaf is a Type III category environmental labeling program in Japan. The results are shown in Table 3. It shows that reuse of the paper feeding module, document feeder module, scanning module, and electric module has a larger effect on the reduction of environmental load.

For evaluating a ratio of reused modules used in the module production r_{jy}, a life cycle simulation is executed. In the simulation, the models proposed based on the analysis of the actual data [10] are used for providing the amount of sales and collection of the products. The result is represented in Figure 8. The figure shows that the transfer and transport modules are not reused regardless of the production period y, and the rate for the fuser module remains at a low level because these modules do not have enough life for reuse. In the simulation, the remaining life of the collected module is examined to determine whether it is longer than the term of guarantee of the product. Since other modules have enough life for reuse, in contrast, their rates of the reused modules used in the production increase with the increase of the production period in the same manner as shown in the figure.

Based on the results shown in Table 3 and Figure 8, the effect of reuse of each module on environmental load for each possible combination of production period within the planning horizon can be calculated as shown in Table 4.

With regard to the required improvements of product characteristics, we have surveyed the improvements actually implemented in monochrome digital copying machines with medium to low copying speed from 1998 to 2004 and made an approximation with a linear function. Those for image quality, usability, and paper jamming are, however, determined by the experts due to lack of the data.

Table 3: Reduction of environmental load induced by reuse of one module.

M_j	L_j (kg-CO2)
Paper Feeding Module	77.0
Document Feeder Module	40.4
Scanning Module	38.5
Electric Equipment Module	23.1
Fuser Module	7.7
Image Exposure Module	5.8
Transfer and Transport Module	5.8
Driving Module	5.8
Photoconductor Dram Module	3.8
Image Development Module	1.9
Delivery Module	1.9

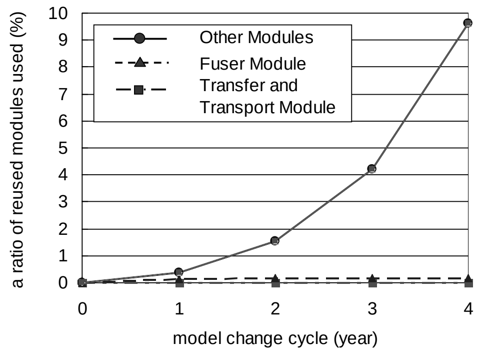
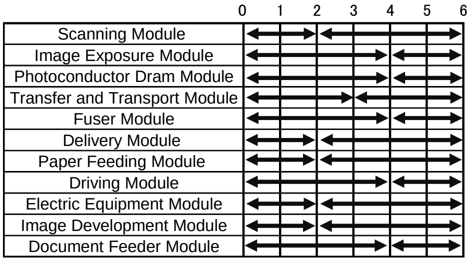


Figure 8: A ratio of reused modules used in the production against the production periods.

Table 4: The effect of reuse of each module on environmental load for each possible combination of production period.

	Model Change Pattern (kg-CO2)	Scanning Module	Image Exposure Module	Photoconductor Dram Module	Transfer and Transport Module	Fuser Module	Delivery Module	Paper Feeding Module	Driving Module	Electric Equipment Module	Image Development Module	Document Feeder Module
1	←———————→←———→	1599.2	239.9	159.9	0.0	8.4	80.0	3198.3	239.9	959.5	80.0	1679.1
2	←———————→↔↔	1504.8	225.7	150.5	0.0	8.0	75.2	3009.7	225.7	902.9	75.2	1580.1
3	←—————→←—————→	975.8	146.4	97.6	0.0	8.4	48.8	1951.7	146.4	585.5	48.8	1024.6
4	←—————→←———→↔	621.0	93.1	62.1	0.0	8.0	31.0	1241.9	93.1	372.6	31.0	652.0
5	←—————→↔↔↔	528.6	79.3	52.9	0.0	7.5	26.4	1057.3	79.3	317.2	26.4	555.1
6	←———→←———→←———→	359.2	53.9	35.9	0.0	8.0	18.0	718.5	53.9	215.5	18.0	377.2
7	←———→←———→↔↔	267.4	40.1	26.7	0.0	7.5	13.4	534.8	40.1	160.4	13.4	280.8
8	←———→↔↔↔↔	175.9	26.4	17.6	0.0	7.1	8.8	351.7	26.4	105.5	8.8	184.7
9	↔↔↔↔↔↔	84.7	12.7	8.5	0.0	6.7	4.2	169.4	12.7	50.8	4.2	88.9

Table 5: Proposed model change plan.



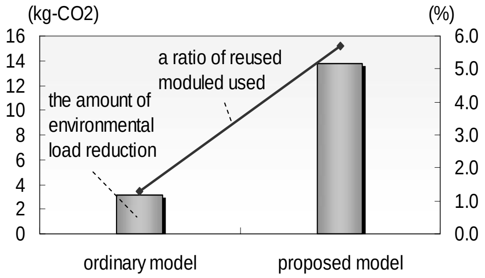


Figure 9: Effects of module-based model change plan compared with the ordinary model change.

By using Table 4, the plans, which provide the greatest reduction of environmental load, are generated. They are, then, checked so that we can judge whether they fulfill the requirements for the improvement of the product characteristics. An example of a module-based model change plan obtained in this way is shown in Table 5.

4.5 Discussion

To verify the effectiveness of the module-based model change plan, the plan shown in Table 5 is compared with a ordinary model change, in which a full model change is executed every two years, in terms of reduction of environmental load by module reuse. The result is shown in Figure 9, where the usage rates of reused modules are indicated as well as the amount of reduction of CO_2 emission. The figure shows the effectiveness of the module-based model change plan. However, the absolute value of CO_2 reduction is about 14kg per one product, which corresponds to about 2.5% of the total CO_2 emission during the life cycle of one copying machine. The relatively small effect results from the limitation of the production period of four years. Since about 61% of users of copying machines use them more than 4 years, the extension of production period from two to four years is not enough to increase the usage rate of a reused module, which increased only up to about 6% in this example, as shown in Figure 9. To solve this problem, we need to develop a modularization method, with which modules can be constructed that relate more directly to product characteristics.

With regard to the planning procedure, there could be many possible plans having the same effect in reduction of environmental load and fulfilling the requirement of improving product characteristics. It is necessary to introduce other criteria, such as cost, to prioritize the candidate plans in practical applications.

5 CONCLUSION

This paper proposes the concept of module-based model change planning for facilitating module reuse, which is effective in reducing environmental load while providing customer satisfaction in closed-loop manufacturing. In making the plan, the level of customer satisfaction is related to the module functions through the product characteristics by means of conjoint analysis and the QFD method. The model change timing of each module is determined so as to maximize the reduction of environmental load and to temporally distribute the model change of all modules as uniformly as possible.

The proposed planning procedure is applied to copying machines. The result verifies the effectiveness of the method. However, there are several issues that need to be studied further. Especially, we need to introduce other criteria to differentiate the plans generated by the planning procedure but which are not prioritized by the current criteria.

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Eco-Innovation: Product Design and Innovation for the Environment

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Abstract

The seriousness of environmental impacts of products and processes justifies the introduction of stricter regulations. This paper examines, through literature research initially, why eco-innovation is the approach industry should adopt and evaluates strategies through the lessons learned from a real case study. The paper, as a useful guide, is intended to motivate businesses to integrate eco-innovation into their product plans so that they not only reduce the environmental impacts of their products and processes, but also provide value to the customer.

Keywords:

Eco-Innovation; Strategies, Drivers and Barriers; Case Study

1 INTRODUCTION

During the last decade, research has been conducted such as that reported by Utterback [1] and Kemp [2] on eco-innovation. However, how efficient this is and to what extent companies really adopt this kind of thinking has not been fully analysed. This research was conducted in order to provide insight into the detrimental impacts of products and processes on the environment to justify the need for sustainable development and eco-efficiency and to encourage businesses to respond through eco-innovation. The primary objective is to identify the drivers and barriers which businesses are facing in their move towards sustainable development. The paper then focuses on a real case study from the engineering sector to validate the literature research findings with regards to opportunities and difficulties.

The pressures the world faces today are environmental, social and economic ones. The rapid development of technology and the abundance of cheap raw material have increased consumption, which in turn has increased waste generation. Approximately 306 million tonnes of municipal waste (food, garden waste, paper, cardboard etc) and 740 million tonnes of manufacturing waste are estimated to be collected in Europe each year [3]. The world population has also increased from 4.4 billion (1980) to 6.6 billion (2000) and it is expected to be 7.5 billion in 2020, which means the generation of even more waste [4]. The OECD actually estimates that by 2020 people could be generating 45% more waste than they did in 1995. The current technologies of waste management do not allow complete elimination of waste. It is vital that people change their consumption lifestyle in order to reduce the environmental impacts. On the other hand, companies often underestimate the real cost of waste. In addition to the increased taxes, hidden costs exist including the purchase cost of discarded raw materials, the value of any rejected product and the cost of discarded packaging as well as the other resources (energy, water, machines etc) used count for a great percentage of a company’s expenditure [5].

The over consumption of energy and materials is in turn the main cause of global warming. Industry and human activities, such as driving cars, have been blamed for greenhouse gases with related impacts, such as the temperature rise by 0.6ºC over the last 100 years. The worrying statistic though is that the mean temperature is projected to increase by 1.4-5.8ºC until 2100, unless we change our production and consumption customs. One way of convincing industry - and people in general - to change their practices has been legislation or other framework conventions. The most popular agreement type is the Kyoto Protocol that set targets for industrialised countries to reduce their greenhouse emissions by 5% by 2008-2012 compared to 1990, in order to achieve sustainable reductions [3]. However, instead of finding real solutions which reduce the environmental impact of their products or processes, EU businesses are actually spending their environmental budget on fighting regulation, which is the most un-sustainable solution [6].

It is generally accepted that industry is primarily responsible for the severe environmental impacts of its products and processes and governments are trying - through legislation - to motivate organisations to adopt a more environmentally friendly attitude. To be able to respond to the pressures identified above, businesses should move towards a more efficient management of natural resources and reduction of the material flows by incorporating the sustainability concept. To achieve that they need to integrate innovation in their strategy so as to satisfy the real market needs while being more in harmony with the environment.

2 SUSTAINABLE DEVELOPMENT

The world is facing severe environmental problems that affect people’s quality of life. There is an urgent need for governments and companies to collaborate and take a holistic approach. Most companies adopt “end of pipe” solutions, whereas they should be redesigning systems to satisfy customers and win the environmental bid for technologies that will last throughout time. Besides, human needs are becoming ever more intense for environmentally sound products and processes.

The sustainable development concept integrates environmental, social and economic policies to provide the products and services that people need while reducing their environmental impacts [7]. It is a vision of the future on which businesses invest at present. To start with they need to regard the whole business from a different perspective and by using relevant sustainability indicators which the organisations can evaluate to monitor achievement of their goals.

Sustainable development will help a better maintenance of resources, protect biodiversity and secure the standard living of future generations. It extends organisations' productive life and maintains corporate high performance. However, in order to grab the opportunities that arise from sustainable development businesses need to base their strategy on a more efficient and environmentally responsible use of the society's scarce resources – natural, human and economic.

3 ECO-EFFICIENCY

National and international legislation is used as a driver to promote environmental protection, but political pressures alone will not be able to establish sustainable development. Businesses should realise that ecological responsibility should be integrated into the business. That practically means evaluating their environmental performance with main objective to reduce their ecological impacts and increase productivity so as to gain competitive advantage, which is actually the main driver for eco-efficiency.

Eco-efficiency is a management strategy that links financial and environmental performance to create more value with less ecological impact. According to the World Business Council for Sustainable Development, eco-efficiency is reached by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life. At the same time, it stimulates productivity, increases competitiveness and progressively reduces ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity [8]. Eco-efficiency maximises value, while minimising resource use and adverse environmental impacts [7].

The principles of eco-efficiency are usually combined with the life-cycle thinking and translated into certain goals [9]:

- Minimise energy intensity
- Minimise toxic dispersion
- Minimise the material intensity of goods and services
- Maximise the use of renewable resources
- Extend product durability
- Increase processes efficiency
- Promote recycling

Businesses can change course towards sustainable development by promoting eco-efficiency via technological innovations, developing market demand for distinguishing environmental products and building green supply chain through strategic sourcing. Above and beyond, eco-efficiency means finding environmentally better and more cost effective solutions [10]; it represents moving from the traditional linear product life (manufacture, use and dispose) to a more cyclical one (manufacture, use, recycle, reuse). This way, not only the extraction of natural resources is reduced, but also the waste disposed to the environment [11]. Besides, efficient product design involves identifying how a product affects the environment during its life cycle (raw materials, manufacture, distribution, use and end-of-life) and then take action to limit these impacts through design [12]. Then eco-efficiency indicators can be used to measure the company's effectiveness and efficiency in the resources consumption, which proves that ecology and economics can go hand in hand, even for an upstream/primary producer.

Even though companies can achieve much by continuous improvement, it is more challenging to use change to meet better human needs and values. Eco-efficiency is not sufficient; it is just a short-range solution and businesses should move beyond this to achieve real sustainable development. Without technological change, eco-efficiency means only optimisation: reducing the use of resources and the amount of waste, which is not enough for long-term success. The world today needs innovation as a driver of maintaining natural resources, increasing economic competitiveness and ensuring human well-being.

4 ECO-INNOVATION

A leap in business performance is necessary to achieve long-term solutions and the effective design, development and use of better technologies can make this possible. Eco-Innovation is the future development strategy that companies adopt not only to develop new products and processes that provide customer and business value, but also to alter existing ones so that they are more in harmony with the environment [4]. Eco-Innovation is the implementation of radical ideas for environmentally friendly products and processes that will meet future needs. It involves organisational changes and any other changes in economic activities from a product or process design to its marketing strategy [13].

Proactive companies use eco-innovation to exploit further a market, while reactive ones develop incremental improvements to comply with the specific external demands [1]. Eco-Innovation in large organisations can be a driver for other smaller companies that are part of its network, to be sustainable and efficient. These companies have to comply with the first tier's environmental requirements. Therefore, big companies have the power to motivate Small/Medium Size Enterprises towards eco-innovation. An example of an eco-innovative product is presented in the case study discussed later in this paper.

4.1 Drivers

Amongst the main drivers that motivate business to move towards eco-innovation is the attempt to achieve sustainable development by strategies that lower production costs through improved quality and product function. Another factor is the interest in the share of the market value rather than the actual share of the market. Customers' power is more important than the power of the actual product. Additionally, by extending the transparency and the tools of corporate social responsibility to embrace the whole innovation process, including the research and development, technology selection, product and service design, investment and employment policies, business is increasing the shareholder value [4] [10], [12].

From the customer's point of view, green consumer organisations and other environmental organisations are drivers for environmental design. It is people's commitment and desire to fight for a better world that will bring the change. Increased pressures due to the waste disposal regulations as well as bans and taxes on certain materials act as eco-innovation drivers [14], [15].

Figure 1: Eco-Innovation driving forces.

The eco-innovation driving forces can be summarised under the technology push (eco-efficient technologies) and the market pull factors (preferences for environmentally friendly products or better image). This is called the push/pull effect and is illustrated in Figure 1 [16].

4.2 Benefits

Based on Kemp [2] and further literature research [11], [14], [17], [18] the main benefits of eco-innovation can be increased competitiveness and creation of new markets for environmentally desirable products. By being proactive they gain the potentials of market leadership and greater customer satisfaction. Furthermore, eco-innovation is expected to offset burdens and costs incurred by environmental regulations, as - on average - 80% of a product's overall cost is due to its design. Therefore, eco-innovative design offers great opportunities to companies to improve their financial and environmental performance. Eco-Innovation definitely improves a company's image as well as relations with suppliers, customers and authorities. Employees are also informed on environmental and health and safety issues, and more capable of dealing with them. Finally, it seems that eco-innovation has a positive effect on unemployment, due to the creation of new jobs.

4.3 Barriers

Due to the fact that eco-innovation is a whole different way of thinking there are potential obstacles that might slow down or even inhibit the process. First of all, lack of clear government policy framework for environmental goals and long-term targets; governments need to provide more incentives and new policies to promote sustainable development. Other economic barriers, such as the cost of research and development as well as marketing to convince people to accept the new product or process is usually high, making it more difficult, especially for small businesses, to invest. Furthermore, the environmental technologies for controlling pollution and improving environmental performance often cause high expenses to businesses and therefore minimising the potentials for competitiveness by cost leadership. Process inflexibility or inexistence of innovative technology can also inhibit eco-innovation [9], [10], [19].

On the other hand, other cultural and psychological issues, such as inertia as well as the security of well proven techniques and no or little environmental sensitivity hold eco-innovation back. Moreover demand is vital at certain points, as technology users have different needs at different times, as the time-to-market, the cost pressures and the risk involved can be eco-innovation inhibitors. Finally, infrastructure difficulties, such as reluctance to train or employ experienced engineers on environmental issues and a lack of communication between the departments can slow the eco-innovation process remarkably [2], [20].

4.4 Strategies

Facing all these environmental, social, economic pressures, the businesses need to respond. The main four approaches that companies could adopt are [21]:

- The indifferent strategy that the business pays no attention to the environmental issues and does nothing.
- The defensive strategy that the company takes a reactive approach and the environment is viewed as a threat, which can bring about minor alterations in products and processes.
- The offensive strategy is the one where the company regards the environment as an opportunity, in which case the research and development focuses on new product development.
- Finally, the innovation strategy that puts environmental research and development as a strategic activity to develop radical alternative solutions. The five key steps in the eco-innovation process are presented in Table 1.

	Eco-Innovation Steps
1	Set outrageous goals; think outside of the box, target the real market need to satisfy customers.
2	Whole-like thinking; a product/service that adds value and increases efficiency at the same time.
3	Dematerialise; regard businesses as solution providers rather than a product/service.
4	Make it fit; offer to customers what they really need, no more or less.
5	Restore rather than take; i.e. The Volvo car manufacturer introduced a new catalyst system that not only reduces the impact of the car's emissions on the environment, but also destroys some of the ozone created from other cars

Table 1: Eco-Innovation steps.

5 CASE STUDY

5.1 Market Background

Since 1975, according to the International Maritime Organisation in order to prevent pollution, naval ships are required to install onboard equipment to deal with bilge water. Bilge is the lowest point of a ship's inner hull, where the waste water and oil tends to collect in. This equipment is used to separate the oil, which is being collected in a different tank to the water which (if satisfies the allowable levels) can be discharged directly into the sea. The collected mixture of oils is stored until reaching the next shore, where waste management companies gather it and transfer it to treatment plants. Another option for the oily mixture is to be incinerated as a fuel on some naval ships if has a satisfactory low level of water (0-2%).

Traditional bilge water separation equipment (i.e. traditional gravity and tilted plate separation, centrifuges) could remove only a percentage of oil from the water, as a quite significant concentration is trapped in oil as oil/water emulsions. Although this was acceptable for many years, since the advent of the revised regulation of the International Maritime Organisation in 2003 [22], introducing an emulsified oil phase test, conventionally designed systems are not able to comply.

5.2 The New Eco-Innovative Filtration System

Flight Refuelling Limited (FRL) as a leading company within the greater Cobham Group, specifies on developing refuelling equipment in the Aerospace sector. Within FRL, the Fluid System Group is a world leader in the provision of systems, services and support for the storage, treatment, handling and distribution of specialist fluids in the global market. FRL, amongst others, manufactures filtration systems particularly for the navy. For more than 25 years FRL has successfully supplied naval and commercial ships with conventional filtration units based on pre-filter and coalescence cartridges, where strainers baskets remove the solids and the free water form the oil. Their main drawback is bad water quality, as with this method the emulsified water cannot be separated effectively.

Over a period of 5 years FRL have developed a new bilge water separation unit which significantly outperforms existing traditional equipment. This compact, high performance system has been developed to meet the stringent standards and controls imposed by Harbour and Maritime Authorities in the foreseeable future. The system meets the objectives of British Ministry of Defence requirements and anticipated Environmental Agency and international standards.

5.3 Eco-Innovative Concept

The unique design is based on the innovative cross flow micro- filtration technique. Instead of taking the oil out of the water (centrifuge technique, settlement etc), cross flow takes the water out of the oil. In this process the fluid to be filtered flows parallel to the filter area, rather than directly through it as shown in Figure 3. The membranes and the cross-flow feed and bleed used, result in lower pumping energy requirements compared to other separation systems (Figure 4). The main advantage of the new equipment is that it requires minimum man interference and even though the capital expenditure is higher comparing to other conventional methods, the running cost is lower leading to life cost savings.

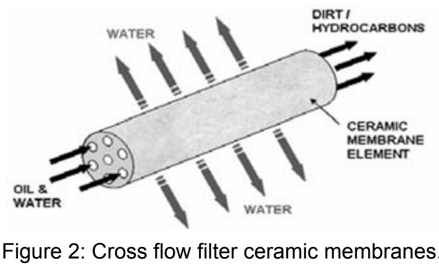

Figure 2: Cross flow filter ceramic membranes.

The separation cycle times are also smaller but not compromising on discharge quality, reducing the waste treatment time and increasing the plant's capacity. It should be however noted that in some cases relying on gravitational techniques to separate the oil and water or more complex oil / water emulsions can result in having the mixture to remain stable for weeks or even months. Another advantage is that the new oily water separator can be used not only to cover for its primary objective – to remove the water from the oil – but also to collect the free-of-water oil and sell it, for instance to heating companies, in order to make revenue instead of loss. At the moment customers are paying other companies to collect and treat the oil by-product.

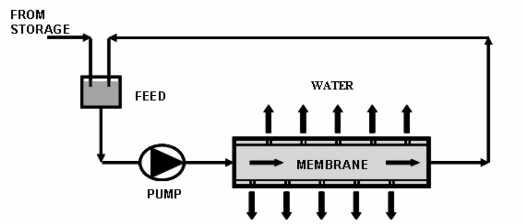

Figure 3: Detailed filtration process.

The new oily water separator that has been tested and certified by an approved third party risk management organisation that provides risk assessment and risk mitigation solutions and management system certification and found not only to be complaint with the essential Pollution prevention requirements for use on ships and offshore installations (water discharge less than 15ppm), but also to achieve as low as 2ppm of oil in the final discharge. It deals successfully with emulsions while other filtration systems fail.

5.4 Drivers

Regulation push - The main driver for FRL to focus on the development of this new product was legislation. The new legislation MEPC.107(49) regarding the ppm levels of oil in the sea water set by the International Maritime Organisation (IMO) were being discussed since the late 90s, but were only introduced in 2003 [22]. Therefore, FRL had enough time to plan its strategy towards the development of environmentally preferable alternatives before legislation would make it mandatory.

Technology push - The new product came out of the collaboration of two companies; one provided the new innovative design ceramic membranes which have been traditionally used for standard water applications and FRL developed the filtration technology. Moreover, manufacturing the same type of filtration system for over 25 years forced FRL to consider alternative products and markets. Being at the mature stage of a products' lifecycle is the right time to plan for other opportunities.

Market pull - Another driver was the fact that FRL wanted to create a more user friendly product. Taking into account that these filtration systems target ships (military and commercial), which is a rather difficult environment to work, a new improved product that requires minimum interference in order to set it to work and run, would definitely improve customer satisfaction. The increasing demand for environmentally friendly products coming from certain markets, such as government controlled groups, was another driver.

Overall, the drivers highlighted in this case study were identified in the literature review. It seems that regulation is the major motivator that drives change, while customer requirements actually give shape to the business strategy. Moreover good market research is essential to identify the opportunities available in the market and provide solutions that would be embraced by the customers.

5.5 Benefits

Strategic - The primary benefit, according to FRL, is the fact that this equipment currently is the only one of its design that reliably meets the environmental regulations. This means that FRL could expand into a new business area and gain a competitive advantage, by being the first in the market and the first to satisfy the customer, which in turn means more customers, sales and revenue, as highlighted in literature research as well. If FRL had not invented a new product able to meet the stricter legislation, its sales would have been significantly lower. Since every new build ship would require an advanced oily-water separation system, it would only be able to supply the older ships with the cartridge equipment.

Economic - Economic support provided by governmental agencies due to the environmentally friendly nature of the product. The extended lifecycle (approximately 5 years, compared to the 6 months of cartridges) and the reduced running cost comparing to other separation systems attracts more customers. What is also interesting is the fact that the new bilge water separator produces no waste at all, compared to the conventional systems that require the disposal of cartridges or other bio-chemicals, re-agents used to separate emulsions.

Environmental - Even from the manufacturing point of view, the new product requires less harmful materials (i.e. resins, insulators, cartridges), which reduces the environmental impacts and enhances sustainable development. Additionally, as highlighted in literature, the employees became educated on environmentally related issues due to the research on environmental legislation preceding the actual built and promotion of the new product.

Internal - The technological developments and the enhanced company's knowledge contributed to increased company value and built a good reputation amongst shareholders. It is interesting that having such a successful and innovative product made the FRL employees proud of their company, a benefit that has not been discussed in literature research.

External - The reaction is similar on the customers' point of view since their perception towards the company's environmental values and its products has changed. FRL supplied them with a product of significantly improved quality and extended life cycle, fact that led to enhanced product and company value.

5.6 Barriers

The main barriers that slowed down the FRL eco-innovation strategy are summarized under five main categories below.

Economic - One of the main inhibitors was the research and development investment. It seemed to be quite difficult convincing the business to invest in a new eco-innovative product, especially when other quite successful products exist at the same time. It was difficult to make the decision when it was the right time to look for other markets. From the customer's point of view, another barrier was the higher capital expenditure. But what customers have to bear in mind is the continued life cost savings that they can achieve with the new filtration unit as it produces no waste and has low maintenance and spares requirements.

Infrastructure – A barrier that has not been discussed in literature is the fact that manufacturing fluid systems is not the core business activity of FRL (as its main activity is aerospace manufacturing); therefore it was difficult to convince the rest of the business to invest in this area. Additionally, the higher cost of the equipment due to the quite advanced technology slowed down the development process.

Regulations - Lack of specific legislation can be another inhibitor. Even though environmental products are highly desirable as people become environmentally conscious, the majority of them are not willing to spend on equipment that they are not obliged to use. In this case study it was shown that no one wanted to get the new filtration unit until they actually had to do so by law.

Demand - One common barrier is customers' uncertainty initially to invest on new equipment, not being proven in real world. Customers often hesitate to be the first to try a new piece of equipment and this was true for the filtration system, until it was proven that it can achieve what it was advertised to do.

Resources/Strategy - Lack of resources to look for new markets and promote the product later to more customers can be an inhibitor for every new product. This is even more obvious in eco-innovative products since they require double effort and time to convince customers; generally, lack of marketing strategy to increase customers' awareness, which was not identified in the literature research.

5.7 Lessons Learned

Overall, FRL seems to have followed the main steps to eco-innovation presented by Arundel [21] by:

- Stating the real market need in simple terms "an on board ship filtration system to clean the water from the oil, so that the water can be discharged directly into the sea instead of being kept in the bilge".
- Increasing the efficiency by reducing the running costs of the unit, while at the same time adding value, by giving the customer the opportunity to make profit by selling the previously regarded as waste oil by-product.
- Making it fit, listening carefully to the customer and capturing their specific requirements in an ever man-power reducing environment.

FRL has increased its environmental responsibility and by adopting an innovative strategy - through eco-innovation - managed not only to comply with regulations but also to gain competitive advantage, by being one of the first in the market place to offer a reliable solution.

6 CONCLUSIONS AND RECOMMENDATIONS

In the past, the environment was seen as cost burden and a responsibility for environmental departments, whereas today it is increasingly seen as an element of quality, a source of savings, a potential source of competitive advantage, and part of the social contract with society necessary for the continuity of the company. Eco-Innovation through sustainable design contributes to the economic and environmental aspects of sustainable development. Eco-Innovation can help businesses meet the environmental challenge and not only avoid the process capability impact but also enhance it.

The eco-innovation benefits, as well as the main drivers and barriers, were identified and assessed through literature review and then validated via a case study. It is encouraging that most of the drivers, barriers and benefits identified in the literature research appear in the case study. Eco-innovative products can enhance corporate social responsibility, innovation and competitiveness more than the filtering on smoke stacks or lowering the office lights. This in turn ignites the enthusiasm and commitment of the public, the media, employees and investors to do more for the environment. There is a great opportunity for businesses to establish themselves as environmental leaders rather than defensive polluters. Of course, to incorporate eco-innovation in the organisation, a whole change of companies' attitudes is needed. Companies should give enough time to allow employees to familiarise themselves with the new values and assimilate the knowledge provided through training. On the other hand, governments should motivate companies by focusing more on funding research to address eco issues. Technological breakthroughs are actually a pressing necessity for step changes in eco-friendliness allied to incremental improvements in energy and waste management.

The filtration case study highlighted that business should invest in knowledge, skills and technologies to create eco-efficient products and services. Amongst the major benefits of eco-innovation were legislation compliance, efficiency, business growth, reduced environmental impacts and increased profits. The industry needs great breakthroughs to deal with the environmental, economical and social pressures. In order to achieve eco-innovation, businesses should form a long-term strategy and set the relevant goals as well as the measurements to control their performance. The case study evaluates the literatures conclusion that companies need an Innovative Strategy to help them keep themselves profitable and in the market for the years to come.

The case study examined was from a large well established organisation that understands eco-innovation thoroughly. The next step is to use a questionnaire to understand why some businesses are un-willing to eco-innovate even though they have understood the opportunities hiding behind this strategy. After all, the non participants are also stakeholders in the drive for producing innovative products and processes in harmony with the environment. The survey's objective will be to examine the potential barriers that inhibit companies from eco-innovating and then work on eliminating them by providing practical business solutions.

7 ACKNOWLEDGMENTS

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Towards the Use of LCA During the Early Design Phase to Define EoL Scenarios

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Abstract

In order to identify and bring answers to the problematic of sustainable development posed to the industrials, we develop a methodology aiming at designing sustainable products, which we define as clean and recoverable. In order to help designers to integrate the environmental criteria in the decision making process which will lead to the choice of a design alternative, they need to have access to robust indicators based on environmental assessment of the product and its associated end-of-life scenario. In this article we propose in a first part to model the product as an assembly of components lifecycles in order to build pertinent indicators for designers. Then we develop the concept of “lifecycle bricks” which permits to easily build the products life over many usage cycles, and thus allow on one hand to measure the benefits or loss of one strategy, and on the other hand to gradually focus until the environmental hot spots of the products have been revealed.

Keywords:

Life Cycle Assessment, End of life strategies, Product and lifecycle model building, Product Design

1 INTRODUCTION

Designing sustainable products and processes has become, or will become a major task for product developers. The problem is that designers already have to deal with a dense raft of constraints. Everyone knows that the design process is not a sequential process anymore but a complex task mobilizing multiple competences. The complexity of the decision making process is thus highly increase, and so the designers task. Indeed, in a concurrent engineering universe, the designers’ mission is to integrate very soon different prerogatives from various fields of competences. Adding the environmental constraint to this multicriteria decision process is hence not obvious [1]. Actors are seldom environmental experts and don't have the time and resources to take a deep look into the environmental matter. Therefore, methods or tools have to be integrated and easy to handle to overcome the lack of knowledge of designers, but also robust to guaranty the quality of the results: the objective is to make the environmental criteria a vector for the development of smarter design alternatives.

Methodologies and tools have been developed in order to make the integration of the environment feasible, responding to the more and more demanding EU regulations such as WEEE, RoHS, ELV or EuP. These lasts emphasize on the necessity to design products that will be taken back at their end-of-life and treated to minimize their environmental impact. Designers are thus in the heart of the overall industrial changes: they are responsible of developing products that are clean and will fit the end-of-life (EoL) process. In order to handle this, they have access to different methods that we classify here in two categories [2]:

- Bottom-up methods: these methods are based on quantitative assessment of the product, but generally require that the whole information on the product is available (LCA)
- Top-Down methods: these methods are based on experience or expertise and mainly give key success factor (Guidelines, DFE...)

The major problem of bottom-up methods is that they can only be performed after the product is fully developed and therefore will only enable corrective actions. Top-down methodologies make it possible to integrate environmental thinking very soon, but independently from the product in development. Thus, a gap needs to be fulfilled by developing a method which allows taking decision related to the design of products but driven by an environmental justification: scientific environmental indicators need to be built in order to make the designers choices robust.

Our proposition is to develop a new way of modelling products in LCA in order to make the environmental information available early during the design phase by going down at the component level and assuming the lack of information does not hamper the evaluation. In a second part, we insist on the fact that the EoL has also to be considered during the design phase, and therefore new entities have to be developed in order to give the designers the ability to compare design alternatives comprising EoL strategies.

2 BUILDING ENVIRONMENTAL INDICATORS FOR DESIGN

The Life Cycle Assessment method is today the only method available to assess an environmental impact. The paradox of LCA enounced by Lagerstedt [3], i.e. the fact that a LCA can only be performed when full information on the product is available but thereby when no action is possible on the product itself, can be solved by the use of Streamlined LCA (SLCA). A SLCA enables the environmental assessment of product by reducing the assessment to some impacts for example, or by investigating only one single phase of the products lifecycle.

2.1 SLCA as an answer to the lack of information

As a part of the answer to the problem we propose to solve here, the use of Life Cycle Assessment is necessary. We will thus use SLCA to permit the building of indicators that are needed by designers. However, we will not focus on one single impact category or on a lifecycle phase, but we assume that the lack of information on the products lifecycle is not preventing from the evaluation, as we will always compare two design alternatives, and thus will focus on the difference between these two. So in our LCA, the entire lifecycle is taken into account, even if data are missing. This means we will compare what is comparable: if there is a lack of data in one alternative, the comparison cannot be made on that element, but the calculation still can be processed. As the design process go further and the knowledge on the products lifecycle increase, the quality of the environmental evaluation will also increase.

2.2 Going down at the component level

The LCA methodology allows the production of environmental quantitative indicators [4]. However, the classical use of LCA is not adapted to the designers' task as demonstrated in a former publication [5]. Therefore, the model has to be revised to adapt the LCA to the design activity: the product has to be considered as an assembly of components. Moreover, if the End-of-Life scenario is often associated to the product as a whole, in order to develop products that are recoverable, designers have to design the components in a certain way. Thus, it is the EoL scenario of components that needs to be taken into account. Our research has proved on one example that the recovery strategies do permit environmental benefits at the condition that components are designed taken this into account. All these considerations have driven us to propose a way to model products in a LCA software as an assembly of components lifecycle.

2.3 Illustration on a case study

In order to highlight the needs and characteristics of environmental indicators for designers, we have studied on an example the data that could be obtained from a classical LCA compared to a LCA performed with a product modelled as an assembly of components lifecycles. We have firstly verified that we obtain the same quantitative results with the two models to justify the validity of the approach. We briefly present the product used for the model here, and then show some results and highlight the advantages of the approach by components.

Introduction with an example

In order to illustrate our research we use a simple product: a connecting hub. It comes from a case study from students from DTU Copenhagen. It is not a EuP, but this is not essential as an introduction to the component-based approach. We have modelled a lifecycle based on the information we owned. This product enables the transmission of current and data for a period of five years, twenty-four hours a day. It consists of seven components and a packaging. It is manufactured in Leeds (UK) assembled in France, and then distributed in the capitals all over Europe. Different EoL scenarios have been determined for the product and also components, comprising reverse logistics, disassembly and remanufacturing, or end-of-pipe strategies. We have then had the possibility to create design alternatives: we focused on improving the recovery of the added value of components: the objective was to compare the performance of different EoL scenarios.

Suitable Results for designers

A classical LCA give results in terms of a score for a certain phase of the lifecycle. This result can be obtained for a lifecycle phase or for the total product. This is mandatory to be able to target the hot spots of the products lifecycle regarding environmental matter. However, we believe in a design context, it is possible to get such result much quicker with a qualitative method like the MECO matrix for example [4]. Moreover, designers manipulate components, and we have shown that, if willing to design for recycling, remanufacturing or reuse, the designer has to get a feedback on the components performance relating to a given EoL scenario. The classical LCA does not enable such results.

With the model we propose, the designers are able to have relevant information concerning two different design alternatives:

- The environmental performance of the whole product throughout its lifecycle.
- Impacts of the different lifecycle phase.
- Impacts of all the different components separately considered throughout their lifecycles.
- Impact of the components for a given phase.

The difference of score between the two alternatives will allow the building of pertinent indicators weighting in favour of a design or another. On the figure 2 (see next page) we can observe results of the computing of the SLCA with Simapro6. The different columns represent the impacts (Single Score) of components lifecycles or processes that are imputed to the product (Distribution, Reverse Logistic…). (All LCA results emanate from the connecting hub case study, see figure1)

On the figure 3 (see next page), the process tree shows that it is possible to put in parallel the components lifecycle to visualize the more impacting. This is an example of the results the designer can obtain while just having few information on the future product and its associated supply chain, generally known from former generation of product. By getting such results, he is enable to target the products phase or components that impact the most. Then he can focus for example on one component in order to redesign it or to change parameters such as the materials used or the EoL scenario envisaged.

2.4 Conclusion

Utilizing the information that he possessed at the conceptual phase and by modelling the product by components lifecycle in a LCA software tool, the designer is able to get indicators to measure the environmental performance of a design alternative. The interest lays in the fact that, by modelling the product as an assembly of components lifecycle, he can observe the components performance according to the design changes he made. These changes can concern the design itself as well as the end-of-life scenario.

Figure1: Connecting hub, Steelcase

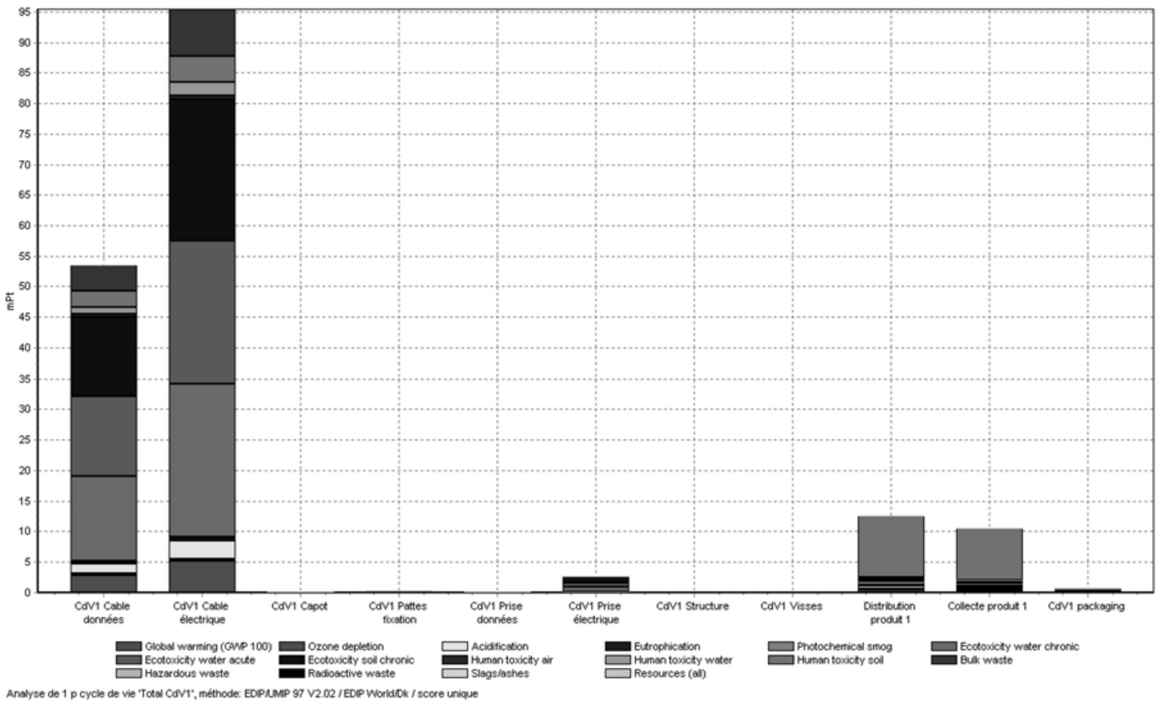

Figure 2: Impact of Components lifecycle and products level phases (Simapro6).

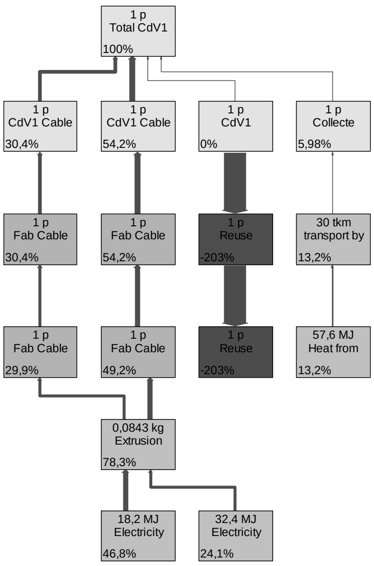

Figure 3: Process tree of a model by components.

3 MODELLING EOL STRATEGIES IN LCA

As introduced at the beginning of the article, in order to reduce the environmental load of a product, the processes of Reuse, Remanufacture and Recycle (3R) are perhaps the more promising, as they allow environmental and economical benefits [6]. For this last reason, they will inevitably seduce industrials. If recovery strategies imply many changes in the supply chain, they are also dependent of if the product itself that is in the heart of the system: it has to be designed for being collected, disassembled and finally treated before being put back in the normal chain. Besides the fact that the designer will have to design the components of the product to be remanufacturable for example, he also needs to ensure quickly that remanufacturing a certain component is the best environmental solution. The problem now is to be able to efficiently model EoL scenarios, and consequently to multiply lifecycle in the LCA model while still getting pertinent indicators.

3.1 Revisiting the lifecycle representation

The products lifecycle is classically represent as a series of phase, namely and to make it simple: Material extraction, Manufacturing & assembly, Use and End-of-life. However, the designers work on components, and not on the product as a whole. Hence we propose to highlight different levels in the products lifecycle: the product level and the component level (End-of-pipe strategies such as incineration or landfill are either available for products or components). The figure 4 (see next page) shows the new representation we make of the products lifecycle. End-of-pipe strategies can be applied to the product and components, but in the former section we have shown that recovery strategies are only imputer to the components lifecycle. Thus, when developing the product, designers have to determine an EoL scenario for each component, as components do not have the same ability to be recovered at their end-of-life. Hence recovery strategies are defined at a component level in the figure 4.

3.2 3R implies modelling several lifecycles

As soon as the product is at its end of usage, it might be remanufactured and some of its components will be reused many lifecycles as some others have only one usage cycle.

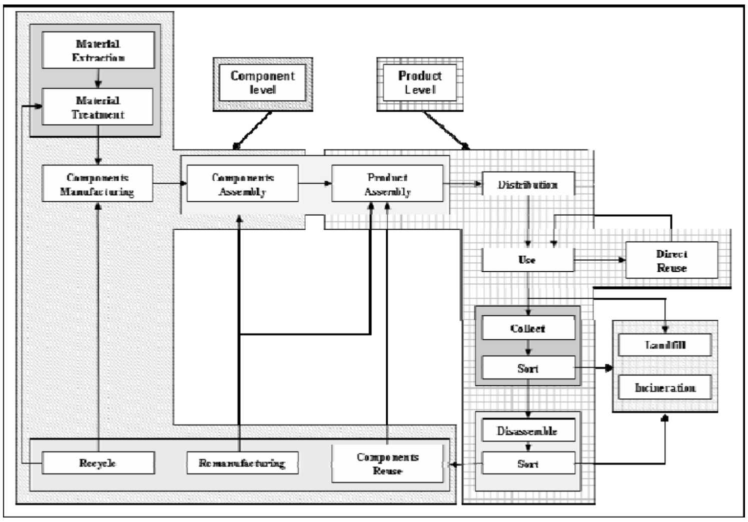

Figure 4: Representation of a lifecycle with the products level and components level.

Therefore, in order to measure the products performances, we have to compare the different alternatives taking into account many usage cycles. In a classical lifecycle, the performer knows exactly the system that is studied and usually can investigate some unlit points. During the design, not much information is available and strong assumptions have to be made, also because of the lack of 3R processes existing in the LCA databases. We have demonstrated it is worth the effort though. Indeed, formulating strong assumptions (such as considering the distribution channel as the same as the collect channel) guaranty a strong veracity in the conclusion that a recovery strategy can still be better than an end-of-pipe one. We also observed that the difference of environmental score increases between an end-of-pipe strategy and a recovery strategy when taking into account many usage cycles. The ability to manipulate the components and their EoL can only be made possible through the use of new entities which we call lifecycle bricks.

3.3 The lifecycle bricks and illustration

Concept and modelling method

A lifecycle brick represents one lifecycle phase of a component: it becomes the object that is handled for the modelling of the product during the design process. Using the former example to illustrate our theory, we propose in Figure 5 to represent the lifecycle of the product throughout two

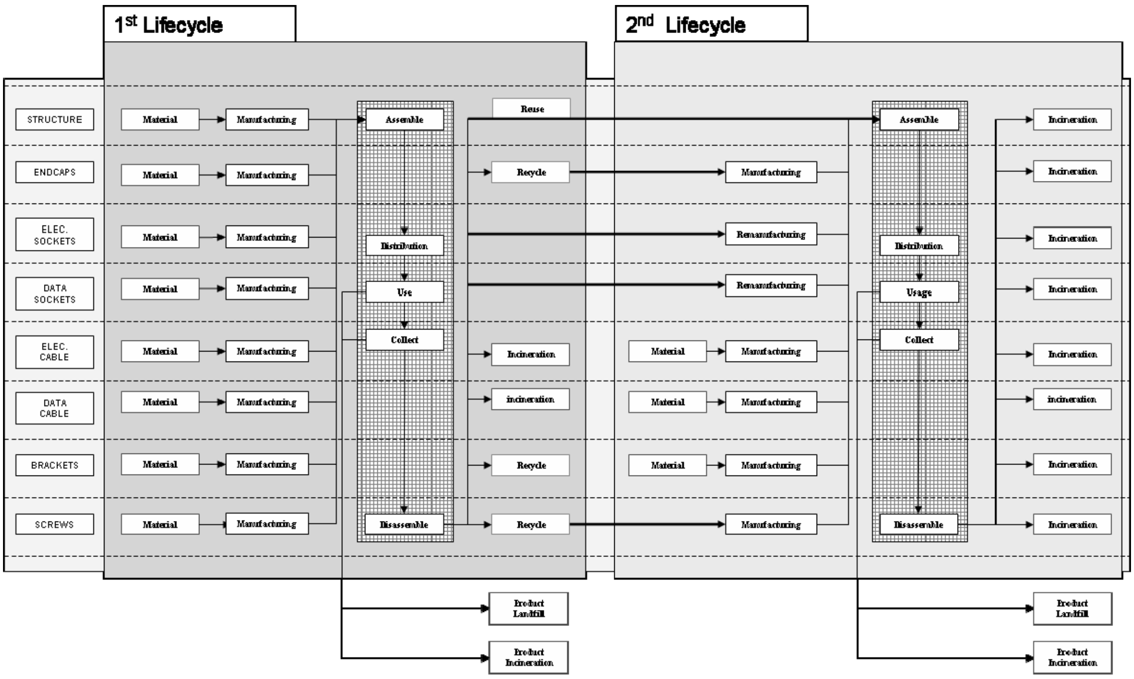

Figure 5: Modelling the product with lifecycle bricks for the consideration of EoL.

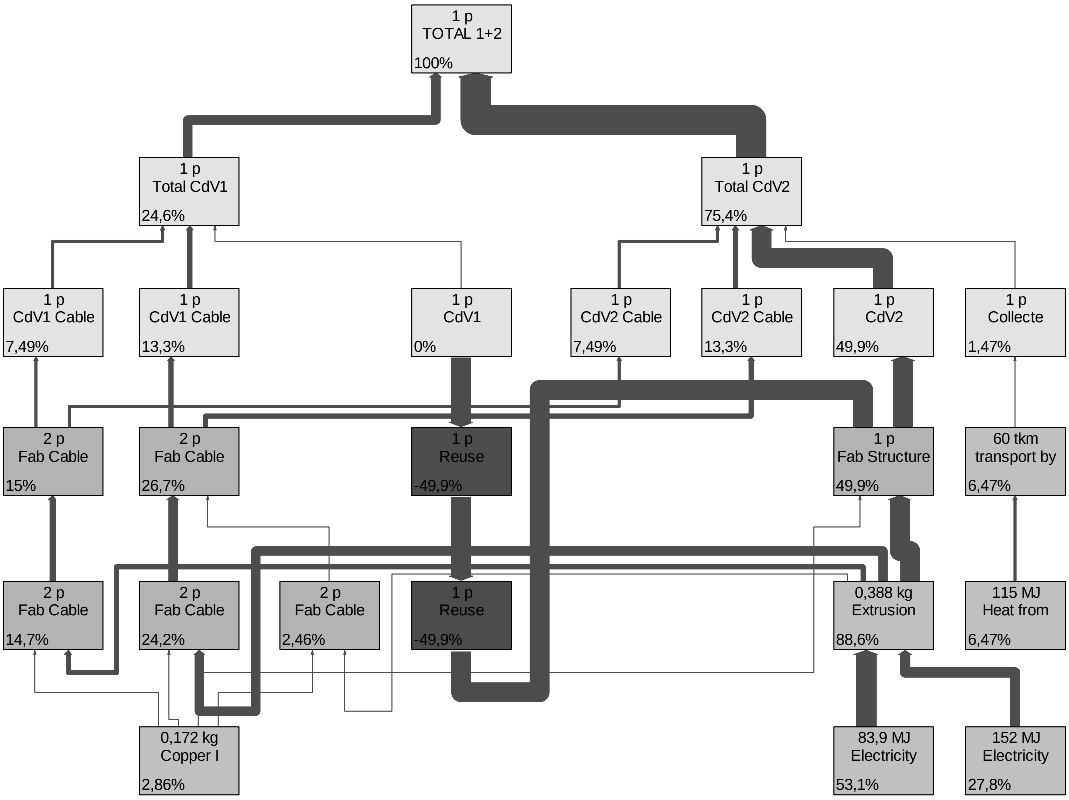

Figure 6: Process tree of two use cycle of a product having some components remanufactured or reused.

usage cycles as some components can be reused or remanufactured one time.

Implementing the model in Simapro6, we first model each lifecycle phase for each component: this is the components level. Then we aggregate the ad hoc data in order to create components lifecycle. The components lifecycle are also aggregated in a product lifecycle, in which we add the processes that are attributed to the products level. It is possible next to create other products lifecycle by aggregating different bricks, and finally to create a scenario that is the sum of products lifecycle. Thanks to this modelling, it is then very simple to develop design alternatives by modifying some attributes of the bricks: materials, processes, transport, distance etc. Moreover, the most interesting results are to measure the potentiality of environmental benefits through the implementation of recovery strategies by easily multiplying the number of usage cycles that are modelled.

In the implementation whose results we present here, we have modelled two usage cycles. In one alternative, the product is incinerated at its end-of-life, or disassembled for the recycling of certain parts. In the other design alternative (Figure 5), the product is collected and components are either incinerated, recycled for the manufacturing of other products or the same components, remanufactured or reused. The recovery strategies only happen once in this example. With the lifecycle bricks, it is however very simple to compare lifecycles with recovery strategies that happens N times with N reference lifecycles.

Results

By looking at the results obtained with Simapro6, it is obviously much easier to target more impacting bricks of the total picture, by analysing bit by bit the different level of aggregation. We show in figure 6 the process tree in relation with the model represented in Figure 5. We can observe the two products lifecycles composed of the different components lifecycles, whose relative contribution to the total are over the 2% threshold. We observe that negative impacts due to the remanufacturing reduce the environmental load of the manufacturing of the same part in the second lifecycle. For each one of the two products lifecycles, we identify the components that impact the most, and also precisely which phases contribute the more to the impact. The designer has then the possibility to progressively zoom into the model and focus on the environmental hot spots, to finally identify the lifecycle bricks that may need to be reworked.

3.4 Conclusion

Designers need to be able to easily model recovery strategies and to obtain quick results related to the design alternatives they envisaged. Thanks to the concept of bricks, they are able to easily manipulate the future life of the product and to measure benefits or loss. Compared to classical LCA or even SLCA, this modelling method permits to act efficiently during the early design phase and to model many usage cycles.

4 CONCLUSION AND PERSPECTIVE

In this article, we outline the fact that designers are in lack of methodologies to efficiently integrate the environmental criteria during the early design phases, namely the conceptual design phase: information on the product and its lifecycle are at that time lacunars. We demonstrate though that, by using LCA software anyway but modelling the product as an assembly of components lifecycles, it is possible to obtain intelligible environmental data very soon and to target the hot spots relative to the environment.

Taking into consideration the more and more demanding regulations, we believe the recovery strategies will take a growing place in the industrial strategies, and therefore, again designers will have to deal with product whose components might be reused, remanufactured or recycled to be used a second time, or more. In order to enable the quick building and assessment of products throughout many lifecycles, we have developed the concept of lifecycle brick. This entity is also easy to manipulate and let designers the ability to assess very quickly design alternatives.

The perspective of this research is to implement these bricks in a design tool that supports the functional product model.

5 ACKNOWLEDGEMENTS

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Development of Description Support System for Life Cycle Scenario

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Abstract
This paper proposes a method for describing product life cycle scenario and a description support system for the life cycle scenario. Our idea is that a designer can determine the life cycle strategy easily by describing the life cycle scenario at the early stage of life cycle design. We define a representational scheme of the life cycle scenario and develop the support system by using the idea of the design rationale. As a result, it is clarified that the life cycle scenario is successfully represented on a computer and a designer can easily determine the life cycle strategy by using this system.

Keywords:
life cycle scenario, life cycle design, life cycle strategy, design rationale

1 INTRODUCTION

Recently in order to solve the global environmental issues, we should construct stable circular product life cycle systems for minimizing environmental impacts. For this purpose, life cycle design plays a crucial role; especially, it is necessary to determine life cycle strategies at the early stage of life cycle design. For supporting this stage, we propose to employ product life cycle scenario. Our idea is that a designer can determine the life cycle strategy easily by describing the life cycle scenario. Here, the life cycle strategy is a combination of life cycle options of a product and its components (e.g., maintenance, product reuse, component reuse, and recycling) and the life cycle scenario is a description of expected product life cycle. In other words, by describing a life cycle scenario, a designer can easily find out appropriate life cycle options and requirements for product design. Many kinds of life cycle design support tools have been proposed; examples include life cycle planner [1], life cycle option selection support tool [2] (e.g., Disposal Cause Analysis Matrix [3]), life cycle assessment [4] and life cycle simulation [5]. However, the computational representation of the life cycle scenario has not been formalized yet and, therefore, no computational support tool for describing the life cycle scenario has been developed.

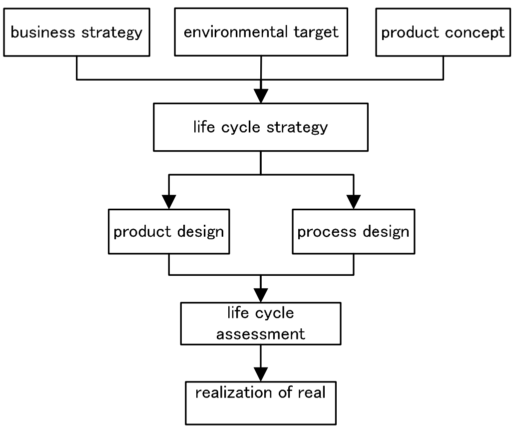


Figure 1: life cycle strategy in life cycle design.

The objective of this study is to formalize representation of life cycle scenario and its description process and to develop a description support system for life cycle scenario in order to support life cycle design efficiently.

2 APPROACH

As mentioned above, the description of life cycle scenario is a hopeful method to clarify life cycle strategy. Here, life cycle strategy is the second step of life cycle design in Figure 1. In other words, environmentally conscious product design should be executed only after appropriate life cycle strategy is fixed. In determining life cycle strategy, a designer should consider business strategy, environmental target to fulfill, and product concept for providing values to customers. And, the product and its life cycle processes should be designed so as to realize the life cycle strategy.

In order to support such design stage for the life cycle strategy, we intend to provide a workspace for a designer to examine various scenarios by the description support system. Therefore, we identified five main requirements for the system as follows:

1. To support describing life cycle scenarios in a trial-and-error manner

   Because the environmental issues as a whole is a typical ill-structured problem that requires a designer to consider a life cycle from various viewpoints, the system should support a designer to examine various plausible scenarios in a trial-and-error manner by considering various kinds of trade-offs. For this purpose, Section 3 proposes a representational scheme of the scenario and its description process.

2. To clarify requirements for product design and process design

   In order to embody the life cycle strategy as a product in the later stages of life cycle design, it is necessary to clarify requirements for product design and process design. We show this method by describing flow of product and its situation in Section 3. We realize this requirement by explicitly representing them in the life cycle scenarios.

3. To represent design rationale explicitly throughout the scenario description process

   There are no general and uniform criteria for environmentally conscious products. This means that a manufacturer has to declare the reason why its product is environmentally conscious. An approach for this is to express rationale of a designer's decision during a life cycle design. To do so, we record the reasons why a designer made a decision as the design rationale. We represent the design rationale by using cognitive design process model as shown in Section 4.1. Moreover, as discussed in the research of the design rationale (e.g., [6]), it is quite useful for reusing design knowledge.

4. To manage alternatives

   On each step in the scenario description process, a designer generates alternatives and makes a decision for choosing one of the alternatives. Therefore, for supporting the design process, the system should appropriately manage these design alternatives. We show the method to manage them in Section 4.2.

5. To integrate results from life cycle design support tools

   The scenario description support system should not be a closed system. Rather, the system assumes that a designer generates alternatives and makes decisions by using various life cycle design support tools described in Section 1. Therefore, the system should be able to import the results from these external support tools.

3 REPRESENTATION OF LIFE CYCLE SCENARIO

Life cycle scenario represents all scenes of a product life cycle in the form of 5W1H (who, where, what, why, when, and how) [1] [7]. In this paper, we define a life cycle scenario by the following five elements:

1. Objective of the life cycle: Declaring objective of the life cycle is important to clarify the target and the objective is used for evaluating the scenario in the later step of the description process. We represent the objective by using a sentence and parameter values that indicate the objective. An example of the objective is "to keep profits of the manufacturer and to reduce CO2 emission into half" and the parameter values are "profit: more than 100%." and "CO2 emission: less than 50%"
2. Life cycle concept: According to our preliminary study, it was difficult for a designer to draw a life cycle scenario directly from a life cycle objective. Therefore, we introduce life cycle concept, which indicate a basic direction for constructing a scenario such as upgrading scenario and recycling scenario, as a medium between the objective and the scenario.
3. Life cycle options: Life cycle options of the product and its components determine basic structure of the scenario. For example, a motor is reused in the first life and, then, recycled at the end of its second life.
4. Life cycle flow: It is the central model of a life cycle scenario and represents flows of products, components, and materials as a network of life cycle processes and links. Figure 2 is an example of the life cycle flow where component A is reused and component B is recycled.
5. Situation: We describe each life cycle process as a "situation" by using 5W1H. Furthermore, in the situation, we describe income and expenditure of the operator of the process, for evaluating economic aspect of the life cycle, and design requirements indispensable for this situation. We represent "How" with UML (Unified Modelling Language) [8] in order to formalize it.

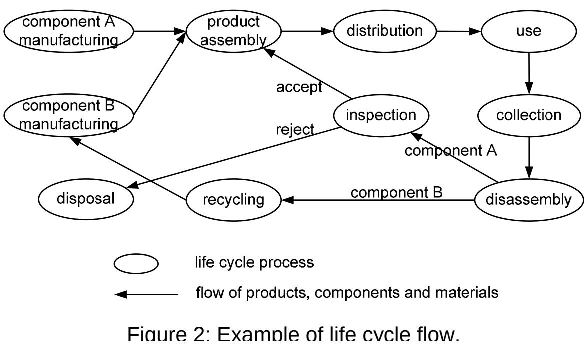


Figure 2: Example of life cycle flow.

4 MANAGEMENT OF LIFE CYCLE SCENARIO

4.1 Representation of design rationale

In this paper, in order to represent designer's decision explicitly, we represent the scenario description process as shown in Figure 3 by extending the cognitive design process model [6]. As shown in Figure 3, all information described by the designer is classified into seven kinds of nodes, i.e., "problem," "result from external tools," "fact," "assumption," "assessment result," "solution candidate," and "selected solution" and nodes are related with each other according to "positive" or "negative" causality.

The process here assumes that, after identifying the problem to be solved, the designer derives facts and assumptions from his/her knowledge and the result from external tools, and proposes the solution candidate based on this information. Then, the designer weighs up solution candidates and selects one or more solutions among candidates. As a result of this process, the design rationale is represented as a sub network of these nodes related to the selected or unselected solutions.

So far, this network should be constructed manually by the designer. Rather, we expect that the designer describes his/her thought process by enforcing him/her to construct this network.

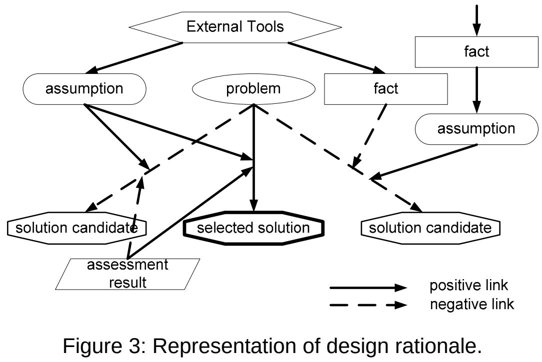


Figure 3: Representation of design rationale.

4.2 Management of alternatives

Because a designer should examine various trade-offs in describing the life cycle scenario as described in section 2, a designer have to find out and evaluate various alternatives (solution candidates). Therefore, it is necessary to manage these alternatives at each step of the process. Moreover, alternatives must be associated with the alternatives on the former and later stages as shown in Figure 4. Each alternative in the same stage is recorded by the difference form. Relationship of the nodes in Figure 3 is recorded based on the idea of Truth Maintenance System [9]. As a result, a lot of alternatives are able to be managed effectively.

5 PROCESS FOR DESCRIBING LIFE CYCLE SCENARIO

We propose a process for describing a life cycle scenario as shown in Figure 5. First, a designer describes product characteristics, component characteristics and market information. Next, the designer describes life cycle scenarios as described in Section 3. Moreover, in each step, the designer describes the scenario with design rationales as shown in Figure 3. Here, the designer uses life cycle scenario external tools in each step. The designer repeats this cycle in a trial-and-error manner until all life cycle objectives are satisfied.

6 DESCRIPTION SUPPORT SYSTEM FOR LIFE CYCLE SCENARIO

We developed a prototype system based on the method described in Sections 3-5. Note that among five requirements discussed in Section 2, “management of alternatives” has not been implemented yet. Figure 6 indicates the system architecture. The designer describes a life cycle scenario with each sub tool based on Figure 5; Objective Description Tool, Life Cycle Concepts Description Tool, Life Cycle Option Select Tool, Life Cycle Flow Modelling Tool, Situation Modelling Tool, and Life Cycle Scenario Evaluation Tool. And, Life Cycle Scenario Manager integrates these sub tools. These sub tools provide workspaces to describe easily scenarios for a designer. Moreover, there are two databases

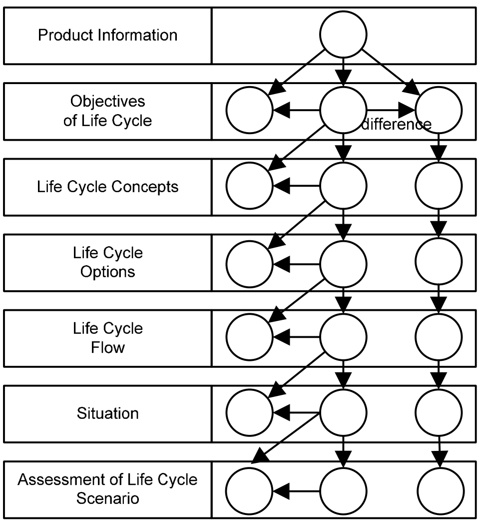


Figure 4: Management of alternatives.

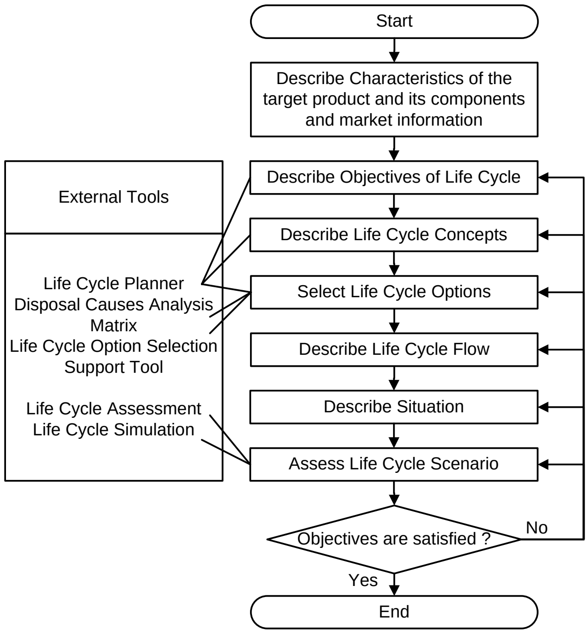


Figure 5: Process for describing life cycle scenario.

for supporting description of life cycle flow and situation. These databases record templates of life cycle flow and situation. The other sub tools; Design Rationale Manager and Alternative Manager manage design rationales and alternatives as described in Section 4. Moreover, we added a sub tool for exchanging information with the external tools.

7 CASE STUDY

We described a life cycle scenario for a personal computer with the prototype system as a case study. The example of PC consists of PCB, HDD, CPU, case, and liquid crystal display.

First, the objective of the life cycle is set to be “to decrease

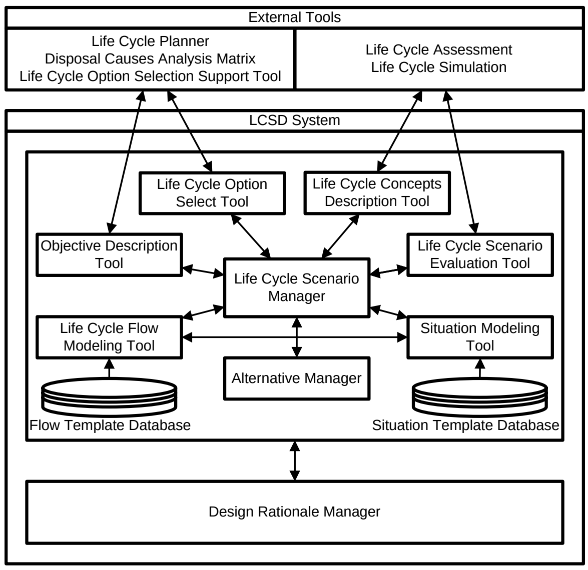


Figure 6: System architecture.

the amount of disposal without decreasing the manufacturer's profit," and, as parameter values of the objective, manufacturer's profit and disposal amount are set to be 100% and 50% of the existing life cycle scenario, respectively.

Second, we determined life cycle concept. Figure 7 depicts the thought process of this step. The objective of this life cycle is to decrease the amount of disposal. We analyzed that the disposal amount increases because of shorter life of PCB and HDD than other components by using an external tool called "disposal cause analysis matrix" [3]. Therefore, a long life scenario, rapid circulation scenario and current scenario were set as solution candidates of life cycle concept. Among these candidates, long life scenario was set as a solution of life cycle concept because we consider the node "The objective of this life cycle is to decrease the amount of disposal" is important.

Third, we selected life cycle options. For example, the process of life cycle option selection for PCB is shown in Figure 8. We examined upgrading, cascade reuse, which means to be adapted to other product or component, cascade material recycling, and proper disposal as alternatives because of shorter value life which is the result from "disposal cause analysis matrix". Then, we compared these options; for example, we prefer cascade material recycling to proper disposal because of noble metals included in PCB. As a result, we selected global reuse, upgrade, and cascade material recycling as life cycle options for PCB.

PCB is upgraded in usage process and collected PCBs are

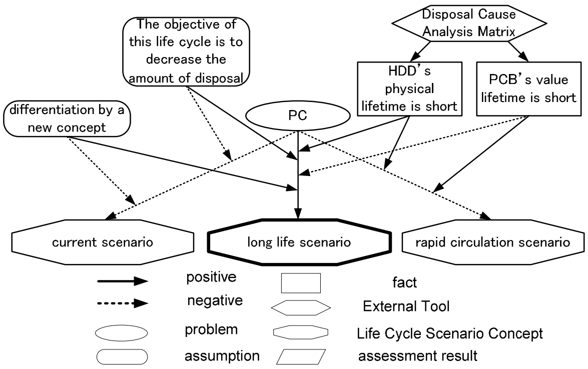


Figure 7: Life cycle concepts of PC.

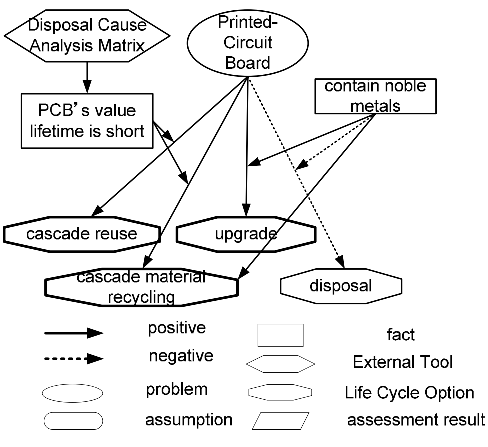


Figure 8: Life cycle option selection for printed-circuit board.

reused or recycled after inspection. In the same way, life cycle options for HDD, CPU, case, and liquid crystal display are selected. These life cycle options are shown in Table 1.

Next, life cycle flow is described as shown in Figure 9. Then, we described situations of processes. For example, Table 2 shows the situation of exchange upgrading of PCBs. We assumed that a user brings the product to the shop, and pays the upgrade fee of 30,000 yen to the PC manufacturer.

In the next step, this scenario was evaluated by using the idea of Life Cycle Simulation [5]. Here, we assumed that cost of manufacturing process, sales price, and upgrade fee of PCB, CPU and manufacturers' cost of PCB, CPU are set as 100,000 yen, 150,000 yen, 30,000 yen, 20,000 yen, 20,000 yen and 10,000 yen, respectively, in order to assess manufacturer's profit. Moreover, sales volume of the personal computer, weight of a personal computer and exchange rate are set as 10,000, 8kg, and 30%, respectively, in order to assess the amount of disposal. Here, "exchange rate" means

component	life cycle options
PCB	upgrade
	cascade reuse
	cascade material recycling
CPU	upgrade
	cascade material recycling
LCD	cascade material recycling
HDD	cascade material recycling
case	thermal recycling

Table1: Selected life cycle options.

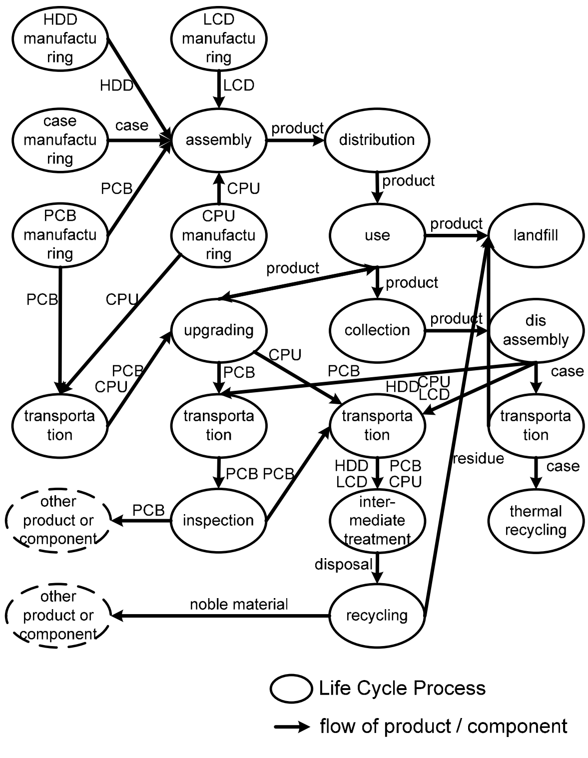


Figure 9: Life cycle flow for PC.

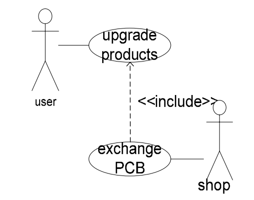
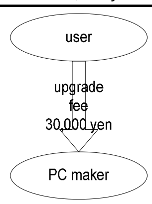
When	upgrading PCB
What	product
Who	shop, PC maker, user
Where	shop
Why	In order to upgrade PCB
How	
assumptions	- the number of exchanging / product amount 30% - cost to exchange 2,000 yen - upgrade fee 30,000 yen
income and expenditure	

Table 2: Situation for PC.

	benefit of PC maker	amount of disposal
traditional scenario	100%	100%
scenario A (before modification)	104.5%	58.6%
scenario B (before modification)	102.5%	48.8%

Table 3: Scenario assessment.

step	design requisition
assembly	cost of manufacturing process 100,000 yen
distribution	sales price 150,000 yen
	sales volume 10,000 units
disassembly	disassembly time is less than 10 min be able to disassembly in hands
PCB manufacturing	manufacturers' cost of PCB 20,000 yen
CPU manufacturing	manufacturers' cost of CPU 10,000 yen
upgrading PCB	exchange time is less than 15 min the number of exchange / product amount 60% be able to exchange in hands
upgrading CPU	exchange time is less than 15 min the number of exchange / product amount 60% be able to exchange in hands
collection	the number of collection / product amount 60%
thermal recovery for case	materials of case are able to recover energy

Table 4: Design requisition.

the rate of the number of upgrade exchange to the product amount. These parameters are written as "assumptions" in situations. The result of the evaluation indicated that, while the profit satisfied the target value, the amount of disposal is more than the target.

For solving this problem, we modified the scenario (named Scenario A) into Scenario B which improves the exchange rate of PCB and CPU up to 60% by advertising the exchange with the budget from the increased profit. Table 3 compares the reference scenario of the traditional life cycle of PC, Scenario A, and Scenario B. As shown in this table, since Scenario B satisfies all target values, we chose this scenario as the final scenario and the scenario describing process is completed. Design requirements gained from this process is summarized in Table 4.

8 DISCUSSIONS

We described the life cycle scenario and derived requirements for product and process design from the scenario by using the developed system as shown in Section 7. This case study clarified that the life cycle scenario is successfully represented on a computer by our representational scheme and the proposed procedure successfully supported the description process. As a result, we can conclude that a designer can determine the life cycle strategy easily by describing the life cycle scenario with this system and derive requirements to the later processes from the scenario.

Section 2 identified five system requirements. We achieved requirements 1-3, however, we have not achieved 4 yet. The requirements 1 and 2 are achieved by the proposed representational scheme. We proposed a process to break down life cycle scenario from life cycle objectives to the life cycle flow and situations. By doing so, a designer can systematically detail plausible life cycle that satisfies the objectives by clarifying facts, assumptions, his or her decisions, and requirements for the later processes. In terms of the requirement 3, the case study verified that the system successfully records the designer's process in describing scenarios and this information represents design rationale. However, since it is difficult to understand his or her rationale by reading such raw data, it is one of our future issues to reconstruct such raw data into design document explaining the design rationale. Moreover, it is difficult to differentiate solution candidates that designers should select, since there are only two kinds of links. We should introduce other kinds of links such as "more positive". For managing alternatives (the requirement 4), we will develop a method of recording alternatives at each step by using Truth Maintenance System. Finally, in order to realize the requirement 5, we added a sub tool for exchanging information with the external tools. Since this sub tool employed CSV format files, we have to extend this mechanism in order to exchange information with various external tools.

9 CONCLUSIONS

We proposed a description support system for life cycle scenario in order to support determination of life cycle strategy, which is an essential stage of life cycle design, in a trial-and-error manner; namely, we proposed a computational representation scheme of life cycle scenario, scenario description process, and the support system. We described life cycle scenario for a personal computer as a case study. Based on this result, we conclude that life cycle strategy can be easily determined by supporting the description of life cycle scenario. Future works include proposal of management mechanism of alternatives and management and utilization of design rationale.

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Conceptual Design of Product Structure for Parts Reuse

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Abstract:
End-of-life products are taken back constrainedly by the laws and disassembled to a mass of reusable parts. Design for reusing these taken-back parts into new products has more constraints than conventional design. A new method based on the set theory and constraint digraph is proposed to model design for taken-back parts reuse and to get all feasible designs. The eco-cost which considers product cost and eco-efficiency of parts reuse concurrently is applied to get an optimal design. A structural design of stamping mold is examined as a case for the validity of the proposed method.

Keywords:
Parts reuse, Conceptual design, End-of-life product

1 INTRODUCTION

Environmental treatment strategy for End-of-life products, here called as EOL-Eco-Strategy, is being emphasized and implemented by governments, society, legislators, and manufacturers. Due to industrialization and mass production, a large number of products are produced and sold to customer everyday, and meanwhile, many products are discarded. According to the legislations, e.g. the EU Directive of WEEE, certain disused products need to be taken back and recycled by their manufacturers or distributors, called as take-back responsibility. How to treat these end-of-life products economically and ecologically is the main researching issue of EOL-Eco-Strategy. There are some ways to treat these End-of-life products, such as maintenance, product reuse, part reuse, recycling and disposal, proposed by Ricoh's Comet circle [1].

The '3R' strategy of Reduce, Reuse, and Recycle is spreading over industry and society in the world. 'Reduce' aims to reduce consumption of materials, energy and other natural resources, and to reduce emission of pollutant while producing or using products. 'Recycle' aims to recycle materials or energy from used products. Many kinds of technologies are developed to implement strategies of 'Reduce and Recycle' widely, and economical and ecological efficiency is got from them. 'Recycle' has become the main selection to EOL-Eco-Strategy. In Figure 1, there shows 4 main EOL-Eco-Strategies: recovering or upgrading to second-hand products for product reuse; disassembling for parts reuse; dismantling or shredding for materials recycle and disposal by landfill or by incineration for energy recovery.

'Reuse' means any operation through which one can continue to utilize the function and value of products or parts, which are discarded by customers and taken back to collection points, distributors, recyclers or manufacturers. Obviously, reuse is one of the efficient EOL-Eco-Strategies. Some kinds of taken-back products, such as computers and home electric appliances, could be repaired or upgraded and be sold as second-hand products, it is called as product reuse. However, only a part of taken-back products which have enough physical and valuable lifetimes could be recovered to second-hand products. All products need to be finally dismantled for reusing parts thereof or shredded for recycling materials. The option of parts reuse seems to be an ideal alternative. Since reusable parts are reconfigured into new, advanced products or used to replace worn parts for maintenance as spare parts, so that their residual added value are utilized. However, it is not easy to be applied in reality. There are some uncertainties and risks related to parts reuse, such as quality, residual lifetime, quantity, reliability, safety and so on. So nowadays the strategy of parts reuse is not so successful to spread over our society.

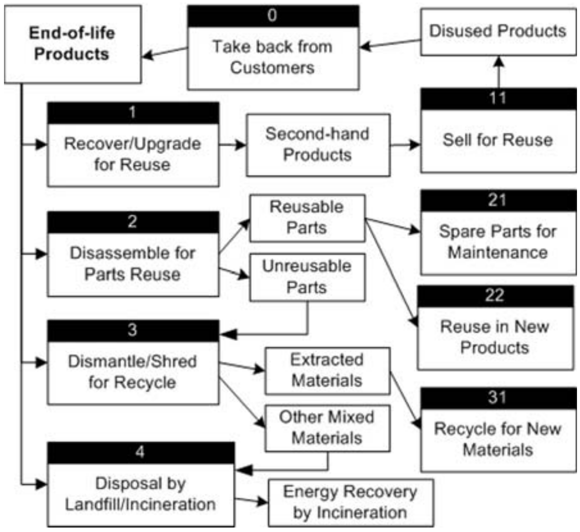


Figure1: Eco-Strategies for End-of-life Products

For promoting to reuse taken-back parts into new products, design for parts reuse (DFPR) is an intension-driven way by which manufacturers can know how and where to reuse which taken-back parts and then make their decision of EOL-Eco-Strategy. DFPR has two directions. While designing a new product and its parts, if the probability and ease of reusing them in the future is taken into account, it is called as Design for future-oriented parts reuse. On the other hand, how to realize reusing taken-back parts into new products in the design process, here called as Design for Taken-back Parts Reuse (DFTPR).

Nowadays, most of products have not been developed by means of Design for future-oriented parts reuse but they are being taken back for recovery. So it is necessary to research their reuse by means of DFTPR. Here supposes enough quantity of taken-back parts were checked to be of good quality for reuse and our research will just focus on the issue of DFTPR.

Facing a quantity of taken-back parts those may be designed and manufactured several years ago, how to design a feasible product structure for reusing part of them is one key problem to designers. To solve the problem, a new method of conceptual design of product structure based on the set theory and the constraints digraph is mainly proposed and researched in this paper. A case of stamping mold is studied to illustrate the proposed method.

This paper is structured as followings. In Section 2, the related research is overviewed. In Section 3, the process of DFTPR is analyzed and the importance of conceptual design for DFTPR is indicated. A method for product functional modeling for parts reuse based on the set theory is proposed in Section 4. In Section 5, a method for obtaining feasible conceptual design schemes of product structure from the constraints digraph is researched. Conclusions and future works are discussed in Section 6.

2 OVERVIEW

Now, 'Reuse' begins to attract many researchers and manufacturers to research and develop some specific methods or technologies.

Remanufacturing [2] is a production batch process of disassembling, cleaning, and refurbishment or replacement of parts to implement products reuse and parts reuse. Remanufacturing is a good way for implementing reuse and is necessary to develop specific technologies for it. There are just a few remanufacturing instances, such as single-use camera, photocopying machines and toner cartridges of printers. However, because many second-hand products which are renewed through remanufacturing are not so attractive to most customers in style and function, that many manufacturers are becoming willing to remanufacture taken-back parts and then to reuse them into new products.

A few papers discussed the issue of parts reuse. F. Kimura [3] proposed a new product modularization strategy across a family of products and successive generation of products, based on product functionality, product commonality, and life cycle similarity. S. Okumura and Y. Sakabe [4] developed a simulation model to study the optimal physical life span distribution of a reusable unit. The model considers the time series behavior of the value and demand of reusable units and sustainable products including reusable units. S. Kondoh, Y. Nishikiori, and Y. Umeda [5] designed a conceptual factory model of a closed-loop manufacturing system where products were made from used products, parts and materials and various kinds of fluctuations could be handled. H. Kobayashi and T. Kumazawa [6] apply life cycle simulation (LCS) and decision tree analysis embedded LCS to support decision making for reuse business with consideration of the uncertainty of various business scenarios. M. I. Mazhar, S. Kara and H. Kaebernick [7] apply the Weibull Analysis to time-to-failure data to analyze the technical feasibility of reusing the gearbox and the electric motor from washing machines.

International standard, `IEC 62309(2004): Dependability of products containing reused parts – Requirements for functionality and tests` [8] was released in July 2004. It may be the first definite program and a guideline on Reuse in 3R proposed for the society and industries in the worldwide. Fundamentals of this program is to use used parts twice after qualification based on the same specification on the concerned part, and a product containing these reused parts will be able to be declared as a new product.

3 DESIGN PROCESS FOR TAKEN-BACK PARTS REUSE

Reusing taken-back parts into new products is a challenge for designers. It requests designers to change their conventional design methods to consider how to select and reuse taken-back parts which might be designed and manufactured several years ago. In the conventional design process, designers consider product design just according to its requirements, but in the design process for parts reuse, they must consider the requirements and taken-back parts concurrently, so there are more design constraints. The different issues of reusing taken-back parts in the different design stages of new product development (NPD) are analyzed in the following. Two Processes of NPD and parts reuse are shown in Figure 2.

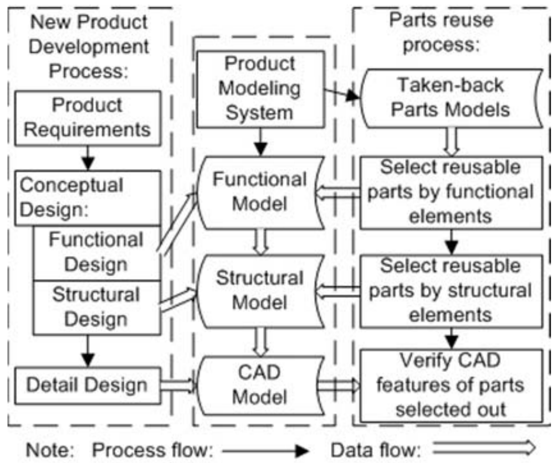


Figure 2: Parts reuse process in new product development

(1) In the stage of product conceptual design, there are two steps, one is functional design, and the other is structural conceptual design. In the stage of functional design, product function is divided into a few of functional elements according to the requirements. By comparing functional elements and their parameters between the functional models of the new product and taken-back parts, some taken-back parts that have independent functions could be selected out for reuse. For example, if the new product needs an engine, it is able to be selected from the taken-back engines by the power and

rotation and other functional requirements.

In the stage of product structural conceptual design, a product structure is often divided into some modules initially, here called as structural elements. Their main parameters are decided according to the requirements. Most of product functions are realized by combination of these structural elements in general. The taken-back parts could be selected for reuse in terms of structural elements. If there are no suitable taken-back parts for a structural element, a new part or component is necessary to be designed.

For one functional or structural element, it is possible to have several optional taken-back parts for reuse. So the problem is, how to design the product conceptual structure according to these optional taken-back parts and then to select feasible taken-back parts? If there are several feasible conceptual designs, it is necessary to select an optimized one in terms of the requirements of structure, process, quality, cost, and so on.

(2) In the stage of product detail design, all new parts are designed in detail, and all parts including taken-back parts, are assembled to a product in the CAD system. Here it is necessary to design new parts to fit for the taken-back parts or to verify the taken-back parts in the level of geometrical features whether they fit the structure of the new product. If some of taken-back parts are needed to change a few of features, the requirements of remanufacturing or replacing them should be proposed.

Obviously, according to the discussion above, it is beneficial to realizing parts reuse in the conceptual design stage, and the later design can be done or easily modified in terms of selected taken-back parts. Otherwise, if considering parts reuse in or after detail design, it would spend more time and cost to redesign the product to fit the selected taken-back parts. Therefore, this paper focuses on the issue of product conceptual design for taken-back parts reuse.

Through the analysis above, a new mathematical method is discussed in the following to design conceptual structure for parts reuse.

4 FUNCTION MODELING FOR PARTS REUSE

The set of product functional elements can be represented as follows:

$F = \{ F_j \mid j = 1,2,...,n\}$

For every functional element F_j , there need some parts or components to realize its function. Here these parts or components are called as structural elements. Some structural elements can be selected from taken-back parts and others need to be designed newly. That is:

$$S(F_j) = TC_j \vee NC_j = \{TC_{ju}, NC_{jv} \mid u = 0,1,...,a, v = 0,1,...,b\}$$

In which, $S(F_j)$ is the set of structural elements for F_j , TC_j is the set of taken-back parts whose number is a, and NC_j is the set of new parts whose number is b. For one of structural elements in $S(F_j)$, here say it has direct effect to realize the function F_j .

The union set of every $S(F_j)$ (j=1,2,…,n) consists of a set of all structural elements: $S=\{S_i \mid i=0,1,2,…,m\}$, m is number of all structural elements in the product.

For one functional element F_j , we may search many taken-back parts and insert them into its TC_j which may be reusable but not all of them would be reused into the new product in the end. Therefore, the key problem is how to design the structure of the new product according to these structural elements in the set S.

The aim of designing product structure is to realize product function. Here we use a Boolean vector to represent the status of function realization, called as functional Boolean vector (FBV): $\mathbf{F}(u)$ = (F(1), F(2), ..., F(j), ..., F(n))

In which, F(j)=1 means the functional element F_j is realized or satisfied, otherwise, F(j)=0 means F_j is not satisfied. When $\mathbf{F}$(u0)=(1,1,…,1) for a product, means all product functions are satisfied and the product structure is feasible. Similarly, a FBV of one structural element:

$\mathbf{F}(S_i)$=(F(i,1),F(i,2), … ,F(i, j), …, F(i, n))

It represents the structural element S_i has some direct effects on realizing functional elements.

The mapping relationship between the set S and the set F can be represented as a Boolean matrix, called as structure-function (S-F) mapping Boolean matrix:

$\boldsymbol{M} = [M_{i \times j}] = [S \times F]$

In which, '$M_{i \times j}$ =1' means the structural element S_i has direct effect on realizing the functional element F_j , otherwise, '$M_{i \times j}$ =0' means there is no effect.

For illustrating the method in this paper, a design of simple stamping mold is studied as a case. A stamping mold has 6 functional elements in general: Working (F1), Locating (F2), Unloading (F3), Guiding (F4), Supporting (F5) and Fixing (F6). So its functional elements set is: F={F1,F2,F3,F4,F5,F6}

These functional elements have related structural elements to realize their function according to the design guidebooks, e.g., the structural elements for Working (F1) have upper die and lower die. In a manufacturer of stamping mold, there may be many used parts that need to be reused. For example, the structural elements for Supporting (F5) have upper and lower die seats which could be reused.

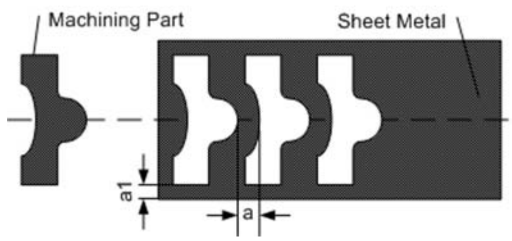


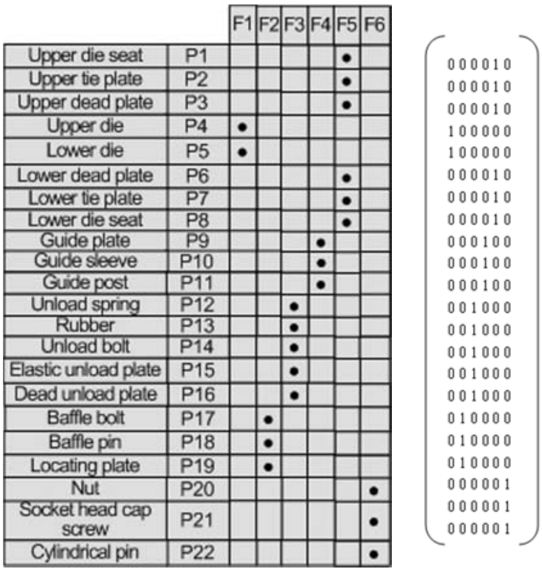
Figure 3: Machining disks and sheet metal

As a case study, suppose to design a blanking die which is one kind of stamping molds to machine parts from sheet metal (shown in Figure 3). The distances 'a' and 'a1' are decided by materials and thickness of the sheet metal, so the location is needed in the machining process.

Through a reference to related guidebooks of stamping mold, the following parts or components are selected out and some of them are taken-back parts.

P1—upper die seat (die shrank is attached on); P2—upper tie plate; P3—upper dead plate; P4—upper die; P5—lower die; P6—lower dead plate; P7—lower tie plate; P8—lower die seat; P9—guide plate; P10—guide sleeve; P11—guide post; P12—unload spring; P13—rubber; P14—unload bolt; P15—elastic unload plate; P16—dead unload plate; P17—baffle bolt; P18—baffle pin; P19—locating plate; P20—nut; P21--socket head cap screw; P22--cylindrical pin.

These 22 kinds of parts consist of structural elements set S. The relation matrix and its Boolean matrix M between the set S and the set F are shown in Figure 4. Many feasible design schemes of the stamping mold could be got according to these 22 parts. For example, one design scheme which consists of 15 parts is shown in Figure 5. Therefore, next issue is how to get these feasible design schemes.



		F1	F2	F3	F4	F5	F6	Boolean
Upper die seat	P1					●		000010
Upper tie plate	P2					●		000010
Upper dead plate	P3					●		000010
Upper die	P4	●						100000
Lower die	P5	●						100000
Lower dead plate	P6					●		000010
Lower tie plate	P7					●		000010
Lower die seat	P8					●		000010
Guide plate	P9				●			000100
Guide sleeve	P10				●			000100
Guide post	P11				●			000100
Unload spring	P12			●				001000
Rubber	P13			●				001000
Unload bolt	P14			●				001000
Elastic unload plate	P15			●				001000
Dead unload plate	P16			●				001000
Baffle bolt	P17		●					010000
Baffle pin	P18		●					010000
Locating plate	P19		●					010000
Nut	P20						●	000001
Socket head cap screw	P21						●	000001
Cylindrical pin	P22						●	000001

Figure 4: S-F mapping matrix and its Boolean matrix

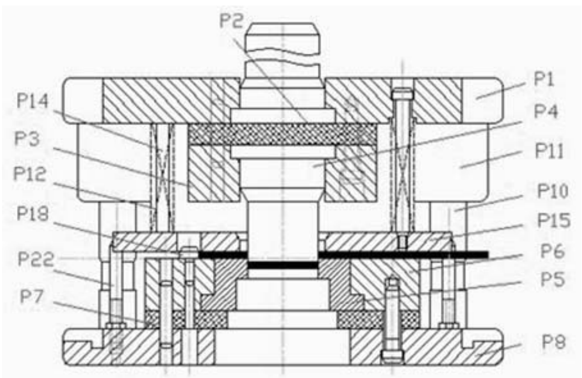


Figure 5: Structure of one stamping mold

5 DESIGNING FEASIBLE CONCEPTUAL STRUCTURES

The structural elements are assembled to a whole product through mate constraints. The constraint graph: G=(*S*, *C*), usually represent the constraint relationship among structural elements, in which, nodes *S* are structural elements and edges *C* represent mate constraints.

The graph G has two types: undirected graph and digraph. This research applies the digraph G to represent constraints propagation and to analyze constraint routes. In the studying case, the necessary part P8 is assembled firstly and selected to an end node and the necessary part P1 is assembled finally and selected to a start node. The digraph G is shown in Figure 6. Here not all of the directions are represented assembling sequences, and circular loops ought to be avoided.

The digraph G includes all optional parts and components which are probable to be used in the new product. So it is a constraint digraph of product structural elements for all design schemes which is not only for an assembly of one product.

A functional element is generally realized through a set of parts linked by their constraints, so the constraint routes are applied to analyze the realization of functional elements.

An accessible constraint route (ACR) is defined to be a link route from a start node to an end node in the digraph G, e.g. P1→P22→P8 is an ACR and represented as U1=(P1,P22,P8).

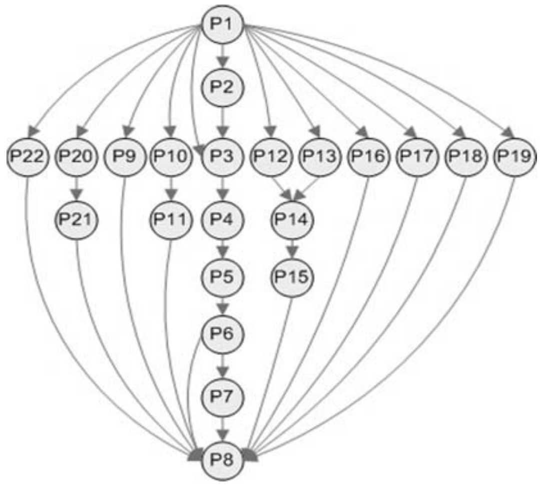


Figure 6: Constraint digraph G of product structural elements

ACR:	FBV:	Group
U1=(P1,P22,P8)	F(U1)=(0,0,0,0,1,1)	1
U2=(P1,P20,P21,P8)	F(U2)=(0,0,0,0,1,1)	
U3=(P1,P9,P8)	F(U3)=(0,0,0,1,1,0)	2
U4=(P1,P10,P11,P8)	F(U4)=(0,0,0,1,1,0)	
U5=(P1,P2,P3,P4,P5,P6,P7,P8)	F(U5)=(1,0,0,0,1,0)	3
U6=(P1,P3,P4,P5,P6,P7,P8)	F(U6)=(1,0,0,0,1,0)	
U7=(P1,P2,P3,P4,P5,P6,P8)	F(U7)=(1,0,0,0,1,0)	
U8=(P1,P3,P4,P5,P6,P8)	F(U8)=(1,0,0,0,1,0)	
U9=(P1,P12,P14,P15,P8)	F(U9)=(0,0,1,0,1,0)	4
U10=(P1,P13,P14,P15,P8)	F(U10)=(0,0,1,0,1,0)	
U11=(P1, P16,P8)	F(U11)=(0,0,1,0,1,0)	
U12=(P1,P17,P8)	F(U12)=(0,1,0,0,1,0)	5
U13=(P1, P18,P8)	F(U13)=(0,1,0,0,1,0)	
U14=(P1, P19,P8)	F(U14)=(0,1,0,0,1,0)	

Table 1: All ACR and their realized FBV

A FBV of an ACR is a union of FBV of structural elements in the ACR, and it is represented as follows:

$\mathbf{F}(U_r) = \bigvee_{i=1}^{n} \mathbf{F}(S_i)$

In which, *n* is num of structural elements in an ACR U_r .

For example, for ACR: U1=(P1,P22,P8),

F(U1) = **F**(P1) ∨ **F**(P22) ∨ **F**(P8)

=(0,0,0,0,1,0) ∨ (0,0,0,0,0,1) ∨ (0,0,0,0,1,0) = (0,0,0,0,1,1)

That means U1 has direct effect to functional elements: F5 and F6. In Table 1, all ACR and their FBV are listed.

From Table 1, No one ACR has realized all functional elements. It is necessary to combine these ACR to get feasible design schemes, called as ACR combination: C_t . Its FBV is:

$\mathbf{F}(C_t) = \bigvee_{r=1}^{p} \mathbf{F}(U_r)$, *p* is num of ACR.

If $\mathbf{F}(C_t)$ = **F**(u0) = (1,1,…,1), that means C_t is a feasible design scheme.

In Table 1, ACR are grouped to 5 according to their FBV. The ACR in a group have the same FBV and realize the same function. An ACR combination is combined from every group to select one ACR. To reduce num of ACR combinations and get optimal schemes, all ACR need to be evaluated according to other concrete technical requirements and design knowledge rules, and some obvious unfeasible ACR in a group can be ignored. Here ACR should be ignored carefully for not losing good design schemes. For example, in this case to design a blanking die, for reducing vibration and improving precision, it's suited to use the upper tie plate (P2) and the lower tie plate (P7), so only U5 is selected in Group 3. Therefore, 36 ACR combinations those satisfy $\mathbf{F}(C_t)$=**F**(u0) to be feasible design schemes are got and listed in Table 2.

ACR Combinations:	Structural Elements (Numbers):
C1=(U1,U3,U5,U9,U12)	(1,2,3,4,5,6,7,8, 9,12,14,15,17,22)
C2=(U1,U3,U5,U9,U13)	(1,2,3,4,5,6,7,8, 9,12,14,15,18,22)
C3=(U1,U3,U5,U9,U14)	(1,2,3,4,5,6,7,8, 9,12,14,15,19,22)
C4=(U1,U3,U5,U10,U12)	(1,2,3,4,5,6,7,8, 9,13,14,15,17,22)
C5=(U1,U3,U5,U10,U13)	(1,2,3,4,5,6,7,8, 9,13,14,15,18,22)
C6=(U1,U3,U5,U10,U14)	(1,2,3,4,5,6,7,8, 9,13,14,15,19,22)
C7=(U1,U4,U5,U9,U13)	(1,2,3,4,5,6,7,8, 10,11,12,14,15,18,22)
⋮	⋮
C36=(U2,U4,U5,U11,U14)	(1,2,3,4,5,6,7,8, 10,11,16,19,20,21)

Table 2: All feasible design schemes (ACR combinations)

6 OPTIMIZATION OF FEASIBLE DESIGN SCHEMES

Next work is to select an optimal design from above 36 feasible schemes. There are two steps to optimize these feasible schemes.

In the first step, the KBE (Knowledge-based Engineering) method is applied to evaluate every design scheme by defining some rules. Because the feasible schemes are derived just by product functional requirements, they must be checked more by other technical requirements to ensure whether they are technically feasible. There are two types of rules, one is necessary rules which are basic technical requirements and must be satisfied for every feasible scheme. The other is contrastive rules which are to compare feasible schemes by qualitative analysis. These rules are applied to evaluate the feasible schemes in terms of designers' experience knowledge and some other facts. Those schemes which could not satisfy the necessary rules might be ignored. For some feasible schemes, if one is obviously better than others evaluated by contrastive rules, it could be selected out for an optimal scheme and the others could be ignored. The remainder schemes are thought to be technically feasible.

Next step is to evaluate these technically feasible design schemes to find their quantitative difference in some attributes, such as cost, quality, production efficiency, environmental efficiency, and so on. By comparing their difference, an optimal feasible scheme could be selected out. If there is just one different attribute and other attributes are almost the same, the optimal scheme could be easily selected out according to some related facts. If there are many different attributes each other, it becomes a multi-objective optimization problem, and the AHP (Analytic Hierarchy Process) method is suggested for solving the problem to get an optimal design scheme. Limited by the length of this paper, the AHP method for optimizing these schemes is not discussed here.

As an example, the following is to evaluate some similar feasible schemes from the viewpoint of cost. There are two requirements in DFTPR: One is to make the best of reusing taken-back parts for a good environmental efficiency, and another is to make the best of using low cost parts that is attractive for many manufacturers. Apply these two rules to analyze three similar schemes: C1, C2 and C3. Obviously, the three schemes just have one different type of parts: baffle bolt (P17) in C1, baffle pin (P18) in C2 and locating plate (P19) in C3. So only the cost of the three types of parts needs to be calculated. For a type of parts, here defines some variables:

Pd: output of the blanking die;

Tp: num of reusable taken-back parts;

Tpc: recovery cost of one taken-back part;

Np: num of new parts. If the taken-back parts are not enough, new parts need be supplemented. *Np=Pd∗n1-Tp*, *n1* is num of the parts needed in one product.

Npc: cost of one new part.

The expression for calculating the total cost of one type of parts is:

Cost_Tp = Tp∗Tpc + Np∗Npc

However, the expression of *Cost_Tp* considers the cost of parts just from economical viewpoint but does not consider environmental efficiency of reusing taken-back parts. How to calculate the environmental efficiency? Because energy and materials could be saved by reusing taken-back parts instead of the same num of new parts, here the saved cost of energy and materials is calculated and thought to be the environmental efficiency which variable is named as *Eco_Tp*. The environmental efficiency *Eco_Tp* should be subtracted from the cost *Cost_Tp*, and its residuary cost is the environmentally conscious cost of reusing taken-back parts, called as eco-cost. The variable of the eco-cost is *Eco_Cost_Tp* and its expression is:

Eco_Cost_Tp = Cost_Tp – Eco_Tp

In the recovery cost of one taken-back part (*Tpc*), the percent of the cost of energy and materials is defined as *tem*. In the cost of one new part (*Npc*), the percent of the cost of energy and materials is defined as *nem*. So the environmental efficiency of reusing taken-back parts is:

$$Eco\_Tp = Tp*(Npc*nem - Tpc*tem)$$

Therefore, after synthesizing above four expressions, the eco-cost could be calculated as the following expression:

$$Eco\_Cost\_Tp=Pd*n1*Npc-Tp*[Npc*(1+nem)-Tpc*(1+tem)]$$

In general, for one type of parts in products, if more taken-back parts were used, its eco-cost would become lower. Therefore, the optimal feasible design scheme should be that of the lowest eco-cost among all schemes, if other attributes were almost the same.

In the above example of three similar schemes, suppose that the baffle pin (P18) has the lowest cost and has a lot of taken-back parts for reuse and the three schemes have almost the same attributes except for cost, C2 is an optimal feasible scheme among the three similar schemes. Similarly, for C4, C5 and C6, C5 is an optimal feasible scheme.

For a feasible design scheme, its eco-cost is sum of *Eco_Cost_Pt* of all types of parts; its variable is named as *Eco_Cost_Des*. By means of comparing *Eco_Cost_Des* of every feasible scheme, one optimal feasible design which making the best of reusing taken-back parts could be selected out. The optimal design has the lowest eco-cost and lower cost, but it may be not the lowest cost.

In the study case, for the feasible design scheme C7=(U1,U4,U5,U9,U13), its structural elements is (P1,P2,P3,P4,P5,P6,P7,P8,P10,P11,P12,P14,P15,P18,P22). Suppose it satisfies all technical requirements and many types of parts have lots of reusable taken-back parts, its eco-cost is the lowest; so it is an optimal feasible design. Its structure drawing is shown in Figure 5.

For a complicated product, its function and structure could be divided into hierarchy trees, and the above method could be applied to design its every level of components recursively by bottom-to-up, until to finish the whole design.

7 CONCLUSIONS AND FUTURE WORKS

How to reuse taken-back parts into new products? Designers can replace some new parts with taken-back parts after they finished product design. Because there would have some difference between new parts and taken-back parts, it may need to spend more time and cost to modify the design repeatedly. In this paper, design for taken-back parts reuse (DFTPR) is proposed and its realizing process is analyzed. It indicates that conceptual design of new product structure is the key stage for realizing taken-back parts reuse.

A new method is developed to realize taken-back parts reuse in the conceptual design process of product structure. By means of the method, designers have freedom to select taken-back parts according to the product functional elements, even more than the requested types of parts for one functional element. So the set of selected taken-back parts may be redundant. The structure-function mapping Boolean matrix is built to represent the mapping relationship between structural and functional elements. The constraint digraph is applied to represent constraint relationship among all structural elements. All feasible design schemes which satisfy all functional requirements are derived from the matrix and the digraph. The method is a mathematic approach based on the set theory and the constraints digraph and easy to be realized in the computer system.

The rule-based evaluating method and the eco-cost calculation of parts reuse are proposed from all feasible design schemes to get an optimal design scheme which satisfies technical requirements and makes the best of reusing taken-back parts.

The future work is to develop the method further to fit in with complicated products and to research an effectual method to optimize the feasible design schemes.

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A web-based collaborative decision-making tool for Life Cycle Interpretation

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Abstract
The Interpretation phase of Life Cycle Assessment raises important issues, both from a theoretical and an application point of view, particularly if a decision-making procedure is involved during this phase. In this paper, an advanced web-based collaborative decision-making tool, which includes several argumentation and knowledge management features, will be presented. Argumentative discourses, which may be carried out through this tool, can be utilized in order to arrive at collaborative decisions. The paper will demonstrate the utilization of the tool for Life Cycle Interpretation.

Keywords:
Life Cycle Interpretation; Life Cycle Impact Assessment; Argumentative Decision Making; Web-based Tool

1 INTRODUCTION

Life Cycle Assessment (LCA) is a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle of a product, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, and others [1]. Although LCA has gained wide acceptance among researchers and companies, its last phase, that is, Life Cycle Interpretation, is still under development and has been lately a field of intense research efforts.

The contribution of Interpretation may occur in two levels. The first one refers to the assumptions and choices that have been made in the whole extent of the study and may be regarded as a review of the methodology that has been followed. The second one refers to the issues related to the specific product system examined. In particular, analysts have to shape some conclusions concerning the environmental performance of the examined product system, to identify areas for improvement/change as well as to relate and combine the results of LCA with other decision criteria, such as economic, societal, etc. Usually, these issues cannot be addressed by individuals working alone or even by several people working separately and then merging their pieces of work. Instead, they have to be addressed through collaborative work among stakeholders with diverse views and perspectives. As such, Collaborative Decision Making (CDM) may provide a means for a well-structured decision-making process.

In this paper, CDM is demonstrated in the case of two alternative scenarios for used mobile phones management, based on the LCA results presented by Pappis et al. [2]. In particular, the following issues are segregated and examined:

- Choice of the environmentally significant processes
- Life Cycle Impact Assessment (LCIA)

In the remainder of the paper, the issues that have to be addressed during the Interpretation are briefly discussed. Then the proposed CDM tool is presented and applied in the case of used mobile phones management. The paper ends with some concluding remarks.

2 ISSUES TO BE ADDRESSED

The International Organization for Standardization (ISO) has defined the following two objectives for Interpretation [3], corresponding to the contribution of Interpretation mentioned earlier:

- To analyze results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of LCA and to report the results of Interpretation in a transparent manner.
- To provide a readily understandable, complete, and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study.

In order to be able to serve these objectives, it is necessary to analyze the results derived from Inventory Analysis (LCI) and LCIA in line with the goal and scope of the study. Based on these objectives, Tsoulfas et al. [4] have proposed the following checklist of issues that have to be addressed during Life Cycle Interpretation:

- The assessment that has been made is in line with the goal and scope of the study stated in its very beginning.
- The choice of the environmentally significant processes has been properly made.
- Data quality requirements are fulfilled.
- LCI has been performed consistently.
- The LCIA method(s) is (are) the appropriate one(s).

After having communicated the results of the ‘preliminary’ Interpretation with the previous phases of LCA and having made the necessary modifications, the focus is drifted in the utilization of the results of the assessment of a specific product system in order to:

- compare alternative scenarios
- identify hot spots that may be used in the formation of a Streamlined LCA

- identify areas for improvement/change
- prioritize actions
- reach final conclusions.

As stated in the Introduction, we will focus on some of the above issues, which are briefly presented in the remainder of this section.

2.1 Choice of the environmentally significant processes

In this step of Interpretation, analysts should ensure that they have made the right choices regarding the environmentally significant processes and the assumptions referring to the allocation of environmental impacts. In particular, when alternative scenarios are compared, analysts should examine whether the comparison is feasible and realistic so that there are no overlaps or omissions.

2.2 Impact Assessment

The choice of LCIA method is an important subject that has to be reviewed during Interpretation, as quite a few methods have been developed that may lead to different results. It is suggested, though, that more than one LCIA method is applied, if possible, in order to have a better view of the environmental performance of the product system examined. Moreover, analysts may not be able to have a complete overview of the impacts associated with human activities. It becomes evident that revision of assumptions regarding characterization in LCIA is necessary. Analysts should ensure that they have selected the right method based on various criteria: the carrier of the assessment, the assessment's goal and scope, the kind of the product system examined, the accuracy required, the geographical region examined, how old is the method, the requirements in raw data and the length of the study, including time constraints.

3 COLLABORATIVE DECISION MAKING: THE PROPOSED TOOL

It has been extensively argued that contemporary collaborative decision making needs to be tackled through a holistic perspective, in that the conceptual, methodological and application-oriented aspects of the problem have to be simultaneously taken into account. To satisfy the related requirements, new formalisms based on what people do while acting and communicating have been proposed; these representation schemes have been founded along two directions: on the one hand, on the human activity models of Soft Systems Methodology [5] to accommodate the "softness" of organizational life, and on the other, on the Language/Action perspective [6] and the Speech Act Theory [7] to emphasize the conversational nature of human-centered organizational activity. The latter consider the utterance of various types of communicative actions as the backbone of the business process models. In both cases, related structures and methodologies concentrate on the representation of knowledge (content), but they barely consider knowledge creation through interaction.

As far as interaction is concerned, ICT infrastructure to support people working in teams has been the subject of interest for quite a long time [8]. Such systems are aiming at facilitating group decision-making processes by providing forums for expression of opinions, as well as qualitative and quantitative tools for aggregating proposals and evaluating their impact on the issue in hand. Current systems exploit intranet or internet technologies to connect decision makers in a way that encourages dialogue and stimulate the exchange of knowledge. In the same line, the more recent computer-based Knowledge Management Systems (KMS) intend at providing a corporate memory, that is, an explicit, disembodied and persistent representation of the knowledge and information in an organization, as well as mechanisms that improve the sharing and dissemination of knowledge by facilitating interaction and collaboration among the parties involved [9]. Compared to problem structuring methodologies and tools, they lack a concrete theoretical basis, as well as any methodological support with respect to social interaction.

Taking into account the above issues, we have implemented a web-based tool that supports the collaboration conducted in a decision making context, by facilitating the creation, leveraging and utilization of the relevant knowledge. We have followed an argumentative reasoning approach, which extends the one conceived in the development of the Hermes system [10], by providing additional knowledge management and decision-making features. According to our approach, discourses about complex problems (such as those in LCA) are considered as social processes and, as such, they result in the formation of groups whose knowledge is clustered around specific views of the problem. Following an integrated approach, we have developed a system that provides experts engaged in such a discourse with the appropriate means to collaborate towards the solution of diverse issues. In addition to providing a platform for group reflection and capturing of organizational memory, our approach augments teamwork in terms of knowledge elicitation, sharing and construction, thus enhancing the quality of the overall process. This is due to its structured language for conversation and its mechanism for evaluation of alternatives. Taking into account the input provided by the individual experts, the proposed tool constructs an illustrative discourse-based knowledge graph that is composed of the ideas expressed so far, as well as their supporting documents. Moreover, through the integrated decision support mechanisms, experts are continuously informed about the status of each discourse item asserted so far and reflect further on them according to their beliefs and interests on the outcome of the discussion. In addition, our framework aids group sense-making and mutual understanding through the collaborative identification and evaluation of diverse opinions.

The tool builds on a server-client network architecture. It is composed of two basic components, namely the *collaboration visualization module* and the *collaborative decision making module*. The former provides a shared web-based workspace for storing and retrieving the messages and documents deployed by the discussion participants, using the widely accepted XML document format (http://www.w3.org/XML/). This module actually provides the interfaces through which participants get connected with the system via Internet (by using a standard web browser; there is no need of installation of any specific software in order to use the system). Exploitation of the Web platform renders, among others, low operational cost and easy access to the system. The knowledge base of the system maintains all the above items (messages and documents), which may be considered, appropriately processed and transformed, or even re-used in future discussions. Storage of documents and messages being asserted in an ongoing discussion takes place in an automatic way, upon their insertion in the discussion. On the other hand, retrieval of knowledge is performed through appropriate interfaces, which aid participants explore the contents of the knowledge base and exploit previously stored or generated knowledge for their current needs. In such a way, our approach builds a "collective memory" of a particular community. On the other hand, the collaborative decision making module is responsible for the reasoning and evaluation purposes of the system. Alternative mechanisms for these purposes can be invoked each time, upon the participants' wish and context under consideration. These mechanisms follow well-defined and broadly accepted algorithms (based on diverse decision making approaches, such as multi-criteria decision making, argumentation-based reasoning, utility theory, risk assessment, etc.), which are stored in the system's model base.

The basic discourse elements in our system are *issues, alternatives, positions,* and *preferences*. In particular, issues correspond to problems to be solved, decisions to be made, or goals to be achieved. They are brought up by users and are open to dispute (the root entity of a discourse-based knowledge graph has to be an issue). For each issue, the users may propose alternatives (i.e. solutions to the problem under consideration) that correspond to potential choices. Nested issues, in cases where some alternatives need to be grouped together, are also allowed. Positions are asserted in order to support the selection of a specific course of action (alternative), or avert the users' interest from it by expressing some objection. A position may also refer to another (previously asserted) position, thus arguing in favor or against it. Finally, preferences provide individuals with a qualitative way to weigh reasons for and against the selection of a certain course of action. A preference is a tuple of the form [position, relation, position], where the relation can be "more important than" or "of equal importance to" or "less important than". The use of preferences results in the assignment of various levels of importance to the alternatives in hand. Like the other discourse elements, they are subject to further argumentative discussion.

These four types of elements enable the users of the tool to contribute their knowledge on the particular problem (by entering issues, alternatives and positions) and also to express their relevant values, interests and expectations (by entering positions and preferences). In such a way, the tool supports both the rationality-related dimension and the social dimension of the underlying collaborative decision making process. Moreover, the tool continuously processes the elements entered by the users (by triggering its reasoning mechanisms each time a new element is entered in the graph), thus facilitating users to become aware of the elements for which there is (or there is not) sufficient (positive or negative) evidence, and accordingly conduct the discussion in order to reach consensus.

4 A CASE STUDY : ALTERNATIVE USED MOBILE PHONES MANAGEMENT

Mobile phones and other electronic devices contain a number of toxic and hazardous substances. These substances have the potential to pollute the air when burned in incinerators and leach into soil and drinking water when buried in landfills. For example, the printed wiring board contains a variety of toxic and precious metals like lead, antimony, beryllium, arsenic, silver, tantalum, and zinc. Apart from metals, mobile phones contain also flame retardants, which are used in the plastic parts and cables in order to reduce the risk of fire.

The case of mobile phones may be assessed under different perspectives, depending on the scope of the assessment. That is, several modules constituting supply chains could be examined. However, there is lack of reliable data regarding the whole supply and the reverse chain of mobile phones and related parts (batteries, adapters, etc). The analysis presented by Pappis et al. [2] is based on the data presented in Table 1 and is focused on the comparison of the following options:

- Recovery of metals and incineration of the rest of the materials contained in handsets
- Disposal of handsets.

The Characterization and Normalization LCIA results using the CML2 method are presented in Table 2. For this purpose, the software package SimaPro was used. Following Normalization, Pappis et al. [2] employed the aggregation procedure, which has been developed by Tsoulfas et al. [4] (Tables 3 and 4) that finally led to the results presented in Table 5.

Based on the modeling of the product system as well as on the results presented above, the proposed collaborative decision making tool can be employed to address issues such as those discussed in subsections 2.1 and 2.2. Figures 1 and 2 correspond to instances of collaboration concerning the *"choice of the environmentally significant processes",* and *"impact assessment"*, respectively. In these instances, three stakeholders, namely A, B and C, participate in an argumentation-based decision making process. More specifically, in the instance shown in Figure 2, the issue under consideration is *"Which LCIA methods should additionally be used?"*, while three alternatives, namely *"Eco-Indicator 99"*, *"LIME"* and *"EDIP 2003"*, have been proposed so far (by B, C and A, respectively). The three stakeholders have argued about them, by expressing positions speaking in favor or against them. For instance, *"it is quite new and complete"* is a position (asserted by C) that argues in favor of the second alternative, while *"it is outdated"* is a position (asserted by A) that argues against the first alternative. As also shown in Figures 1 and 2, argumentation can be conducted in multiple levels.

As noted above, users may also assert preferences about the already expressed positions. As shown in the bottom part of the main pane of Figure 2, user C has expressed a preference concerning the relative importance between the positions *"it is outdated"* and *"it is well established"*, arguing that the first position is (for him) of bigger importance. Users may also express their arguments in favor or against a preference.

When selecting a discourse item (by clicking on it), detailed information about this item is provided in the lower pane of the basic interface of the tool. More specifically, this part contains information about the user who submitted the selected discussion element, its submission date, any comments that the user may had inserted, as well as links (URLs) to related web pages and multimedia documents (containing diverse types of data) that the user may have uploaded to the tool in order to justify this element and aid his/her peers in their contemplation.

CONSTITUENTS	ABS-PC	Cu	Glass	Al	Fe	PMMA	SiO_2	Epoxy	PC	Si	POM	PS	TBBA	Ni	Sn	LCP	Minor Constituents
%	20	19	11	9	8	6	5	5	4	4	2	2	2	1	1	1	< 1
G/UNIT	16	15	8.8	7.2	6.4	4.8	4	4	3.2	3.2	1.6	1.6	1.6	0.8	0.8	0.8	~0

Table 1: Substance list of a Nokia mobile phone handset (battery and accessories are not included). See: http://www.basel.int/industry/mppiwp/guid-info/guiddesign.pdf

		CHARACTERIZATION			NORMALIZATION	
IMPACT CATEGORY	NOTATION	UNIT	DISPOSAL	RECYCLING & INCINERATION	DISPOSAL	RECYCLING & INCINERATION
abiotic depletion	AD	kg Sb eq	3.10E-03	-1.78E-03	2.06E-13	-1.19E-13
global warming	GW	kg CO2 eq	3.16E-01	-1.58E-01	6.69E-14	-3.34E-14
ozone layer depletion	OLD	kg CFC-11 eq	5.86E-08	8.74E-09	7.03E-16	1.05E-16
human toxicity	HT	kg 1,4-DB eq	8.88E-02	-8.87E-03	1.17E-14	-1.17E-15
fresh water aquatic ecotoxicity	FWAE	kg 1,4-DB eq	4.18E-03	-1.60E-03	8.27E-15	-3.18E-15
marine aquatic ecotoxicity	MAE	kg 1,4-DB eq	7.07E+01	-3.89E+01	6.23E-13	-3.43E-13
terrestrial ecotoxicity	TE	kg 1,4-DB eq	4.39E-04	-9.18E-05	9.31E-15	-1.95E-15
photochemical oxidation	PO	kg C2H2	2.19E-04	-5.84E-04	2.65E-14	-7.06E-14
acidification	AC	kg SO2 eq	5.10E-03	-1.44E-02	1.87E-13	-5.28E-13
eutrophication	EU	kg PO4--- eq	6.80E-05	7.39E-06	5.45E-15	5.93E-16

Table 2: Characterization and Normalization - CML2

	AD	GW	OLD	HT	FWAE	MAE	TE	PO	AC	EU
AD	0	-1	1	-1	-1	-1	-1	-1	-1	-1
GW	1	0	1	1	1	1	1	-1	-1	-1
OLD	-1	-1	0	-1	-1	-1	-1	-1	-1	-1
HT	1	-1	1	0	-1	-1	-1	-1	-1	-1
FWAE	1	-1	1	1	0	-1	1	-1	-1	-1
MAE	1	-1	1	1	1	0	1	-1	-1	-1
TE	1	-1	1	1	-1	-1	0	-1	-1	-1
PO	1	1	1	1	1	1	1	0	1	0
AC	1	1	1	1	1	1	1	-1	0	-1
EU	1	1	1	1	1	1	1	0	1	0
	7	**-3**	**9**	**5**	**1**	**-1**	**3**	**-8**	**-5**	**-8**

Table 3: Sequencing procedure

	EU	PO	AC	GW	MAE	FWAE	TE	HT	AD	OLD
β_ζ		1	1.1	1.1	1.7	1.2	1.1	1.1	5.4	1.6
w_ζ	1	1	1.1	1.21	2.06	2.47	2.72	2.99	16.1	25.8

Table 4: Calculation of weights ($w_\zeta = \beta_\zeta \times w_{\zeta-1}$, $\zeta = 2,...,n$, $w_1 = 1$, $\beta_\zeta \geq 1$)

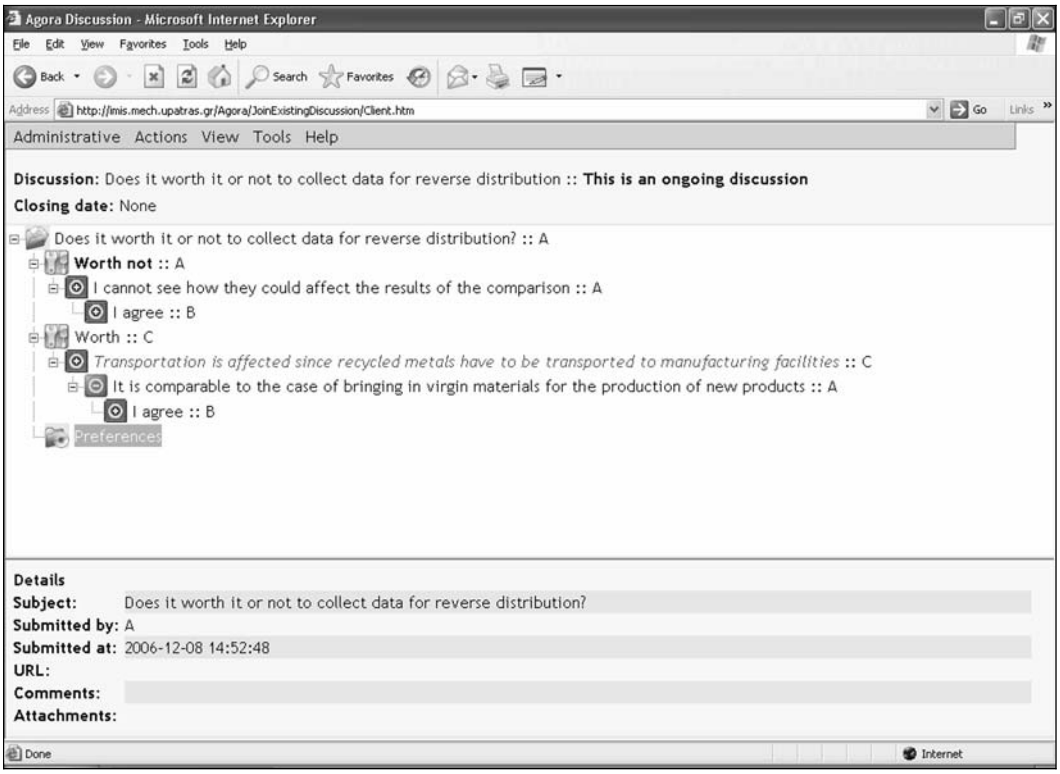

Figure 1: Collaborative decision making about the choice of the environmentally significant processes

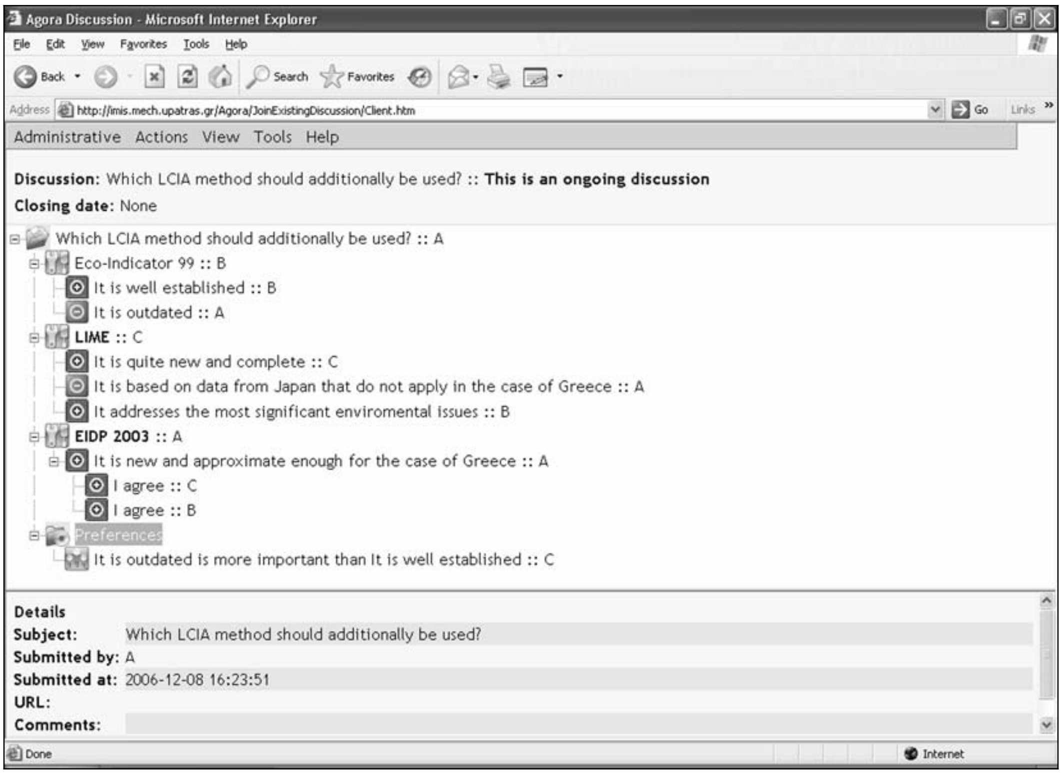

Figure 2: Collaborative decision making about alternative LCIA methods

	WEIGHTED VALUES	
IMPACT CATEGORY	**DISPOSAL**	**RECYCLING & INCINERATION**
AD	3.32E-12	-1.92E-12
GW	8.09E-14	-4.04E-14
OLD	1.81E-14	2.71E-15
HT	3.49E-14	-3.49E-15
FWAE	2.04E-14	-7.85E-15
MAE	1.28E-12	-7.06E-13
TE	2.53E-14	-5.29E-15
PO	2.65E-14	-7.06E-14
AC	2.06E-13	-5.81E-13
EU	5.45E-15	5.93E-16
AGGREGATED INDICES	**5.02E-12**	**-3.33E-12**

Table 5: Weighted values and aggregated indices for the two alternative scenarios

Further to the argumentation-based structuring of a discourse, the tool integrates a reasoning mechanism that determines the status of each discussion entry, the ultimate aim being to keep users aware of the discourse outcome. More specifically, alternatives, positions and preferences of a graph have an *activation label* (it can be *"active"* or *"inactive"*) indicating their current status (inactive entries appear in red italics font – see Figure 1). This label is calculated according to the argumentation underneath and the type of evidence specified for them. In the instance of Figure 1, the position "*Transportation is affected since recycled metals have to be transported to manufacturing facilities*" is inactive because, according to the argumentation rule holding for this specific discussion, it has been defeated by the position "*It is comparable to the case of bringing in virgin materials for the production of new products*". Activation in our tool is a recursive procedure; a change of the activation label of an element is propagated upwards in the discussion graph. Depending on the status of positions and preferences, the mechanism goes through a scoring procedure for the alternatives of the issue. A detailed presentation of more technical details concerning the argumentation-based reasoning and scoring mechanisms of the tool can be found in [10]. At each discussion instance, the tool informs users about what is the most prominent (according to the underlying argumentation) alternative solution (this is shown in blue bold font). In the instance shown in Figure 1, *"worth not"* is the better justified solution so far (while in the instance shown in Figure 2, "LIME" and "EDIP2003" are equally justified as best solutions). However, this may change upon the type of the future argumentation; each time an alternative is affected during the discussion, the issue it belongs to is updated, since another alternative solution may be indicated by the tool.

5 CONCLUDING REMARKS

Like LCIA, the Interpretation phase of LCA raises important issues, particularly if a decision-making procedure is involved during this phase. Multiple criteria, corresponding to the different Impact categories, have to be taken into consideration in such a procedure. In addition, other criteria have to be considered and taken into account in the decision making procedure. All these criteria are of different importance; therefore, they have to be weighted against each other. Questions raised during the Interpretation include how to arrive at the set of criteria to be considered, how their weights should be assessed and, generally, which decision making methodology to be employed in order to arrive at acceptable decisions based on the results of LCIA and the interests of the decision makers. Several approaches have been proposed in order to tackle such issues. In this paper, an advanced web-based collaborative decision-making tool, which includes several argumentation and knowledge management features, has been presented and its utilization in Interpretation has been demonstrated.

6 ACKNOWLEDGEMENTS

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Module Configurator for the Development of Products for Ease of Remanufacturing

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Abstract
Remanufacturing of products is already a profitable business field, but the potential is not fully exploited yet. Complex and manual processes, missing product information, high spare-part costs, quality problems as well as technological and stylistic obsolescence are the main obstacles for profitable remanufacturing. Vital elements for sufficient remanufacturing are efficient adaptation processes as well as advanced product design. Modularity is introduced as an approach to improve product design. For the development of appropriate modular product architectures, a methodology for the development of use-oriented modular product architectures based on module drivers is illustrated. A procedure for identifying future-robust requirements necessary for the specification of the module drivers is proposed. The approaches are finally discussed in the case study development of a Modular Mobile Phone Kit.

Keywords:
Modularity, Remanufacturing, Module Configurator

1 INTRODUCTION

The situation on earth is strained since global challenges related to socio-policy, environment and economy, e.g. famine, increasing resource consumption and greenhouse gas emission, movement of labor, and unemployment, are becoming more visible. The worldwide growing resource consumption results in a limited availability of resources, e.g. oil, gas, aluminum, and steel. With the end of the 21st century the global average temperature will be increased about two to seven centigrade compared to the actual value. In addition, oil will deplete in approximately 40 years, gas in approximately 50 years and coal in approximately 150 years [1].

To face these challenges, the current trifling with the resources and the ecosystem has to be stopped, so that current and future generations have the possibility to satisfy their needs. This goal cannot be achieved with current products expressing the life style of the Western world. A paradigm change in engineering has to be performed to increase the use productivity of resources.

Approaches to increase the use productivity of resources related to products are expanding the use phase, increasing the utilization ratio, and multiple use phases (Figure 1). Means for expanding the use phase are modification, maintenance and repair. Hereby the changes in physical and functional condition of a product are eliminated. Increasing the utilization ratio can be achieved by multiple uses of product functionality in different applications and by increasing the flexibility of products. Moreover, selling use instead of selling the product can contribute to this approach as well. Multiple use phases can be realized by remanufacturing and adaptation of products. *Nasr* defines remanufacturing as reviving a product to a like-new condition in terms of performance and durability by disassembling, cleaning, inspecting, repairing, replacing, and reassembling the components of a product [2]. Remanufacturing can also be interpreted as the adaptation of a used product to a new use phase characterized by changed physical and functional requirements. Kinds of adaptation are repair, up- and downgrading, enlargement and reduction as well as rearrangement and modernization [3].

Current product design often does not support the efficient and profitable realization of the identified approaches. Modularity has a high potential to improve product design respectively. A multi-criterion modularization methodology based on the idea of module drivers, also called Module Configurator is introduced and discussed exemplarily on the development of the Modular Mobile Phone Kit (MMPK). Module drivers are reasons and implications for grouping functional carriers to modules [4]. The developed methodology considers criteria related to the Product Life Cycle (PLC) and the identified approaches. A guideline for the identification of future-robust product requirements, necessary for the Module Configurator and for further development steps in the Product Development Process (PDP), complements the modularization methodology.

2 MODULARITY OF PHYSICAL PRODUCTS

Modular product architectures are composed of functional and physical independent assembly groups thus modules [5]. Functional independency is given if a module fulfils its designated function(s) autonomously not limited to specific products or product variants. Modules interact with other modules by exchanging energy, signal and material flows by means of module interfaces. Physical independency is given if the module interfaces allow ease of assembly, non-destructive disassembly, and reassembly.

2.1 Physical Independency

Module interfaces can be defined as technical interfaces describing the relations between modules [6]. According to *Pahl*, possible relations of interfaces are limited to an energy, material, and signal flow [7]. *Pimmler* adds geometric relations [8].

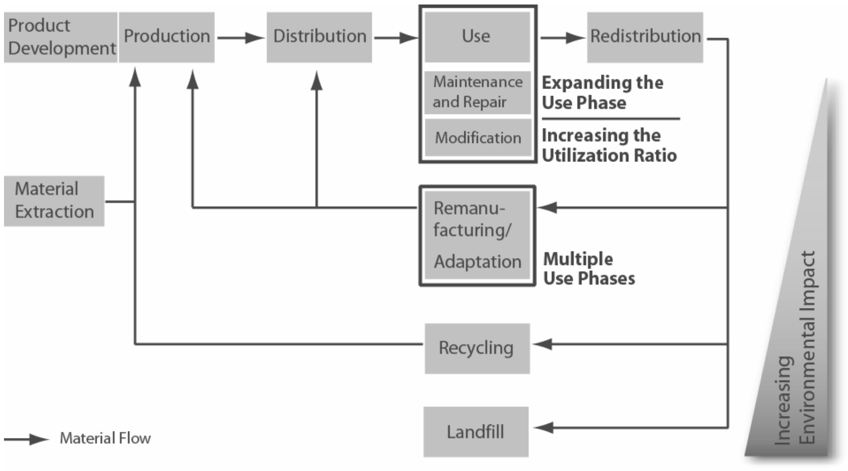

Figure 1: Product life cycle and approaches to increase the use productivity of resources, based on [3]

(Re)assembly and disassembly suitable designed module interfaces allow a postponement of the final assembly step thus contributing to Mass Customization [9] and increase the efficiency of manufacturing, maintenance, modification, and remanufacturing processes. Module interfaces should be standardized [5] to allow an efficient adaptation of a product as well as a module reuse in different products, product variants and generations. In order to assure the functionality of module interfaces, a definition early in the design process is crucial. Module interfaces have to be designed simple and in a way that they safely allow the transfer of energy, signal, and material flows [10]. Thereby, the disassembly and reassembly frequency has to be considered.

2.2 Functional Independency

The functional independency can be achieved by combining functional carriers of at least one product function in a module. In this context a function performs the transformation of an input in an output by considering a set of parameters. Input and output can be energy, information, and material. The product functions and its dependencies can be illustrated in function structures [7].

The potentials of modularity have a particular effect if more than one function represented by a functional carrier is incorporated in one module. For example the effort for design and manufacturing of module interfaces is increasing with a growing number of modules.

The complexity of developing modular product architectures is increasing with the number of functional carriers of a product thus with the number of feasible modular product architectures with varying technological, ecological and economical impacts along the PLC. Therefore, the product designer has to be supported by a tool to handle this complexity.

2.3 Module Configurator

The principal idea of the multi-criterion modularization methodology is based on the evaluation of all feasible module configurations by module drivers and a target scheme characterized by a variable weighting of module drivers assigned to the PLC phases. Consequently, changing the target scheme effects a change of the module configuration. That means by changing the target scheme with focus on reuse, the modular product architecture can be optimized for ease of remanufacturing.

The module drivers are identified by analyzing and comparing modular and non-modular products according to the identified approaches and the PLC phases. Hereby, potentials and risks of modularity are considered. In addition relevant criteria and module drivers of the analyzed methodologies are implemented in the list of module drivers (Table 1).

Product life cycle phase	No.	Module Driver	Specification for mathematical description
Product development	1	Time-to-market	Development time
Product Development and Production	2	Assembly/ Configuration (Complexity of module interfaces)	Energy flow intensity
			Material flow intensity
			Signal flow intensity
	3	Core competences and supply chain	Manufacturing location
Production, Use and Remanufacturing	4	Reuse of functional carrier	Other product class
			Other product model
			Other product generation (carry over)
Use and Remanufacturing	5	Use of functional carrier	Use ratio
	6	Product innovation	Innovation cycle
	7	Maintenance	Inspection cycle
			Maintenance cycle
			Repair cycle
	8	Adaptation/Modification	Substitute function
Remanufacturing, Recycling, and Landfilling	9	Treatment after the first use phase	Remanufacturing possibility
			Recycling possibility
			Landfilling possibility

Table 1: List of identified module drivers based on [11]

In order to reduce the complexity of the optimization problem the number of feasible modular product architectures is reduced by defining two constraints. The first constraint predefinition of functional carrier combinations is aiming on excluding combinations of functional carriers to modules thus limiting the number of possible modular product architectures. The second constraint pre-clustering of functional carriers is aiming on the grouping of functional carriers according to standardized, market-specific, and additional functionality. The grouping of functional carriers to modules is carried out within these groups [11].

Functionality

The generation and evaluation of all feasible modular product architectures characterized by different module configurations is supported by the developed web-based Module Configurator. A C++ program generates modular product architectures and formulates an Integer Linear Program (ILP), which is processed by a CPLEX solver. The product related data and the weighting of the module drivers are entered in a MySQL data base via a website. The result, the modular product architecture with the highest benefit, is stored in the database and illustrated on the website.

The ILP is a special form of a Linear Program (LP), which is an essential tool for Operation Research. Thereby, an optimal solution for a linear objective function is calculated. The value of the objective function is restricted to equations and inequalities, the so-called constraints of the LP. LPs are strong tools and do not require a specific development of an algorithm. The variables of the multi-criterion modularization methodology have to be integers. Therefore an ILP was chosen [11].

The objective function of the Module Configurator is:

$$\max \sum_{S} \sum_{K} W_s \times N_{sk} \times X_k$$

The value of the objective function is maximal for the most beneficial modular product architecture. The benefit of the modular product architectures is composed of:

- W_s, the weight of the module driver *s*,
- N_{sk}, the benefit of the module combination *k* for a module driver *s*, and
- $X_{k,}$ the decision variable, which determines the chosen module combination,

for a set of feasible module configurations *K* and a set of module drivers *S*. The benefit of each module configuration N_{sk} depends on the properties of the respective functional carriers *i*. The decision variable X_k can have the value 1 or 0. Consequently the result of the ILP depends on the values of the module drivers weight W_s. The definitions of the mathematical constraints for the ILP are:

1. $$\sum_{K} \left(a_{ik} \times X_k\right) = 1 \qquad \forall i$$
   The constraint defines that each functional carrier *i* has to be in one module combination *k*. Thereby the parameter a_{ik} describes if a functional carrier *i* is contained in module configuration *k*.
2. $$\sum_{S} W_s = 1$$
   The sum of all module driver weights W_s is one.
3. $$\sum_{B} a_{ck} \times X_k + a_{dk} \times X_k \leq 1$$
   $$\forall (c,d) \in B$$
   Two incompatible functional carriers *(c, d),* element of all incompatible functional carriers *B*, have to be in different modules.

Limitations

The developed Module Configurator is capable to calculate the modular product architecture with the highest benefit for a defined task characterized by a target scheme. The target scheme describes the weighting of the module drivers. Limitations of the existing Module Configurator version are the following [11]:

- Depending on the amount of selected module drivers, many product specific data have to be entered in the database. This step can be skipped, if the functionality of the Module Configurator is enhanced with a software interface allowing the import of product data from other applications, e.g. a product data management system.
- For the calculation of the optimal modular product architecture the Module Configurator is limited to a task with a total number of 20 to 30 functional carriers. The pre-clustering of functional carriers is a powerful mean to enhance the task beyond 30 functional carriers and to reduce the calculation time.

Needed Information

According to the product development process of VDI 2221 and *Pahl* and *Beitz* the process of developing the modular product structure is located in the embodiment design stage [7], [12]. In this stage the function structure and the principal solution are given. Prerequisites for the application of the Module Configurator are the following:

- Classification of product functions, according to target market, standard functionality, etc.,
- Function structure with energy, material, and information flow intensity,
- Principal solution and properties of the identified functional carriers,
- Information about vertical integration, suppliers and manufacturing location for each functional carrier,
- Information about the product spectrum of the manufacturer, the suppliers and the customers today and in the future,
- Estimated utilization ratio of functional carriers,
- Estimated innovation, inspection, maintenance, and repair cycles for functional carriers, and
- Estimated reuse, recycling, and landfill potential after the first use phase for each functional carrier.

Most of the required information about the product is generated in the preliminary product development stages, product planning and conceptual design. A procedure for the development of future-robust requirements about a product, e.g. future customer demands, as well as about every functional carrier of the respective product, e.g. reuse potential after the first use phase, which are crucial for the development of lasting modular product architectures, is introduced in the following chapter.

3 GENERATION OF FUTURE-ROBUST REQUIREMENTS

A two phased strategy advancing a prior approach [13] for defining the above described prerequisites for the application of the Module Configurator is introduced. The first phase is situated at the beginning of the conceptual design of a product [7], [12]. In this phase, the classification of required product functions is supported by analyzing possible scenarios which are set up using scenario management [14]. The scenarios are created according to the PLC, for the first and second use phase, and for the remanufacturing process.

In the second phase, parallel to the conceptual design, the behavior of each functional carrier in each of the defined scenarios is analyzed. By comparing the predicted behavior with prior gained knowledge about e. g. the remanufacturing of used products, the specifications for each functional carrier are derived and can be used for the calculation within the Module Configurator.

With the scenarios for the first and second use phase, the target market of the product is analyzed. For the first use phase, important influencing parameters are the customer expectations towards the functionality of the product, combined with business models for the considered markets. Further boundary conditions are e. g. infrastructural or ecological and environmental issues, both in general and specific for the products target markets. Depending on the field of application, also legal provisions, like the WEEE, may have to be concerned.

For the second use phase scenarios, the same influences as for the first use phase are relevant, supplemented with estimated technological developments. Technologies are developing in time, so that technologies not available for implementation today may reach the stage of maturity until the beginning of the second use phase of a product and would have to be considered then. Besides the scenarios for the first and second use phase, scenarios for the remanufacturing process between the use phases are created. For these scenarios, the main influences are logistical issues (reverse logistics, redistribution, and amount of used products), available processes for disassembly, cleaning, testing, and repair as well as available process chains.

After creating the scenarios, it becomes possible to derive product functions and resulting requirements for each scenario by assuming the projected situation as given. Common methods for identifying product functions and associated requirements, like Quality Function Deployment (QFD) or product market matrixes, can be utilized in this step. By matching the outcome with the probability for coming true of the several scenarios, current and future requirements towards the product can be defined. By formulating the requirements list and the function structure, the strategy again merges with the product development process according to VDI 2221 and *Pahl* and *Beitz*. Subsequently, working principles for fulfilling the sub-functions defined in the function structure will be selected, and functional carriers are developed [7], [12].

In the following phase of the product development process, the modular product architecture is created by applying the Module Configurator. As mentioned above, information for several module drivers has to be provided for obtaining a suitable modular product architecture. The relevant information can be derived by examining the use phase and remanufacturing scenarios again, together with the defined functional carriers. The behavior of each functional carrier is analyzed for the defined scenarios.

Possible findings are, for example, functional carriers which are no longer relevant to the product in the second use phase due to changed customer requirements or advanced technologies. The estimated treatment after the first use phase of these would therefore be recycling prior to disposal, besides being reused. In the same way, a functional carrier which is required during the first and second use phase would gain a high remanufacturing and reuse potential.

By comparing the use scenarios with the customer behavior today, customer influenced specifications like the utilization ratio of functional carriers can be estimated. In the same way, comparing gathered technological knowledge instead of the customer's behavior, technological specifications like estimated innovation, inspection, maintenance, and repair cycles of the functional carriers can be defined.

Further relevant specifications of the functional carriers, like flow intensities can be derived directly from the function structure, defined earlier in the PDP. Cross product information, like the overall product spectrum of a manufacturer and supplier, or about supplier and manufacturing locations, will have to be drawn from e. g. business strategies, corporate roadmaps or similar.

4 DEVELOPMENT OF A MODULAR MOBILE PHONE KIT

The case study Modular Mobile Phone Kit (MMPK) has been carried out in parallel to the development of the Module Configurator. Therefore the case study is limited to the application of module drivers without a mathematical optimization. In addition, the developed scenarios for the specification of the module drivers and for the detailed design of the MMPK are focusing on the second use phase. Nevertheless, the idea and the feasibility of the described modularization methodology Module Configurator supported by scenario management for the identification of future-robust requirements can be illustrated in this case study.

Background of the case study is the environmental impact of mobile phones due to their large production volumes and characteristically short time scales of technological and stylistic obsolescence. This is unsurprising taking into account the total number of mobile phone users in 2003 estimated with over 1.3 billion [15] and an average use time between 18 to 24 months.

The finding of a recent study estimating the environmental impact of the end-of-live options remanufacturing, recycling, and landfilling for two life cycles of an identical mobile phone is that 270 MJ of energy can be saved by remanufacturing compared to landfilling. This amount of energy represents approximately 10 days of energy consumption for an average German household [16], [17].

Third party remanufacturers, e.g. Recellular, have identified the collection and treatment of used mobile phones as a competitive business field. Most of the collected mobile phones are sold in markets of emerging and less developed regions [18]. These activities are mainly driven by profitability and not by legislation, such as the WEEE [19].

However the remanufacturing of mobile telephones is not fully exploited yet. Complex and manual processes, various product models, missing product information, high spare-part costs, quality problems as well as technological and stylistic obsolescence are the main obstacles for profitable remanufacturing of mobile phones. In fact, current activities are predominantly focused on refurbishment. The applied processes are manual sorting, cleaning, data deletion and firmware upgrade, and packaging. Disassembly, reassembly, and adaptation are carried out for only 10% of the mobile phones. Therefore, the remanufacturing of many mobile phones, with e.g. broken housing components, is not carried out. These devices are usually disposed and recycled [18]. Especially the low grade of modularity and standardization contributes to less profitability in remanufacturing of mobile phones.

Goal of the case study is the development of a MMPK suitable for efficient maintenance, repair and modification as well as for remanufacturing and adaptation. Additional requirement is the standardization of the housing components for the form factors candy-bar, slide, and flip phone so that a reconfiguration supported by simple disassembly and reassembly operations of the mobile phone is possible. For the development of the modular product architecture the multi-criterion modularization methodology is applied. In order to derive the necessary information for the module drivers, e.g. remanufacturing possibility, the above described approach is used.

The objective of the scenario management is the identification of product requirements for the first and second use phase. The focus of the case study is on the remanufacturing suitability of the MMPK. Therefore only “Reuse” scenarios have been developed to estimate the remarketing potential in Asia and Africa and the profitability of remanufacturing. The time horizon for the scenarios was chosen for five years.

Based on the scenarios weak-points of current mobile phone models, recommendations for the design of the MMPK, and the weights of the modules drivers has been derived. Weak points of current mobile phone models are, e.g. low grade of modularization and standardization, complex disassembly by snap-fit, glue and screw connections, different assembly and disassembly directions, high costs for cosmetic part supply such as housing and keypad. Recommendations for the design are, e.g. modularization of the product architecture, standardization of modules, module interfaces and housing components, disassembly and reassembly suitable module interfaces, and decoupling of the electronic interior components from the housing. The most important module drivers assigned with a high weighting are: core competencies and supply chain, reuse of functional carrier, product innovation, and treatment after the first use phase.

After the development of the principal solution of the MMPK the modular product architecture is developed by applying the multi-criterion modularization methodology. The necessary specifications of the functional carriers are derived by analyzing the developed scenarios, the technical specifications, and the list of requirements. Based on the best modular product architecture the alignment of the modules has been generated by considering the different form factors of mobile phones. The final arrangement of the modules is characterized by a platform, the printed circuit board, and several attached modules (Figure 2) [20].

5 SUMMARY AND OUTLOOK

A combined approach for the application of the Module Configurator, a multi-criterion modularization methodology based on module drivers, and the identification of future-robust product requirements necessary for the specification of the module drivers has been introduced. Parts of this approach have been exemplarily discussed on the development of a Modular Mobile Phone Kit (MMPK).

Further work is focusing on testing and improving the respective methodologies. In a closer perspective is the development of manufacturing equipment, supporting efficient adaptation to changing functional requirements in multiple use phases. Manufacturing equipment in industrialized countries may have other functional requirements on accuracy, productivity, grade of automation, and maintainability, than for use in emerging and developing countries. Reasons are different conditions related to the skills of employees to operate the manufacturing equipment, the availability and the affordability of spare parts and auxiliary supplies, and the production volume. Concerning further methodology development, the introduced procedure for defining future-robust product requirements could be extended in order to generate design indices and constraints for the embodiment design of functional carriers as well as for the designed product.

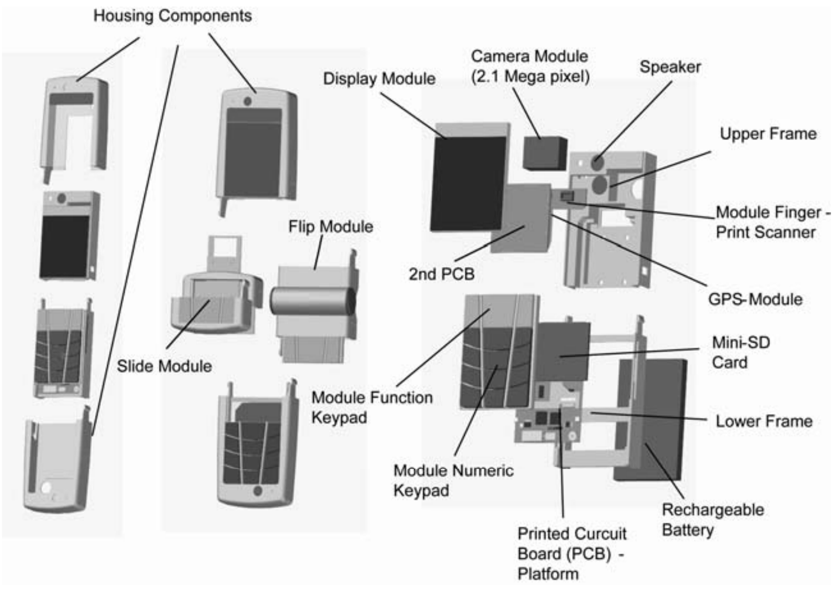

Figure 2: Prototype Modular Mobile Phone Kit (MMPK) [11], [20]

6 ACKNOWLEDGMENTS

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Life-Cycle Assessment simplification for modular products

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Abstract
As experience in EcoDesign increases, academic and industry thinking is moving towards the more advanced stages of EcoDesign; moving away from product improvement and product redesign into the more holistic approaches of Alternative Function Fulfilment (AFF) and system innovation. This paper investigates how modularity concept, applied to product design, allow much degrees of freedom for the designer, more possibility to reduce environmental impact related to product life-cycle and increase the interaction between LCA and the earlier stages of the (Eco)design process. A method, based on the product modularity concept, to increase LCA usability for the designers is proposed in this paper.

Keywords:
EcoDesign; LCA; Modularity; Alternative Function Fulfilment

1 INTRODUCTION

Since the Brundtland commission first coined sustainable development in 1987, society has become aware that it has to find solutions “that meet the needs of the present without jeopardising the needs of future generations” [1]. Companies are challenged to contribute to sustainability by improving the environmental performance of their current way of doing business. This means reducing the amount of natural resources, energy consumption and toxic emissions related to the manufacturing, use and disposal of their products and services.

It is evident that we are faced with a challenge. If we are to take up this challenge, these targets for improvements will need to be operationalised. That is when the discipline of cleaner production and more specifically the field of ecodesign emerged.

Ecodesign can be defined as design which addresses all environmental impacts of a product throughout the its complete life cycle, without compromising other criteria like function, quality, cost and appearance’ [2].

The aforementioned challenge has been visualised by using the hierarchy of the Rathenau Institute [3], which takes an ecodesign viewpoint.

The hierarchy illustrates that environmental improvements can be made in four stages, with each stage increasing both potential environmental benefit and the degree of innovation that is required in the design process [4]. This hierarchy is shown in Figure 1.

The four stages can be explained as follows [3]:

Stage 1. *Product improvement*—improvement of aspects of products that are already on the market.

Stage 2. *Product redesign* or *eco-redesign*—optimising the environmental quality of existing or newly developed products.

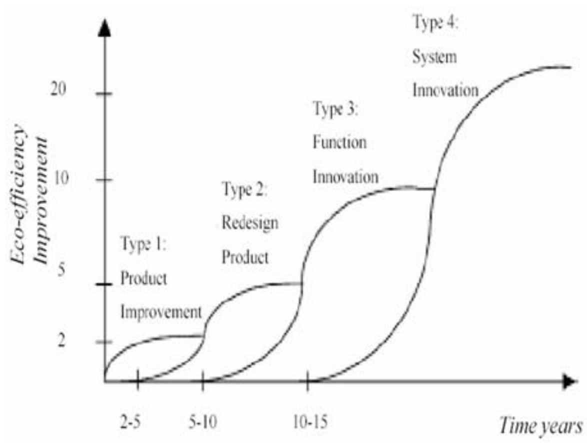

Figure 1 : The four stages in Ecodesign.

Stage 3. *Function innovation* or *alternative function fulfilment (AFF)*—this type of change is no longer confined to the existing product concept; the way the function is fulfilled, is changed.

Stage 4. *Sustainable systems innovation*—replacing whole product systems with more ecoefficient ones, that usually require less energy, materials- and space-intensive infrastructure.

As experience in ecodesign increases, academic and industry thinking is moving towards the more advanced stages of ecodesign; moving away from product improvement and product redesign into the more holistic approaches of Alternative Function Fulfilment (AFF) and system innovation. This paper focus on the third stage of ecodesign, AFF, proposes some reflection on its application to modular products and investigates how this approach could be facilitated by their intrinsic characteristics. Modularity has been deeply investigated during the past years and the implication of its application to the design of product involves all its lifecycle. The link between modularity and the AFF approach is that both concepts are focused on products functions, while AFF has the target to changing the physical principles a function is fulfilled by, the application of modularity concept helps to investigate how this deep changing involves the whole product architecture.

Moreover the modularity concept implies many aspects which allow some simplifications on the application of the Life Cycle Assessment (LCA) methodology, simplifications that are presented in this paper too.

LCA is the most commonly accepted method for assessing the environmental impact of a product through all its life cycle stages: from extraction and processing of raw materials to manufacturing, transportation and distribution, and final reuse, maintenance, recycling, but its application is not simple, time-consuming and it is more complex in the first stages of the product design but at this stages is the main possibility to improve products environmental performance.

When a (Eco)design process is in progress, especially when AFF is the target, LCA is not ever so usable for many operational factors which limit the integration of the three LCA components (inventory analysis, impact assessment and improvement assessment) with product development.

This paper investigates the LCA interaction with the earlier phases of the AFF ecodesign approach and provides a method, based on the product modularity concept, to increase LCA usability for the designers.

2 RELATED WORKS

Designing a product is mainly the task of a multi-disciplinary team trying to consider as soon as possible the constraints of each people involved in the product life cycle. Research work done in this field was concentrated on developing methodologies and tools to support the environmentally conscious design [5], but they provide essentially qualitative suggestions not sufficiently deep to adopt new solutions.

However, the complexity and generality of LCA systems, which provide quantitative comparisons, generate restrictions to their use in current mechanical products and systems development, especially for SMEs [6], because it is apparently in contrast with a desirable short time to market and a low product cost.

Furthermore, environmental assessment is typically performed after the design process, when the product data are more consistent but the possibility of influencing the design is minimal. In according to Bhander et al. [7], LCA tools need to be integrated into the design process and the environmental impacts need to be evaluated concurrently to the other design procedures providing an immediate feedback to the design team.

Similar concepts are reported in Dewulf and Duflou [8] and Rosemann and Meerkamm [9]. In both cases interesting methodologies are proposed to evaluate product alternatives during the early phases of design process. In the last years the discussion about LCA methodology regarded the feasibility of simplifying it and adapting to the designer needs [10].

Different methods have been proposed. The simplification regarded the reduction of data needs by excluding different levels of life cycle stages and/or substituting external databases for them [11], by using a qualitative and semi-qualitative LCA [12] .

3 MODULARITY AND PRODUCT LIFE CYCLE

As described above, ecodesign is the integration of environmental consideration in the traditional design process.

From the opposite point of view it is possible to affirm that ecodesign can and must take advantage of the most powerful design tools and practises. In the following paragraphs, a brief introduction to modularity concept is given and is described how ecodesign can take advantage of it and its application to the product architecture.

3.1 Introduction to modularity

The purpose of modularity is to gain flexibility for mass customization and obtain scale and scope advantages and economies in part sourcing.

In an increasingly competitive and segmented global marketplace, the need to diversify is greater than ever before.

Advances in production technologies has rendered out many of the differences in product quality, and thus changed the competitive environment companies find themselves in.

Traditional mass production has in the past decade been replaced by the concept of mass customization, mass production of customized products. To overcome the great complexity that customization potentially creates in the manufacturing systems, modularization is used as a tool to break the product structure into smaller, manageable units [13]

Modularity allows greater reusability and sharing of components among different products.

The definitions of a module used in the article are as follows.

Modules are defined as physical structures that have a one-to-one correspondence with functional structures. They can be thought of quite simply as building blocks with defined interfaces [13].

A module is fairly loosely connected to the rest of the system allowing an independent development of the module as long as the interconnections at the interfaces are well thought of [13].

This consideration on how modularization of product can benefit enterprises business and efficiency and the given definitions of modules have many implication with product life cycle and the interaction between LCA methodology and the early design stages.

3.2 Modularity and AFF

In the previous paragraph we gave two of the most useful definitions of modularity.

From the above description and the given definitions it is clear that modularization of product gives a great advantage to the manufacturer in terms of costs reduction, easier mass customization, faster development, and so on.

For this reason, in the industrial production world, modularity is seen as one of the goal of a good design. Many industries are moving in this direction.

From a ecodesign and in particular AFF process point of view modularized product have some characteristics which facilitate this innovation process.

Modularization often means tradeoffs with performance or other factors but the advantages can often override the disadvantages. Modularity decisions are often done to re-engineer existing products but modularity can be also considered at the technology research and development phase in order to decide what physical principles should be looked into [14]. This early planning for modularity allows more flexibility in the design of the product. Flexibility means more product variations, room for environmental improvement, and changing of modules without difficult changes to the rest of the system.

In an AFF prospective modularity can be seen as a great advantage in radical product development.

From a modularity point of view a function of a product is fulfilled by one or more single modules. Choosing different solution principles which a function is performed by, only single modules are involved by this changing. Modularity tries to enable independent development of a module. This evaluations allow much degrees of freedom for the designer and more possibility to reduce environmental impact related to product life-cycle.

3.3 Modularity and LCA

The consideration made in the previous paragraphs about modularity have some consequences on the way to apply LCA methodology to modular product. To understand which simplifications are allowed in the execution of the LCA analysis for a modular product it is necessary first to investigate how modularity influences each modules life-cycles after a deep changing on the physical principle by a single module fulfil its function.

High grade modular products present the following characteristic regarding their life-cycles:

Attribute Independence: Component attributes have fewer dependencies on attributes of other modules, called external attributes. If there are dependencies, fewer attributes are dependent upon one another and attributes that are related to external attributes are less dependent. E.g., Lego® pieces which can be of any colour, size, shape, or material as long as they have the correct dot to attach to other pieces and an impression to accept other pieces. Attribute independence allows for the redesign of a module with minimized effects on the rest of the product. Attribute similarity is excluded because having similar but unrelated components is not detrimental as long as attribute independence is maintained [15].

Process Independence: Each task of each life-cycle process of each component in a module has fewer dependencies on the processes of external components. This requires that the processes a module undergoes during its life-cycle are independent of the processes undergone by external modules. Any dependencies that do exist are minimized in number and criticality. E.g., in separation for recycling, techniques that utilize grinding and separation by material density are dependent upon the disassembly of all components containing materials that are not compatible and are of a similar density. If the disassembly process occurred later in the retirement process, grinding and density separation would not be possible. Process independence allows for the reduced cost in each life-cycle process and the redesign of a module in isolation if processes should change [15].

It is now possible to affirm that modifications introduced in a single module influences just its own life-cycle and have no or not so remarkable influences on the other modules lifecycles.

Any interaction is limited to same stage of the life-cycle and they are not relevant.

Therefore to assess the environmental advantage deriving by product improvement just the LCA analysis of the new module should be conducted.

These considerations are very powerful when LCA methodology is applied to modular product. In an AFF approach we can affirm that modifications in the way a function is fulfilled by a single module does not influence other modules life-cycles which can be treated as a single product and life-cycle can be analysed singly.

This simplification strongly decreases both time need for the application of the methodology and the quantity of necessary data during the inventory phase, improving the possibility to apply the LCA also in products at the developing stage.

Moreover this research tries to verify the possibility that modules of different products that fulfil the same function using the same technology have similar LCA results.

If this assumption would be verified, lack of data and the consequent difficulty on evaluating the environmental impact of a radically changed product should be managed both taking the needed information from the life cycle of the same module, from a functionally point of view, used by another product and adopting its entire LCA when necessary.

Increasing complexity of technological development, shortened innovation cycles and cross-fertilization of technologies make it hard for a company to compete on its own [16]. Modularity is applied to product also for individuate scope, joint tasks, and objectives of the collaboration between enterprises for collaborative Research and Development [14]. This is because minimum interactions to the outside of the object reduce the apparent complexity of the end products as well as the development process [15]. Now days many technologies are developed inter-firms and consequently modules of different products are designed together.

This affirmations seems to suggest that the above assumption could be verified but investigations are needed. Preliminary results supporting this theory are presented in this paper.

4 CASE STUDY

The theory presented in the previous paragraph could be very useful during the early stage of the design process.

To support the above affirmation and to present the preliminary results of this research activity a case study has been conducted.

A dishwasher and a bathtub have been chosen to conduct the two compared LCA.

4.1 Modules identification

First of all modules of the dishwasher and the bathtub have been identified using the heuristic method [17]. A detailed description of the heuristic method can be find in literature but the following paragraph give a brief introduction of it.

A functional model has been created. The first task of the functional model derivation is to create a Black Box model, a representation of a product's overall function and input/output flows. The overall function of the product is expressed in verb-object form. For each input flow, a chain of sub-functions that operate must be developed on the flow. Here, the designer must 'become the flow.' Think of each operation on the flow from entrance until exit of the product (or transformation to another flow) and express it as a sub-function in verb-object form [17].

The designer could empirically individuate each module analyzing the functional model of the whole product and following the input flows through the model. Figure 2 shows the functional model of the water's conveyor module of the dishwasher and of the bathtub, these modules will be called water modules for simplicity in the future,. The functional model of the whole product could not be shown for obvious space problem.

The water modules have been chosen as the subject of this study. The main function of the water modules is to carry water from the aqueduct to the final output in the sewer.

The both modules of the dishwasher and of the bathtub, perform aforesaid function fulfilling the following sub-functions:

- To carry water from the aqueduct to the dishwasher pump.
- To distribute the water for the product operations.
- To carry water from the washing module to the sewer.
- To guarantee watertight.

This main sub-functions are performed by both the two water modules of the dishwasher and bathtub so it is possible to affirm that from a functionality point of view the two modules can be considered equivalent.

To be sure of the similarity of the two modules their architectures have been compared and differences between modules architectures will be discussed in the following paragraph.

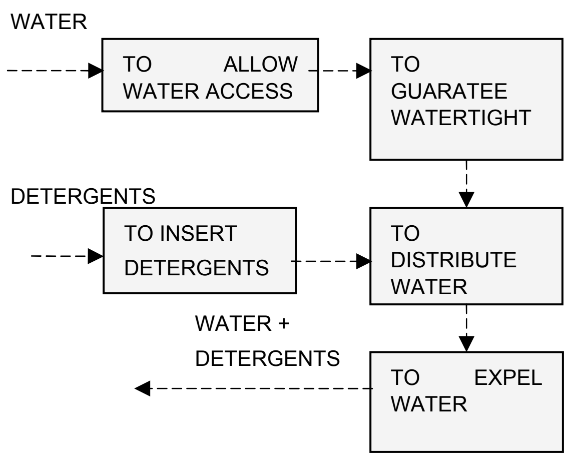

Figure 2: Functional model of the water's conveyor module.

4.2 LCA of modules

Identified the object of the study, before conducting the two LCA analysis, more consideration on the architecture of the two modules are needed. The differences between sub-functional groups of component are managed as a designer at the early stage of the development process could do, differences that could not be recognised when just a rough layout is defined have not been corrected before the analysis.

- The dishwasher contains less component with the function to guarantee the watertight (o-ring, gasket, etc.) than the bathtub but this difference could not be identified at an early design phase so all the bathtub components are included in the analysis.
- The bathtub distribution system carries water to 4 jet while a dishwasher have 2 of them, this information could be available at a early design phase and it has been managed including only 2 distribution systems in bathtub LCA.
- The bathtub module has been designed for a higher flow of water than the dishwasher one, therefore pipes and other components dimensions are greater and their mass too, the module has been analyzed as it is.

Table 1 summarizes the main component for the two product modules.

	Bathtub	Dishwasher
watertight	ring (steel), Oring (EPDM), gasket (EPDM), ring nut (PP)	ring nut (ABS, steel scrap), Oring (EPDM), gasket (EPDM)
Water distribution	Injection moulded part (PP,PE,PVC)	injection moulded part (PC, ABS, PVC)
water input	Pipe (PVC)	Pipe (PVC)
water output	pipe (PP), small sump (EPDM), Filter (steel)	pipe (PP, PVC, Polyester resin),

Table 1 : Main components of modules.

After this preliminary considerations LCA of the two modules has been conducted under the following operational condition:

- End of life life-cycle stage has been neglected because there were not enough available information.
- Distances for the transportations for material and components acquisition have been considered from dishwasher manufacturer's traditional suppliers.
- Use phase has not been included in the study because these modules does not need any particular maintenance and there is no energy or auxiliary material use.
- Databases have been used for the inventory phase

4.3 Results

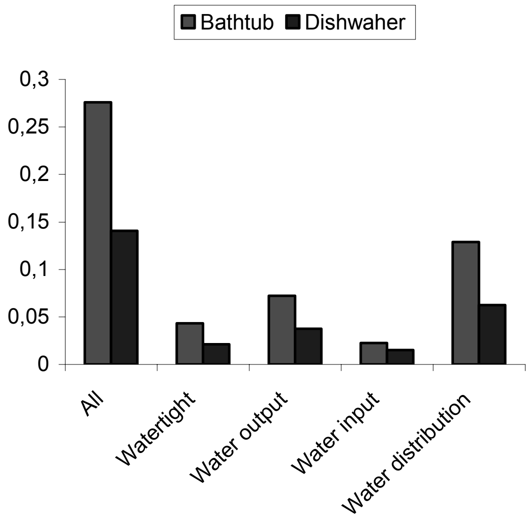

Figure 3 : EI 99 value for the two modules.

Figure 3 shows the results of the analysis classified not in life-cycle stages but in the sub-functions fulfilled by each modules. The EcoIndicator 99 (EI 99), Hierarchist Approach, method have been used to calculate results [18].

These results show that the values of the EI 99 are higher for the bathtub and its component but there is a proportionality between results that can be underlined by the graphic in figure 4 which shows the results in percent. Evidently functionality is not the only parameter that guarantees that modules life-cycle can be considered the same in both the product; volume, mass and flow could influence the absolute values of the indicators. A scaling factor of around 2 can be recognised between the values of the two modules, this factor seems to be mass or flow dependent but more investigations are needed to support this affirmation.

Although different in the absolute values, percent values for the EI of each sub-functional group of components have no more than a 3% difference, the bathtub LCA results can be used, in this representation, to analyse the dishwasher life-cycle environmental hot spot. Moreover to underline the reliability of this results the value of environmental indicators that they contribute in maximum part to the composition of the absolute value of the EI 99.

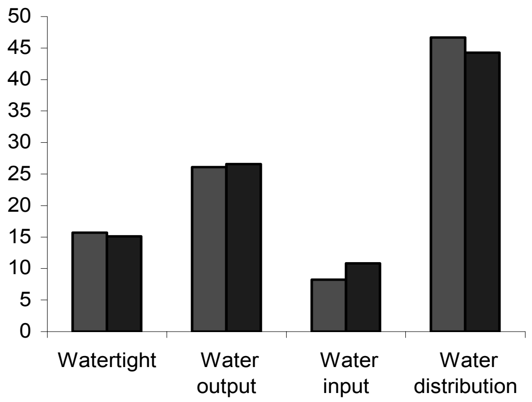

Figura 4 : EI 99 percent value.

Graphic in figure 5 shows the Climate Change category impact indicator, graphic in figure 6 shows the Ozone Layer Depletion category impact indicator and graphic in figure 7 shows the Carcinogenic Effects category impact indicator.

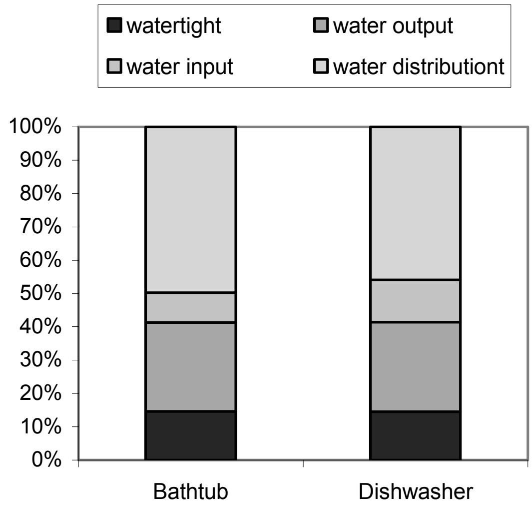

Figure 5: EI99, HA, climate change [DALY].

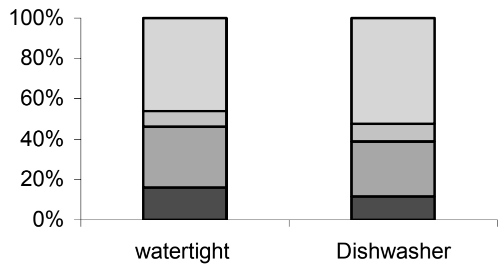

Figure 6: EI99, HA ozone layer depletion [DALY].

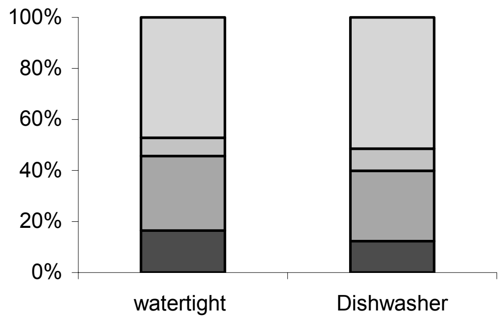

Figure 7: EI99, HA Carcinogenic effects [DALY].

Same graphics for each environmental impact category indicator could be presented and each one would show high proportionality between each value of all sub-functional groups of the two modules. Moreover each single environmental indicator gives quite the same contribution to the EI 99 values for the two modules and each sub-functional groups have the same contribution too.

5 CONCLUSION AND FUTURE WORKS

It is possible to affirm that graphics in figures 5,6,7 represent a an encouraging result.

The proportionality between each sub-functional groups of components of the two modules results on the composition of the EI 99 final value (Figure 3) and between each sub-functional groups of components results on the composition of each single environmental indicator (Figure 5,6,7) makes the results useful to individuate the environmental hot spot also in the dishwasher life-cycle without perform a full LCA on it. At a early stage of the design phase many choices on product architecture and functionality are still available and radical change on product architecture could be analyzed trough other products LCA.

Of course, more investigations are needed to support the presented theory on this LCA simplifications.

Causes of the discrepancy between absolute values of the indicators must be deeply investigate maybe to give a method to predict the scaling factor based on the modules functional characteristic.

In this case, if the hypothesis of relationship between the flows value for the two modules and the scaling factor of the environmental indicator would be demonstrate, association between Life-cycle and functionality could be underlined.

Moreover this research must be extended both analyzing more product functions and different technologies applied in many production field.

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The Optimization of the Design Process for an Effective Use in Eco-Design

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Abstract
Nowadays the importance of the environmental sustainability of industrial products has become significant because of the ever-stricter environmental legislation in the field, and thanks to the higher awareness of customers concerning environmental problems. The development of sustainable products leads engineers to take into considerations environmental aspects in concurrency with traditional technical and economical aspects since the beginning of design activities. It is clear, then, the importance of using a suitable design framework for the products' development. The output of the study consists of the development of easy-to-use guidelines, which is able to indicate in practice to designers the addresses that can be followed for a more effective action.

Keywords:
Sustainable Design; Ecodesign Methods, Design Process

1 INTRODUCTION

The evolution of the concept of Sustainability in modern industrial world has brought to light the importance assigned to the early stages of the product's development, i.e. the design activities. It is of common knowledge that making decisions in these stages allows producers both to guarantee the products' optimization from the performances point of view, as well as to be more market competitive, drastically reducing the costs related to subsequent modifications and corrections of the product during the manufacturing phases or even after its introduction in the market.

At the same time, it has to be considered that the growing attention for the environmental impact of industrial products in recent years is being accompanied by the effort of public bodies of different countries in issuing new indications and regulations in the field. In such a context it is fundamental for designers to have at their disposal a specific ecodesign framework able to lead them in carrying out the project in the most effective and efficient way.

For these reasons, starting from the analysis of the various schemes for the product development presented in literature, the research work was focused on the definition of the most significant aspects, which characterize the first stages of the "Design for Environment" activities, considering all the stakeholders involved in the product's life cycle.

The final goal of the study was the definition of an easy-to-use design process' scheme of a general nature that can lead engineers in their activities, optimizing at the same time both the use of most common Eco-Design tools, as well as the integration with recent Environmental Regulations.

More in details, in section 2, a brief analysis of the "state of the art" of the Sustainable product development is discussed. Then in Section 3, the attention is focused on the analysis of the latest schemes of Design Process. In section 4 our research approach is discussed and some examples of its application are given. In section 5 and 6, results and conclusions are discussed.

2 TOOLS FOR THE DEVELOPMENT OF SUSTAINABLE PRODUCTS

In last years a considerable research work has been carried out in order to investigate different ways of supporting engineers in the development of environmentally friendly products. The industrial world has changed its approach to the Environment, gradually shifting from the end-of-pipe approaches, which have characterized last decades, to the trend of Design for the Environment approaches, starting from early 90s' and after. As a matter of fact, the importance of the environmental sustainability of industrial products has become the more and more significant because of the ever stricter environmental legislation in the field, as well as because of the higher awareness of customers concerning environmental problems [1, 2, 3].

In fact, beside prevention and control of local pollution from factories, the industry has to deal with more and more complex environmental concerns, which affect a wider cause-effect chain. From designers' point of view, the development of sustainable products leads engineers to take into considerations environmental aspects in concurrency with traditional technical and economical aspects since the beginning of design activities. It is clear, then, that this change of direction brings to light the importance of operating from the first stages of the products' development.

Such a need is strongly underlined by the latest issue of regulations and guidelines at international level, such as:

- EuP Directive (2005) [4].
- ISO/TR 14062:2002 [5].
- IEC Guide 114:2005 [6].
- HB 207.5-2005 [7].
- etc.

which focus the attention on the integration of environmental aspects into the design and development activities of electrotechnical products. Needless to say, such indications concern, more or less, most of industrial products thanks to the ever greater integration of electronic components into modern mechanical systems. Beside these, researchers and companies have made a significant effort in promoting ecodesign activities; numerous tools and guidelines have been provided to help engineers in performing such a difficult task. Nowadays a large number of methods and techniques, characterized by different approaches and level of difficulty are at the designers' disposal, starting from simple checklists, to complex methodologies, which require experienced users to be applied. In such a context, many examples can be given. For instance, there are tools oriented to the life cycle analysis of the product, mainly based on the application of the LCA method, such as:

- EPS (Environmental Priority System) [8].
- Life Cycle Planning (LCP) [9].
- ERPA (Environmentally Responsible Product Assessment) [10].
- MET Matrix (Material cycle, Energy use and Toxic emissions) [1].
- and so on.

Other tools are based on the use of checklists and provide useful guidelines of a general nature (e.g. Ecodesign PILOT [11] and Ecodesign Strategy Wheel [1]); others are aimed at the improvement of specific products, such as:

- The ecodesign manual by Philips [12],
- The handbook of Volvo [13],
- ECMA standard 341 [14],
- Environmental guidelines by Electrolux [15],
- etc.

Furthermore, a large number of "optimized" tools have been developed, modifying already existing design tools used for different aims. In such a context, a particular mention has to be made about the Environmental Effect Analysis (EEA) [16] and the various environmental versions of the Quality Function Deployment (e.g. Quality Function Deployment for the Environment, [17]; Green QFD, [18]; etc.). On the other hand, in spite of the great variety of Ecodesign tools presented in the field, the large number of them, together with the need to comply with stricter and stricter environmental regulations, represents an hindrance for engineers [19, 20, 21]. In fact, many of these often fail because they do not focus on design activities, but are aimed at management or at retrospective analyses of existing products, or they are too specific to be applied in different contexts from the ones where they were developed for. The most significant difficulty, as underlined by many Authors in the field, is the lack of coordination of design activities, i.e. how to put into practice the indications provided by the ecodesign tools and guidelines [22, 23, 24]. For these reasons, the study on the design process and its optimization in order to meet environmental requirements was carried out, with the aim of finding a way to reduce the gap between theory and practice.

3 THE ECO-DESIGN PROCESS

The need to define the various activities which designer should follow in the product development is not a novelty in the field of Engineering Design, of course.

Numerous schemes are available in literature and some of them are very well known and largely used. Among the whole, it worth mentioning the ones proposed by Pahl and Beitz [25], by Hubka [26] and by the VDI (VDI 2221). Also recently, as mentioned above, some specific indications were provided in field by the issue of the following guidelines: IEC Guide 114:2005 and ISO/TR 14062:2002.

3.1 ISO/TR 14062

This technical report represents one of the first attempt to address designers towards an integrations of the traditional design activities and the environmental ones. The scheme proposed reflects the influence of the above mentioned studies (Figure 1), and the guidelines provided focus mainly on the first stage of the process ("Planning"), giving a very few indications concerning the following stages, and mainly underestimating the "Conceptual Design" phase. Moreover, also the review activities might lead less expert designers to think that they are concentrated in the last phase of the design process, when the product is already defined.

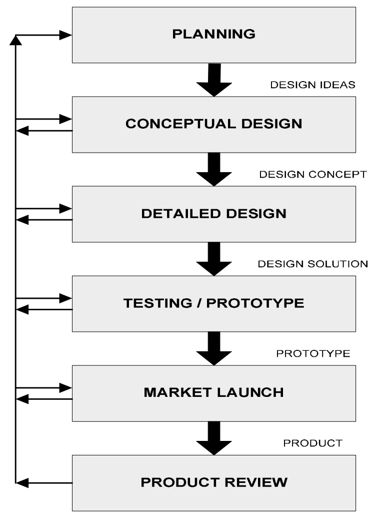

Figure 1: Scheme of the Design Process proposed by the ISO/TR 14062:2002.

3.2 IEC guide 114

The IEC guide is more recent and probably for this reason more detailed than the ISO 14062. On the other hand, also in this case the attention is focused on the Product Planning stage, providing a few indications about the following stages (Figure 2). Moreover a certain confusion might be generated in less expert designers by the presence of different stages respectively named "Product Concept" and "Conceptual Design".

On the other hand, a series of checklists are provided in order to make the indications less abstract and theoretical.

4 THE RESEARCH APPROACH

Starting from the analysis of these models, we tried to develop a design process scheme with the following characteristics:

- More details concerning the "Conceptual Design" and "Detailed Design" stages.
- Definition of the main activities which designers should carry out in each step, including the use of specic ecodesign methods.

- Definition of the relationships between the design activities and the recent Environmental Regulations RoHS, WEEE and EuP.

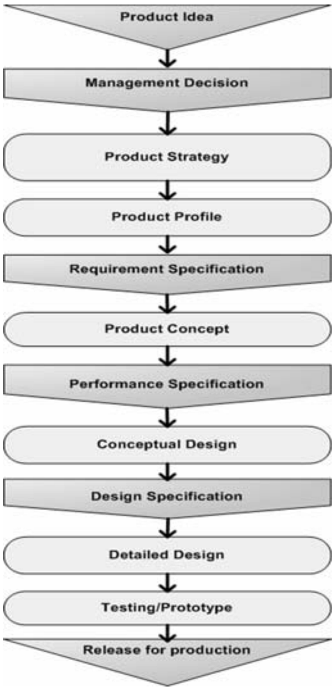

Figure 2: Scheme of the Design Process proposed by the IEC Guide 114:2005.

4.1 The Design Process scheme

In Figure 3 the general scheme of the design process developed is shown. In the first phase of the process, a specific stage concerning the identification of the product strategy is foreseen: this is because ecodesign "strategies" have to be investigated in order to achieve successful business. In fact, nowadays, green products are not always well accepted by consumers and current ecodesign approaches lack the effective identification of the target customer categories, suitable for the specific product.

Moreover, many of the environmental properties of products, which traditional ecodesign methods support to be implemented, are becoming established as part of regulations or legislations that manufacturers have to be in compliance with [27].

In the second phase of the design process, the traditional activities aimed at the definition of the optimal concept were considered. This is because of two main reasons:

- Avoiding the study of the system functions and sub-functions, could reduce the freedom of designers.
- Environmental concerns have to be treated at the same level as the traditional products characteristics, foreseeing also the development of life cycle models of different conceptual solutions.

In the third phase of the design process a particular attention should be paid to the selection of materials and processes for the product development, considering at the same time all the regulations requirement which affect these characteristics of the product.

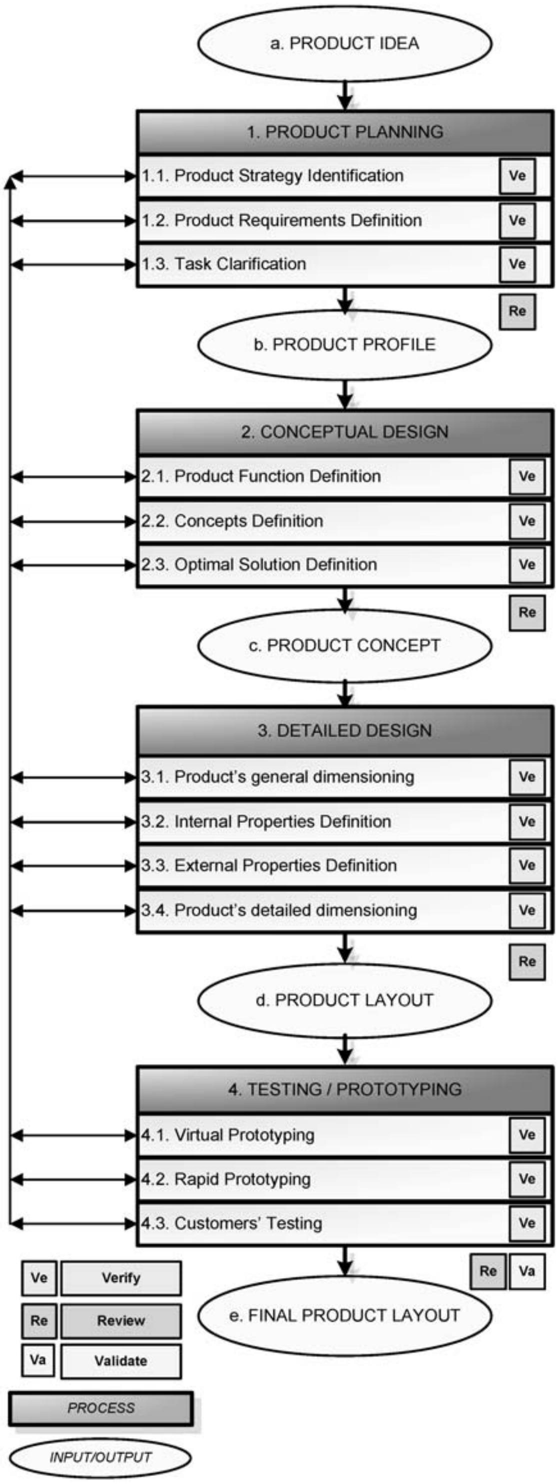

Figure 3: General scheme of the Design Process proposed.

Then, in the last phase of the design process a specific stage concerning the validation of the project is considered. Moreover, at the end of each stage a verification/review activity is foreseen.

4.2 The use of Ecodesign Methods

The integrated use of the design methods for the development of sustainable products has been analyzed by means of different case studies carried out in last two years [28, 29]. The correct use of a suitable design method at the right time is a crucial factor in design activities: the problem is not due to the lack of tools, of course, but mainly to the few information concerning "how to use" these tools. For these reasons, a series of guidelines considering the application of the most common ecodesign tools was developed focusing the attention on:

- The right moment of use of the method along the design process stages.
- The co-ordinated use of different tools in order to improve the effectiveness of results.

In Figure 4 the possible coordination among different design methods is shown.

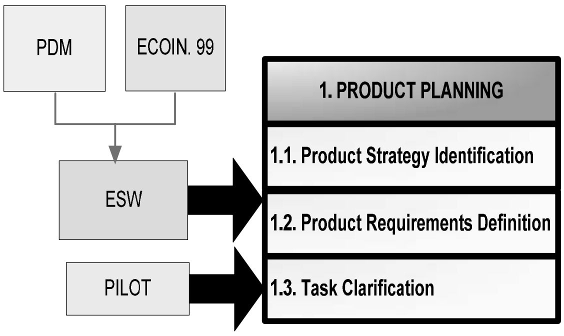

Figure 4: Example of the synergic use of different ecodesign tools: PDM, Pa Product Design for the Environment Matrix; ECOIN. 99, Ecoindicator 99; ESW, Ecodesign Strategy Wheel; PILOT, Ecodesign PILOT [28].

In Figure 5 the example of the use of the Quality Function Deployment for the Environment (QFDE) is shown.

4.3 The Environmental Regulations requisites

The analysis of the latest environmental regulations concerning the product development was carried out, focusing the attention on the following European directives:

- RoHS,
- WEEE,
- EuP.

The reason why we selected these regulations is due to the fact that they are quite recent (in particular the EuP) and represent in their complex a real change in the industrial sector of many countries. It has also to be noticed that such regulations present many similar aspects to the ones issued or to be issued by other non-European countries (for instance, the so-called "China-RoHS" and "China-WEEE" [30, 31]). The results of this study consisted in the development of a series of checklists aimed at helping engineers in the applications of the above directives; in order to make easier their use, they were organized both according to the design process stages, and to the product's life cycle. In Figure 6 an example is schematized, representing main relationships among the regulations and the product's life cycle from a qualitative point of view. Nevertheless, from a broader point of view, it has to be underlined that all decisions made during the design activities have a certain influence on the product life cycle.

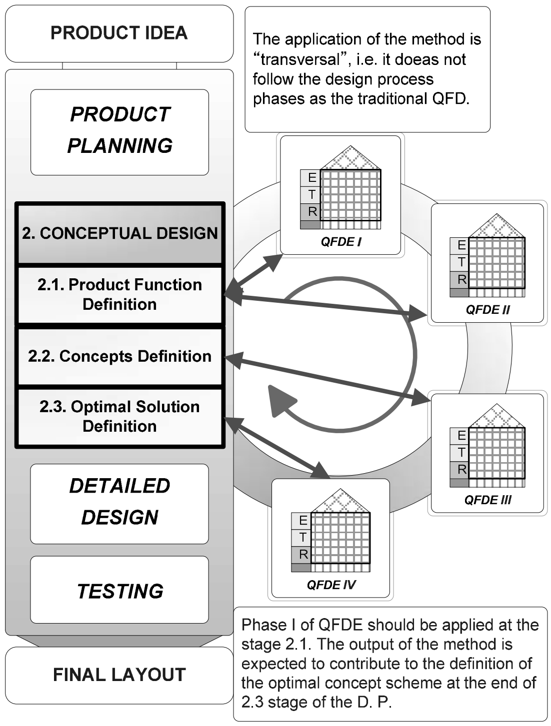

Figure 5: Use of the QFDE.

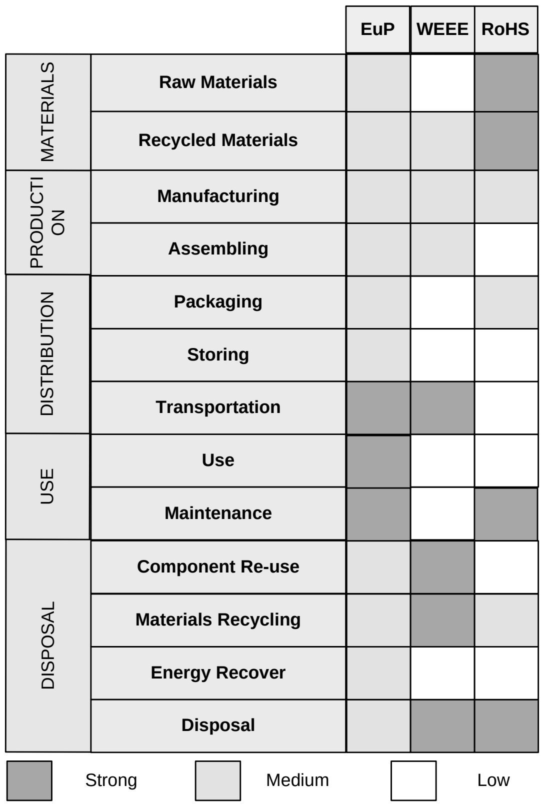

Figure 6: Influence of the environmental legislations on the product's life cycle.

5 RESULTS

The research approach developed was verified throughout its application to a case study, with the aim of both integrating the different checklists and guidelines developed, as well as evaluating their effectiveness. For this reason, the redesign of a refrigerator for domestic use was considered. More in details, in the Conceptual Design phase of the design process the QFDE method was used, as shown in Figure 5. At the same time, also the checklists concerning the application of the environmental regulations were applied, introducing them in the various stages of the design process. The results of such an application brought to light the following weak point of the machine, which have to be improved in order to improve its environmental performances:

- Optimize the consumption of electric energy (EuP).
- Reduce Hazardous substances (RoHS).
- Reduce the number of components.
- Reduce the number of different materials.

Following these indications, the concept of a new refrigerator was carried out and developed till the definition of both internal and external properties. Apart from the compliance with the Environmental Directives, the other interventions concerned the following aspects:

- Use of a single material (mono-material) for internal components of the refrigerator, such as: handles, compartment doors, shelves, etc. In addition, most of connection systems were changed from metal screws into simpler embedded ones.
- The whole structure is made using polystyrene stiffen by talc (except for the basement, which is made by polypropylene, because of the presence of the capacitor).
- The efficiency of the machine was improved changing the insulation systems, e.g. using a different kind of polyethylene from the existing model.

Using the QFDE method, it was possible to make a first evaluation of the improvement achieved comparing the results obtained by the current model with the ones obtained by the new concept. In Figure 7 main results are summarized. Most significant results concern the point 2, 7 and 11:

- Reduction of Hazardous substances: the improvement was achieved thanks to the implementation of the EU directives and in particular the RoHS (in particular, the use of Cr, Hg and Pb was eliminated).
- Materials reuse: the use of a mono-material allowed us to obtain an higher percentage of material suitable for being reused for the manufacturing of new refrigerators (in the current situation, due to the low quality of plastics obtained after recycling, the material is not re-used in the company: it is sold to other companies for the production of different products).
- Disposal: in this case, the difference between the old system and the new one is not significant as one might expect; the reason is due to the fact that a more environmentally friendly disposal could be made by the company only changing part of the manufacturing plant, in other words, new processes should be implemented and new machines purchased. So far, the company is studying the possibility to make this changes, but when the present research work was carried out, this option could not be considered because of the high costs required.

In conclusion, it is to be mentioned also that, the support of company's technicians helped us in optimizing the checklists, avoiding text crammed full of indications. The general framework developed was considered very useful in order to reduce the number of mistakes and the possibility of "over-designing".

6 CONCLUSIONS

The research work was to give an answer to the question: "how to use ecodesign tools?" which emerged in being the most significant problem of modern engineers, as underlined by many Authors in the field. With this aim in mind, a new design process was developed with the aim of making easier the integration of the numerous indications provided by guidelines and regulations into the various design stages. In fact, such a process is supported by a series of instructions, which provide in details information on how to use the most common eco-design tools, as well as how to apply the legislation requisites. Different types of design tools were analyzed in order to define an appropriate way of using them for the development of sustainable products. First results allowed us to set the main framework of the design process, and to implement the guidelines dividing them in categories according to the product life cycle, in order to make their use easier. On the other hand, more detailed applications to industrial case studies are needed in order to make our approach a flexible tool, able to be applied in different contexts.

7 SUMMARY

This paper summarized the first results of a research work aimed at the definition of an easy to use design process for the development of sustainable products. A particular attention was paid to the integration of environmental legislation requisites into the traditional design activities.

8 ACKNOWLEDGMENTS

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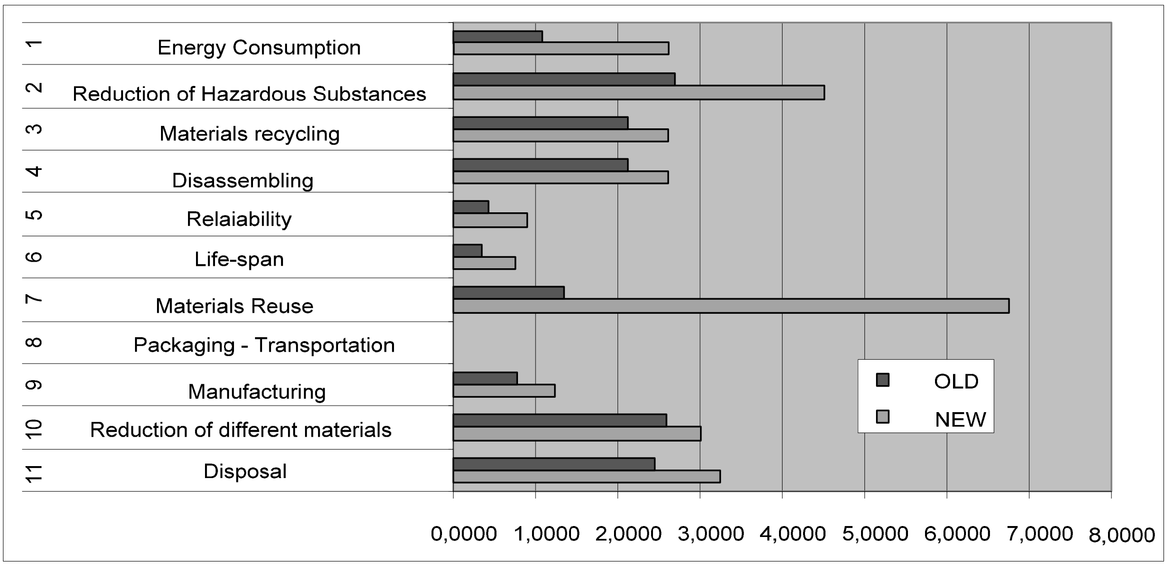

Figure 7: Main results of the environmental assessment of the redesigned refrigerator (the score used is obtained following the evaluation system described in [17]).

Research on Design for Environment Method in Mass Customization

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Abstract
With the productive mode changes from mass production to mass customization, the design for environment (DFE) method has to be adapted to it. The purpose of this study is to realize green design in mass customization mode. In this study, the process of the DFE method in MC mode is systematically discussed, then a concept of green product information model is proposed to support the design process. A product configurator for DFE is presented in detail, at last a green design of refrigerator was used as exemplification of the method.

Keywords:
Design for Environment; Mass Customization; Product Configurator

1 INTRODUCTION

A tendency to develop design for environment (DFE) and environment-friendly products is obvious in the present society which is of increasingly environment problems. With the market's increasing demand for diversification and individuation of products, a mass customization (MC) mode has been adopted by many producers and functioned well in practice. Though the DFE method has played an important role in the mass production (MP) mode, with the changing of manufacturing mode from MP to MC, the DFE method has to be adapted to it. MC is defined as a system that uses information technology, flexible processes, and organizational structures to deliver a wide range of products and services that meet specific needs of individual customers, at a cost near that of MP [1]. In MC mode which takes low cost and high benefit as its guideline, product's design cycle is decreased, which requires the designer to resolve the problem of product's optimized configuration between environment attribute and function, structure, economical attributes in a shortest time.

A number of methods for product configuration in MC mode have been proposed, for example, PCM (Product Configuration Manager) framework proposed by Niya Li et al [2]; UNIK-SES expert system which supports product customization by Sang Kee Lee et al [3]; GBOM-based product configuration method by Hegge et al [4]; product configuration method based on constraint satisfaction problem algorithm by Ryu [5]; and a new product structure description method to optimize product configuration by F.J.O'Donnell et al [6]. However, the above-mentioned product configuration methods failed to consider product's environmental characteristics. And there is almost no satisfying environment-friendly product configuration method.

The present paper systematically discusses the process of design for environment in MC mode. Section 2 proposed the design process of green product, and based on it, a green product information model supporting DFE method in MC mode is established. In section 3, the product configurator of design for environment in MC mode is presented in detail which should include: the customer's requirements collector, the product model builder, the optimum model selector and the product environmental performance assessor. A green product design system supporting mass customization developed by the author is introduced in Section 4, and a case study of the refrigerator design is given.

2 DFE METHOD IN MC MODE

Mass customization is different from traditional design methods in that it utilizes previous product information and existing product modules and components as much as possible to design new product which meets customer's needs of individuation and diversification. Moreover, for green products, designers' work are greatly increased since they not only need to consider many factors in traditional product design, but also need to weigh the product's environmental attribute. Therefore, to realize green products' mass customization manufacture, assistant design tools (such as product configurator etc.) are necessary to reduce designers' work, increase design efficiency and shift the designers' work focus from complicated raw materials and components choosing (repeat work) to designing and perfecting target products which meet customers' requirements.

2.1 Green Products Configuration Design Process

Green products configuration design belongs to the category of concept design. Emphasizing the combination of green design ideas and configuration technology in MC, and taking existing products in DFE database as prototype, it transforms customer's requirements into configuration mechanism, and works out new products through borrowing, amending or redesigning components of prototype products. The specific design process is indicated in Figure1.

Step1. Mapping from customer's requirements (sales view) to product engineering view is established, and customer's requirements is transformed to product design information;

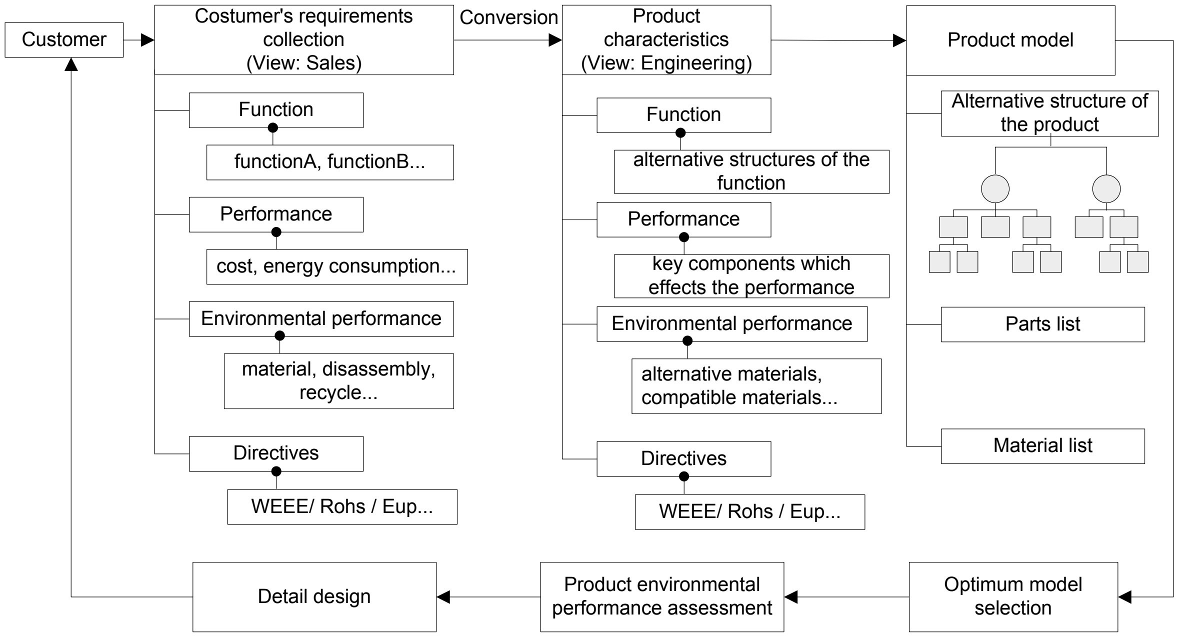

Figure 1: Green products configuration design process

Step2. Under the precondition of ensuring product function, taking function structure alternative collection, key components alternative collection, raw materials alternative collection, compatible materials alternative collection as basis, exerting configuration mechanism to build product model, several alternative product models which meet the function requirements are made out;

Step3. Alternative product models are screened to eliminate those which can not meet requirements on use and green performances;

Step4. Product's environmental performance is assessed and detailed design is implemented if the product model passes the optimum evaluation;

Step5. After the design is completed, the product is put into configuration database according to the data structure of green product information model.

2.2 Green Product Information Model

By analyzing green product configuration design process, it is not difficult to find that green product configuration design takes complete green products designed as data foundation. The more the complete products that can be referred to, the more the product models generated in the process of product model building, and greater the possibilities of working out product model that meet customer's requirements. Therefore, enriching usable resource in green products configurator and expressing them reasonably according to configuration design requirements is the key problem influencing the performance of green products configurator.

In green products design, product information should be composed by detailed requirements of product functions, product costs, laws and regulations restricting the product, targets and restrictions of product green performances (such as noise level, energy consumption level, disassembly and recycle performances etc.). They express the product's detailed requirements on certain level. Product structure's level characteristics decides the level characteristics of green product information model. To support the design idea in Figure 1, green product information model is divided into four levels: product level, system level, component level and part level. Product level depicts the product's function, use performance and environmental performance, which is mainly used to collect cutomer's requirements, optimize product model and assess product's environmental performance. System, component and part levels include product use performance, enviormental performance and configuration information on the respective level, which are the main parts involved in configuration design and assessment. Frame of green product information model is indicated in Figure 2.

3 PRODUCT CONFIGURATOR OF DFE

Product configurator, abbreviated as configurator, is defined as an information system which can interact with its user, assist and support its user to configurate product. Green product configurator not only should be able to realize the functions of establishing product structure in broad sense and its constraint relationship, reasoning, resolving, product registration and so on, but also should ensure the product's environmental attribute. Therefore, traditional product configurator should be adapted. According to green product configuration design process, green product configurator should be composed of customer's requirements collector, product model builder, optimum model selector, and product environmental performance assessor.

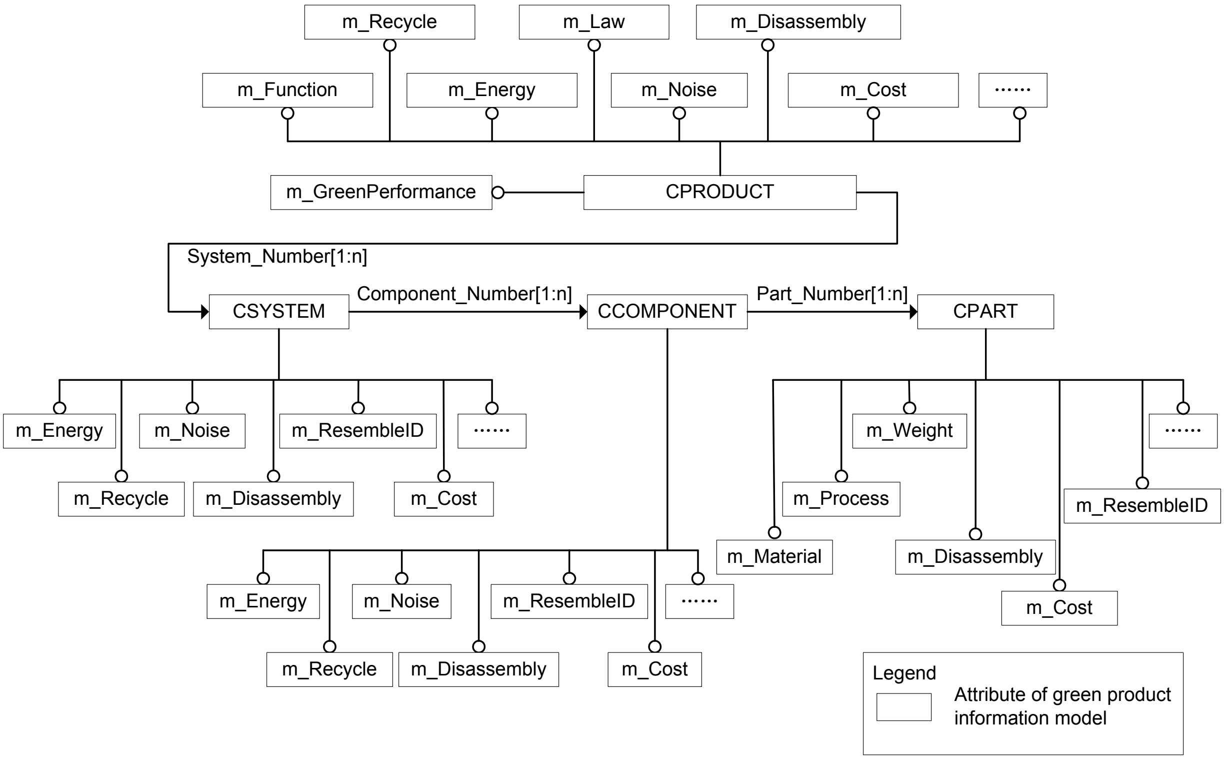

Figure 2: Frame of green product information model

3.1 Customer's requirements collector

Customer's requirement is the basis of product configuration. However, information from customer usually is qualitative and vague, which is not suitable for the processing of product configurator. Therefore, it is necessary to standardize customer's requirements into quantitative and specific configuration technology requirements. Requirements collector's basic operating principle is explained in Figure 3.

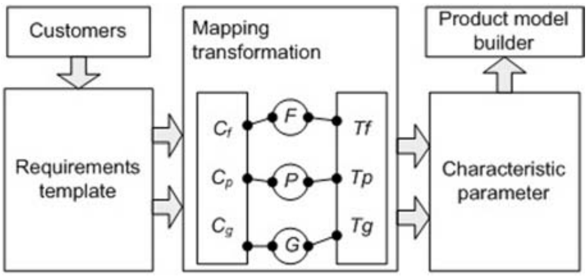

Figure 3: Customer's requirements collector

Realization of requirements collector includes the following steps:

Step1. Product Modularization. On the foundation of detailed analysis of a great amount of customers' requirements, product functions, structures and environmental performances, make sure customer's general and individualized requirements on the product, and subdivide product modules (function module, use performance module and environmental performance module) which are mainly specific structure modules of the product or may be material, technics and other modules influencing the product's environmental performance.

Step2. Establishing Customer Requirements Template. It is difficult to establish uniform product requirements information model since different customer's semantic description of product requirements differs greatly. Thus, it is necessary to express and organize vague requirements information in uniform format, collect and process information in standardized form. The requirements template established in the present paper depicts the product systematically from function, performance, green attribute, economical and other aspects. At the same time, it adopts cluster analysis algorithm to process customer's requirements to a standardized form on the foundation of green product information model. Processed by requirements template, many customer requirements $C=\{c_1,c_2,\ldots\ldots,c_n\}$ can be transformed into triple $C=\{c_f,c_p,c_e\}$, among which c_f is function requirements, c_p is use performance requirements, c_e is customer's requirements on product environmental performance.

Step3. Establishing Mapping Mechanism. By using transfer function $f(c_f)$, $p(c_p)$, $e(c_e)$, customer's requirements on product function, use performance and environmental performance will be transformed into the product structure, key components, material used, manufacturing technics and other modules composing of the product, i.e., transform of $C=\{c_f,c_p,c_e\}$ to $T=\{t_f,t_p,t_e\}$ is realized, among which t_f is function module collection, t_p is the module collection which influences product's use performance , t_e is the module collection which influences product's environmental performance.

Step4. Determining Technical Parameter. Mapping mechanism only qualitatively transforms customer's requirements into forming modules of the product (structure, key components, material used, manufacturing technics, etc.), but it fails to prescribe specific technology parameter. Therefore, relationship between specific parameters of each product modules and customer's requirements should be determined to realize mapping from customer's requirements to modules' technical parameter.

3.2 Product model builder

According to alternative module collections given by requirements collector (structure, key components, material used, manufacturing technics, etc.), combining product model in broad sense, module correlation and other factors, alternative product models collection will be established. It is necessary to point out that the present model should not only be product structure model building, but also include the following product information :

1. Product Structure Information. Generally speaking, structure design influences product function greatly. Therefore, several structure modules should be chosen from structure alternative collection which meets the product's function to establish a product structure frame which meets customer's requirements on function.

2. Components' Parameter Information. After the completion of product structure frame, components should be chosen. Generally considering components' influence on green product's configuration design, components' parameters are divided into three categories: Performance parameter, e.g., appearance, power, work characteristics, etc.; Environmental attribute parameter, e.g., cost, raw material, manufacturing difficulty degree, etc.; Configurable attribute parameter, e.g., interface standardization degree, assembly constraint number, component number, function structure affiliated to, etc..

3. Information for Disassembly and Recycle. Disassembly and recycle characteristics are important indexes embodying product environmental performance. They are mainly reflected on specific product structure and product components' material compatibility. Therefore, in product model builder, aiming at product structure information and component parameter information, alternative collector of structure information which is helpful to disassembly and compatible material alternative collector should be given to ensure the possibility of partial amendment of product structure and material when the disassembly and recycle characteristics of the product are low.

3.3 Optimum model selector

Due to different design strategies adopted in the process of configuration, plans generated by configuration of product model builder will be different in product function, use performance and environmental performance. Several different design strategies sometimes can promote and complement interactively, but sometimes can be contradictory to each other. Contradictory design strategies will influence product function, performance and environmental performance, and will even cause unfeasible design scheme. Therefore, design schemes generated should be screened to eliminate those that are of no implementing meaning. During the screen process, the following principles should be abided by.

1. Component and Product Matching Principle. Not all components realizing certain function are suitable for the function of certain product structure. Design scheme of mismatching component and product structure should be eliminated;
2. Product Safety Principle. Some configuration combination will influence the safety of product. For example, mismatchings of control system component power, structure instability caused by product weight lightening, etc.. Thus, design plan influencing product safety should be eliminated;
3. Cost Control Principle. Adopting green material, structure easy to disassemble and reclaim, high quality component and other design strategies are all of possibility of increasing product cost. When product cost exceeds customer's affordable scope, the plan should be eliminated;
4. Material Compatibility Principle. Compatibility between materials has great influence on the work amount of disassembly and reclaim. Compatibility problem also exists between environment-friendly green materials. If incompatible materials are chosen, product disassembly and reclaim difficulty will be increased. Design scheme with low compatible component material should be eliminated.

3.4 Product environmental performance assessor

By using the analytic hierarchy process (AHP) method, and aiming at screened product model, integrated enviromental performance assessment can be carried out on four levels: part level, component level, system level, and product level, to decide the most suitable product model for detailed design. Level structure of product evaluator is indicated in Figure 4.

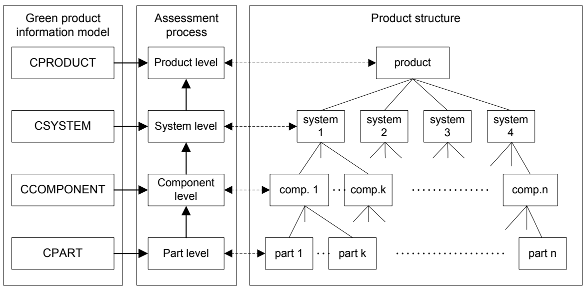

Figure 4: Product environmental assessment process based on AHP methodology

4 PRACTICAL EXAMPLE

On the foundation of the above-mentioned method, a refrigerator product DFE configuration prototype system is developed. It mainly includes design information collection module, product model building and optimum model selecting module, and product model environmental assessment module.

4.1 Design Information Collection Module

According to design characteristics of refrigerator, on the foundation of customer requirements analysis, custom requirements template of this product is established, transforming customer's requirements into design information composed of three parts: product basic function and performance, cost and design constraint, and environmental performance. A product design information collecting interface is indicated in Figure 5.

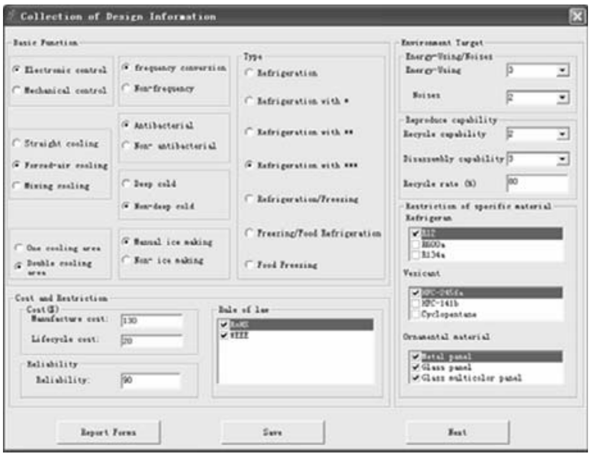

Figure 5: Design information collection

Being processed, those customer's requirements can be transformed into the data structure depicted by green product information model. See indication in Figure 6.

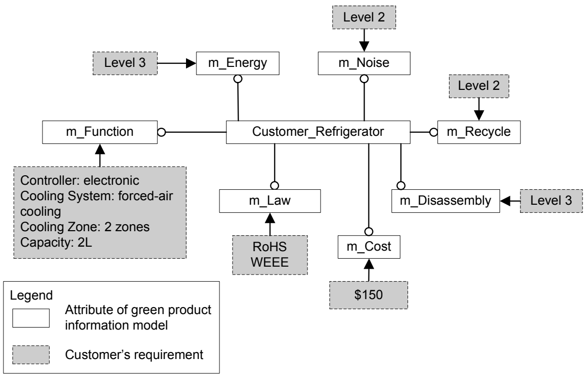

Figure 6: Mapping from customer's requirements to green product information model

Then, aiming at some key parts, design target of product level can be transformed to detailed requirements of parts. In this example, since compressor is the main energy consumption and noise source of refrigerator, specific refrigerator structure's influence on energy consumption and noise can be ignored and the above-mentioned two design targets can be transformed to specific requirements on compressor performance attribute. And for satisfied directives and regulations, the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) can be transformed to requirements on raw material component (m_Material) and manufacturing process (m_Process) of each specific part. Waste Electrical and Electronic Equipment Directive (WEEE) can be transformed to requirements on recycle performance of product parts.

4.2 Product Model Building and Optimum Model Selecting Module

According to customer's requirements on product's basic functions, based on similar design case in DFE database, product model alternative collection is built in top-down method and is screened; Taking customer's requirements on product environmental performance into consideration, this alternative collection is evaluated and the most suitable product model is chosen. See indication in Figure 7.

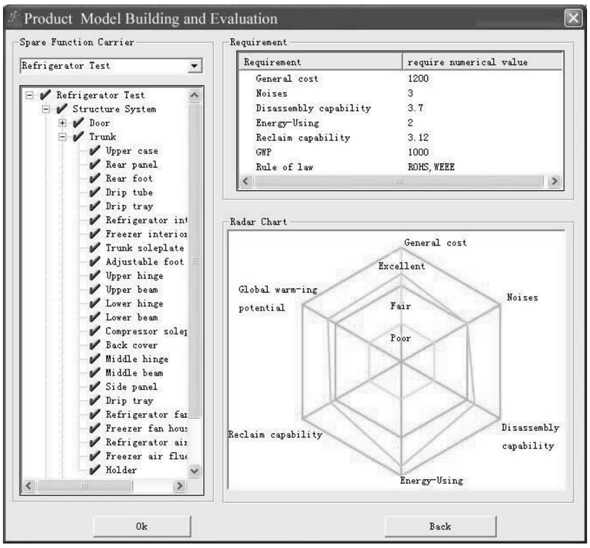

Figure 7: Product model building and its evaluation

4.3 Product Model Assessment Module

An assessment interface of the refrigerator product model which adopts inverted method is indicated in Figure 8. By using this evaluation method, green product information model's supporting function to respective product level structure is exerted fully. Therefore, correction can be made promptly when design deficiency is found on certain level. And product green performance assessment efficiency can be improved.

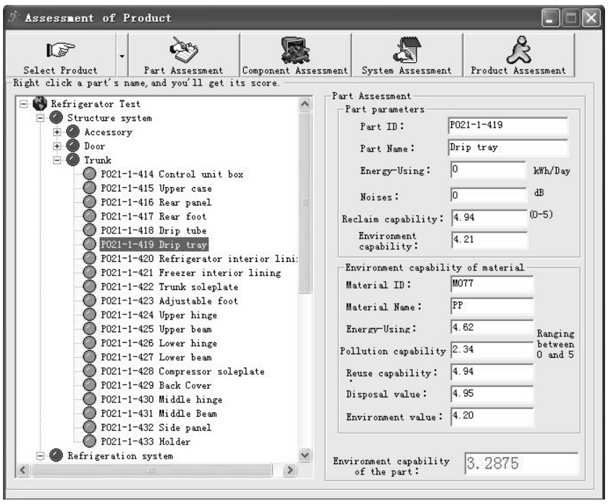

Figure 8: Product model assessment

5 SUMMARY

Mass customization technology shortens product design cycle, and resolves the contradiction between product individualization and mass manufacture. However, with increasingly prominent environmental problems, full consideration on product's environment-friendliness has been a must in mass customization technology. Based on product environmental design method in mass customization mode, the present paper puts forward graded green product information mode, and analyzes the composing and realization of green product configurator in detail. Under the guidance of this method, the deficiency that there is only consideration on product function and structure during the process of product configuration and no consideration on product environmental performance will be made up. Thus, environment-friendly product can be developed.

6 ACKNOWLEDGMENTS

The authors would like to acknowledge all the collaborators and colleagues of the Institute of Green Design and Manufacture Engineering in HFUT.

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Definition of a VR Tool for the Early Design Stage of the Product Structure under Consideration of Disassembly

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Abstract
Under the legislative pressure and to deal with an economy of raw materials and energy used to transform this matter, designers have to consider more deeply the aspects related to the disassembly of the products for recycling, remanufacturing or reuse. Indeed, these "recoveries" of product/components/materials will modify the production and recycling processes as well as the design choices. In particular, the disassembly operations have to be taken into account in the first stages of the product design, during the conceptual design phase, to obtain a good compromise concerning the final structure of the product. We will present in this article the principles for a future tool using virtual reality. This tool will be used during the conceptual phase of the design to assist the designer to jump from a functional model to the structure of the product by helping the definition of the components, of the connections and thus of the first structure of the product.

Keywords:
DFD, end of life, Virtual reality, Product design

1 INTRODUCTION

The disassembly becomes a specific point of view during the design process. Indeed, since regulations constrained the producers to be responsible and to treat their products in end of life, we can observe a progressive development to facilitate the extraction of materials or components in the product to generate benefits. The disassembly costs are then put in balance with the benefits (financial in most of the cases) that can be generate by the valorisation of materials and components. This implies that the disassembly that was minimized in the past and only used for the evaluation of maintenance operations, becomes a new objective during the design of products. To improve the taking into account of the disassembly during the design process, we have to develop two main aspects:

- Traditionally, disassembly has been viewed as the reverse of assembly. However, a novel view considers just the opposite, leading to a more optimized disassembly process taking into account assembly, maintenance, reuse, and recycling in the context of the entire product life cycle [1].

- Usually, the disassembly is considered very late during the design process, not at the same level than other design aspects that influence the design of the product structure (functions, materials,…). If designers want to modify the product structure without reconsidering the choices already realized, that mean without increasing costs and delay, the disassembly must be considered very early during the design process.

Many researches try to consider these two aspects by the integration of end of life disassembly recommendations early during the design process. Deng and al. [2] for example, underline that it is necessary to bring material and structure consideration from the detail design stage to the conceptual design stage and to solve the problem in an integrated manner. In fact, these approaches are useful to establish the whole requirements before the detailed design phase. Indeed, it is the only way to obtain a compromise concerning the product structure before its design. So, we have to propose evaluation methods to designers who have to use at this design stage intermediate and non finalized representations of the product.

In this paper, we propose a tool to help the definition of these intermediate non finalized representations of the product during its design process. We want in particular to develop a tool that allow designers to sketch the structure of the product while considering the product service functions but either the future disassembly criteria. In a first part, we will present the different existing models that support the product structure definition and the information linked to the disassembly process during the conceptual design phase. In a second part, we will present the needs and requirements linked to a tool able to assist the transition from a functional definition to a structural definition of the product with a disassembly point of view. In the last part, we will present the product model and the first orientation retained for our future virtual reality software.

2 CURRENT TOOLS AND MODELS TO SUPPORT THE DESIGN/EVALUATION OF PRODUCT STRUCTURES

In this part, we present current models that support the definition or the evaluation of a product structure considering its life cycle, and more particularly its future disassembly in end of life. This literature review is a mean to highlight some of the characteristics needed for our future product model that will be manipulated in the future VR tool.

In [3] Germani and al. describe a multi-level product structure and a preliminary dedicated classification of design information to support the LCA use in the early design phase. This work has been realized while examining the correspondence between the information generated along the design process and the Life Cycle Analysis (LCA) inputs. For the authors, the identified design support system for product design development should have the following characteristics: the functionality **to define components on the basis of functional and technological requirements**, the functionality **to represent components at different level of geometric detail**, an environment where **to define the**

overall architecture of the product and to set the product functional and technological specifications. This system should be interfaced with a tool able to elaborate the LCI_X features that are elements interpreting the explicit and/or implicit product attributes (figure 1). With this approach, the designer is able to describe components as illustrated on the figure 1 and to identify the necessary information to realize a LCA at different stages of the design project.

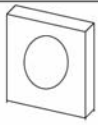
SCC graphical representation	SCC description	*LCI_X features*	*LCI_X feature* values
	Bounding box	LCI_Name LCI_Material LCI_Amount_Material LCI_Manufaturing_ Process LCI_Assembly_Process	Frontal frame Steel 6 Kg Punching or injection moulding Null ....
	Detailed 3D geometric model	LCI_Name LCI_Material LCI_Amount_Material LCI_Manufaturing_ Process LCI_Assembly_Process	Frontal frame 10A50 Fe P 10 5,45 Kg Cutting Bending Punching Painting Drilling Welding ....

Figure 1: View of a frontal frame for washing machine at different design phases (conceptual and detailed) [3]

Yu and al. [4] propose a structure representation to support the assembly and disassembly planning of electromechanical products. They underline that the structure layout design should consider all the life cycle issues such as manufacturing, maintenance, and recycling. But, according to them, the lack of design representation of product layout constitutes a limit to the analysis of product assembly and disassembly. So, this analysis usually occurs late at the prototyping stage, which often incurs higher design cost if any modification is required.

To solve this problem, they propose a Relationship matrix to describe the assembly architecture. The Relationship Matrix describes both the information of the component connectivity and the layout precedence, and considers only the functional elements to greatly reduce the searching space. The functional elements are the constituents that realize certain customer requirements. The fasteners, such as screws, rivets, retaining rings, etc, on the other hand, are auxiliary objects necessary to maintain structure stability and rigidity. According to them, because the fasteners are always linked to the corresponding parts to fasten during the assembly procedure, **once the correct assembly order of the functional elements is determined, the complete assembly steps can be readily derived.**

For the relationships among functional elements, they divide them into two categories:

- The **Physical Link** represents direct connection of two objects by either geometrical interlock or auxiliary fasteners.

- The ‘‘**Layout Interference**’’ exists when an object affects the assembly sequence of other objects due to spatial arrangement, even though there is no direct contact among these objects.

Gries and al. [5] propose a software based system to support the design for disassembly. They mention the fact that a lot of disassembly and recycling related software tools exist today but that their usefulness as a whole is often limited by lacking **possibilities to interchange product data – especially with existing applications, such as CAD or LCA software**. Consequently, the designer often has to manually enter the output of one application as input for another. So, the software system they present in their paper, intends to support the designer of disassembly and recycling-oriented products by relieving him of this task. The model of product they present (figure2) allows a direct interfacing to CAD tools to perform evaluation during the detailed design phases.

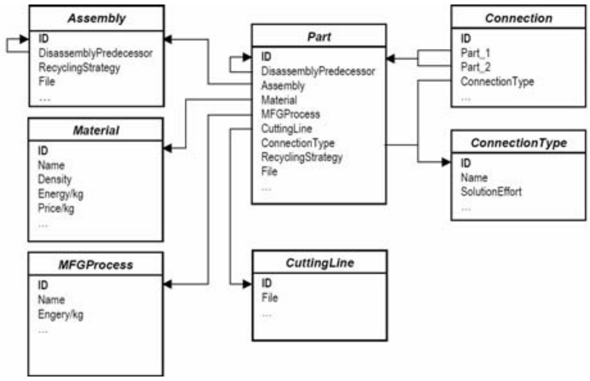


Figure2: The product model as relational data structure (each box represents a database table) [5]

To evaluate the EOL disassembly, Haoues [6] propose a Conceptual Disassembly Model (CDM) that can be used in the early design phases. The CDM of a product includes : The **environmental requirements** and the **disassembly objectives**, the **main components** of the product and their **functional links**, a global estimation of the **weight and material of the main components**, some components end of life treatment and **a first draft of the future solution** (figure 3 : example for a bathroom scale).

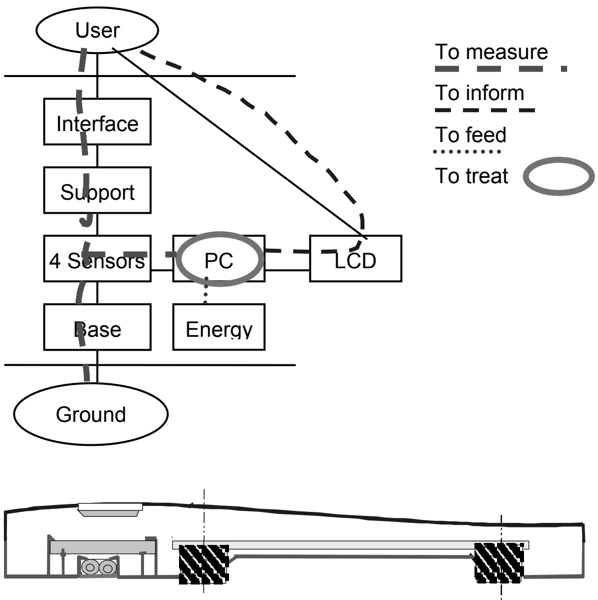


Figure 3: The simplified FBD (SFBD) for a bathroom scale and a related first draft for the product [6]

With the CDM information, it is possible for a designer to generate disassembly sequences corresponding to the disassembly objectives. This model is used to help designers to improve the disassembly of components concerned by the identified sequences.

To represent some of the information included in the CDM, designers can use a tool called "**Simplified Functional Block Diagram**" (SFBD) (figure 3). In the SFBD, only the main components are represented (boxes) with their contacts (black lines) that support the functions of the product (for the bathroom scale: to measure, to inform, to feed, and to treat). This representation gives a first representation of the functional structure of the product and is a support to analyze the transition between the functional structure and the technical structure of the product.

3 A TOOL TO HELP THE DESIGN OF THE PRODUCT STRUCTURE DURING THE CONCEPTUAL DESIGN STAGE

According to Giampa, the conceptual design is the crucial phase in the activity of product design. Therefore, the primary task of the conceptual design phase is to satisfy the functional requirements. However, it is important to consider the fact that, satisfying the functional requirements, the designer must take decisions which significantly condition all aspects of a product and, in particular, its cost is determined by the correctness of the operated choices.

Bruno [7] underlines the fact that a useful development in the field of conceptual design would be tools able to support the designer when he/she is manipulating abstract elements that roughly approximate their final shape and placement in the definitive layout. Indeed, CAx systems are widely used in many phases of product development (modelling, analysis, simulation, optimization), but they are not employed in the conceptual phase. This could be explained considering that it is difficult to support this phase without limiting the designer's creativeness and that designers in that case simply prefer using their intuition and experience.

The obstacle encountered during the study of the disassembly in the conceptual design phase, is linked to the fact that the structure "view" is difficult to define and to evaluate. Indeed, designers often need to draw sketches of the future product to be able to think "disassembly sequences". But these product sketches are realized by hands and considered as simple drawings. They are not capitalized by the project group and their existence is more linked to the draftsman than to the whole members of the design team trying to find a compromise on the product. Moreover, these sketches could be a mean to confront the proposed structure solution to disassembly rules.

So, to improve the design of a product structure taking into account the functional needs, and others life cycle needs (maintenance, end of life,…), we propose to develop a tool to assist the designer during the first definition of the product structure. This tool will use virtual prototyping and a virtual environment to help the designer to evaluate and to design the solution with an interactive manner.

3.1 An interactive tool to elaborate solutions

The proposed tool will be present at the conceptual design stage, when designers have raised the major choices concerning the decomposition of external functions into technical functions and when the main components are chosen [8, 9] . At this stage, the designers can establish a simplified functional block diagram (SFBD) of the solution. But it is not possible for tem to make a direct transition between the SFBD of the solution and the functional block diagram (FBD) of the solution (figure 4) with all the components, because the final design choices are motivated or influenced by the choices realized on the structure.

So, we need a 3D intermediary representation of the future solution. This representation will permit in a first time the visualization of the FBD. Then, the designer will be able to put volumes to some of the components, he will have to decide the number of parts constituting each main component, he will have to define the final components and the necessary connections,…

Finally, he will be able to obtain the FBD with:

- The different components of the product and particularly, those necessary to the function realization. (crossed by the functions necessary to fulfil the customer's needs)
- The contacts between the components, represented with black lines
- The functional interaction and physical connection between components
- The design choices (green buckles) that are for example technical solutions used to assemble components or to put them in position.

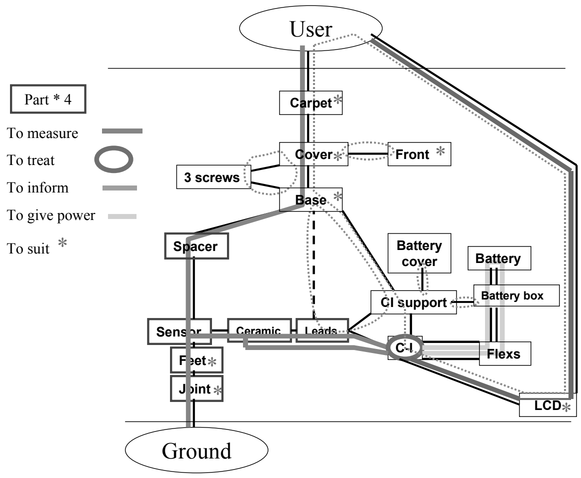


Figure 4: A FBD of a developed solution for a bathroom scale

To start from the SFBD is particularly interesting, because this representation can be used during the conceptual design stage, and don't presume the technical solution used to link the components. Only the functional links are presented and discussed. Our objective with the use of a virtual reality tool is to give the ability to the designer to position the functional elements while minimizing the interference relation for the components that needs to be disassembled. Here the interference relation is a general concept and does not differentiate the interfering direction because the detailed object geometry is often undecided at the conceptual design stage [4].

The use of the VR is motivated by the fact that, as mentioned by [10], VR can be used as a tool to enhance the cognitive abilities of humans. Indeed, VR techniques have been applied to better "sense" the colour, style, and space of a virtual product [11]. That means that VR techniques could play an important role in realizing virtual prototyping. These techniques give the ability to the designer to interact in real time with the data, without time and material consuming. At this stage of the design process, it is very interesting to obtain a 3D prototype of the product that you can interact with.

Moreover, many VR applications in the assembly/disassembly area have already been realized, but to define the planning or the manufacturing process, not the product. Collaboration in design is another use for VR visualization in many industries. Virtual mock-ups are presented on large displays, and design review attendees observe a stereoscopic image with shutter glasses. These kinds of reviews could be also well adapted at the early stages of the design process when defining the product structure. It is the same remark for reviews between remote locations that are conducted in the same virtual environment [12]. Such VR needs could be met with visual devices and very simple manipulation devices used only for navigation. They could be realized very early during the design process. On the figure 5, you can see a first definition of the future representation of a product structure with our VR tool. The boxes are progressively transformed into parts, and links that represent a contact between 2 components will be progressively replaced by contacts or connections. Indeed, as mentioned by [4], once the correct assembly order of the functional elements is determined, the complete assembly steps can be readily derived while using DfD rules.

3.2 A tool to apply DfD rules

DFD initiatives lead to the correct identification of design specifications to minimize the complexity of the product structure by minimizing the number of parts, increasing the use of common materials and choosing the fastener and joint types which are easily removable.

As mentioned by Güngör and al. [13], one of the important issues in DFD guidelines is related with the selection of the connectors used in the product. In general, DFD guidelines deal with issues related to disassembly activities. The results obtained in their paper have demonstrated that **DFD issues must consider all aspects of life-cycle of a product** even if the objective is to design the product for disassembly. Eliminating certain stages of the life of a product may lead to different choices in the design stage.

For Tonnelier and al. [14] a complex problematic must be resolved to solve a DfD problem, resulting from the diversity of the materials (plastics, metals, etc.); the fixing elements between components, the architecture, the disassembling procedures; and the recovery procedures. They have shown the necessity for **a qualitative evaluation tool to allow the evaluation of the recovery potential earlier in the product design process**. In their case, they start from the disassembly sequence and try to evaluate this sequence early during the design process.

For Desai and al. [15] the disassembly ability of a product is a function of several parameters such as exertion of manual force for disassembly, degree of precision required for effective tool placement, weight, size, material and shape of components being disassembled, use of hand tools, etc. To consider all these aspects, they have established an evaluation while **weighing several factors such as technical and economic feasibility, overall functionality and structural rigidity of the product as a whole.**

To be able to consider all these different aspects and to be able to work on the product structure, we want to apply disassembly rules starting from the functional model. The objective is to allow the designer to draw many solutions while having a measure that show how simple DfD rules are respected. So, our proposition to apply DfD rules early during the design process consists in two steps:

- Firstly, the designer starts from the SBDF of the product, and try to roughly establish the position of the different components. To assist the designer, we want to implement some rules to check if the solution respect or not basic rules related to the product life cycle (Table 2). At this stage, if needed, the designer can choose to divide a main component in several parts, and has to define the related new links necessary.
- Secondly, we want to assist the designer in the choice of the final joints techniques, taking into account many criteria (time, costs, efforts, ergonomics,….)

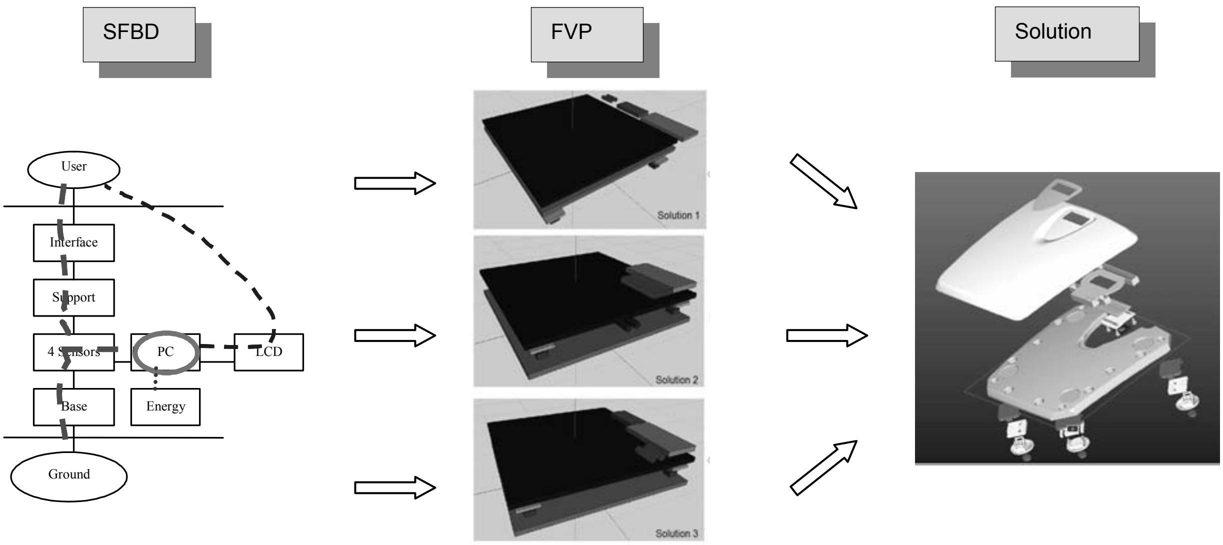


Figure 5: A virtual reality tool to assist the design of the solution from its functional definition

EoL option	Disassembly rules
Cleanup	Reversible fastening No destructive Remove components with hazardous substances
Reuse of the product	Reversible fastening Non destructive Minimum component to remove Minimum cost for the disassembly and re-assembly task
Reuse of the components	Reversible fastening Non destructive Minimum component to remove Minimum cost for the disassembly
Materials recovery	Minimum component to remove or materials compatibility or High potentiality to be separable

Table 2. Some basic rules depending on the EoL options

4 FIRST MODELS AND ORIENTATIONS FOR THE VR TOOL

The proposed tool is based on a Functional Virtual Prototype (FVP) of the product as quoted above. As for the SFBD four elements are used to build the FVP: part, external agent, link and flow.

The core element of the FVP architecture is the “part”. Thus we have to focus on the definition of the part model data structure that is to say all the data carried by the part model. These data should inform the designers about the disassembly and the remanufacturing procedure of the product. In addition to this, the part model should include all the geometrical data of the part prototype. Therefore we classified four type of data contained in the part model;

- Geometrical data: These data are embodied by 3D models. Two types of model will be used in our method. First, we will use basic geometrical forms (cube, cylinder sphere, torus…) to represent the product parts. Then, the 3D part model could be refined using simplified CAD models. The geometrical data will be hold by normalised VR compatible files formats such as VRML or Inventor.
- Spatial position: The spatial position of the parts and the relative position these parts are fundamental data in the FVP, because they will define the final structure of the product. These positions will be modelled by standard 3D coordinates (x,y,z,H,P,R).
- Functional data: They are used to encapsulate all the data which are useful to identify the components life cycle strategy. For example, we should find in the functional data criteria describing the EoL strategies: remanufacturing, recycling, reuse,… of the product part.
- Physical data: Here, we consider some elements of the physical part description such as estimated weight, material, toxicity...

Other elements of the FVP architecture are “external agents”. These elements represent the interactors existing in the outer environment of the product. These interactors could be the users or background elements that the product will react with. The external agents are the source and/or the destination of functional flows.

In order to embody the functions realised by the objects we use flows. The flows are divided in two categories. The first type of flow is the functional flow which characterizes the path which crosses a function. The second type of flow is the conceptual loops which are closed flows between components. These loops illustrate technological choices made by the designers. Links are used to model the contacts between components. These contacts will support the flows either functional or conceptual loops.

Description of the FVP operation:

When the FVP will be generated from the SFBD the user should be able to perform some modifications on the FVP. These modifications must be reflected in the SFBD. In the same way the modification performed on the SFBD must be reproduced on the FVP.

Four types of possible actions on the FVP have been identified:

- To modify the position of the parts,
- To remove, modify or create links between components,
- To remove, resize or create components,
- To remove, modify or create conceptual loops.

The modifications on parts (creation, positions,…) should be easy to achieve in the FVP since they are done in a virtual reality scene. Elsewhere, the links and/or flows modifications could be done more comfortably in the SFBD view of the product. Thus, the designer should be able to switch between the two views while keeping changes in the product functional model.

Implementation of the solution:

We will use the OpenMASK virtual platform in order to model the FVP. OpenMASK is an open source platform which has modular core architecture to enable programming independently from the environment (external devices, render engine…). An OpenMASK module is a prototype of a C++ class containing among others the following methods:

- A method for the initialization;
- A method of behaviour computing;
- A method for events handling …

The behaviour is programmed in C++ language in the computing method. The way to program the behaviour of an object is completely free for the user. The communication is realized over the data bus (figure 6) thanks to the input/output interfaces of the modules.

An OpenMASK module (OM) can be considered as a pure behavioural or virtual building entity. To model the geometry of virtual elements 3D file (VRML, Inventor …) are used. This way of modelling the geometry is well established in the virtual reality scientific community [16].

The most natural way to model the FVP using OpenMASK is to implement each element of the FVP in an OpenMASK module. Only the modules which correspond to components and links will handle geometrical file. So only these elements will be seen in the virtual scene. On the other hand, the flows and the external agents will be modelled by pure behavioural modules (figure 6).

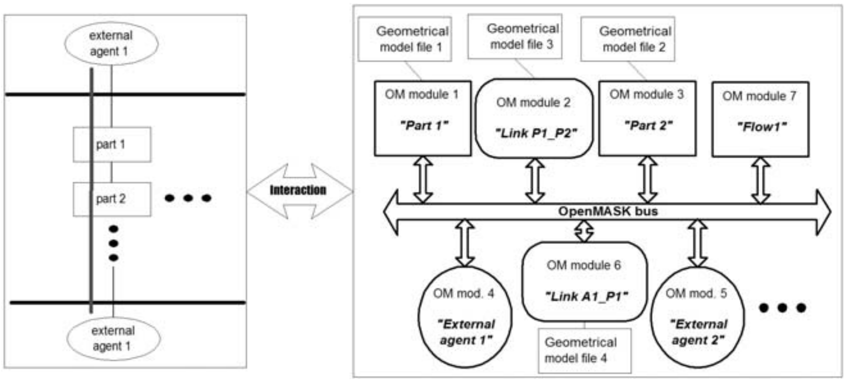


Figure 6. SFBD and FVP interactions

5 CONCLUSION

Any design change made to improve retirement modularity will be practical only if the benefits accrued from an environment-friendly design are coupled with decreased costs due to the design change [17]. This has leaded us to propose a VR tool to help designer during the definition of the product structure during the conceptual design stage. Our proposition is an interactive VR tool to assist the design of the product structure without limiting the creativity of the designer and promoting limited and selective intervention of an environment adviser [18] during the conceptual design phase.

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Green Line – strategies for environmentally improved railway vehicles

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Abstract
In 2004 the Vienna University of Technology and Siemens Transportation Systems in Vienna launched a project, called Green Line, focused on optimizing the environmental performance of metro vehicles. Green Line should create design strategies for a new generation of environmentally sound transport vehicles based on Life Cycle Assessment (LCA). As a reference project the new metro train for Oslo has been chosen. The improvement potentials indicated by the LCA are discussed in this paper to increase the environmental performance of the train. The recommendations given are discussed considering feasibility studies and prospective trends.

Keywords:
Ecodesign, Life Cycle Assessment, railway design

1 INTRODUCTION

More than 75% of the population of the European Union (EU) live in urban areas. Therefore, urban transport accounts for a significant share of total mobility. One fifth of all person kilometers travelled within the EU are urban trips of less than 15 kilometer. Between 1995 and 2030, total kilometers travelled in EU urban areas are expected to increase by 40%. Urban areas suffer heavily from congestion and nuisances caused by the excessive use of private cars. Pollution, noise and accidents are particularly acute in large urban environments and affect the lives of thousands of people. Urban transport is a significant contributor to climate change. 28% of greenhouse gas emissions in the EU presently emerge from transportation, 84% of that refer to road transportation alone. The Kyoto Protocol calls for an 8% cut in total EU CO_2 emissions by 2008-2012 based on 1990 levels. If current trends continue, CO_2 from transport will be some 40% higher by 2010 than it was in 1990. Innovative solutions to clean urban public transport are therefore fundamental for achieving the EU targets set under the Kyoto Protocol and improving air quality [1].

This target can be requires also environmental product design of transport vehicles. The intention of environmental design is to reduce the environmental impacts along the entire life cycle of a product [2]. The rail vehicle should achieve requirements such as a low energy demand, high recycling rate, low emissions, etc. The implementation of those requirements is the key to solve a huge part of the environmental problem arising from the increase of traffic emissions.

The paper intends to give an overview about the aspects concerning environmental design of metro trains and discusses solutions how to improve metro vehicles in an environmentally sound manner.

Figure 1 : Metro train Oslo in operation

2 LIFE CYCLE ASSESSMENT OF THE METRO OSLO

This chapter gives an overview about the Life Cycle Assessment study, which was prepared in the time period 2005/06. The LCA was done in accordance with ISO 14040 [3]. The life cycle assessment data for materials and energies were provided by Siemens Transportation Systems and their suppliers.

The functional unit of the study is related to a fully occupied three car train (the tare weight of the train is approximately 100 tons) operated in Oslo (Norway) for a time period of 30 years.

2.1 Goal and scope of the LCA study

The reasons for carrying out the LCA study are the following:

- The detection of product improvement potentials for prospective metro design strategies. The inventory results are used to identify improvement potentials and design recommendations for vehicle components as well.
- Presenting key environmental performance indicators of a metro vehicle, to be able to draw comparisons with similar transport vehicles. These environmental performance (e.g. tonne CO_2 per kilometer - tonne) indicators are mostly used to describe the environmental performance of transport vehicles.

This LCA study is a stand-alone study with the intention to achieve base information about the environmental performance of metro vehicles.

2.2 System boundaries

The LCA model for the Metro Oslo is defined by three kinds of boundaries.

1. System environment
The system boundary considers six life cycle stages (see figure 2) of the metro, which are "Raw materials", "Manufacturing", "Distribution", "Use", "Maintenance" and "End of Life".
Some life cycle stages ("Manufacturing", "Maintenance" and "End of life") are generating waste, which has to be treated by recycling, incineration or landfill.
In the applied LCA model neither manufacturing processes of the suppliers nor transport from the suppliers are considered.
2. Location (geographical) and time
There are different locations in the life cycle of the metro train. The manufacturing of the train is done at the Siemens Transportation Systems factory site located in Vienna, Austria. Then the train has to be transported from Vienna to Oslo in Norway by using a freight train. The metro train operates for a time period of 30 years in Oslo. Additionally the maintenance procedures are done by the operating company. Finally after 30 years running the metro will be disposed at a regional recycling plant.
3. Technology
The metro train consists of an aluminium lightweight carbody structure, which is built by modern welding robotics at the factory site in Vienna. Furthermore all components are designed to minimize the energy demand by using high end electronics.
In the "End of Life" stage most of the train materials can easily be recycled in consideration of current recycling technologies. The energy recovery due to incineration within the end of life process was not considered.

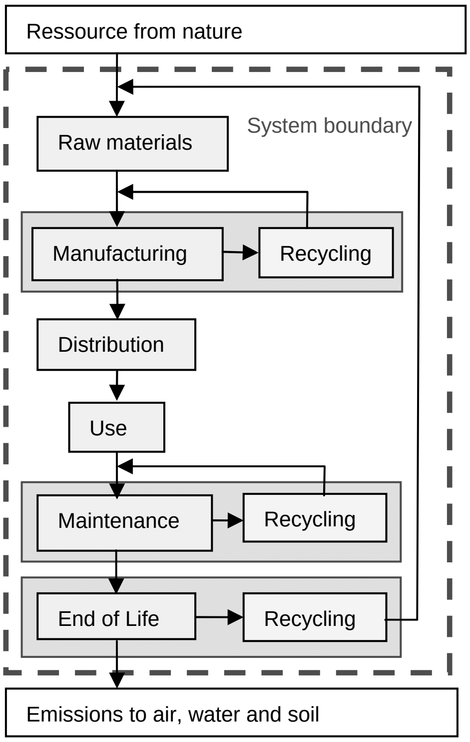

Figure 2: LCA system boundaries

2.3 Impact categories and impact assessment method

The impact assessment has been carried out by using the EDIP (Environmental Design of Industrial Products) method [4], which is implemented in the Software SimaPro 7 by Pre Consultants/Netherlands. Within the scope of the LCA study no normalization and weighting has been done.

The environmental impact categories included in this study can be divided into three groups as shown below.

Environment:

- Global warming
- Ozone depletion
- Acidification
- Eutrophication
- Photochemical smog

Toxicity:

- Human toxicity
- Ecotoxicity

Waste:

- Bulk waste
- Slags and ashes
- Hazardous waste
- Radioactive waste

2.4 Life cycle inventory analysis

The life cycle inventory analysis has been done using Ecoinvent data. [5] For all recycling activities during the product life cycle the concept of closed loop recycling has been applied. The detailed assumptions for each life cycle stage are mentioned below.

Raw materials

This stage includes extraction of resources from nature, transport to the processing sites and the production of raw materials. All data for the materials of the train (see table 1) are provided by Siemens Transportation Systems and their suppliers. The cut off criteria for the material quantities have been set to 5% of each component mass. Energies and resources for mining, transport and processing are included in the Ecoinvent data sets.

Material	Percentage	Kilogram
Aluminium	30.8%	28416
Ceramic	0.1%	121
Chemicals	1.2%	1105
Copper	2.6%	2389
Elastomere	5.3%	4848
Electronics	5.7%	5247
Glass fibre reinforced plastic	2%	1840
Minerals	0.1%	75
Steel, high alloy	26.4%	24282
Steel, low alloy	22.1%	20365
Thermoplastic	1.9%	1758
Wood	1.8%	1681

Table 1: Material composition for the metro train Oslo

Manufacturing

This stage includes the entire energy, processes and supply-materials for the manufacturing of the carbody structure and the assembly of the final metro train. Data for the manufacturing model were provided by Siemens Transportations Systems' annual environmental report for the business year 2004/05. Applied data for energies and materials are allocated by using following calculation method:

$$LCA\ Data = \frac{Energies\ and\ materials\ manufacturing\ site\ per\ year}{\text{Produced vehicles per year}}$$

The recycling scenario was considered by using the allocation model for the recycling process. The electrical energy at manufacturing has been modelled using Austrian electricity mix. In case of the recycling process an Austrian electricity mix for shreddering, sorting, etc has been used. The energy data for the recycling process were taken from a study prepared by the Fraunhofer Institute [6]. The transport distance for all materials has been assumed with 100 kilometer.

Distribution

This stage includes the rail transport necessary to deliver the metro from the manufacturing site located in Vienna to Oslo. The transport process considers the freight train process. There is no packaging considered.

Use

This stage includes electricity consumption for operating the metro train in Oslo for 30 years based on a total transport distance of 120000 kilometer per year. During operation the fully occupied train requires 12.36 kWh per kilometer. That means for each tonne an energy consumption of 0.09 kWh per kilometer is needed. [7] This data is based on an energy simulation for the metro vehicle Oslo. The simulation results are representative for utilization in summer and wintertime with an average passenger load. Note that the energy consumption calculation includes the regenerative braking effort, which approximately saves up to 46% net-energy. The train is supplied by the Norwegian electricity net for 30 years.

Maintenance

This stage includes all required replacements including the exchange of car components. For the replaced parts, recycling, incineration and landfill are considered. The material consumption over the entire life time (see table 2) was taken from the Maintenance Program Plan for the metro train Oslo. Grease, lubrication, sealing and other small parts that weigh less than 5% of the replacement part unit have not been considered.

Material	kilogram
Steel, high alloy	75261
Oil	10470
Elastomere	30834
Steel, low alloy	1517
Electronics	971
Aluminium	119

Table 2: Material consumption for maintenance over a time period of 30 years

Energies and tools for dissembling have not been considered either.The material list for the LCA model comprehends only replacement parts in the predefined time period of 30 years. Failure or repair parts are not included.

The recycling scenario with its recycling rates and energies is comparable to the process in the end of life stage.

End of life

A recycling study has been performed, showing a recycling rate of the complete train of 84.7%. [8] The percentage of thermal energy recovery with 10% enhances the total recycling behaviour up to 94.7% (see table 3). Only 5.3% of the complete metro train have to be landfilled. These recycling rate percentages have been developed in cooperation with an Austrian recycling company.

The energies for the recycling processes (mostly melting and shreddering) and the transport (100 kilometer) to the recycling company were considered using Norwegian energy mix.

Recycled material	kilogram
Aluminium	-27848
Copper	-2341
Glass	-637
Steel high alloy	-23796
Steel low alloy	-19958

Table 3: Quantity of recycled material related to the metro train

2.5 Impact assessment results

This section represents the main results of the LCA based on the assumptions for the metro train Oslo. The impact category "global warming" (GW) has to been chosen for further investigations.

Environmental impact categories	Unit	Life Cyle metro train
Global warming	tonne CO2-eq.	1360
Ozone depletion	gram CFC11	152
Acidification	tonne SO2-eq.	8.14
Eutrophication	tonne NO3-eq.	6.68
Photochemical smog	tonne C2H4-eq.	0.845

Table 4: Characterized impact assessment results for the entire life cycle of metro Oslo.

The overall result for the metro train Oslo is 2.6 gram CO_2-eq./tonne-kilometer. The operation of the metro train Oslo is contributing 1.6 gram CO_2eq./tonne-kilometer, which is low compared to other transportation systems. The reason for this low global warming potential is the energy management of the train but also the energy generation in Norway, which is based on renewable energy sources. The effect of energy sources during and the recycling behaviour along the entire life cycle were investigated within the scope of a sensitivity analysis.

The knowledge about the correlation between recycle behaviour and energy sources to the quantity of environmental impacts are basic conclusions for the recommended product improvements.

3 ENVIRONMENTAL PRODUCT IMPROVEMENTS FOR METRO VEHICLES

The investigation of the LCA results has lead to product design strategies that can be implemented in the next series of metro vehicles.

3.1 Tracing environmental improvement potentials

The essential question within this investigation is: "Which component of the metro train needs to be improved in a environmentally sound way and how much is the impact contribution of this part?"

To answer this question figure 3 will display the GW contribution of different metro parts along the entire life cycle. For instance the heating system of the passenger compartment causes up to 40% of the GW contribution in the use stage. As shown in the figure the life cycle stage "Use" and "Raw materials" have the biggest impact according to the global warming potential. The third important life cycle stage is "Maintenance", which is contributing emissions together with the use stage over a time period of 30 years. I.e. the most relevant impact stage related to the global warming potential is "Raw materials", followed by "Use" and "Maintenance".

For each life cycle stage there are different reasons for the impact potentials. For further investigations the relevant impact sources shall be identified in each life cycle stage:

1. Raw materials

The contributions of the global warming potential are mainly present in the carbody structure with 40% and the boogie with 23% according to the total GW-potential. The reason for the high GW-potential is the energy intensive production of implemented aluminium and high alloyed steel.

2. Use

Measurements have been evincing that the mechanical losses exceed the electrical losses by nearly 20%. The contribution of approximately 40% for the heating system of the metro train is remarkable.

3. Maintenance

In the maintenance stage the biggest contribution to the GW potential (about 95%) arises from the raw materials steel and elastomer plastics, mostly used for the boogie. Along 30 years every second year the entire wheel set and the damping elements have to be replaced.

The improvement potentials are located in following component systems:

- Carbody
- Heating system
- Boogie

3.2 Recommendation for improvement strategies

After identifying the critical parts of the metro train the environmentally related improvement recommendations have been carried out in table 5. The relative saving potentials are based on international investigations concerning energy efficiency for railway vehicles. [9]

Life cycle stage	Component	Recommended design strategy	Relative savings potential
Raw material	Carbody	Lightweight materials (Reducing 10 % carbody weight means 10% less energy demand) [8]	10%
		Using recyclable materials (actual recycling rate Metro Oslo 84,7 %)	Up to 10%
Use	Heating system	Using better Insulation of carbody (actual heat transfer coefficient 2,95 W/m^2K)	Up to 20%
		Reduce temperature exchange due to entry and exit of passengers	Approx. 40 %
		Using lost heat of brake resistors for heating system	Approx. 30 %
	Boogie – Wheel set	Gearless traction with permanent magnet motor	Up to 35%
		Reducing the driving resistance between wheel and rail	Up to 5 %
	Power - Traction	Using capacitors for energy storage	Up to 40 %
	Power - Control	Energy saving driving behaviour	Approx. 25%
Maintenance	Boogie	Loose (single) wheel technology.	15%

Table 5: Recommendations for environmental improvement strategies considering saving potentials compared to the actual metro vehicle components.

In most of the cases the recommended strategies help to save energy due to reduction of the weight or the increase of efficiency during operation. The second approach is to enhance the recycling rate and the endurance of particular metro components.

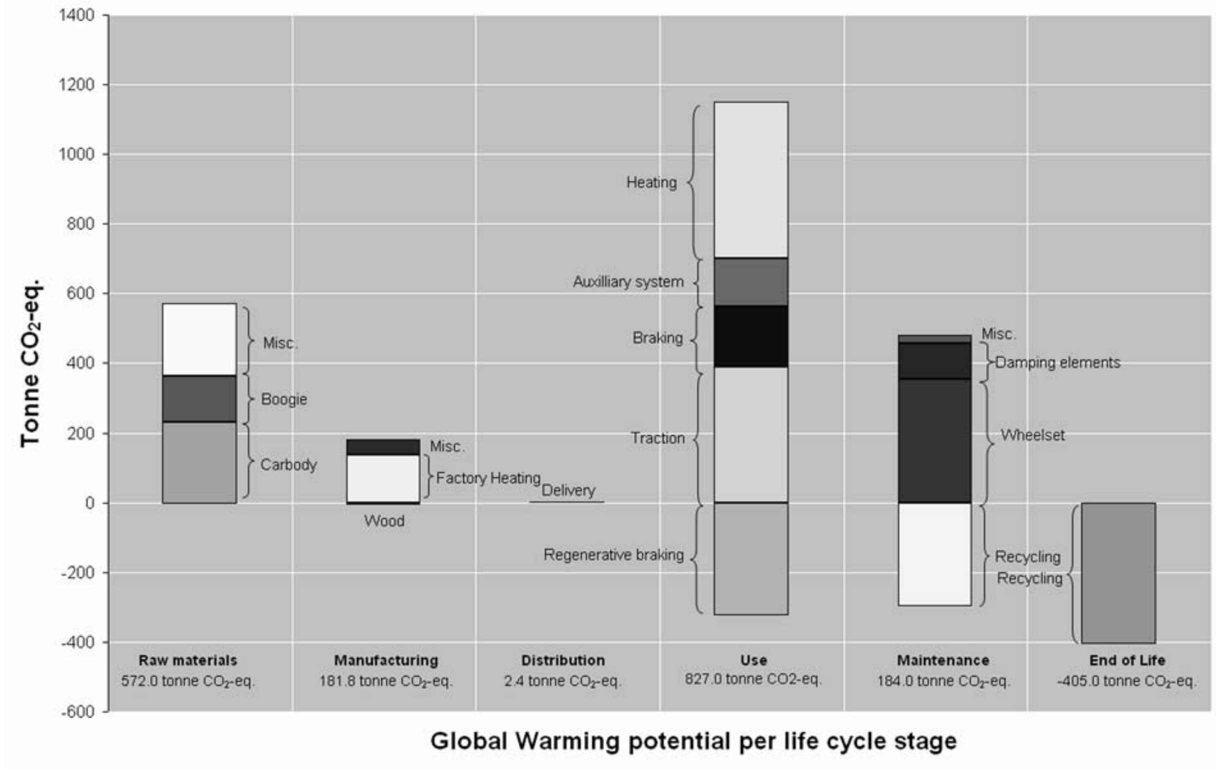

Figure 3: Contribution of environmental impact per metro vehicle component and life stage. Important contributors are named.

3.3 Evaluating environmental improvement design strategies

Before implementing the recommended improvement strategies the feasibility has to be considered. The feasibility is based on the estimated effort for implementing improvement recommendations in the current metro design project.

In accordance with figure 4 the following design strategies are suggested:

1. Lightweight structure
2. Using lost heat of brake resistors for heating system
3. Using capacitors for energy storage
4. Gearless traction with permanent magnet motor
5. Energy saving driving behaviour

The selected strategy for the final implementation in the metro train will be based on cost evaluations and engineering decisions.

4 SUMMARY

The intermediate results of the project can be summarized as follows:

- The most significant stage related to the environmental impact category “Global Warming” is the “Use” stage of the metro train, followed by the stages “Raw materials” and “Maintenance”.
- For the environmental impacts during operation the energy losses due to traction and heating of the metro vehicle are most relevant.
- The recommendations for an environmentally improved metro train are high efficient traction systems, a lightweight vehicle structure together with improved heat insulation in the passenger compartment.
- With focus on material consumption during the stages “Raw materials” and “Maintenance” an enhanced recycling behaviour should be considered as well.

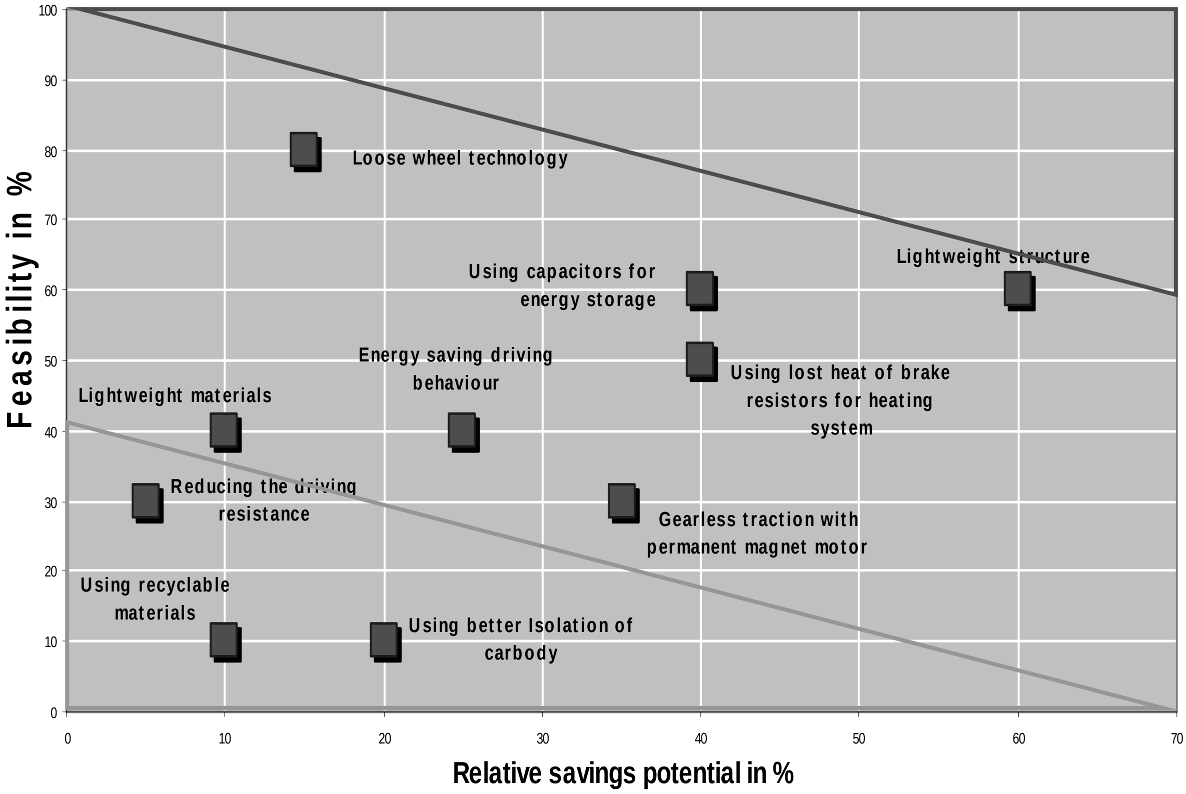

Figure 4: Evaluating improvement strategies

5 OUTLOOK

Next step in the project will be the investigations in consideration to future trends. Future trends will depend on new technologies and resources as well. The final aim is to develop a design concept which considers these future scenarios.

6 ACKNOWLODGMENTS

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TRIZ Based Eco-Innovation in Design for Active Disassembly

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Abstract
Active disassembly technology provides the designer a useful unmanned disassembly processes to achieve efficient recycling for products. Currently, many types of smart active fasteners are developed by using shape memory plastics (SMP). This technology has been testing in cell phones and LCD TVs to confirm the concepts. This paper presents an eco-innovative design methodology by using TRIZ method to innovate the new concepts of smart active fasteners for active disassembly at the end-of-life stage of products. The tools of TRIZ, such as contradiction matrix, inventive principles, and substance-field analysis, are chosen in this study to develop this eco-innovative design methodology. Examples are demonstrated to illustrate the capability of proposed methodology.

Keywords:
Active Disassembly; TRIZ; Eco-innovation, Eco-products.

1 INTRODUCTN

The development of technology plays a crucial role in modern economic growth, but is also is the key factor of environmental crisis. It is usually emphasizing the novelty and economic usefulness of an innovation product but neglects its environmental impact. Currently, many eco-design methods have been combined with eco-innovation. The use of TRIZ method in eco-innovative design tasks is one of the interests, which have been proposed since 2000 [1-2]. They identified ways in which tools and methodologies from TRIZ might be used in eco-innovation.

The simplest way to adapt TRIZ into eco-innovation is using TRIZ classical method by identifying the contradiction parameters and finding suitable principles from contradiction matrix [1, 3-6]. Chen and Liu established the link between seven major eco-efficiency elements from WBCSD (World Business Council for Sustainable Development) with TRIZ engineering parameters and developed an inventive design method to solve engineering innovative design problem without contradiction information by using TRIZ inventive principles [7-9].
Chen [10] developed green evolution rules and ideality laws for eco-innovative design, which can help designer to locate an evolutionary direction in eco-design process. Chang and Chen proposed a design around and extension method [4, 11] and collected 40 eco-innovative examples for TRIZ inventive principles [12], which cover a wide range of products and processes design. Many eco-design tools were selected to link with TRIZ-based eco-innovation processes, such as eco-compass [1], green QFD [5, 13-15], green FMEA [16-17] *et al.* Chang [18-19] applied TRIZ su-field analysis tool for eco-innovation. Chen and Andrew [20] combined one parameter method [7-9] and TRIZ new matrix 2003 [21] to develop an eco-innovation software tool from the perspective of product's life cycle stages. Justel and his co-author [22-23] applied TRIZ method in design for disassembly.
Smart materials such as shape memory alloys [24-25] and shape memory plastics [26-28], were tested to develop active disassembly fasteners. One-to-many fasteners [29-30] had been proposed to achieve cost-efficient active disassembly. A systematic design approach [31] was developed to invent easy disassembly connections.

This paper presents an eco-innovative design methodology by using TRIZ method to innovate the new concepts of smart active fasteners for active disassembly at the end-of-life stage of products. The tools of TRIZ, such as contradiction matrix, inventive principles, and substance-field analysis, are chosen in this study to develop this eco-innovative design methodology. Examples are demonstrated to illustrate the capability of proposed methodology.

2 ACTIVE DISASSEMBLY

2.1 Active disassembly by shape memory alloys

The ideas of active disassembly can be defined as a technique by which a product can be self disassembly with the aid of special fasteners at its end-of-life stage. The shape memory alloy (SMA) has the properties of returning to their original shape after heating to exceed their transformation temperature A_f. Therefore, SMA fasteners could be used as fasteners embedded into products to achieve active disassembly performance. SMA spring [24], SMA washer [25] and SMA snap fastener [24] had been developed and applied in cell phone and LCD TV [25].

2.2 Active disassembly by shape memory plastics

Some plastics contain shape memory effects. One of these effects is that shape memory plastics (SMP) may be set in a particular shape above the glass transition temperature, T_g, and hold this particular shape as it cooled to a temperature below T_g. The SMP will return to its original shape when its was heated to a temperature above T_g. The properties of SMP offer an opportunity in developing SMP fasteners for active disassembly. SMP screw and nut [26], SMP LCD bracket [27] had been developed and applied in mobile phone industry [28]..

3 TRIZ METHODS

3.1 Contradiction matrix and 40 inventive principles

When a design engineer tries to solve an innovative design problem, it is usually a system incompatibility or conflict design problem. As the designer changes certain parameters of the system in his design problem, it might make other compromise with this kind of contradiction situations and restricts himself on performing innovative design tasks. The TRIZ method was developed in the former Soviet Union by Altshuller, who had analysis over 400,000 patents to build the contradiction matrix and 40 inventive principles. For using TRIZ method in innovative design problem solving, the designer needs to first find corresponding contradictions for his problem at hand. Next, the designer matches the meaning of each contradiction with two appropriate parameters from 48 engineering parameters that defined in the TRIZ contradiction table [21]. The designer can find 3-4 most frequency used principles for solving innovative design problem from contradiction matrix when he confirms the parameters of contradiction for an engineering system. Details of TRIZ methods can be found in publications [32-33].

3.2 Su-field analysis

Su-field analysis is a modelling approach in TRIZ for the analysis and innovation of physical phenomena in product systems. This method is performed by building a substance - field model for your design problem and analyzed the modification possibility of this model to innovate new solution for your design problem. Substance is any objects or tools within product system. Field refers to the energy required for the interaction between two substances. Two substances (objective and tool) and the energy of their interaction are the minimal requirements to build a minimal su-field model for performing one function. Several standard modification rules can help the designer to modify su-field model to eliminate harmful effects [18-19, 32-33].

3.3 Green evolution rules and ideality

Identify the current position of today's design within an evolutionary pattern and the designer can predict future designs along this pattern. It is obvious that there exist some patterns of evolution rules for green products. These green evolution rules provide the designer a useful tool for filtering and selecting solutions of eco-innovative design problem. These technical evolution trends determine the direction and character of technical revolution in the next generation. Hence, it can help the designer forecast the future of the technique and concentrate research and development in the most promising directions. Some patterns of green evolution rules of different green products have been observed and identified [10].

The ideal system is a non-existent system with all of its functions still being executed. In other words, function is ideally by already existing resources. Nevertheless, actual systems approach the ideal by increasing their beneficial functions and eliminating harmful factors. In green design area, the harmful factors are the materials, components, or processes during life cycle of products that produce severe environmental impacts. The ideal final result of green products is to perform desire functions without any environmental impacts. Therefore, looking at eco-innovation design problem of products from an ideal final result perspective is usually a very good first step towards success. The green evolution rules can provide assistance in formulating the ideal final result.

4 TRIZ BASED ECO-INNOVATION

4.1 Using eco-efficiency concept to find TRIZ parameters

WBCSD has pointed out seven major elements for a company in considering the eco-efficiency of developing environmental friendly products or processes to reduce environmental impacts.

A. Reduce the material intensity of its goods and services

B. Reduce the energy intensity of its goods and services

C. Reduce the dispersion of any toxic materials

D. Enhance the recyclability of its materials

E. Maximize the sustainable use of renewable resources

F. Extend the durability of its products

G. Increase the service intensity of its goods and service.

As each element improves or more elements improve simultaneously, it produces high eco-efficiency products or services.

The designer can identify the required improving elements of eco-efficiency based on environmental regulations or product's LCA evaluation results. Then, the relationship of each element of eco-efficiency with the 48 engineering parameters of TRIZ method is examined. For example, reducing a product's "material intensity", that can be achieved by changing its properties, such as weight, dimensions, shape or the amount of material used. Next, reflecting these properties to closely related engineering parameters of TRIZ. Therefore, the problem of improving eco-efficiency is transferred to TRIZ problem.

4.2 Eco-innovation by TRIZ contradiction matrix

An eco-innovative design method based on guidelines of eco-efficiency, TRIZ 48 engineering parameters, TRIZ 40 inventive principles and TRIZ new 2003 contradiction matrix [21] is presented in Figure 1. First of all, the designer can utilize LCA tool or other eco-design tools to assess the environmental impact loads from each life cycle stage and identify the required improving elements of eco-efficiency. Next, the designer can find the corresponding TRIZ engineering parameters by guiding of improving eco-efficiency elements. Moreover, using new 2003 contradiction matrix, the designer can get some inventive principles with high priority. Finally, these inventive principles can be used by the designer in innovating new design ideas.

As for the situation that the designer has difficulty in defining contradiction parameters for eco-innovative design problem, the method [7-9, 20] for using TRIZ inventive principles without contradiction information can be applied in this kind situation.

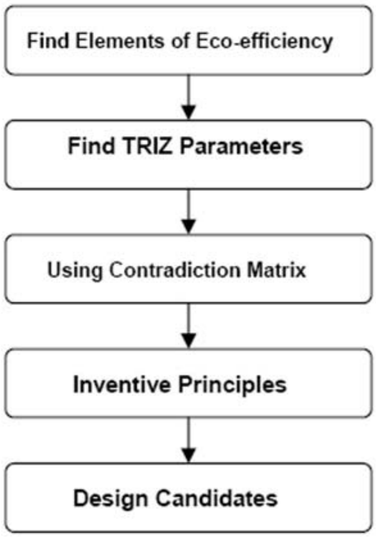

Figure 1: Flowcharts of eco-innovation method by TRIZ contradiction matrix.

4.3 Eco-innovation by su-field model

The designer can identify the required improving elements of eco-efficiency based on environmental regulations or product's LCA evaluation results. Then, the designer can build a su-field model and analyze its environmental harmful effects. Finally, applying the su-field analysis techniques to modify su-field model, the designer can innovate new eco-product concept by the new su-field model.

5 EXAMPLES

5.1 Smart nuts innovation

For reducing the number of screw and also keeping the strength of screws to avoid damage in LCD monitor, the designer has to transfer design problem into TRIZ problem in order to solve this problem. Therefore, it can get corresponding TRIZ engineering parameter 35 "reliability/robustness" for increasing reliability of new fastener. Then, the designer can find corresponding contradiction feature for avoiding the decreasing on disassembly capability. The designer can find the corresponding TRIZ engineering parameter 36 "repairability". After getting TRIZ engineering parameters, the designer can find corresponding inventive principles from contradiction matrix.

The corresponding inventive principles are inventive principle #1, #11, #15, and #2. Applying inventive principle #15 "dynamization", to come out innovative ideas of smart nut design is to use SMP as material of smart nuts. Therefore, the LCD panel can perform active disassembly by heating smart nuts. The smart nuts will loose and self disassemble when the temperature was above the glass transition temperature, as shown in Figure 2. Furthermore, the combination of other inventive principles may have chance to invent other new smart nuts concepts.

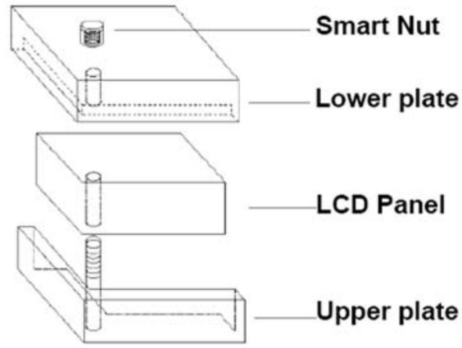

Figure 2: Innovation ideas of smart nuts.

5.2 Central empty machine screw with SMP ball

Machine screws are used a lot in products. The design problem of machine screw is trying to improving disassembly capability and avoiding reduction in its mechanical strength. Therefore, it can get corresponding improving TRIZ engineering parameter 36 "repairability". Then, the designer can find the corresponding avoiding TRIZ engineering parameter 20 "strength". After getting TRIZ engineering parameters, the designer can find corresponding inventive principles from contradiction matrix.

The corresponding inventive principles are inventive principle #1, #4, #17, #9, and #24. Applying inventive principle #1 "segmentation", to innovative design of machine screw problem is to form the central part of screw empty and insert a SMP ball in center of empty part, as shown in Figure 3(a). Therefore, at end-of-life recycle stage, one can heating SMP ball to let SMP ball changing shape. As a results, the machine screw will loose the fasten function, as shown in Figure 3(b).

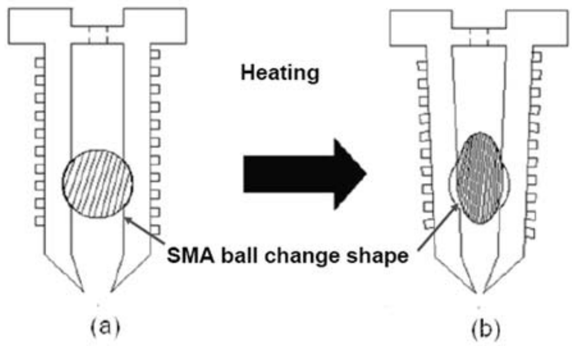

Figure 3: Machine screw with SMP ball.

5.3 Improving snap fit fastener

Snap fit fasteners use a lot in plastics part of electronic products. The design problem is to improve the disassembly capability without increasing its complexity. Therefore, it can get corresponding improving TRIZ engineering parameter 36 "repairability". Then, the designer can find the corresponding conflict TRIZ engineering parameter 46 "control complexity". After getting a pair of conflict TRIZ engineering parameters, the designer can find corresponding inventive principles from contradiction matrix.

The corresponding inventive principles are inventive principle #2, #35, #4, #10, and #1. Applying inventive principle #2 "Taking out", to snap fit design problem is to change the connective part of plate in snap fit fastener assembly into SMP material, as shown in Figure 4(a). Therefore, after heating the connective part of plate in snap fit fastener assembly, the SMP part will change its shape and the snap fit disassembly actively, as shown in Figure 4(b).

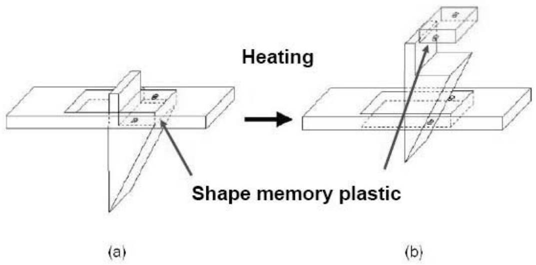

Figure 4: Snap fit fastener by shape memory plastic part.

5.4 Magnet fastener by su-field model

Currently, most SMA or SMP fastener is actuated by the thermal, optical, electrical, or chemical driving force during disassembly process. In this example, a new concept of smart fastener without SMA or SMP material is developed by using su-field model. The driving force of this new smart fastener is changed to magnetic force. Therefore, the su-field model of magnet fastener is illustrated in Figure 5. Based on this su-field model, a concept of new smart fastener actuating by magnetic force is shown in Figure 6. It is using electricity to provide magnetic force for joining, as illustrated in Figure 6(a). Active disassembly of the magnet fastener is performed by turning off the electricity to eliminate magnetic force, as shown in Figure 6(b).

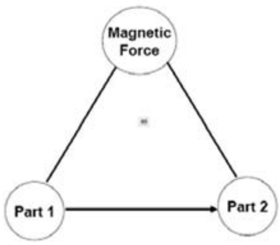

Figure 5: Su-field model of magnet fastener.

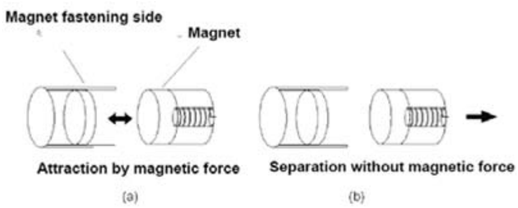

Figure 6: innovation ideas of magnet fastener.

6 CONCLUSIONS

This paper developed product eco-innovative design methods for active disassembly based on the TRIZ contradiction matrix and su-field model. Successful product examples demonstrated the feasibility of the proposed new methods for eco-innovative design tasks. These methods provide the designer a supporting tool to develop new concepts of smart active fasteners for active disassembly at the end-of-life stage of products with less environmental impact. The eco-innovation design methods will be one of the several approaches towards sustainable development.

7 ACKNOWLEDGMENTS

This study supported by the National Science Council of Taiwan, grants number NSC 94-2621-Z-006-009.

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Need Model and Solution Model for the Development of a Decision Making Tool for Sustainable Workplace Design

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Abstract
In this paper, we present a project with the world leader of office furniture and workplace solutions. The goal is to build a decision-making tool combining a need model and a solution model to be used by designers and sales people to simulate different planning scenarios having different contributions to company performance. This decision-making tool is based upon a model of need (for a new workplace design project) and a solution need (roughly describing a solution sketch). We describe the ontology of the tool and illustrate with a case study about a decision making process in a limited perimeter of lighting system.
Keywords:
Sustainability performances, workplace design, multicriteria decision making, AHP, Pairwise comparison

1 INTRODUCTION

In this electronic/information age, work teams form and reform to meet organizational needs, technological innovations, and changing business relationships. Buildings and interior spaces need to be flexible to anticipate and support this changing nature of work. Within the past few years, designers have sought to create a new generation of "flexible" buildings and workplace environments within buildings that have infrastructures and structures that fully support change and create value to the company.

The changing nature of work means greater mobility for workers, a lot of workspaces within and external to buildings, geographically dispersed groups, increased dependence on social networks. This creates a greater pressure to provide for all of these needs and behaviors an adequate work environment. The idea of designing a workplace to support organizational effectiveness is not a new idea. Many workplace experts have written on the topic [3; 5; 6].

Furthermore, current workplace research tends to address a limited number of topic areas (such as ambient conditions) and a limited number of outcomes (particularly occupant comfort and perceptions). There is much less attention paid to sustainability performance and potential benefits for organization and individuals. However, there is clear interest in fashioning a new agenda for workplace research to understand how workplace design can influence organizational success and business performance.

In this direction and with the rise of sustainable development issues, some companies and workplace/building experts are convinced by the contribution of workplace to the achievement of sustainability objectives. This assumption is due to the way that a workplace encapsulates different categories of performances (Economic, social and environmental) having direct and indirect impact on company performance.

These findings about the workplace systems put the accent on the complexity of the decision making in design process, where designers are no comfortable with all the performance parameters. There is a clear need for decision support tools current design process to take the right decision regarding client and legal requirements.

In the paper, we present our project with an office furniture manufacturer and workplace service provider about the development of a sustainability performance evaluation tool aiming to support decision making process current design and proposal of workplace scenarios to clients. Clear definitions of ontological concepts are provided on the proposed model and a clarification of need and solution models as well as an example on a decision making process in a limited technical perimeter of a workplace.

2 AIM OF THE PROJECT

2.1 Industrial partner needs

The industrial partner is an US Company, world leader of office furniture and workplace solutions. The company has gained a recognized know-how in ecodesign of products the last years, and had an innovative orientation toward managing sustainability performance of workplace. This preoccupation is today demonstrated by the consideration of LEED-CI [8] certification as one of the main strategic objectives of the company buildings around the world. The goal of this type of certification (e.g. the corresponding certification is named HQE in France [7]) is to improve and promote environmental performance of building in order to generate economic and social benefits.

Today, the company wants to increase client awareness about the strategic importance of this kind of performances by developing an evaluation tool dealing with different parameters in the workplace and enabling to provide indication about the sustainability performance of workplace solution. The tool has two applications, the first to support design process and the second to argument sales process.

2.2 The expected tool

The decision making tool to be developed consists on a computer based information system linking workspace design to sustainable business performance (in economic, social and environmental terms). The aim of the tool is to support decision making in design process and the proposal workspace scenarios to clients [4].

We defined 3 using scenarios for the tool enabling to cover different needs:

- *Generation of General Recommendations (GGR):* gap analysis between current performances of an existing workplace and target then top-down propagation to give general design recommendations
- *Solution analysis (SA):* a bottom-up scenario to give decision making support of design elements selection (solutions) corresponding to performance targets.
- Solution optimization (SO): optimization of existing technical solution regarding target need.

3 THE STRUCTURE OF THE TOOL

We want to define functions and targets with clients (need model) and propose design recommendations of preferred *design elements* (solution model) that best match the targets. The *Need Model* represents the definition of need in the form of service functions, performance criteria and corresponding targets (for the new workplace to design). The *Solution model* refers to the different technical domains (e.g. lighting, heating and ventilation...) in which design elements will be defined which characteristics impacting the aforementioned *performance criteria*. However, a critical stage consists on linking the two models by defining an appropriate *semantic of correlation*. The semantic is under construction and we just present the principle in section 4.

3.1 Structure of the Need model

We define the need model for a new workplace on three layers or hierarchical levels.

- Service functions (SF) or High level objectives expressed in term of company requirements from the workplace dealing with sustainability issues and influencing company's business results.
- Technical Functions (TF) are the sub-functions (which are means) contributing to service functions and for which we can measure the accomplishment regarding performance criteria.
- Performance criteria: under each technical function, we have a list of performance criteria specified by a measurement context. A measurement context is defined considering the type of scale (qualitative or quantitative scales) and the nature of target (fixed by codes, standards, legislation or client needs).

Service Function (SF) layer

Companies want to translate strategic objectives into workplace solution. The company requirements are translated into objectives expected for workplace (Service Functions). The workplace objectives address not only the investment on physical products and the financial impacts but also the social performances potentially improved by the work conditions, as well as, the environmental benefits which potentially provides economic savings (reduce energy consumption, recyclability of building or workplace products, renewable resources…).

Technical function layer

The mean to fulfil or support Service Function. It's a practical mean to economically but efficiently measure a part of a functional performance. Technical functions ensure that the product works and performs well.

Performance criteria and measurement

A TF is assessed by different performance criteria from different nature and measurement protocols. The last define the way of measuring a performance (unit, localisation, timeframe...). For example, the assessment of the performance of "visual comfort" in open plan space and in meeting room is different because the requirements are not the same. When investigating the different performance criteria under a common Service Function, we identified a list of quantitative and qualitative criteria. These performances have existing indicators in the quantitative case with target values fixed by codes and standards [1].

The qualitative ones require the development of scale. In this case, we need to define a general scale presenting different levels of performance, ranging between 1 and 5 characterized by a grid of levels. A general pattern of a qualitative scale is used for the different qualitative performances (Table 1). We assume that the satisfaction of a current performance is acceptable from level 3 and more. For each qualitative performance, the general scale pattern is interpreted for generating meaningful scale levels (see for instance table 2 about "individual control of artificial lighting).

1	No possibility to adjust light
2	Luminaire switching - Occupancy sensor
3	Calling up lighting scenes - Manual call-up of lighting scenes
4	Task lighting - Luminaire dimming
5	High level of lighting system control for individual occupants and specific multi-occupant space.

Table 1: Example of qualitative Scale for "Individual control of artificial lighting systems".

Difficulties & potential solutions

At the moment, difficulties are to bring indicators to the same measurement unit because we have Indicators originally incommensurate or expressed in different units.

We propose to transform performances into *Utility Functions* Ui (Ei; Ti) of the current evaluation and target value.

For that purpose, we propose to embed this compromise into an objective function expressing the overall *utility* of a conceptual solution. Then, we propose to transform the performances into *Utility Functions* U_i which are function of the current evaluation of the performance criteria (E_i) (current meaning for the conceptual solution under study) and the corresponding target value (T_i). We have decided to use a simplified form of Utility theory (see [2] for a general presentation of preference aggregation models). Here, the designer must choose a utility function of the trapezoidal (see Figure 2) or the triangular shapes (see Figure 3) and model the target for the corresponding performance criterion through constant values a_{ij}. The value of utility for a given performance criterion is then given from an assessment of the current criterion value; it is comprised between 0 representing the worst preference (dissatisfaction) and 1 the best (total satisfaction).

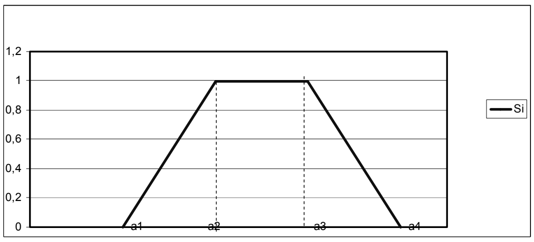


Figure 1: Curve Type 1: Trapezoidal function.

$$S_i \begin{cases} 0 & for\ x < a_1 \\ \dfrac{x-a_1}{a_2-a_1} & for\ a_1 \le x \le a_2 \\ 1 & for\ a_2 \le x \le a_3 \\ \dfrac{a_4-x}{a_4-a_3} & for\ a_3 \le x \le a_4 \\ 0 & for\ x > a_4 \end{cases} \quad (1)$$

Example: The performance criteria "Level of Illumination", the satisfaction equal 1 between 300 lux and 500 lux.

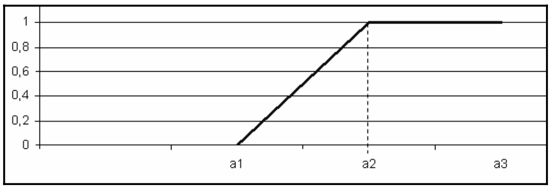


Figure 2: Curve Type 2 (Triangular Function)

$$S_i \begin{cases} 0 & for\ x < a_1 \\ \dfrac{x-a_1}{a_2-a_1} & for\ a_1 \le x \le a_2 \\ 1 & for\ x > a_2 \end{cases} \quad (2)$$

Example: for the performance criteria "light uniformity", the satisfaction equal to 1 when uniformity factor > 70%.

Weighting Criteria

A last thing remains to be done is the aggregation between the contributions of elementary utilities. We propose here to hierarchically weight the contributions of each *Performance Criteria*. We adopt the linear and hierarchical aggregation model of the *Analytic Hierarchy Process* (AHP) methodology [11]. The construction of an AHP aggregation model is made upon successive applications of a *pairwise comparison* process between the elements at a same node-level. This process aims at resulting in a *weighting vector* after pairwise comparing the elements of a node-level. In that way, pairwise comparison methods notably simplify the rating problem by focusing the attention of decision makers on pairs of elements to be compared. The literature is rich of methods of pairwise comparison (PC). We have used a RGM (*Column Geometric Mean) and* LSLR *(Least Squares Logarithmic Regression)* PC method [9; 10] for the case study.

3.2 Structure of the solution model

Technical domain & expertise in workplace

We defined the solution model by modular *design elements* roughly characterizing a solution sketch under an identified *technical domain.* We identified 8 main technical domains (see Table 2). We assume that the 8 technical domains are main contributor domains which permit to roughly define a given solution concept and then to fulfil service functions and corresponding technical functions. Each technical domain may be decomposed into sub-domains, what we call *design element classes* (see Table 3). Each *design element class* may be instantiated into an *elementary solution*, which represents a rough dimensioning of workplace.

Technical domain	Design elements
Lighting Systems	Daylighting - Artificial lighting - Controllability
Acoustics systems	Sound Isolation - Sound Absorption - Sound Masking
HVAC systems	Cooling - Ventilation - Heating
Power& Data Systems	Electrical systems - Data networks - Wire management
Interior Design	Wall - Furniture – Ceiling - Flooring
Safety/Security Systems	Fire systems, Building & Workplace access
Technological Equipments	Computer, Communication, Display, Internet
Space Planning	Transverse domain

Table 2: Design elements under technical domains

Design elements and corresponding attributes or properties

As we said above, a technical domain is decomposed into *design element classes* (Table 3) having proper attributes or characteristics specifying the intrinsic performances (*technical characteristics*). These attributes are defined with regards to performance criteria that they can influence positively or negatively. For instance, *Artificial Lighting class* have attributes like *lamp type*, *wattage*, *luminosity*, *Color rendering index*, *material content*, *maintenance factor*, *maintenance interval* and *cost*. The relationships between attributes of design element classes and performance criteria are casual influences which defines the correlation semantics.

4 CORRELATION MECHANISMS

We can define with expert's knowledge to specify the interactions of elementary solutions with the performances (of technical functions). Some attributes can quantitatively correlate with performance criteria (e.g. illumination and luminosity...). However, there are possibly non linear effects of solutions on performances, this is why semantics of fuzzy rules will be proposed to figure out or simulate this kind of interactions. This process is fundamental in order to be able to recommend solutions regarding need targets.

5 CASE STUDY

5.1 Problem definition

We test a part of our model with a problem of selection of lighting solution for a specific space with Total area of 72 m^2 (see figure 4).

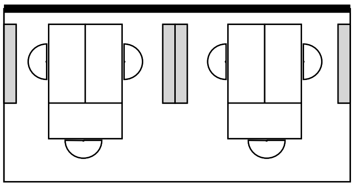


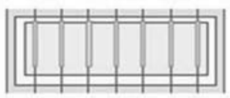
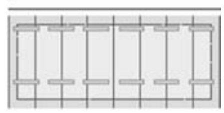
Figure 3: space to light up.

The company Client expects three objectives in this space that we propose to represent based on our Need Model (see table 3).

Service Function	Technical Function
Improve *occupants satisfaction*	Promoting *visual comfort* in task surfaces
Reduce the *energy consumption* & *emissions*	Optimizing *lighting energy use and increase energy savings*
Optimize *operating Costs*	Reducing *maintenance and energy costs.*

Table 3: Need modelling

The designers have two alternatives (Figure 5-6) for artificial lighting systems provided by supplier with the same initial cost, service life (15 years) and operating hours/year (2000 h). Maintenance consists mainly on luminaire cleaning and room painting in time interval along service life.

 Figure 4: Alternative (1)	 Figure 5: Alternative (2)
6 luminaires (1/54 W + 2 x 2/24 W T16) - switching control Energy Use: 2100 kwh/year Maintenance: 6 times (1415 €/time)	**12 luminaires** (2/35 W T16) dimming control Energy Use: 1680 kwh/year - Maintenance: 6 times (2510 €/time)
Conversion factor 1kwh=0,43 kg CO2	

The space luminance is described by reflectance factor of surfaces in space. On average, these factors are: Partitions (50%), Floor (30%), ceiling (70%) and work surface (60%).

5.2 Decomposition of the decision problem

In the first stage, the decision making criteria were chosen based on past experience. Hierarchical relationships were drawn between the criteria and are presented in figure 7. Those mentioned in the figure have been selected from a given list of criteria. The first level (upper level) corresponds to four groups of criteria: artificial lighting performance, daylighting performance, energy & emissions and operating cost. Each group consists on a list of criteria (see table 4).

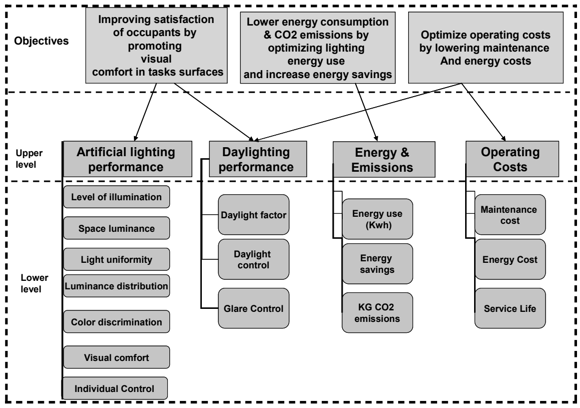


Figure 6: The hierarchy of the decision making process

We note that for this case study the daylighting performance is not part of the decision making process.

Level 1 (upper level)	Level 2 (lower level)
C1: Artificial Lighting performance	$C_{1.1}$. Level of Illumination in space
	$C_{1.2}$ .Light Uniformity
	$C_{1.3}$.Space luminance
	$C_{1.4}$. Luminaire distribution of Luminance
	$C_{1.5}$. Level of Color discrimination
	$C_{1.6}$. Visual ambiance
	$C_{1.7}$.Individual Control of lighting
C2: Energy & Emission	$C_{2.1}$. Lighting energy use
	$C_{2.2}$. Energy savings
	$C_{2.3}$. Kg CO2 equivalent
C3: Operating Cost	$C_{3.1}$. Maintenance Cost
	$C_{3.2}$. Energy Cost
	$C_{3.3}$. Service life

Table 4: level and groups of performance criteria

5.3 Relative weighting

In the second stage, the weighting matrices were generated and filled with pairwise comparisons between criteria with respect to each element of the next level. The result of calculation is criteria *weighting vector*. The comparison matrix represents all possible combinations of pairs. Each pairwise comparison (PC) has been assessed by an expert group on a qualitative scale that in practice indexed onto a numerical scale (see Table 5). As it has been mentioned, we have used a *Column Geometric Mean (RGM)* procedure (Table 6-7-8). However, to obtain a consistent matrix with multiple comparisons like for C1 sub-criterions, we use the method of *Least Squares Logarithmic Regression* (LSLR) based on qualitative comparison (<<, <, ~<, ≃ , ~>, >,>>) indexed onto a numerical scale (10%, 25%, 40%, 50%, 60%, 75%, 90%) corresponding to the estimation of the relative part of the score of criterion i over the sum of both scores of criteria. (see Table 9).

When the comparisons are done for all matrices of lower level, the resulting weighting vectors must be multiplied by weights associated to the corresponding upper level criterion. We talk about *absolute weight vector*.

Table 5: Comparison scale used

Value	Preference
1/9	Extremely less Preferred
1/7	Very Strongly less Preferred
1/5	Strongly less Preferred
1/3	Moderately less Preferred
1	Equally Preferred
3	Moderately Preferred
5	Strongly Preferred
7	Very Strongly Preferred
9	Extremely Preferred

Table 6: The scores of PC of level 1.

	C1	C2	C3	Weighted vector (%)
C1	1	1/3	1/5	11,11
C2	3	1	3/5	33,33
C3	5	5/3	1	55,56

Table 7: The scores of PC of level 2 (energy & emission).

	$C_{2.1}$	$C_{2.2}$	$C_{2.3}$	Weighted Vector (%)	Absolute weighted vector (%)
$C_{2.1}$	1	1/3	7	24,14	8,05
$C_{2.2}$	3	1	3/7	72,41	24,14
$C_{2.3}$	1/7	7/3	1	3,45	1,15

Table 8: The scores of PC of level 2 (Operating Cost).

	$C_{3.1}$	$C_{3.2}$	$C_{3.3}$	Weighted Vector (%)	Absolute weighted vector (%)
$C_{3.1}$	1	5	7	74,47	41,37
$C_{3.2}$	1/5	1	7/5	14,89	8,27
$C_{3.3}$	1/7	5/7	1	10,64	5,91

5.4 Evaluation

After calculating the *absolute weight vector* of criteria, the two alternative solutions were rated resulting in a level of satisfaction or utility between 0 to 1. The calculation is done by using the equations of utility functions (Equations (1) and (2)) based on the technical characteristics of luminaires and space. In addition, the utility with some criteria related to cost, energy and emissions are determined by the preference of decision maker. Thereafter, a multicriteria evaluation following the AHP process is adopted.

Let U_{ij} be the utility for criterion i and alternative j, the AHP theory requires that the utility values be normalized over the alternatives under each criterion [12]. This is given by the formula:

$$\overline{U_{ij}} = \frac{U_{ij}}{\sum_{j=1}^{N} U_{ij}} \tag{3}$$

Let W_i be the absolute weight of criterion i, N the number of criterion. The final evaluation of alternative j is given by:

$$U_{Solution} = \sum_{i=1}^{N} W_i \overline{U_{ij}} \tag{4}$$

Using the calculated rates of the two alternatives, we are able to evaluate the potential alternative solution satisfying the overall criteria. The best higher rated solution is that meeting the problem criteria. The alternative (1) meets the best the different criteria with **an overall rating around 55%.**

	$C_{1.1}$	$C_{1.2}$	$C_{1.3}$	$C_{1.4}$	$C_{1.5}$	$C_{1.6}$	$C_{1.7}$	Weighted Vector (%)	Absolute Weight Vector (%)
$C_{1.1}$		>	>	>>	>>	>>	>	38,99	4,49
$C_{1.2}$			~>	≃	~>	>>	>	17,07	1,97
$C_{1.3}$				~>	~>	>>	~>	14,59	1,68
$C_{1.4}$					~>	~>	<	8,12	0,94
$C_{1.5}$						~>	~<	8,96	1,03
$C_{1.6}$							~<	3,30	0,38
$C_{1.7}$								8,97	1,03
								100	**11,52**

Table 9: The scores for PC of level 2 using LSLR method (artificial lighting performance)

	W_i (%)	Utility values				Final evaluation (%)	
		Alternative (1)		Alternative (2)		Alternative (1)	Alternative (2)
		U_{ij}	$\overline{U}_{ij}$	U_{ij}	$\overline{U}_{ij}$		
C1: Artificial lighting performance							
$C_{1.1}$. Level of Illumination	4,49	1	0,5	1	0,5	2,245	2,245
$C_{1.2}$ .Light Uniformity	1,97	0,8	0,444	1	0,556	0,876	1,094
$C_{1.3}$.Space luminance	1,68	1	0,5	1	0,5	0,840	0,840
$C_{1.4}$. distribution of Luminance	0,94	0,5	0,333	1	0,667	0,313	0,627
$C_{1.5}$. Level of Color discrimination	1,03	1	0,5	1	0,5	0,515	0,515
$C_{1.6}$. Visual ambiance	0,38	1	0,5	1	0,5	0,190	0,190
$C_{1.7}$.Individual Control of lighting	1,03	0,2	0,2	0,8	0,8	0,206	0,824
C2: Energy & Emissions							
$C_{2.1}$. Lighting energy use	8,05	0,5	0,333	1	0,667	2,683	5,367
$C_{2.2}$. Energy savings	24,14	0,2	0,286	0,5	0,714	6,897	17,243
$C_{2.3}$. Kg CO2 equivalent	1,15	0,5	0,333	1	0,667	0,383	0,767
C3: Operating Costs							
$C_{3.1}$. Maintenance Cost	41,37	0,8	0,8	0,2	0,2	33,096	9,952
$C_{3.2}$. Energy Cost	8,27	0,5	0,417	0,7	0,583	3,446	9,678
$C_{3.3}$. Service life	5,91	1	0,5	1	0,5	2,955	2,765
						54,646	**45,764**

Table 10: Criteria Weights, utilities values and final evaluation of alternative solutions

6 CONCLUSION

Workplace design is clearly about making many decisions often under uncertainty and with multiple conflicting criteria. The decision making problem has been solved with several conflicting criteria: occupant comfort, environmental performance (energy and emissions) and avoid extra costs. To evaluate system efficiencies, engineering data were extracted from solution technical data for two proposed design alternatives and weighting patterns and utility functions was used to rate the performance of design alternatives regarding various criteria. The presented methodology provided a systematic approach to evaluate the overall efficiency of a design and help designers to see the differences of various design alternatives and to make design decisions on them. Further works will consist on refining the solution model and developing the appropriate correlation semantics to link the two models.

7 ACKNOWLEDGMENTS

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A method for supporting the integration of packaging development into product development

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Abstract
This paper aims to support the decision-making tasks regarding the integration of packaging development into product development. Based on the study of the interactions of the product and packaging during the whole product life cycle, a set of packaging-related factors was extracted and mapped to a general product development model, which at a strategic level can be used to define an integrated product development policy. At a tactical level, the mapping matrices are used to support the product development projects planning. At an operational level, they can be used to make packaging-related decisions during an ongoing product development project.

Keywords:
Integrated Product Policy

1 INTRODUCTION

At present, very few companies have developed a policy concerning the integration of packaging development into their product development model, even if three surveys performed in Swedish industry show that companies are aware of its importance and that involving the development of packaging at an earlier stage would speed up the time-to-market [1]. The barriers to such an integration of packaging and product development seem to be two-fold. Firstly, packaging is not considered to be an integral part of the product, so it is not part of the product "culture" of the company. In most companies, packaging is considered only at the production phase. Secondly, and as importantly, there are multiple ways of integrating packaging into product development – and packaging development is often performed by several external suppliers – but no general decision-making supports are available to develop a thorough policy in favour of this integration. This paper suggests a way to overcome these issues.

After a clarification of the concept of integration in the given context, a range of current product and packaging development process models utilized in Swedish companies are presented. These examples show that there are no "right or wrong" integration policies, since this depends on the context of the company. Rather than a general integration model, there is also a need to develop methods to support the decision maker, to guide him/her through the decision tasks regarding the product and packaging integration strategy. Section 4 presents the different decision-making activities where the integration issues are tackled: they occur at all levels, strategic, tactical and operational. What is common to all the decision levels is that the decision maker needs to know when packaging has to be taken into account in a product development project, and act accordingly. For that purpose, the interactions of the product and packaging during the whole product life cycle (PLC) have been studied. From this study, a set of factors was extracted: the factors are the elements of the interaction that had been designed earlier, or were considered during the design activity. These factors could also be mapped to the steps, phases and organization functions of a general integrated product development model (GIPDPM) [2]. Thus, the decision-maker is aware of which step and which function can be concerned by packaging. These mappings facilitate the strategy building as how and to which extent integrate packaging development in the company's product development policy. These mappings also help the project manager to take actions concerning packaging development and design during the product development project. This set of factors, their mappings and their use are described in the last sections of this paper.

2 THE CONCEPT OF INTEGRATION

The concept of integration in a product development model encompasses the following:

- The parallelization of the development tasks (main target of the concurrent engineering or simultaneous engineering),
- Collaboration among the different functions of the company (engineering, manufacturing, marketing, etc.),
- Sharing of relevant data between the functions.

Although there is a general consensus on this concept of integration, the integrated product development models proposed in the literature focus solely on vertical integration among the three functions: marketing, design and manufacturing (e.g. [3]). Only in [2] is financing/business also considered as a function. A complete integration concept should take into account all actors in the product development process, among other packaging-related actors.

Moreover, these models are generic and correspond in reality to the particular case where all the functions of the company and the tasks are highly interrelated (i.e. there is a total integration). It is then up to the decision maker to adapt these models to the company.

These aspects set up the frame for this study. The model of [2], presented in Figure 1, is the point of departure. Based on the study of the system product-packaging along the whole product life cycle, a list of factors was extracted. These factors were mapped to the steps, phases and functions of the model of Figure 1. As mentioned Section 1, these mappings will allow the manager to make more informed decisions.

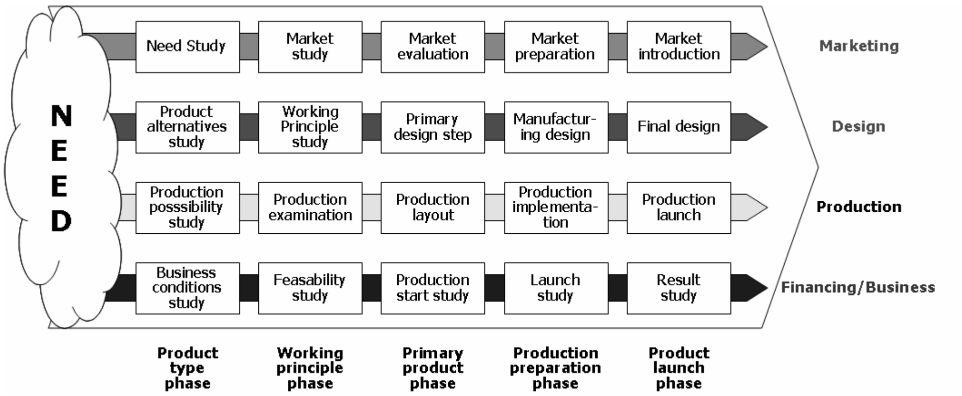

Figure 1: General Integrated Product Development Process Model [2].

3 PACKAGING AND PRODUCT DEVELOPMENT IN SWEDISH INDUSTRY

What follows is the illustration of three scenarios of integration based on empirical data from three surveys in Swedish industry (concerning Swedish pharmaceutical, mechanical and food industries) [1].

3.1 Case 1: complete integration of packaging and product development

Case 1 represents a major furniture producer in Sweden with many years experience of integrating product and packaging development on a functional level. The company has several thousand employees worldwide. The importance of the package for the product design is essential as the whole company policy is built upon a distribution idea in which the package-product-system is the core. Packaging design is a transversal function in the GIPDPM, with the same importance as the marketing, (product) design, production and financing/Business functions.

3.2 Case 2: partial integration

Case 2 represents a major company developing, producing and distributing exhaust products. The company employs approximately 500 persons worldwide. It operates its own sales companies in 19 countries, but products and systems are also marketed via a network of independent retailers in over 30 countries. Annual sales are about €90 million. In this company, one employee is responsible for packaging design, perform some packaging development tasks and outsource others to external suppliers. The main actors in this case are generally the main product developing organization, the design bureau providing industrial design knowledge, the package supplier and the packaging machine supplier.

3.3 Case 3: Sequential product and packaging development

Case 3 represents a major company developing, producing and distributing gasoline pumps for the international and Swedish market. The company has been on the market since 1892 and operates today in 120 countries utilizing its own company structure and distribution network.

For this company, the package is an addition to the product, a feature that is not essential for the product to function but important for aesthetic reasons and for protecting electronic elements sensitive to transient loads. The case is typical for the majority of the companies that participated in the three surveys [1]: most companies apprehend product and packaging development in a sequential manner. As such, a large number of companies are totally dependent on suppliers and industrial design consultants' knowledge of the development of suitable packaging.

4 PACKAGING INTEGRATION

Section 3 showed how complex the problem of integration of packaging development into product development really is. There is a strong dependency on context; there is no general "right" product development model, no right decision at the strategic, tactical or operational levels independent of the context. For the same situation, two different companies can act totally differently, based on company history, resources, core competencies, organization flexibility, etc.

The next section describes the activities that deal with the integration of packaging in integrated product development. These activities occur at the strategic level, at the tactical level and at the operational level.

4.1 Packaging integration issues at the strategic level

Defining the company strategy consists of defining the company for tomorrow and to check if it is fit for today. The tasks related to the integration of packaging development into product development include:

- Definition of a General Integrated Product Development Process Model (GIPDPM) (as in [2]),
- Definition of an Organization Model (OM),

- Definition of an Information System Model (ISM).

Prior to the development of a strategy including packaging, it is necessary for the decision maker to know where to make the necessary changes, that is, to know where packaging needs to be considered in the product development process, organization or IS. This is made possible by the mapping between the factors presented Sections 5 and 6 and the elements of the GIPDPM, OM and ISM. This is the main purpose of this document (ISM has not been considered here however). The decision maker has to:

1. decide which factors have an impact on the company product development (discard those that are not important),
2. find the needs or functions related to these factors (see Sections 5, 6 and Table 4),
3. choose whether the functions usually fulfilled by the packaging can be transferred onto the product (e.g. will the handling system used during transportation be a part of the packaging or of the product?),
4. look at the impact of the precedent decision on the other related factors (which related factors are kept or disappear),
5. repeat the precedent steps as long as necessary.

After having performed these tasks, only the relevant factors remain. As they are mapped to the GIPDPM and OM elements, the decision maker knows where packaging issues appear in the product development process and which function is concerned. The decision maker has a better ground to design the company strategy (related here to the integration of packaging development into product development).

4.2 Packaging integration issues at the tactical level

The tactical level involves the planning of a peculiar product development project. If it is assumed that at a strategic level GIPDPM, OM and ISM have been defined, the planner's task is here to adapt the general product development process model, organization and information system to the planned product development project. The planner has to check which factors played a role in the GIPDPM, compare it to the new situation and make the necessary adaptations. The planner's task is relatively similar to the decision maker's; the same factors (almost all) are used.

4.3 Packaging integration issues at the operational level

The operational level concerns the activities during the current product development project. The identified tasks are:

- Identify and establish the needs related to the use of packaging during the establishment of needs and the working principle of the product-to-be.
- If additional needs or constraints arise during the rest of the development project, decide whether to tackle them at the product level or at the packaging level.
- Check if the current product development state corresponds to the planned product development state and act accordingly.

4.4 Conclusion

The same set of factors (with some exceptions) is needed for all three activity levels. As was mentioned in Section 4.1, some factors are related. In order to stress these relations, a product-packaging system model has been developed. It is presented in the next section.

5 THE PRODUCT-PACKAGING SYSTEM MODEL

5.1 Relation between factors

The interactions of the product and packaging during the whole product life cycle take many forms of manifestation:

- physical elements (e.g. handles during distribution, chemical emission emanating from a leaking paint can);
- an "action": grip of the product by an operator, but also the presence of an aesthetic emotion in the consumer;
- different states resulting from a transformation along the product life cycle (e.g. a broken product due to impact).

Some of these elements are designed at some time during the product development process and are related to each other. These relations among structure, action, transformations and needs have to be differentiated and formalized. In this way, a decision maker handling one factor will not only know where to tackle it, but which related factors have to be dealt with, and where in the product development process and in the organization.

5.2 Related models

Two models can be found in the literature that deal with this issue: [4] proposes that a technical system (TS) can be described in terms of process, function, organ and structure (see also [5]); [6] proposes a similar model, denoted function-behaviour-structure (FBS). The structure consists of the elements of the system and their interactions. The behaviour of a system consists of an action that results in a set of system states. The function unveils the purpose of the elements of the structure via the behaviour of a system. These models are developed further in the next section by using a systems approach as a framework.

5.3 Description of a system

There are many definitions of what a system is. We depart from the works of [7-10]. What for us characterizes a system is:

- Its structure (product-packaging) – ontological axis,
- Its interactions with its environment (by performing a process upon the environment or being a part of a process in a given environment) described by a mode of operation – functional axis,
- Its transformations over time (i.e. during its life cycle – product and packaging life cycle, respectively) – transformational axis,
- Its finalities (e.g. the product functions are preserved) – teleological axis,
- Its belonging to a type of system (product and packaging family respectively) – genetic axis.

5.4 Relation among the axes

The definition of the ontological axis by [7] is adopted here: it regroups the system (product-packaging) *and* its environment, as well as their interactions. A mode of operation always implies elements of the system alone (two or more elements), or the system and its environment (one or more elements of each). It occurs at a certain product life cycle phase or step, and at a certain location. The transformations are performed by the modes of operations. These transformations are responsible for the states of the system at time t. These states can be desired or not; they depend on the finalities of the systems. Finally, the genetic axis consists of two axes: the taxonomic axis (represents the family of systems) and the phylogenic axis (represents new versions of an artificial system).

5.5 Determination of the factors

From the definitions above, it is deduced that the modes of operation, the structure of the system (hereafter called PP_System), the finalities, and the genetic aspects are the factors that will serve in performing the decision-making tasks presented in Section 4. The other elements serve indirectly to find those four constituents. For example, transformations permit one to see which functions or constraints are needed to be fulfilled or prevented by a certain mode of operation. The relations among all the elements are presented in Figure 2. The format of representation is from the CommonKADS methodology [11]. This formalism is derived from UML (Unified Modelling Language) but better describes the transformational axis than UML. The second reason why this formalism is used is because CommonKADS is a methodology of Knowledge-Based System (KBS). As will be discussed in the conclusion, this model can serve as basis for further development, and a KBS is one option.

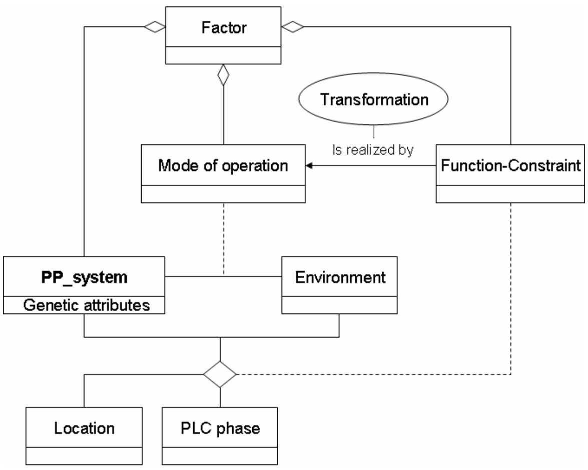

Figure 2: Relations among the system axes that serve to describe the factors.

6 THE SET OF FACTORS

6.1 Search for the factors of the product-packaging system model

The search for the factors is obtained by the meticulous observation of the ontological, functional and teleological axes, taking into account that these characteristics change over time (transformational and genetic axes). a hands-on methodology of search for service functions, constraints and criteria of a product-to-be, developed in the area of functional and value analysis [12], was used. We also studied the technical packaging literature that investigates interaction product-packaging (see [13] for a review).

6.2 The factors

The three classes of factors, “PP_System”, “Function-Constraint” and “Mode of operation”, have been mapped against each other. “PP_System” and “Mode of operation” have also been mapped to each step or phase of the GIPDPM and the functions of the company (design D, marketing M, production P and financing/business F). The “Function-Constraint” elements constitute the needs and are always present at the “product type” and “working principle” phase of the GIPDPM. The elements of “PP_System” and “Mode of operation” often have the same mapping against the GIPDPM and OM in this case because the PP_System is passive. The “Modes of operation” usually manifest themselves earlier during conceptual design as they can constitute working principles. The genetic elements only concern the product type phase of the GIPDPM.

The system model implies theoretically that an element of the “PP_System” is always coupled to at least one “Mode of operation” that fulfils/prevents at least one “Function-Constraint”. However, many of these elements are not interesting to consider for decision tasks (often it is the case for the mode of operation as the PP_System is mainly a passive system). Several elements concern only one or two of the three decision levels but this could not be established with certainty. Thus, it was decided to propose them for all decision levels.

The factors are presented in Tables 1 to 4. The factors have been developed for three types of industries: Mechanical (M), Food (F) and Pharmaceutical (P). The tables indicate which kind of industry involves the given factor (The genetic axis elements concern all three types of industries). The mapping of the three classes of factors would be best represented by three matrices, but the following tables give a more condensed presentation. The other elements of the system model (Figure 2) have not been represented as they are not “factors” (elements directly used by the decision-maker). The elements of “PP_System” (Table 2) present different natures: they are product features, properties, elements, etc. They have not been structured in subcategory to keep it simple for the decision maker to use them. The same applies for “Mode of operation” (Table 3).

	Genetic axis elements	Mapping to GIPDPM and OM
G1	Frequency of change of form among the different products	Product planning: discuss with packaging department (D, P)
G2	Number of products to pack /day	Production possibility study (P), need study (M)
G3	Pallet product shipping	Conceptual design (M), production layout (P)
G4	Mix/Multiple product ship	Conceptual design (M), production layout (P)

Table 1: Genetic axis: factors and mapping to GIPDPM and OM

6.3 Use of the factors

The factor use is described Section 4 : the decision maker finds by means of the mapping tables the GIPDPM steps and OM functions with which the packaging is involved, and he or she can thus decide to act accordingly. These factors have been mapped to the GIPDPM and OM of [2], but can easily be adapted to a more customized model.

	PP_System elements	Mapping to GIPDPM and OM	M/F/P
O1	Nature of the product	product type phase (B, M, D, P), market preparation (M), conceptual design (D)	M/F/P
O1a	Liquid/viscous	P	F/P
O1b	Granulates/powder	P	F/P
O1c	Solid	production layout (P), production preparation (P), manufacturing design (M)	M
O2	PP_System is marked	business conditions study (B), production layout (P)	F/P
O3	PP_System is labeled	business conditions study (B), needs study (M), production layout (P)	M/F/P
O4	PP_System is sterile	Bus. cond. study (B), production possibility study (P), production layout (P)	M/F/P
O5	Product is sterile	production possibility study (P), production layout (P)	M/F/P
O6	(Dangerous) chemical composition, (cutting) surface.	conceptual design (D), embodiment design (D), detailing (D), production layout (P)	M/P
O7	Product composition and/or geometry prevents storage	business conditions study (B), needs study (M), market study (M), P	M/P/F
O8	Grip elements	conceptual design (D), detailing (D)	M
O9	Product structure	embodiment design (D), production layout (P)	M
O10	Product elements	embodiment design (D), production layout (P)	M
O11	Weight	embodiment design (D)	M
O12	Product temperature	embodiment design (D)	M/P/F
O13	Product aesthetic characteristics	embodiment design (D), ID (If industrial design (ID) is integrated into the product development process,add conceptual design phase.)	M/P/F
O14	Surface finish	production preparation (D,P)	M
O15	Product instructions	market preparation (M), conceptual design (D), detailing (D), market study (M)	M/P/F

Table 2: Ontologic axis: factors and their mapping to GIPDPM and OM.

	Mode of operation elements	Mapping to GIPDPM and OM	Mapping Ont.	M/F/P
F1	PP_System made sterile	business conditions study (B), production possibility study (P),	O4	M/F/P
F2	Product is packed/filled in uncontaminated atmosphere	production possibility study (P), production layout (P)	O5	
F3	Product is/can be aggressive against the packaging	conceptual design (D), embodiment design (D), detailing (D)	O6	M/F/P
F4	Product is/can be aggressive against the handling personnel	conceptual design (D), embodiment design (D), detailing (D), production layout (P)	O6	M
F5	Product is stored	production layout (P)	O7	P/M
F6	Product is transported	Bus. cond. study (B), needs study (M), market study (M), P	O7	M/P/F
F7	Impact	embodiment design (D)	O9,O10,O11	M/P/F
F8	Vibrations	embodiment design (D)	O9	M
F9	Sensitivity to temperature change	embodiment design (D)	O12	M
F10	Sensitivity to humidity	embodiment design (D)	O10	M/F/P
F11	Sensitivity to light	embodiment design (D)	O10	M/F/P
F12	Sensitivity to water damages	embodiment design (D)	O10	F/P
F13	Dirt from the environment	conceptual design (D)	O13	M/F/P
F14	Sensitivity to micro-organisms	embodiment design (D)	O10	M/F/P
F15	Sensitivity to corrosion	embodiment design (D)	O9,O10	M/P
F16	The product is pollutant	conceptual design (D), detailing (D)	O1a, O6	M/P
F17	Packaging opening system	market study (M)		M/F/P
F18	Help the user to understand how to use the product	market preparation (M)	O15	M/F/P
F19	Packaging performs the use together with the product	conceptual design (D), detailing (D), market study (M)	O15	M/F/P

Table 3: Functional axis: factors, mapping to GIPDPM, OM and ontological axis.

	Teleological elements	Mapping Func.	Mapping Ont.	M/F/P
Te1	Necessary information must be present on PP_System	F18,F19	O2, O3, O15	M/F/P
Te2	PP_System must be sterile	F1,F2	O3, O4	M/F/P
Te3	Protect the environment against the product	F3,F4,F16	O6	M/P
Te4	Need of packaging for internal distribution: need for storage	F5,F6	O7	M/F/P
Te5	Product shipping constraints		O7	M/F/P
Te6	PP_System easy to handle	F17	O8	M/F/P
Te7	Protect the product from the environment	F7,F8,F9,F10,F11,F12, F13,F14,F15	O9, O10, O11, O12, O13, O14	M/F/P
Te8	Protect surface appearance (against scratches)		O13	M
Te9	PP_System needs to be recovered		O1	F/P
Te10	The packaging needs to be recovered			M/F/P
Te11	The product needs a support to be installed		O9, O10	M/F
Te12	Aesthetic considerations		O13	M/F/P
Te13	Prevent the product from being hazardous to use		O2, O6, O9, O10, O11	M/F/P
Te14	Packaging easy to handle	F17		M/F/P

Table 4: Teleological axis: factors, mapping to functional axis and ontological axis.

7 CONCLUSION AND FUTURE RESEARCH

The actual product and packaging development models present in industry are very different depending on the context of the company; this was also supported by the three cases from Swedish industry. It is thus important to be able to guide companies dealing with product and packaging development. This paper presents a method to support the decision-making tasks regarding the incorporation of packaging development into integrated product development. Section 4 presents the tasks to perform and Section 6 the tools (the mapping matrices) to support them. The tool proposed can be used “as is” or be easily implemented in its current form in a classical relational database system.

It cannot be ensured that the set of factors is exhaustive (and it will surely continue to evolve) but the system approach used to model it ensures its completeness.

The set of factors has not been mapped to the ISM as an IS is more dependent on the general strategy adopted by the decision maker than a on the factors alone.

The tool is meant to evolve and perform some more complex tasks. The CommonKADS methodology (see Section 5.5) allows modelling not only of the factors (which constitute domain knowledge) but also of the tasks and their inferences (primary activities that constitute them). Different ways of helping the decision maker at a strategic level exist: a predefined set of strategies or a set of process, organization or IS modules to assemble. These sets could be mapped to the factors presented here. It will also eventually be possible to model a complete KBS and decide what can be automated and what will be left to the decision maker. These modelling tasks are the next steps of this research project; a first refinement of the decision-making support method at the strategic level can be found in [14].

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Ecodesign: a Subject for Engineering Design Students at UPC

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Abstract
The aims of the Ecodesign subject are to provide students with theoretical knowledge and practical skills in designing new engineering products in accordance with ecological criteria. In this paper, the evolution over time of the subject is discussed, from the "common sense" application of product life cycle analysis to quantitative tools for analyzing alternative solutions and evaluating the final design. The subject's syllabus, the organization of the classes, the projects carried out by the students and three examples of this subject are discussed. Finally, conclusions drawn from the experience of teaching this free elective subject are put forward.

Keywords
LCE teaching evolution, eco-points, engineering eco-design, examples

1 INTRODUCTION

Ecodesign is a free elective subject that was introduced in the 2000-2001 academic year at the School of Industrial Engineering of Barcelona (ETSEIB), which belongs to the Technical University of Catalonia (UPC). A free elective subject is proposed by a lecturer; it must be different to other subjects on the course syllabus and must be approved by the School. The lecturer is free to choose the teaching method and students are free to choose the subject. The aim of the Ecodesign subject is to provide students with the skills needed to design (or redesign) engineering products according to ecological criteria.

The course is based on a doctoral course of the same name [1], which was introduced in the 1995-1996 academic year and is still being taught today. The doctoral subject is part of the Technological Innovation Design in Product and Process Engineering [2] PhD program taught at UPC. The free elective subject is of a more applied nature than the doctoral subject, the emphasis of which is research. This paper focuses on the teaching of the subject to undergraduate engineering students.

2 THE EVOLUTION OF TEACHING ECODESIGN

The first classes of the doctoral Ecodesign subject, taught in the first half of the 1990s, were of a general nature, and covered the environmental problems caused by certain substances, human action and technology, including examples of well-known impacts and the potential impact of toxic substances that can pollute air, water and soil; the problem of the consumption of non-renewable energy; the long-term effects of nuclear waste; environmental consequences for future generations; and the solutions that may be afforded by renewable energies.

The range of products available to consumers and the number of products that consumers own have increased spectacularly in the last decades, particularly in developed countries. Although progress has clearly been made toward the higher levels of welfare and cultural sophistication that human beings generally aspire to, this compromises the planet's resources and its capacity to bear environmental impacts. The idea of the planet's sustainability for the coming generations stems from a consideration of these environmental impacts.

Attempts have been made to find ideal environmentally friendly products that would warrant being called universal eco-products. These would, by definition, be sustainable and suitable for use regardless of differences in gender, culture, age or religion. Even materials used in primitive times have been considered, such as liquid containers made from seashells or hollow pieces of wood, musical instruments made from bone, reeds, hollowed-out pumpkins and tree trunks. One may conclude that there are practically no pure eco-products among the great range of products available today—there are only products that are more or less close to the ecological ideal.

The Ecodesign subject takes this philosophical approach to the ideal eco-product. There are spectacular examples of the evolution of technology toward products that are closer and closer to the ideal, such as computers and televisions that have become increasingly dematerialized; they consume less energy and yet nevertheless have a wider range of functions. These and other products will continue to evolve in the future. Not all products have evolved this quickly, and perhaps some of them will evolve via technology that is different to that which we know today.

This concern with designing products that are more environmentally friendly is based on the idea of saving materials and energy across a product's whole life cycle [3], as well as on using non-toxic, recycled, recyclable and renewable materials. Designing new ecological products as an academic exercise involves applying common sense at every stage in the life cycle—a qualitative move toward sustainability [4].

Some applied research has been carried out and literature has been published on ecological product design and organizational improvements [5], [6].

2.1 Eco-indicator

The move from qualitative to quantitative considerations was possible as a result of the work of organizations that have carried out exhaustive studies of the impacts of the extraction of materials, manufacturing processes and the consumption of energy and that have devised “eco-point” systems.

Impact eco-points are a measure of the environmental impact of a particular product or process. One impact eco-point system is based on characterization, normalization and evaluation factors. Characterization is based on data compared in the laboratory and the equivalence of effects. For each impact type, normalization is the inverse of the previous existent level in equivalent substance per inhabitant; this factor is empirical and has statistical connotations. Evaluation is a debatable factor, because it is based on estimations by groups of experts who value the impact of different levels of harm. A further consideration regarding eco-points is that they are basically Eurocentric, so their value may differ in other parts of the world [7].

The complexity of the data of a current product means that several aspects that are of lesser importance must be simplified. Therefore, only those factors that are highly relevant to the analysis of product designs are considered. Students should be aware of all these issues surrounding impact eco-points if they are to understand the “arithmetic” of these relative values. Although this scoring system is an approximation to an absolute value, it is a highly useful tool that enables one to choose, with greater rigor, the best options for materials and processes.

3 ECODESIGN: A PRODUCT ENGINEERING SUBJECT

Eco-point databases make it possible for an engineer to apply eco-points in the development of more ecological products, which is the aim of this subject.

3.1 Syllabus

The main theoretical subjects on the Ecodesign syllabus for the 2006-2007 academic year are the following:

- Environmental impact: assessing the environmental impact of materials and energy consumption and of human activities that have a direct or indirect effect on the life of the planet.
- Sustainability: preventing environmental problems and preserving the planet’s resources for coming generations.
- Life cycle assessment (LCA): determining the environmental impact of a product from the design stage to the end of the product’s life.
- Eco-design strategies: designing products in accordance with ecological considerations, based on life cycle engineering.
- Eco-indicator: assigning scores to the environmental impact of materials and energies, including values for raw material extraction, production processes, distribution, use and waste disposal, and considering how these values are calculated.
- Eco-design improvements: choosing the best of the various design solutions and comparing them with the assessment of the original product.

3.2 Class organization

The classes are based on eco-engineering design practices. Each class lasts two hours, 20-30% of which is devoted to theoretical explanations and the remainder to group work, which the lecturer supervises. Each group is made up of four to six students and works on one product design. Students are also asked to prepare contributions to theoretical explanations.

3.3 Practicals

The Ecodesign practicals are projects that involve improving product engineering design by, for example, saving on materials, energy and processes. The total number of Ecodesign projects over the seven academic years (2000-2001 to 2006-2007) in which the subject has been taught is 28, giving an average of four projects per academic year. The 28 eco-design projects can be grouped into several topics: 17 eco-designs for typical consumer products, six for energy saving and five for water saving.

The projects involved designing the following: a tap (2); a large street lamp (2); packaging (3); a refrigerator; a liquid dispenser; a domestic wastewater purification unit (2); a pot; a ballpoint pen; a mobile phone cover; a highlighter pen; a glass cover; a torch (2); a toothbrush; a telephone; a lighter (2); a corkscrew; a broom; a hand drill; a lipstick; a soap dispenser; and a safety razor.

Although several of them are repeated (shown in parenthesis), the product solution was different.

These projects can also be classed in the following categories:

- New product ideation with the aim of reducing an impact problem.
- Improvement of an existing product in accordance with qualitative ecological criteria.
- Improvement of an existing product in accordance with quantitative ecological criteria (eco-points).

Three examples of the eco-design exercises are discussed below.

4 EXAMPLES OF PRACTICAL ACADEMIC EXERCISES

The first example is of new product ideation of a liquid dispenser, and the other two examples involved improving existing products: a toothbrush and a soap dispenser, both with eco-point analysis.

4.1 Double-dose liquid dispenser

In the first example, the idea was to design reusable bottle tops that could dispense two exact quantities of a liquid from a bottle, which allows the dose to be adapted to requirements. For example, if the liquid is a detergent, the dispenser will save detergent and so curb excessive lather, which is an environmental problem. In this case, only qualitative eco-design analysis was carried out. Figure 1 gives a schematic view of the bottle top. The product was patented [8] and the design won an award in a university competition [9].

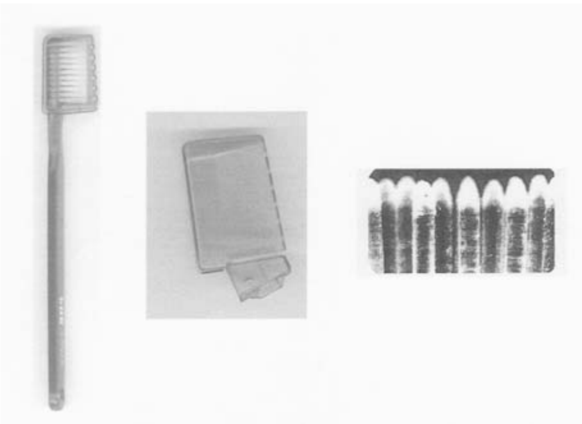
Figure 1. Schematic view of the double-dose liquid dispenser bottle top

4.2 Toothbrush

The problem set involved redesigning a typical toothbrush (Figure 2 a) according to ecological criteria. The first step was to analyze a typical toothbrush, its parts, the materials and processes used in its manufacture and the entire life cycle of the product. All the parts and processes were quantified using impact eco-points. This was followed by considerations such as the redesign strategies and the new design's impact eco-points. Finally, the original and redesigned products were compared and the final difference in their eco-points and the improvement percentage were calculated.

Product analysis

The toothbrush was packaged in cardboard and a plastic blister and had a plastic sheath (Figure 2 a) to protect the bristle brush (Figure 2 b).



(a) (b) (c)

Figure 2 (a): toothbrush; (b): sheath; (c): bristle brush

.1 Materials and processes

The analysis of the toothbrush materials showed that the handle and head were made of polypropylene, as was the sheath. The bristle brush was made of nylon and was fixed to the small head with a thin band of plastic. The blister was made of cardboard and polyethylene terephthalate (PET).

The body of the toothbrush was manufactured by plastic injection, and the bristle brush was fixed to a small head by a complex machine. Other machines added the sheath and then the blister. The amount of electricity used in the manufacturing process was estimated for one toothbrush.

.2 Life cycle

The life cycle of the toothbrush was analyzed, as well as that of each of its parts: the handle, head, bristle brush and the two parts of the blister.

Eco-points

An impact eco-point list [10] gives the following values per toothbrush unit (in millipoints of impact).

Materials (type and weight) and manufacturing processes of the handle, small head, and sheath:	2.80
Manufacture (electricity):	0.26
Packaging:	1.90
Distribution (estimated):	0.20
Final processing:	0.006
Total:	5.17

Redesign

.1 Redesign strategies

The main idea behind the eco-redesign of the toothbrush was to only replace the head when it wears out. It was estimated that one handle could be used with 10 successive heads (Figure 3). In this case, only 1/10 of the handle was considered in comparison with the whole toothbrush of the initial product. Other strategies were to use recycled plastic and reduce the packaging. Volume and weight were also reduced in the distribution stage.

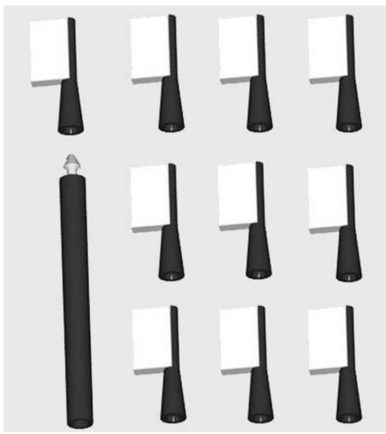


Figure 3. New toothbrush: one handle and 10 heads

.2 Eco-points of the redesigned product

Materials and manufacturing processes of 1/10 of handle, head and sheath:	1.175
Manufacture (electricity):	0.26
New packaging:	1.14
Distribution (estimated):	0.165
Final processing:	-0.015
Total:	2.725

Comparison between the initial and the eco-redesigned toothbrush

The new eco-design yielded a difference of 2.44 eco-points. The relative environmental improvement of this eco-design is about 48%, although the improvement is difficult to assess without analyzing the life cycle, the eco-design strategies and the eco-points. One toothbrush is not an environmental problem, but millions of them may well be. The new design could be a significant eco-improvement, but for it to become a commercially viable alternative other factors, such as economic or hygiene factors, must be analyzed.

4.3 Soap dispenser

A soap dispenser is a more complex commercial product than a toothbrush and it is easy to find ecological improvements, because the design of the original product uses an excess of materials and is thus not environmentally friendly. The soap dispenser was redesigned to carry out the same function as the original product but with a more ecological structure. Figure 4 shows a general view of the soap dispenser before it was redesigned.

Figure 4. General view of the original soap dispenser

The initial analysis of the container involved identifying its parts (Figure 5) and the material composition and weight of each of these parts. The capacity of the inner soap container (the transparent piece) was 0.3 l (33 cl) of liquid soap. An observation of its general structure reveals that the inner soap container has less capacity than the external structure of the dispenser. Much of the material is therefore not justified from an ecological point of view, and that is a reason for redesigning it in accordance with ecological criteria.

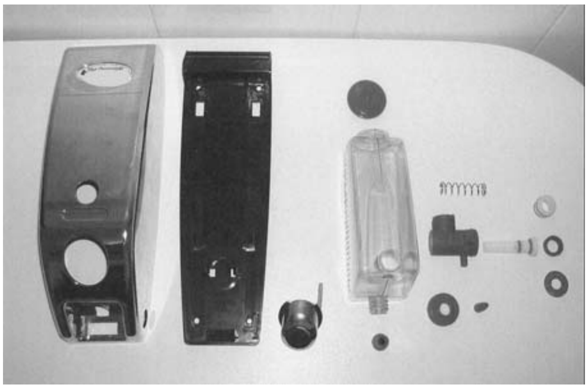


Figure 5. Soap dispenser parts

Impact eco-points of the commercial product

The parts and total impact eco-points of the materials and processes of the product are detailed below.

Front framework:	47.41
Rear framework:	12.19
Push button:	02.17
Soap container:	13.06
Cap:	01.00
External elements of valve (3):	03.33
Internal elements of valve (8):	04.52
Total:	83.68
Packaging (not recycled):	06.90

The estimated value of transporting the raw materials to the manufacturing plant and then transporting the product to the retail outlet where it will be sold was 0.06 per unit. The end of the product's life (when all parts are considered to be ready to be disposed of as waste) was 1.28. Therefore, the total number of impact eco-points was 91.92.

Redesign

The redesign strategy was to simplify the soap dispenser whilst maintaining its functions and the container's capacity (0.33 l), but reducing the amount of material used in the design.

The amount of soap and the number of times the container has to be refilled were not considered in the comparative life cycles, because they were the same. The soap dispenser valve was not changed because it functioned correctly.

The new soap dispenser was designed with the soap container as part of the external structure. The dispenser valve was the same as in original design and was threaded to the bottom of the container (Figure 6). The push button was redesigned according to the new external form.

Figure 7 shows two external views of the new soap dispenser: the container with the top cover, the push button for the soap outlet and the bottom cover.

.1 Eco-points of the redesign

Other eco-strategies employed in the new ecological design were using recycled materials in the container and covers and ensuring that the materials could be recycled at the end of the product's life.

Figure 6. New soap container with dispenser valve

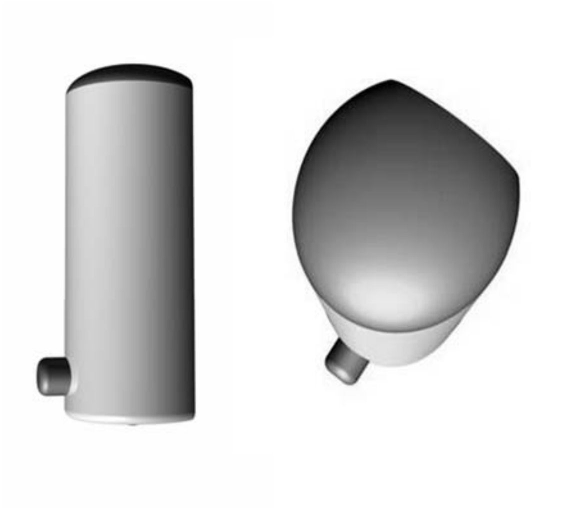


Figure 7. Two external views of the new design

In this case, the eco-point values are as follows.

Soap container:	01.24
Cover of soap container:	00.30
Push button:	00.32
Bottom cover:	00.90
External elements of valve (3):	03.33 (unchanged)
Internal elements of valve (8):	04.52 (unchanged)
Total:	10.61

The estimated value of transporting the raw materials to the manufacturing plant and then transporting the product to the retail outlet where it will be sold was, in this case, just 0.036 eco-points per unit, because of savings in weight and volume. At the end of the product's life, when all the packaging and elements to be recycled have been considered, 6.22 eco-points were recovered. The total number of impact eco-points was 4.42.

Comparison between designs

Several scenarios were considered. The commercial product, which was assumed not to contain any recycled materials and would thus be thrown away at the end of its useful life, had 91.92 eco-points. The number of eco-points of the new design, which used fewer materials and recycled and recyclable materials, was 4.42. In this case, the percentage improvement was 95%.

If only the product design—that is, the original design and the new design with recycled materials—was considered, the assessment yielded 83.68 eco-points for the commercial product and 10.61 for the new design, which was an 87% improvement in eco-points.

Other considerations might have been taken into account but, in all cases, the redesigned product was more environmentally friendly. The new design was a spectacular eco-improvement of the original design, but this new design could also be eco-improved.

The redesign possibilities of the last two examples—the toothbrush and the soap dispenser—were quite different. A toothbrush is a simple, mature product, which is not easy to redesign, although the new design is a good ecological solution. The soap dispenser, on the other hand, was easy to redesign, because the excess of materials used in the commercial product shows that the design is a standard, non-ecological design.

5 CONCLUSIONS

The initial syllabus of the doctoral Ecodesign subject was highly theoretical and covered the importance of environmental impacts, the energy problem and renewable energy solutions. The impact of certain materials was also considered and an overview of improvements in ecological design were put forward. At that time (the mid-1990s), impact eco-points had been introduced, but the ISO 14000 series [11] had not. Ecodesign was a qualitative strategy of ecological design based on life cycle analysis (LCA).

Quantitative impact eco-points constituted a great evolution in this area, especially in engineering applications. Current ecological product design criteria are based on the quantitative analysis of impacts, which lends the engineering eco-design of products a more objective basis. It is a tool for engineers who make new designs, or redesigns, of products.

At UPC, these new tools for ecological product design were introduced in the form of the Ecodesign subject. Ecodesign is a free elective subject taught by one lecturer, for which there is one class, and which students choose because of an increasing awareness of sustainability issues.

The doctoral Ecodesign subject, which was introduced in 1995, was probably the first specific subject of its kind in Spain. At UPC, action is being taken to introduce ecological concepts in a number of disciplines [12], but the Ecodesign subject is particularly suited to engineering design due to the latter's increasingly important contributions to sustainability.

The examples illustrate three types of academic exercises involving eco-design: a new design from an ecological idea (double-dose liquid dispenser); a very simple and common product that is not easy to redesign (toothbrush); and a commercial product that is not eco-designed (soap dispenser). The latter two were redesigns that involved quantitative eco-points analysis. Although these were academic exercises, they may well be of interest to companies that wish to develop ideas for ecological product improvements.

Student motivation was high in the free elective Ecodesign subject because they had chosen it freely and were interested in learning techniques and strategies for environmental product design. Student surveys indicated that they were generally satisfied with the subject, although some of them asked that more credits be awarded for the practical exercises they carried out.

6 ACKNOWLEDGMENTS

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Soap dispenser: Ricard Abate, Daniela González, Daniel López, Antonio Rubio and Juan Vaca (Group 4 of the 2006-2007 Ecodesign course).

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The Human Side of Ecodesign from the Perspective of Change Management

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Abstract

The necessity for new insights regarding industrial ecodesign implementation is leading to an increase of interest for scientific knowledge from other disciplines which may provide such new insights. Research on success factors and obstacles for these introduction processes show the significance of the internal value chain of companies, in which human factors seem to play a significant role. A potentially contributing discipline in this field of the 'human side' of ecodesign is change management. This paper describes several aspects of change management; a cross-linking between the two latter disciplines is made. This leads to the formulation of several propositions, which might serve as a starting point for further research on this topic.

Keywords:

Ecodesign; Human factors; Change management

1 INTRODUCTION

At present, the implementation process of sustainable design strategies in organisations is a point of particular interest in ecodesign. In literature, the current status of implementation of such strategies in the mainstream manufacturing industry is described as 'lacking momentum'. Both researchers and practitioners have increasingly expressed dissatisfaction about the frequency, quality and speed of the process of implementation (Tukker et al. [1], Baumann et al. [2], McAloone et al. [3]). Although recent research has observed and identified several success factors and obstacles for this integration process, not much progress has been made since.

When considering the history of ecodesign, one can observe that the orientation has been mainly of a technical nature. Over the years however, more organisational aspects of ecodesign have been added, in order to raise the applicability of ecodesign in business. But despite these additions, so far the study of ecodesign has always been an isolated study, in which few insights from possibly relevant disciplines have been used. A clear example hereof is the low number of connections made between ecodesign and (auditing) environmental and quality management systems.

In recent times, also the scenery of the manufacturing industry is changing considerably: companies are forced to comply with new legislations on sustainability aspects, more specificly on several environmental issues like the Directives on *RoHS* (Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment), *WEEE* (Directive on Waste from Electrical and Electronic Equipment) and the forthcoming *EuP Directive* (Directive on the eco-design of Energy-using Products) in the European Union. These directives might serve as a starting point for the development of international standards for ecodesign, which are presently lacking. Another consequence of this is that the distinction between companies that are pro-active in the field of ecodesign, and companies that are re-active, may lose its relevance. In other words, the number of companies that will start implementing sustainability criteria will rise significantly, with compliance to the new regulations as their external drive for the changes. This is likely to create a situation where existing ecodesign methodologies – which are commonly addressing companies and more specifically product designers and managers who are already, with a proactive attitude, motivated to start learning about ecodesign – will not sufficiently address potential implementation obstacles. In this context, Seidel and Thamlain [4] state that handling complex environmental challenges in companies will require radical departures from traditional management philosophy, and that traditional management tools and processes are no longer sufficient for generating satisfactory results.

Previous research has already shown that success factors and obstacles that may have an influence on ecodesign adoption processes can be divided in two main groups: those that are closely related to the organisational structures and processes of a company, and those that are more linked to the internal value chain of the company.

Baumann et al. [2] advocate a system perspective to stimulate the development of green products. Their main objective is to improve the study the relation between the single company and relevant stakeholders in the product chain, and they propose that the internal process of product development be related better with other processes in the firm. As far as the human dimension of the internal value chain is concerned, only few studies (Boks [5], Cohen-Rosenthal [6]) emphasize the importance of these human aspects in ecodesign, in particular those factors that are related to communication and cooperation, although with little practical bearing for addressing these issue in industrial practice. Similarly, like in the field of ecodesign, within the broader field of industrial ecology it has also been advocated that, as all activities are carried out by individuals, the human dimension is of utmost importance and should be addressed in order to make implementation strategies more effective. Without understanding the human dimension, the full prescriptive and normative potential of the applied Industrial Ecology is unlike to be exploited (Korhonen [7]). However, these and other publications such as by Cohen-Rosenthal [6] address the human dimension from an enabling perspective and study its role as a success factor. Empirical studies, in which the role of the human dimension is studied as an obstacle, are seldom.

These observations motivate a search for knowledge available in scientific disciplines that are traditionally not well connected to sustainable product design. Consequently, the aim of the present paper is to identify scientific disciplines that may contribute to understanding the role of obstacles in the implementation of ecodesign, in particular those related to communication and cooperation, on departmental as well as on personal level. Section 2 will, based on existing literature, discuss additional insights which are required to further the cause of ecodesign implementation. Section 3 will explore a number of scientific disciplines in which such insights are commonly addressed. Section 4 will further elaborate on the potential similarities of research insights from the identified scientific disciplines. In conclusion, section 5 will propose and discuss a number of research questions that are eligible for further study.

2 OBSTACLES FOR ECODESIGN IMPLEMENTATION

In a study about the electronics industry, Boks [5] suggests the study of the role of socio-psychological factors as a factor of influence for adoption, and focuses the attention on a departmental level. This has been consented by Driessen [8], whereby the various aspects of ecodesign implementation are observed as having different levels of manageability. This is in particular the case early in the design process where dissemination of information, creativity, and awareness creation play a considerable role.

The most important obstacles that were found are gaps between proponents and executors, organisational complexities (unclear responsibilities, cultural differences between departments), and lack of cooperation. Also, limited involvement of other than research and development departments, e.g. the sales and marketing departments, is specifically mentioned as an obstacle. Furthermore, although the role of management commitment was falsified as an obstacle on a corporate level, and even mentioned as an important success factor, the role of management commitment *on an individual project level* is often mentioned as an obstacle. Boks [5] and other authors like Guerin [9] and Post and Altman [10], present anecdotal evidence that illustrates the existence of practical, everyday problems on both departmental and individual level. Relatively often, such practical problems appear to be related to status and/or cultural differences between various internal stakeholders within a company.

Both Boks [5] and Post and Altman [10] suggest that, as these sociological, psychological, emotional and intangible factors that can 'make or break' implementation processes, the involvement of (business) psychologists and business organisation specialists may be crucial. This view gets fortified by Cohen-Rosenthal [6] who thereby emphasises that an effective implementation strategy cannot ignore human commitment, skills and social organisation.

The understanding of this 'soft side' of ecodesign might be one of the key factors to facilitate the process of incorporating sustainability criteria in regular business. This knowledge will have to be acquired from other disciplines.

3 POTENTIALLY CONTRIBUTING DISCIPLINES

Recent explorative research has identified a number of academic disciplines that may function as points of departure for acquiring the desired knowledge and insights which are described in the previous section. These include change management, industrial and organisational psychology. Change management as a discipline is directed towards the management of planned changes, whereas industrial and organisational psychology is the study of the behaviour of individuals and groups in the workplace.

There is a certain overlap between these fields, but as change management considers both the organisational aspects ánd the human aspects of a process of change, we focus primarily on the latter field.

3.1 An introduction to change management

Changes in industry, like the confrontation with sustainability criteria, are under certain conditions confronted with resistance. Many reasons have been identified which clarify this resistance. Several are connected to individual personalities, being either more practical – e.g. new knowledge to be learned - or emotional – e.g. fear of the unknown (Hellriegel and Slocum [11]). Understanding and controlling these human barriers is an important part of the (planned) management of change processes, also referred to as 'change management', that often occurs in organisations.

Change management can have many applications in several situations, but it is mainly applied in organisational change management, thereby *administering planned changes that occur in organisations in order to maximize the collective benefits for all people involved in the changes and minimize the risks and failures that could come along with the implementation of these changes*.

The majority of implementation strategies offers a general philosophy, rather than specific action plans (Lewis [12]). These mostly include:

- what should be changed,
- in which order should the changes take place,,
- how to introduce the change,
- who should be in control,
- and to which factors should the implementer be sensitive,
- how to measure the success of the change?

Aspects that are generally accepted as important and thus should be emphasized during a change process are participation and empowerment, the creation of a change culture, a clear presentation of purpose and vision, the presence of a champion and good communication. These general philosophies can be retrieved in different theories on change, which have already been formulated from the 1950s onwards.

One of the pioneers in social psychology, Kurt Lewin, formulated the Force Field Theory, in which he states that change is *a dynamic balance of forces working in opposite directions* [13].

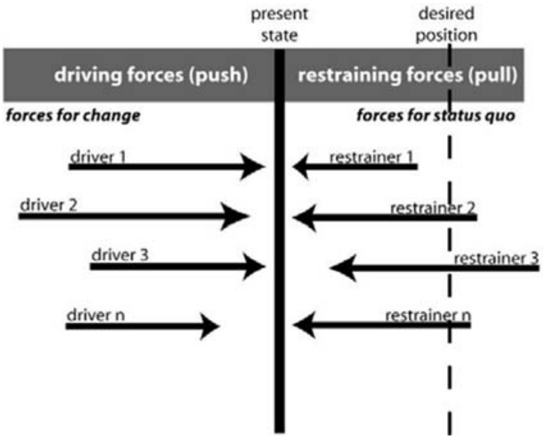

Figure 1: the opposing forces according to the Force Field Theory, adapted from Lewin [13].

He also states that the process of change can be divided into three stages. There is a high consensus in literature on this three stages model of the process of organisational change (Lewin [13], Beckhard and Harris [14], Kanter et al [15], Garside [16]), although in reality, this process is not a neat sequential process (Beckhard [14]). The three stages in the model are:

- unfreezing
- changing
- refreezing

The primary goal of the unfreezing stage is to make the organisation and the individuals within attentive for the need for change. In this phase, providing information on the requested changes is extremely important. In the second stage, the introduced changes are executed. Here, managing the changes combined with good training and efficient communication programmes form important aspects. The refreezing stage is meant to reinforce the implemented changes in the organisation.

According to Pettigrew *et al.* [17], apart from the process of change, it is also important to consider historical, cultural and political features of a company, in order to assure successful change in an organisation. These essential dimensions of strategic change have been developed into a model by Pettigrew and Whipp [18]. Their 'Model of Strategic Change' involves *continuous interplay between the ideas about the context of change, the process of change and the content of change, together with the skill in regulating the relation between the three. Formulating the content of strategic change crucially entails managing its context and process.*

As shown in Fig. 2, the dimension *context* considers the 'why and when' of change, which is subdivided into the inner and outer context. The dimension *content* describes the 'what' of change, and the dimension *process* is related to the 'how' of the change. Another approach is described by Kaplan and Norton [19]; they present a more systematic view in a company's strategic business map.

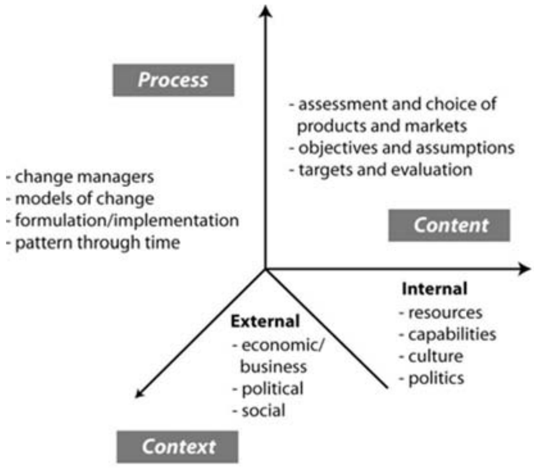

Figure 2: Pettigrew and Whipp's essential dimensions of strategic change, adapted from Pettigrew and Whipp [18].

The described models, together with other diagnostic models for the process of change, offer a framework on implementing changes and indicate different dimensions that should be considered when one is developing a complete organisational change programme [11].
Three of these dimensions which get much attention in change management are human factors, resistance to change and communication. They will respectively be discussed in the following paragraphs.

3.2 Human factors in change management

As previously mentioned, literature stresses the importance of the creation of a culture inside an organisation that is receptive to change. Human factors play a very important role in this cultural shift, which implies a significant influence on the success (or failure) of the implementations. Behaviour is usually one of the hardest and slowest change to implement in an organization (Struckman and Yammarino [20]).

The knowledge from other fields like organisational behaviour and industrial psychology is applied in change management to get more understanding of how humans respond to specific events. In order to comprehend the reasons and motivations of human behaviour, it is important to be aware of and understand differences in personality, environmental settings, emotions, different kinds of communication (both verbally and non-verbally), personal behaviour and attitudes, kinds of cooperation, ways to handle with unplanned factors like stress, different learning methods, etc.

The understanding of these human factors forms an important skill for managers and other individuals which have to deal with changes in an organisation. The awareness and understanding of the human aspects will also lead to a better comprehension of restraining forces against change, which often are of personal origin. Such awareness and understanding will, according to Lewin's Force Field Theory [13], eventually imply a higher chance on success of the implemented change process.

3.3 Resistance to change

Another significant aspect of change management is the supervision on and the reduction of resistance to change. Resistance is often present when changes occur, and insights in the different kinds of restraining forces and the underlying reasons for it, can help to reduce some of these opposing factors. According to Lewin [13], a decrease in resisting forces will, rather than an increase of the driving forces, lead to a higher chance on successful change: intensifying incentives for change will thereby go together with a raise of resisting forces.

When one considers the behaviour in a company during change, different distinctions can be made between the type of resistance, its source and its underlying reason(s). A possible classification, proposed by Hellriegel and Slocum [11], makes a distinction between individual versus organisational resistance (Table 1). Opposition originating from an organisational level is more related to organisational design, resource limitations, interorganisational agreements and other policy related dimensions. Whereas individual resistance is closely related to personality, personal situation like economic reasons, fear of the unknown and other human factors. Moreover, resistance often occurs at a group level, in between the level of individual and organisational resistance, especially when changes can take place within the group structure, their social norms or their power allocations.

Individual resistance	Organisational resistance
Perceptions	Organisational design
Personality	Resource limitations
Habit	Fixed investments
Threaths to power and influence	Interorganisational agreements
Fear of the unknown	
Economic reasons	

Table 1: Distinction between individual versus organisational resistance to change (Hellriegel [11]).

According to Garside [16], resistance to change by, both internal and external, organisational stakeholders, i.e. people with a 'stake' or interest in the organisation, forms a strong restraining force. Garside states that the most recurrent factors for personal resistance to change are:

- self interest
- resentment
- different perceptions of change
- misunderstanding or lack of trust
- low tolerance for change

Within these personal reasons for opposing change, research has shown that the position of the person in the organisation also has an influence on the degree of resistance and the underlying reasons for contending the new situation. These differences are shown in Table 2, where a distinction is made between oppositions from line employees, compared with those of mid-level management.

The top five in Table 2 lists the results of a yearly benchmarking research that represents the findings and best practices in change management of 2005 (Prosci [21]), thereby triggering the factors that are considered as most important for employees and mid-level managers. This study shows that it is important to pay attention to disseminate clear information and clarification towards all levels inside an organisation. An important remark from the authors of the benchmarking report is that the resistance to change is for many participants not specifically caused by the 'change', but rather by the comfort of the 'current state' in which the person feels confident that he or she wants to keep safe. This state of quasi-stationary equilibrium, as Schein [22] calls it, has to get pulled down to make a readiness for change for an individual possible.

Resistance from line employees	Resistance from mid-level management
Employees not aware of business need for change	Loss of power and control
Lay-offs were announced or feared as part of the change	Overloaded with current responsibilities
Employees were unsure if they had the skills needed for succes in the future state	Lacked awareness of the need for change
Individuals were comfortable with the current state	Lacked the required skills
Employees believed they were being asked to do more with less, or do more for the same pay	Fear, uncertainty and doubt

Table 2: Top five reasons for resistance to change from line employees versus mid-level management (Prosci [21]).

3.4 Communication on changes

Overcoming resistance to change is often the result of good, constructive communication during the complete change process. Communication on change functions hereby as a response to expected resistance, but also to ensure a smooth implementation process, thereby aiming to emphasize participation and empowerment, to create a change culture, and to emphasize the purpose and the vision of the changes within the organisation (Lewis [12]).

Many sources describe directive information on communication, in which general communication strategies are often stated. However, more specific guidance on communication channels, frequency, a good mix of communication types, or specific message strategies, are rarely defined. An example hereof is the emphasis that many authors put on a wide participation of various stakeholders in the change process, but a more specific focus on the form and nature of the participation seems to be understudied.

The same situation occurs when a differentiation of communication strategies within the various stages of the change process is considered. There is a clear distinction between communication as a form of input for gathering information and communication intended to serve for the dissemination of information, but apart from that insight, a clear method to find the balance between both perceptions is not often mentioned.

In conclusion, one can state that there is a general consensus on the overall philosophies on communication during a change process, however so far the methods and contingencies are much less understood.

4 PROPOSITIONS CROSS-LINKING CHANGE MANAGEMENT AND ECODESIGN

In the previous sections, a number of ideas or starting points for creating a framework of constructs have been identified. These constructs can be roughly categorized under the headings of individual and organisational resistance, several human behavioural factors and communication on change, under which in turn several potentially relevant aspects were discussed.

Individuals who are experienced in the implementation processes of sustainable design will instinctively recognise several of the outlined ideas in change management, which indicates an overlap and a possible extension of the current knowledge. This recognition may lead to the apprehension that 'ecodesign' should not be considered as an isolated case that, for many reasons, does not sufficiently find its way towards industry, but as a development among many others in organisations.

A preliminary study into cross-linking has identified on one hand obstacles in ecodesign literature, and on the other hand constructs in change management and adjacent literature. This suggests a number of matches. Below, the matches are formulated as research propositions. The main intention of these research propositions is to reach a starting point to explore the potential contribution of change management in explaining the observed status quo in ecodesign implementation.

1. Gaps between proponents and executors of ecodesign strategies can be partly explained by theory on organisational resistance to newly introduced concepts such as ecodesign, as well as by individual resistance.

This proposition is motivated by the presumption that gaps may exist because of the lack of a well-defined and strategic programme for the change process on an inter-departmental system level, which has a significant influence on overcoming organisational resistance. Next to that, distinctions in personalities of involved employees, for different positions within the organisation, offer an insight in the different perceptions about the required urgency for change because of reasons related to sustainability. The hypothesis is put forward that sustainability in itself may have a polarizing effect, creating a gap between those 'in favour', and those with a less positive attitude. Those in favour are likely to experience an increased sense of urgency for action once confronted with an opportunity to take action, thereby considering the introduction of sustainability issues in a company as a driver. This could possibly create a polarising response from those who either do not share sustainability concerns, those who are fearful of being confronted with such concerns, or those who fear unwanted repercussions to their working environment. Possible repercussions could be aspects like threats to power and influence or for pure economic reasons on a departmental level. A well applied communication strategy, integrated within the change programme could potentially prevent or diminish such a polarisation.

Three more, preliminary, research propositions are put forward at this time.

2. Lack of cooperation between departments and individuals does not only exist because of the lack of a (sufficiently mature) required (inter)organisational change programme, which consequently causes organisational resistance, but also because of individual resistance and a possible insufficient communication strategy on the changes.
3. Lack of commitment on individual ecodesign project level can be partly explained by organisational resistance as well as individual restraining forces.
4. Status and cultural differences between departments hampering the implementation of ecodesign can be partly explained from the perspective of the organisational level, as well as with elements of resistance on an individual level.

These propositions are put forward although it remains a topic for further study to see whether the constructs mentioned in the propositions should be dealt with as independent or interdependent variables. For example, it should be studied to which extent gaps between proponents and executors of ecodesign strategies can be partly explained directly by lack of commitment on individual ecodesign project level, or vice versa. From empirical observations, resource limitations as an element of organisational resistance appear to be significant; however, signs of individual resistance have also been observed. Examples include managers that do not share the same perceptions about the importance of sustainability issues within a company, or more importantly, have different interpretations of official corporate statements about sustainability.

Regarding the fourth proposition, Boks [5] presents one anecdote that addresses status differences between departments within one company. From additional unpublished field experiences of the authors, there is sufficient additional motivation which supports this proposition. These experiences include also cultural differences between departments from one company located in different countries.

5 DISCUSSION AND CONCLUSIONS

The current stationary status of the adoption of sustainable design in business has received much attention of many researchers and practitioners; nevertheless, little improvement of the situation has been observed. Several authors mention the need for new ways of handling complex environmental challenges, next to observations on the importance of the human dimension during the adoption process.

Previous research has shown prominent obstacles for ecodesign implementation like gaps between proponents and executers, organisational complexities and a lack of cooperation. So far these critical success factors have not been explained, apart from some assumptions that have been proposed by few authors on the 'soft side' of ecodesign as a possible key factor to facilitate a more successful adoption.

To obtain deeper insights in this implementation process of ecodesign, new contributions are needed from other disciplines. Disciplines like industrial and organisational psychology and change management, are considered as potential contributors, whereby the latter is regarded as the most promising discipline and therefore has been the focus of this paper.

In order to offer preliminary explanations for the obstacles mentioned by several authors on the implementation process of ecodesign, different constructs on resistance to change, both from the perspective of an organisation and an individual, the impact of differences in both organisational and human factors, and the role of clear and profound communication, are discussed from the view of change management. Cross-linking these constructs has lead to four research propositions.

Future research will have to show whether the propositions that have been suggested in this paper can get translated into feasible research, and whether this more profound research on this subject will lead to enriching insights on the implementation processes of sustainable criteria in business. It is the authors' ambition to acquire more insight in the discussed subjects through further research in this field.

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Integration and Complexity Management within the Mechatronics Product Development

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Abstract
Mechatronic products are the result of combining the engineering disciplines mechanics, electrics, electronics and IT. This requires coordinated trans-sectoral cooperation from the people developing the product as well as from the organisational unit. However, the systematic development of mechatronic systems has special demands to a multidisciplinary and holistic development process. Therefore implementing appropriate methods and tools is decisive for an effective product development. This article deals with the approach of integrating discipline-specific processes, applications and partial data models according to the SOA principle, based on the experience of developing PLM methods in the automotive industry.

Keywords:
Mechatronics; Product Lifecycle Management (PLM); Service Oriented Architecture (SOA)

1 INITIAL SITUATION

Complex mechatronic products that originate by combining and integrating solution principles from the engineering disciplines mechanics, electrical and IT, have automatically increased the complexity of development methods and processes as well as the resulting product data.

Many companies are being faced with more and more problems in view of this trend. These problems are making it difficult to cope with the development of mechatronic products regarding increasing quality, reducing development costs and time.

1.1 Process-Based Problems

The particularity of mechatronic systems is that their sub-systems are based on various technical solution principles - mechanics, electrical engineering and IT - which are combined together. Product innovations are obtained through this synergetic interaction [2] and therefore the development processes are so important to be able to realise such systems with multidisciplinary specifications.

However, in most companies established processes show large deficiencies regarding handling multidisciplinary development processes. The mechatronic product development in the involved disciplines is still carried out separately and in a rather isolated fashion, according to established, specific development methods [3]. The results are that:

- It is not possible to regard the product as an integrated mechatronic system.
- Coordinating and synchronising the different domain-specific development processes, activities, tasks and results across all fields is not sufficiently supported.
- The complex coherences and interactions between the disciplines are only considered in a later development phase.
- Comprehensive integration, configuration, change and release management across all disciplines is little or barely supported.

1.2 Data-Based Problems

Tools for developing mechatronic systems have over the years developed to domain-specific and isolated computer-based tools e.g. CAx, EES (Electrical/Electronic Engineering Solutions), CASE, PLM. These create large amounts of product data and product structures, that are only available in incompatible formats to one another. Today, for example, CAx data is stored and administrated in MPDM (Mechanical PDM) systems, EES data in EPDM (Electrical PDM) systems and CASE data in CVS (Concurrent Versions System) systems. These all have their own specific data models and structures that, in general, are incompatible with one another. This diversity of product data, data models and data formats, as well as product structures, has lead to huge problems in developing mechatronic systems:

- The interdisciplinary and functional relations between the various components and systems cannot be shown, understood, constructed as needed.
- The behaviour of the interdisciplinary components, systems and functions that are dependant upon one another cannot be displayed and analysed sufficiently.
- Interdisciplinary and coordinated changes on product data, that build on another is hardly supported.
- No adequate interdisciplinary integration of product data.
- It is hardly possible to interdisciplinarily release product data as well as functions, systems and components.
- Interdisciplinary product data configuration is hardly possible.

1.3 IT-Based Problems

PLM systems - PDM, configuration management and change management- are the hub for all IT tools and processes within the development of mechatronic products because they supply a number of functions and data models for managing product data and for controlling and integrating development processes and activities.

Field-specific and isolated PLM island application systems have evolved in many companies over the years. These do not allow or support managing or integrating development processes along all disciplines. The classic PLM landscape, that is most commonly found in companies, consists of three different heterogeneous, incompatible and independently operating PLM platforms for the particular mechanics, electronics and IT areas. The consequence is that the tool and system support when developing products in mechatronic aspects – combining and integrating solution principles for the engineering disciplines mechanics, hydraulics, electrics, electronics, software and hardware – are inadequate, hardly available.

2 INTEGRATION REQUIREMENTS

Mechatronics has the potential of being successful in creating future products thanks to the close collaboration of mechanical-, electrical engineering and IT. It also has particular requirements for the development process: mechatronic products are characterised by high complexity and they integrate components from various disciplines (heterogeneity) [4].

Integration approaches and mechanisms in process, data and application system levels within the development of mechatronic systems are very necessary in view of this situation to be able to control inter- and multidisciplinary development processes.

The requirements regarding processes, data and IT architecture are illustrated in the following to be able to master the complexity and integration management within the development of mechatronic systems.

2.1 Process Based Requirements

The development of mechatronic products requires a holistic view of the product as an integrated mechatronic complete system. This requires multidisciplinary cooperation and coordination between involved disciplines, to realise an optimised whole solution. [4]

A multidisciplinary and holistic development approach model is needed to be able to work in a multidisciplinary fashion between the various domains and for them to agree on the conditions concerning time, costs and quality. This must fulfil the following requirements:

- The established development processes and activities – already existing sub-processes specified by the company philosophy e.g. mechanic, Electric/Electronic and software development processes – are not to be excluded but should be incorporated in the multidisciplinary development process, with as few alterations as possible. [5]
- It should force integrating all departments at the beginning of the development project. [5]
- The overall system specification, description and definition of solutions in the earlier development stages is to be supported. Consequently the dominance of few departments can be avoided.
- This development approach should contribute to minimising the development risk, by coordinating the domains at an early stage and thus securing their complex connections.

2.2 Data Based Requirements

Viewing the product as an integrated complete mechatronic system not only makes it necessary to synchronise between involved departments, but also between the specific disciplines' partial data models and along the entire development process. Therefore a multidisciplinary and abstract integration data model has to be developed to master the complex coherences in the development of mechatronic systems.

The data model acts as an integration platform for the development of mechatronic systems. Therefore the following criteria need to be fulfilled:

- The data model must allow comprehensive, neutral and abstract mapping of the product functions, their dependencies and their behaviour regarding the mechanical, electrical and IT aspects. The details for the individual disciplines' system designs are to be derived from this model. This data model is to act as an integration model, to merge the disciplines' own development results.
- The data model has to link all domain specific data models e.g. mechanical, electrical/electronic and IT data models with one another, whereby the comprehensive interdisciplinary coherences are to be mapped on the meta-model level. Here the systems' complex and interdisciplinary interdependencies between one another can be displayed and visualised more transparently and with less organisational effort.
- The data model must allow internal changes or further developments within the discipline specific data models, without adjusting other areas data models.
- The data model has to support implementing comprehensive versioning, configuration, change and release management, that allow integrating the various specific development results to a functioning entire system.

2.3 IT Based Requirements

The integration of discipline-specific IT landscapes plays a key role, in order for the above mentioned requirements for the process and data landscape to be satisfied. The comprehensive development methodology requires a comprehensive federative data model, but also a comprehensive IT integration platform. Which must fulfil the following requirements:

Integrating the specific IT integration platforms

The federative integration platform has to link up the already existing and established domain-specific IT integration platforms, which in general are specific PDM systems e.g. mechanical PDM, electrical PDM, CVS [5]. A comprehensive IT integration platform is to be developed, that enables comprehensive controlling, coordination and cooperation of mechatronic systems' development processes. This platform has to enable comprehensive systematic versioning, configuration, change and release management.

Protecting existing IT investments

Lately, many investments have been made in the divers development departments for building up own IT systems and these are already very valuable, so that it is out of the question to entirely replace these IT applications. In addition, such IT systems contain many years of company knowledge and experience that are indispensable for the companies. Therefore the federative IT integration platforms cannot replace the available domain-specific IT integration platforms, but rather build on these.

Flexibility

Mechatronic products and the corresponding technologies are very short-lived, which leads to high change dynamics in the development environment of such products. Companies often have to carry out changes in the process landscape or introduce new technologies and IT applications or shut down old IT systems at short notice in view of this situation. This often involves adapting the entire IT environment e.g. adapting the system interfaces. It is therefore important that the federative IT integration platform does not interfere with the change dynamics in the departments, but allows these with as little effort as possible. The comprehensive IT integration platform needs to be very flexible to satisfy this challenge. This in turn leads to increasing the innovative ability and agility of the company in terms of being able to react quickly according to market requirements and therefore increasing the competitiveness.

The domain specific IT integration platforms have to be integrated according to the principle of loose coupling in the comprehensive IT integration platform, to reach this flexibility in a federative IT integration platform. Unnecessary dependencies and tight couplings between IT components, that lead to a rigid IT architecture, can be avoided in this manner.

3 CONCEPT FOR THE INTEGRATION OF DOMAIN-SPECIFIC MANAGEMENT PLATFORMS

The three main, classical fields – mechanics, electrical engineering and IT – that have grown historically in companies, are usually involved in developing mechatronic systems. This organisational structure is mirrored in the IT architecture, which has lead to the development of three main domain-specific integration platforms that link the domains' specific computer-based tools with one another: CAx tools in mechanics, EES tools in electrical engineering, CASE tools in IT, as well as the sub-processes in the individual domains. Lately product data management (PDM) systems have established themselves in the mechanical and electrotechnical development areas and concurrent version systems (CVS) in IT development. These systems enable integrating the various computer-based tools, managing, organising and steering their created data with the aid of versioning, configurating and release methods and functions [7].

A concept for integrating the above mentioned integration platforms in terms of eliminating the deficits mentioned at the beginning and managing the challenges that arise in mechatronics is described in the following. This concept comprises a generic integration architecture model and a federative data model.

The generic integration architecture model was designed according to the service orientated architecture (SOA) principle. This is a layer architecture that encapsulates the various applications' functions in a service layer as services, which can be used within the process integration, thus the various application systems are loosely coupled. This not only helps to increase the technical connectivity of heterogeneous applications and reduces the diversity of interface technologies, but also permits enhancing and optimising the existing IT, data and process landscapes.

Mechatronic products are a synergy of components, which generally come from the areas mechanics (including hydraulics and pneumatics), electrical engineering and IT. As the electrotechnical components (hardware components) and the IT components (software components) are closely connected and dependant upon one another, it is necessary to describe their functions together (E/E function description) and to later integrate them together (E/E integration). This leads to a two-step function description in the product development – an whole entire and an E/E function description – as well as two-step integration – whole and E/E system integration. Whole system and E/E system integration platforms need to be developed to be able to manage this approach (Figure 1).

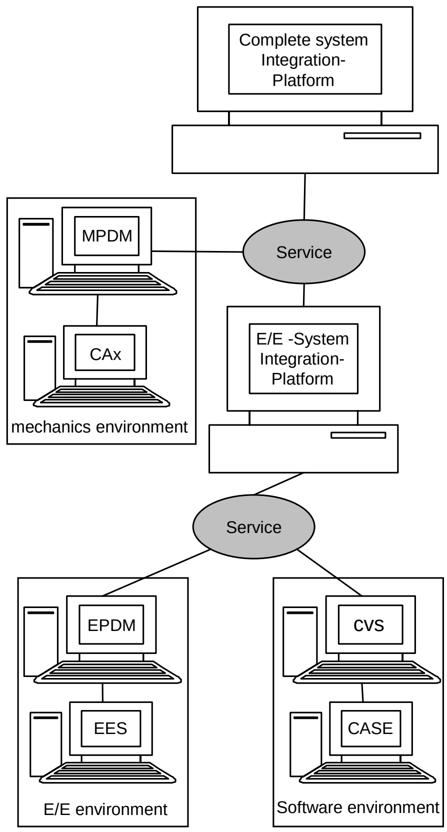


Figure 1: Concept for the integration domain-specific Integration Platforms.

3.1 Generic Integration Architecture Model

An integration model standardises the integration of existing domain-specific application systems and establishes a cross platform integration infrastructure. The aim is to allow a holistic view of the system and thus to establish the basic prerequisite for product development including various disciplines.

The integration model builds on the available specific application landscapes and comprises five layers the application, service, workflow, integration platform and comprehensive process layers (Figure 2).

Application layer

The application layer contains domain-specific application systems that automatically treat, manage and steer information and data in the individual fields. Such applications are to be seen as resources, which provide their own data and functions in encapsulated form using suitable interfaces.

Service layer

Standardised services, which are implemented in the application layer underneath, are offered in the service layer. This decouples the applications and achieves high flexibility in the entire IT landscape.

Services can be split into two separate classes, atomic services and composite services. The first are services that encapsulate the application functions as adapters and make them available for the service layer. Such services are designed bottom-up. The definition of composite services, on the contrary, comes from the business process requirements. Such services support carrying out process activities and sub-processes. Hence composite services are put together from other composite and atomic services [8].

Workflow layer

Development activities and tasks covering various domains generally need functions for various applications. This requires adequately controlling and coordinating the cooperation between the participating applications, in order to achieve the continuity when processing business activities concerning various applications and to avoid the break of information along the development processes [8].

Workflows that assemble, coordinate and steer activities covering various applications are defined on the workflow layer. The individual activities in turn use the composite services on the lower service layer to carry out the required process tasks.

Integration platform layer

All necessary functions and data that enable product development incorporating various domains are provided in the integration platform layer. The functions in this layer are defined by the domain-spanning business processes' requirements and normally make up numerous activities, which make up workflows on the lower workflow layer.

The integration platform layer counts on a multidisciplinary federative data model that makes the communication between the integration platform and the specific applications on the metadata level, as well as a whole system description, possible. The metadata model is a model that abstracts all necessary specific metadata and maps these homogeneously.

Comprehensive process layer

Multidisciplinary process cycles are defined and mapped on the process layer. A number of multidisciplinary tasks, that are to be carried out in a set operation sequence and where required, supported by applications, are merged to one process unit. Functionalities and data, which are provided by the integration platform layer, are used to carry out these process tasks.

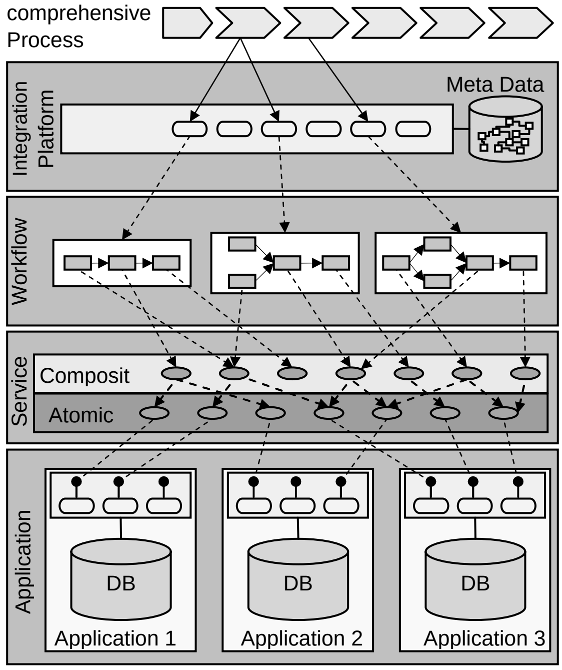


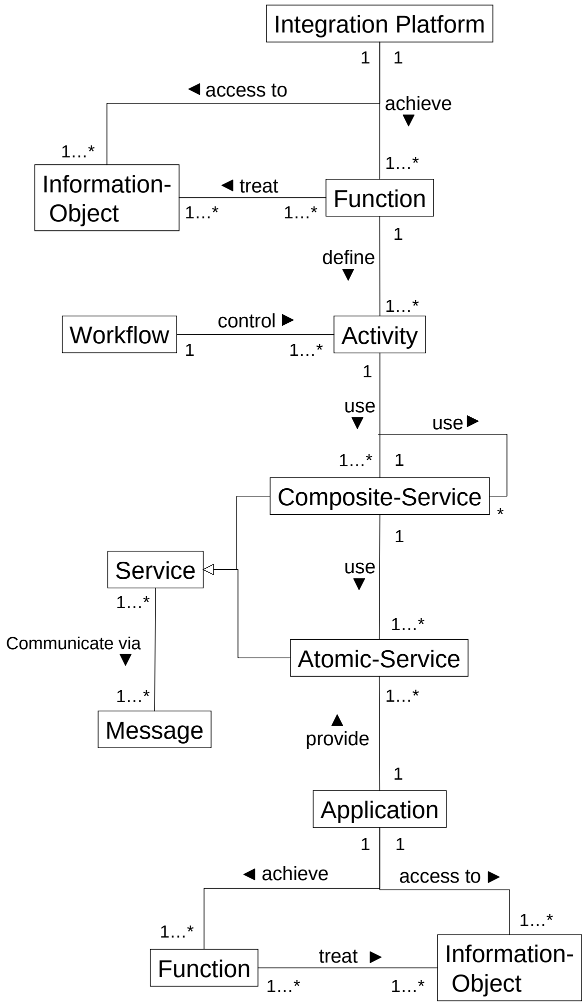
Figure 2: Generic Integration Architecture Model.

3.2 Meta model for the Generic Integration Architecture

A meta-model was designed using the UML modelling language to describe the elements of the generic integration model and its connections. The following classes are intended for this and their ties are shown in figure 3:

- The **Integration Platform** class describes an application that supports domain-specific processes coordination and cooperation in the development of mechatronic products.
- The integration platform disposes of numerous **functions** to take care of process tasks spanning various domains and applications. Here information objects are created, edited, steered, managed or deleted.
- The **Information Object** class describes all metadata that is needed for linking the discipline-specific partial data models. It makes continuous data processing along all processes possible. This class is described in detail by means of the federative data model (see subsection 3.3).
- A spanning-application function can define one or more activities, which are described in one or more self-contained performance units that are realised in one or more domain-specific applications. The **Activity** class is used here to represent all required activities to describe functions spanning applications.

- The **Workflow** class is used to describe all workflows, which synchronise and steer automatically carried out activities. The aim is to carry out domain-spanning process tasks that include various domains.
- One or more Composite-Services are used to carry out activities. This behaviour is described using the association between the Activity class and the **Composite-Service** class. A composite-Service can also use the services of one or more other Composite-Services, but it is required to use the services from at least one Atomic-Service.
- Every domain-specific application function is abstracted and presented on the service layer using an Atomic-Service. This is displayed through the association between the **Atomic-Service** class and the Application class. The Atomic-Service class abstractly describes domain-specific application functions as well as an interface that allows accessing the domain-specific applications.
- The **Service** class is an abstract class that is a generalisation of the Atomic- and the Composite-Service classes. This class serves the purpose of describing the common behaviour and attributes of the two service-types.
- Services communicate among one another and their environment (i.e. applications and activities) by sending and receiving messages that contain data and information concerning the execution of process tasks. This form of communication is mapped in the **Message** class.
- The **Application** class presents all domain-specific application systems that offer several functionalities to create, process and manage data objects. Therefore domain-specific applications are responsible for the technical implementation of Atomic-Services by providing data and functionalities.



Legend:
1 : exactly one
1…* : one or more
* : zero or more

Figure 3: Meta Model for the generic integration architecture

3.3 Federative Date Model

The federative data model is introduced in this section. It allows top-down product structure and description covering various domains, as well as linking discipline-specific partial data models on the meta level. The therefore required classes and their ties are described in the following (Figure 4):

- The **Item** class depicts all kinds of elements from a mechatronic product that represent an object from the development process. Objects in this class are (sub-) systems, (main) functions, (sub-)modules, and components (mechanical, pneumatic, hydraulic, electrotechnical, IT).
- The Item class is further classified using the **Classification** class, to be able to distinguish between the item objects, i.e. if a function, system, module or component is concerned.

- An object from the Item class can have one or more variants that are depicts in the **Variant** class. Variants describe specific object adjustments that differ in complexity and in the technical development and production.
- An object from the Variant class can be versioned using the **Item_Version** class. This makes it possible to discribe a product's specification or its instance at a certain point in time. A clear validity for a new object version can be determined and displayed using the association between the Item_Version class and the **Effectivity** class.
- Objects from the Item_Version class are assigned to one or more domains (e.g. mechanics, hydraulics, pneumatics, electrics, electronics, IT) using the **Context** class. In this way different domain-specific views can be generated for certain tasks and users.
- Relationships between the objects from the **Item_Version** class are described in the association class, **Relationship**. These classes help to define product, system, function and component structures across all disciplines.

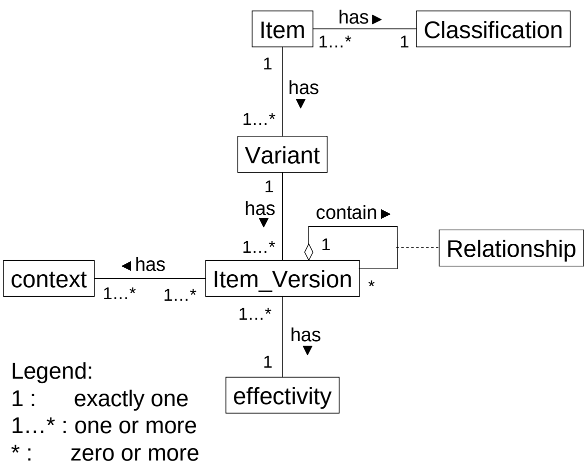


Figure 4: Federative Data Model

4 SUMMARY

The described and discussed problems in this work give an overview of the difficulties and challenges faced by many companies when developing mechatronic products. Mechatronics offers many fascinating possibilities and large success potentials, but at the same time has special requirements not only concerning the development process but also the IT-landscape and information handling [9].

The development of mechatronic products within time, financial and qualitative constraints makes a holistic view of the product as a mechatronic system indispensable. This leads to applications and partial data models needing to cooperate and be coordinated between the domain-specific processes that are concerned with the product development.

The concept presented in this article offers a generic architecture, which makes the synergetic cooperation of all disciplines, including processes, applications and data possible. A meta-model was developed for the generic integration architecture that supports flexible and loose coupling of the domain-specific applications. A federative data model was also developed that allows continuous product structures and descriptions and therefore contributes to linking the domain-specific partial data models on the meta level.

The advantage of this concept is that it is based on already existing and established domain-specific processes, application systems and partial data models. This preserves long standing and valuable company investments in the process, IT and data landscapes. In future, special fields can conserve their internal authority, through the principle of loose coupling, so that they can continue to further develop their internal processes, applications and data models autonomously, without being influenced by other fields. This leads to companies being able to introduce new products, technologies and innovations quickly and economically.

This concept is currently being implemented within the scope of internal work at the Chair of IT in Mechanical Engineering at the Ruhr-University Bochum, where the PDM-System Teamcenter Engineering and the web service technology based on the .net framework is being used.

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Managing Design System Evolution to increase Design Performance: Methodology and Tools

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Abstract
The new stake in design today is to examine the global purpose of the design activities. In this perspective, project design management not only consists in allocating resources, but also in stimulating collaboration among the actors involved in the project. Objective is to increase the performance of design teams. In this paper, we are interested in the factors influencing performance of the design system. We identify the elements of the design performance and propose a framework to manage design system evolution. A prototype of software formalising the exchanges in the design system during a design process is presented.

Keywords:
Design System Modelling, Design System Life Cycle, Performance Management.

1 INTRODUCTION

The Product Lifecycle Management concept refers to the integration of all the information produced throughout all phases of a product's life cycle to everyone in an organization at every managerial and technical level, along with key suppliers and customers [1]. In such a context, one purpose of design management is to define and to organise the design system where the design transformation will take place. Hence, design management requires understanding of design context by considering at the same time the product and process aspects, with a view relative to the human, social and organizational aspects. Objective of this paper is to propose a methodology to model and follow-up evolution of design context to manage design process. First, we present a model describing properly the design context to provide a framework to manage design system. Second, we define a methodology, using our model of design context, to follow-up the evolution of the design context and to evaluate its performance to support engineering management according to structuring of decisions making. Finally, an example extracted from an industrial case study is presented.

2 MODELLING THE DESIGN SYSTEM

Nowadays performance evaluation of enterprises obliges to manage discretionary activities, which are more and more collaborative. Therefore, it is not enough to measure and to manage product data or progress of the design process. Evaluation should focus on interactions between each actor involved in the design process and between all the activities that are generating this design process. Hence, design management requires understanding of design process context in order to adapt actors' work if it's necessary. O'Donnell and Duffy's generic model of design activity performance insists on the necessity to identify components of the design activity and their relationships [2]. This identification is the first step of Performance Measurement System (PMS) designing. Many PMS models exist in literature but few of them provide a framework to achieve properly this step. Furthermore, most of them are centred on the business performance [3] or [4], and few of them are dedicated to the evaluation of the design system.

In our approach a model to analyse and describe the design system is proposed. This model helps to the development of a PMS in order to manage design system evolution.

2.1 Description of global performance inductors

Robin et al. [5] have identified three factors influencing the design system and which have to be considered to follow and manage suitably the design system evolution and the design process:

- The technological factor that concerns the techno-physical environment (*scientific and technological knowledge*).
- The context in which the design process takes place. It includes natural, socio-cultural and econo-organizational environments (*external and internal environments*).
- Human and his different activities during design process (*actor*).

Scientific knowledge regroups the natural science and the engineering sciences. Technological knowledge concerns the manufacturing practices and the technology. Interest is to have a global vision of the knowledge possessed and usable by the enterprise and to identify a potential lack of knowledge in some design tasks.

External environment is the global context in which enterprise is placed (its market, its rivals, its subcontractors…). Internal environment describes the enterprise itself: its structure, its functions and its organization. Internal environment is an exhaustive description of the system in order to take into account all the elements which could have an influence on the decision-making at each decision-making level.

Actor aspects have to consider multi-facets of the designers. Human resources will be described with classical indicators (availability of a resource, hierarchical position, role in a project, training plan…). But factors very close to the actor's personality have to be taken into account too.

These factors influence the design process and more generally the design system. Robin et al. [5] integrate all of them and their interactions on a model composed with a technological axis, an environment axis and an actor one (Fig. 1). Then specific objectives, action levers and performance indicators, dedicated to the design system, have to be identified according to elements of this model. PMS has to consider interactions between these objectives, action levers and performance indicators to supply pertinent information to decision-makers. These interactions are a composition of each element of the model and of relationships between them [6]. They influence actors' deeds and decisions and are global performance inductors during the progress of the design process. The following section focuses now on the local performance inductors.

2.2 Description of local performance inductors

To identify and manage relationships between factors influencing performance of the design process Robin et al. propose to use product, process and organizational models (Fig.1). Product model acts as a link between knowledge and external / internal environments (link 1, Fig. 1). Product is the expression of the scientific and technological knowledge of an enterprise and permits to evaluate its position on a market. It's a technical indicator which allows to make evolve a firm or to identify a possible lack of competency to be competitive on a market. As process corresponds to the place where the knowledge is created and used by the actors to develop the product, it connects actor and knowledge (link 2, Fig. 1). Finally, influences of environments on actors are taking into account by the mean of an organizational model. This model joins up actor and external/internal environments (link 3, Fig. 1). Organization has to favour allocation of adapted human resources to a specific situation in a particular context. These models are local performance inductors for design system and interactions between them provide a dynamic vision of the design system evolution (links 4 to 6, Fig. 1).

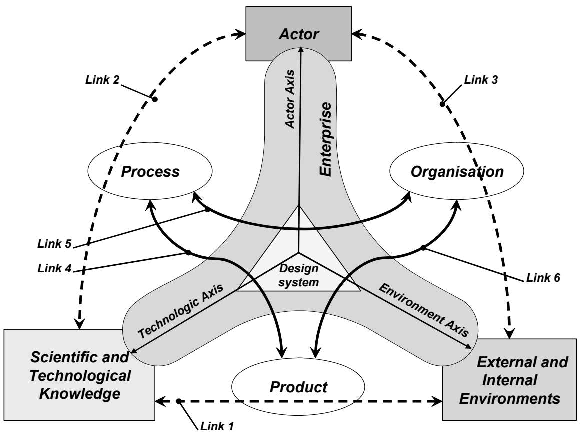

Figure 1: Design system modelling, interactions between factors influencing the design system

In this model, the description of factors influencing the design system, at each decision-making level provides a global vision of the design context. Hence, thanks to such a representation of the design context, the decision-maker can analyse the design situation and identify particularities of each project. He is able to observe evolution of each component (environment, technological and actor one), interactions between them and consequently adapt his project management method by taking the right decision of management to satisfy objectives. To make it possible the model must be completed with a methodology to follow-up the design system evolution and to evaluate design process.

3 METHODOLOGY TO FOLLOW DESIGN SYSTEM EVOLUTION

To favour achievement of the design activities, the actors of the design must have a set of coherent and contextualized information constraining their activity. The definition of this set of information is possible only if the system is modelled, if its dynamic is described and if the performance inductors (global and local) are identified. This obliges to model the enterprise, its design system and to study the evolution of this whole.

3.1 Enterprise modelling for management of design system evolution

Methods for enterprise modelling are numerous but little of them take account the particularity of the design context description. For instance, CIMOSA Architecture [7] provides a framework to analyse requirements and constraints of a company. It integrates them in a system which models the functions of the company and the influences of the external factors on these functions but does not take into account the human aspects event though they are crucial for manage a human activity as design one. A state of the art on enterprise modelling emphasises the fact that only GIM (Grai Integrated Method) [8] takes into account human aspects. This method is based on the GRAI methodology and its components (conceptual GRAI model and specific modelling languages (GRAI grids, GRAI nets,…)). GIM method is well adapted to describe the strategic level of a company and provides a modelling of the existing system composed with:

- a Functional Model modelling the enterprise,
- a Model of the Physical System describing activities that contribute to the achievement of the products,
- a Decisional Model defining the decisional structure,
- a Process Model representing external relationships of the company,
- and an Information System collecting all the information identified in the others models.

When all models are defined it's possible to deploy the performance through all the structure by the mean of the objectives. Each decision-making centre, on each decisional level, has a decision framework in which we will find specific objectives which will come either from the phase of modelling or of the decomposition of objectives of a higher decisional level. We will find the whole of these elements in grids GRAI established at the time of the study of the system with GIM method. The connections between the decision-making centres described in the grids correspond to the interactions between all the elements of the internal environment (internal services of the company) but also their exchanges with the external environment (by the means of their relationships to external information).

The model of design context (Fig. 1) completes the GIM models by adding actors and knowledge dimensions to the enterprise modelling. These aspects are now integrated in the modelling phase of the functional and decisional structures of the company as performance inductors for the design system. When the modelling phase is finished, it is possible follow-up the evolution of the system via the GEM approach. Following paragraph presents management of the evolution of the design context via this approach.

3.2 Managing the evolution of the global context of the design system

In the extended enterprise context, influences of the global context on the design system have to be put in evidence and to be managed. To do that, we are going to consider evolution management of an isolated enterprise, to manage after the combined evolution of several enterprises to obtain a global vision of external influences on the design system. To manage this evolution, we use the Blanc's research work [9] based on GEM approach. Blanc's approach builds system evolution like continuous processes and describes evolution process management of industrial systems. GEM approach makes it possible to hold account and to follow the evolution of the external strategic factors representing global performance inductors for design system (customer requirements, evolution of subcontracting, the market, the competitors...). It offers a general framework for identification of the strategic objectives and constraints which will have an influence on the company and on the design system. The evolution process is made of a sequence of steps representing the evolution of the system status (Fig. 2). *As Is* system represents the model of existing system. The components of the system are here described and formalised: it is possible to understand better how the system is running and also to detect the points to improve. The *Should Be* corresponds to the strategic objectives of the system, and in Blanc's approach it is described through the Business Plan of the enterprise. The *Next Step* is an intermediate stage between the *As Is* and the *Should Be*. It corresponds to the future system which will be implemented. *User Specifications* correspond to the comparison between the *Next Step* and the *As Is* models. From this, the *Technical Specifications* are deduced which include the Organization, the Information Technology and eventually, the Physical part (the human aspects are taken into account). The *Action Plan* determines several evolution projects with a limited duration and investment. The action plan is always accompanied by a performance indicators system. Interest of this approach resides in the integration of the interactions between the performance of each actor and the system one as a whole to manage its performance.

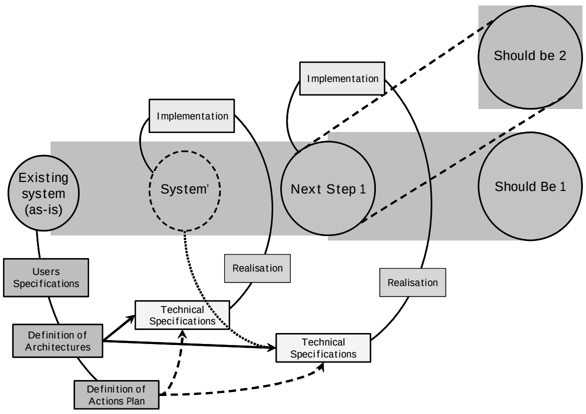

Figure 2: GEM approach [9]

We showed that beyond the global performance of the design system it is necessary to have an interest on its local performance. Thus, we describe now the exploitation of the model of design context at an operational decision level with the GRAI Engineering method.

3.3 Design system modelling to manage its evolution

Modelling of the design system is requested to manage its evolution. It's done thanks to GRAI Engineering method [10]. This method is based on the models defined previously by the means of GIM method and completes them by considering specificities of the design system. The structured approach is composed of three main phases:

- An initialisation phase consisting in a first contact with the enterprise management: information and training on methodology, definition of goals and field of study, planning of study, definition of different groups of actors involved in study.
- A modelling phase concerning the existing engineering design system which leads to the establishment of a diagnostic of necessary improvements.
- A design phase for the modelling of a new engineering design system and for the specifications of the information system that will provide the required assistance to design people for design coordination.

GRAI Engineering method provides a whole of models which makes it possible to describe the design system (Fig. 3).

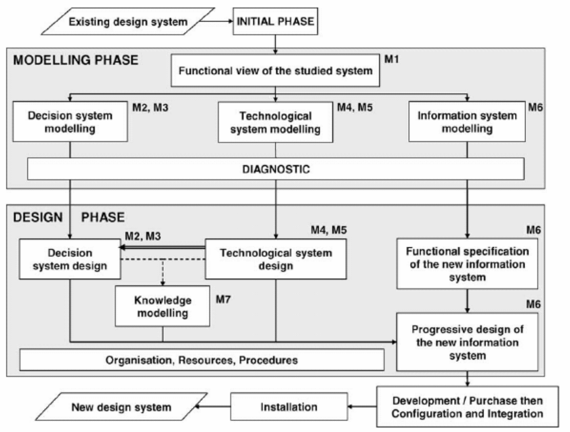

Figure 3: GRAI Engineering method [10]

The model of design context (Fig. 1) completes the modelling phase of GRAI Engineering method while insisting on the elements that have to be taken into account in the various models used in the method.

As for GIM method, GRAI Engineering method allows to deploy the performance through all the design system thanks to the deployment of the objectives.

3.4 Follow-up the evolution of the design system and of the design process and its activities

GRAI Engineering method provides a modelling of the design system that permits to manage its evolution. Evolution of design system is constraint by evolution of the design context (global inductors) and of the design activities (local inductor). Design activities are more and more collaborative and discretionary and design control has to be focus on product model evolution but also on interactions that will create the design process. These interactions appear in the design system, but especially in the activities of the design process. They concerns product, process and organizational viewpoints but also human aspects and management style of design process. In the context of extended enterprise, design control should be more reactive and taking into account external constraints. Therefore, the collaborative design processes control requires understanding of design context in order to modify them to facilitate actors' work [11]. So, we propose a framework, based on GRAI R&D model [12] and centred on the actor, to manage and evaluate the design process. GRAI R&D model permits to control the evolution of design process. As this model is not well adapted to manage collaborative design activities, Girard and Robin have developed the concept of design environment [13]. A design environment is defined as the context in which the project manager decides to place design actors to achieve the assigned objectives. The aim is to influence the design context to favour collaborative design situations between actors. This concept completes the existing GRAI R&D model and gives it a new dynamic in term of management of collaborative design activities.

3.5 Synthesis

The various approaches offer a general framework for the modelling and the follow-up of the evolution of the company, the system of design, its processes and its activities. GIM provides models of the company and GRAI Engineering method [10] models of the design system. These models are a static vision of the systems. Its dynamic is provided by the study of its evolution by the mean of the GEM approach [9] for the company and of the GRAI R&D model and design environment concept [12] [13] to follow-up the evolution of the design process and the design activities. This phase is possible only if a Performance Measurement System (PMS) is set up to evaluate the performance of the company and the performance of the design system. Description of the design system makes it possible to define the objectives, the action levers and performance indicators which composed PMS. All elements of the design system and its context are identified, defined and followed in all the models so a modification on one of them causes the re-examination of the objectives, the action levers and the performance indicators in order to be always in adequacy with the object to be evaluated. This methodology of modelling and follow-up of the company and the design system is build around four stages (Fig. 4):

Stage 1: Modelling of the company and description of the global performance inductors,

Stage 2: Follow-up of the evolution of the company,

Stage 3: Modelling of the design system and description of the local performance inductors,

Stage 4: Follow-up of the evolution of the design process and the design activities.

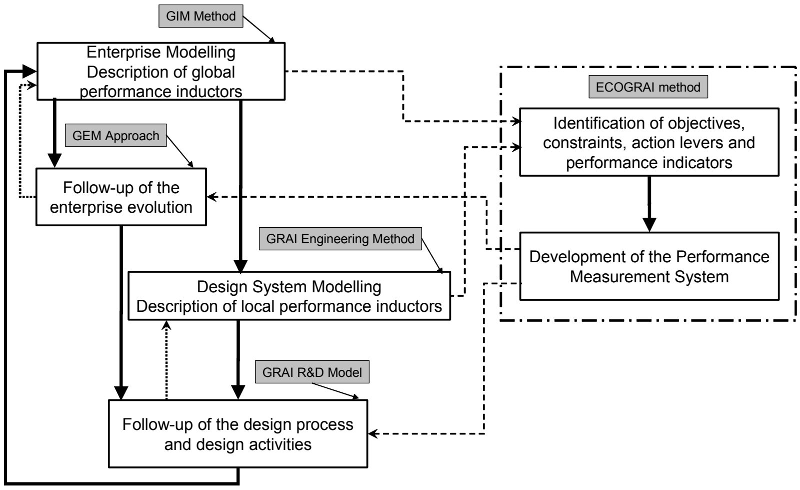

Figure 4: Methodology for modelling and follow-up evolution of the company and the design system

4 SOFTWARE TOOL SUPPORTING DESIGN PROCESS MANAGEMENT

To help decision-makers to manage design process at each decisional level we developed the PEGASE software that integrates all the concepts described before. It permits the modelling of the system and the follow-up of the evolution of each element of the design system and of its context. To show how PEGASE could provide a relevant answer to the problem of design system management, we present an industrial case study concerning the design phase of the reaction engine mast of the Airbus A380. The reaction engine mast is the interface between the reaction engine and the wing. This element is designed by the design department of an Airbus plant in Toulouse and has interactions with the wing (designed by Airbus Industry in England) and with the reaction engine (designed by a subcontractor in United States). Experience of strategic project managers of Airbus allows defining a global structure of the plane. When this structure is described, design departments which have to work together are identified in the structure of the enterprise. This identification depends on the decisional and organizational structures of the company. Finally, the strategic decisional level proposes a general design process to achieve properly design objectives. We obtain a global description of the company, of the design system and of the design process. The decisional and organizational structures of the company are built by integrating GRAI grids dedicated to each plant and are modelled in the PEGASE software

(Fig.5). GRAI methodology and associated tools offers the opportunity to defined objectives, action levers, resources and performance indicators for each plant, at each decisional level but also relationships and influences between each plant and each department of them. All these elements appear in the GRAI grids and in PEGASE too. The nature of the flow of information that will be exchanged during collaboration is also defined. PEGASE permits to model all these interactions and to define the nature of all the exchanges: decisional links (vertical links on Fig. 5) and/or informational one (horizontal links, Fig. 5).

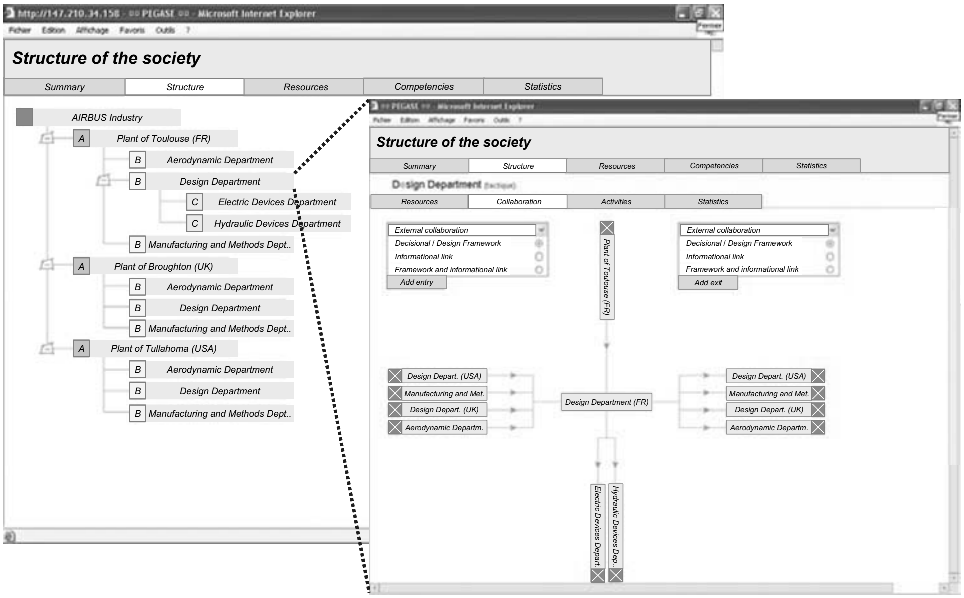

Fig. 5. Modelling of the structure of the company and collaborations between each department

When all elements and interactions in the design system are identified and implemented in the PEGASE software, projects could be created and software will manage their evolution.

At the beginning of the project, thanks to PEGASE software, tactical project manager of each department know his partners and has to initialise internal or external collaboration identified by the upper decisional level. He has especially to create and control workgroups according to knowledge, distribution, culture, collaborative capacities, interoperability of each human and material resource and regarding to design objectives. PEGASE proposes to project manager a specific Graphical User Interface to control his activity and to create and follow-up workgroups by creating specific design framework (Fig. 6).

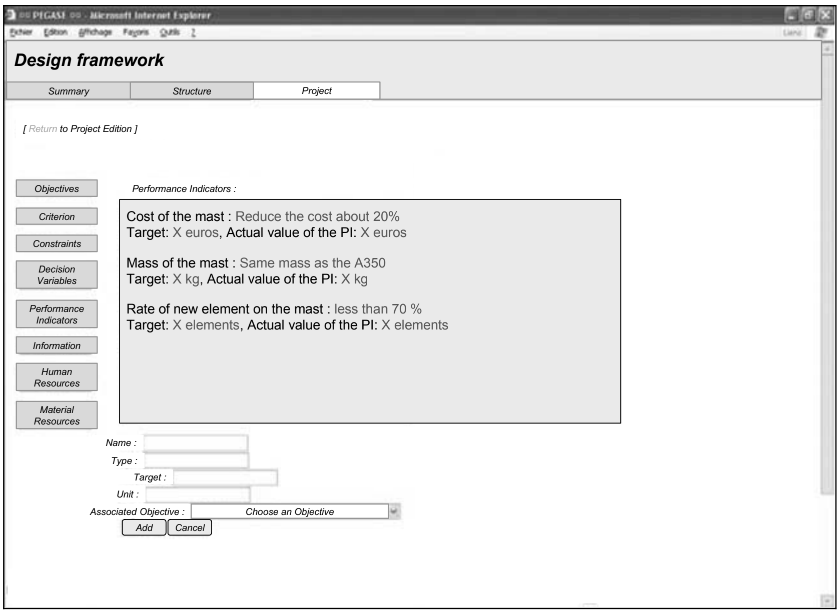

Fig. 6. Example of Graphical User Interface dedicated to a decision-maker at a tactical level

At an operational level, collaborative design activities regroup actors distributed in each plant. Each actor's task is defined and PEGASE provides to each one a set of contextualized information on a specific GUI about his context of work (human and material resources, distribution of these resources, objectives, constraints, influence of the others actors…). This decisional level provides tangible results on the product and information about collaboration that are capitalised and send to upper decisional levels by PEGASE. PEGASE permits to control collaborative activities by the mean of an adapted product model and a specific design system model. All these elements are contained in an organizational model based on the design environment concept and manage in PEGASE too. PEGASE is developed around an integrated model of product, process and organizational models, completed with a specific PMS to obtain a dynamic system for design process management.

5 CONCLUSION

Product design today requires new interaction forms between the various stakeholders involved in this specific process. Management of the design processes is today complex and to improve processes performances, it's necessary to focus not only on the artefact but also on the actor's relations. Therefore, organisation has to integrate aspects centred on the actors in order to be reactive and efficient considering the design process evolution and framework. Software tools must be set up in order to support those aspects. This paper focuses on a model describing the elements influencing the design context of engineering design actors and interactions between them. It presents global trends while considering the design actors and defines a methodology to manage design system evolution. In a first time, the decision-making structure of enterprise is defined precisely with GIM to put in evidence all links between each department of the plants and its evolution is estimate thanks to GEM approach. Objective of this phase is to underline the rule of each actor, at each decisional level, and to judge his influence on the design system. Secondly, GRAI Engineering method permits to describe the design system to manage its evolution. A performance measurement system is developed according to the decision-making structure and previous different models. It has also to integrate actors' influences. Lastly, the GRAI R&D reference model and the design environment concept give the frame to implement the result of the two previous phases and to control design process. In order to validate this framework, we developed a prototype of software: PEGASE. PEGASE helps decision-makers, at each decisional level, to manage design activities. The aim of this work is to support decision makers managing design projects.

6 ACKNOWLEDGMENTS

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PLM Pattern Language: An Integrating Theory of Archetypal Engineering Solutions

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Abstract
Pattern languages are an approach to provide common knowledge in an easily accessible way. They were originally invented in the 70s and first applied in civil and architectural design. During the last decade the approach has been commonly applied in the software community and gained a strong influence on many fields within computer science. In engineering design as well as Product Lifecycle Management (PLM) pattern languages have yet not been applied. This paper introduces the concept of pattern languages and describes approaches to apply pattern languages to PLM to develop a cohesive PLM theory integrating the several subareas of PLM.

Keywords:
Pattern Languages; Engineering Education; Knowledge Management; Product Lifecycle Management (PLM)

1 INTRODUCTION

The management of engineering knowledge is a crucial element of Product Lifecycle Management (PLM) and one of the key enablers to economical success of manufacturing companies. To overcome the increasing complexity of current products and processes the engineers need to have appropriate skills and knowledge at their disposal. Thus, tools and methods to provide engineers with knowledge are getting more important to ensure the competitiveness and sustainability of a company.

Chapter 2 gives a short overview about current approaches to provide knowledge which are expedient to be applied in the area of PLM. Chapter 3 describes in general the concept of pattern languages, before aspects regarding the application of patterns languages in PLM will be discussed in chapter 0. Chapter 5 finally summarizes the main contributions of this paper and concludes with an outlook on further research.

2 STATE OF THE ART

Several approaches to provide PLM knowledge are currently applied in industry. In many technical departments engineering guidance systems are used to provide information about development processes [1]. These systems idealize the addressed processes to provide generally applicable information. The structure of the content is either process oriented or product oriented. If in case of a process oriented system information about products and technology is required, the engineer has to know the appropriate location within the according processes. In case of product oriented systems the engineer likewise has to determine the product according to a certain process in order to get information about this process.

Another approach to supply engineers with knowledge is the usage of tools similar to yellow pages [2]. These cluster the relevant knowledge and assign each cluster to an engineer who is an expert in that field and possesses the according knowledge or skills. The system will provide an engineer who searches for information with the contact data of an expert. This approach supports the exchange of implicit information between staff. It is feasible in case a special problem occurs, but it is not feasible to establish an ongoing flow of information to satisfy the regular need for information.

Even books are tools to provide engineers with knowledge and have to be mentioned in the context of this paper. In their entirety they provide a huge amount of knowledge with various levels of expertise. Each book is structured in a way that the contained information is easily accessible. But the information subsumed by all books as an entirety cannot efficiently be retrieved. Therefore, books are merely used in industrial environments.

3 PATTERN LANGUAGES

3.1 The Pattern Approach

Some current approaches described above are capable to support the retrieval of knowledge according to a certain context utilizing structures or indices. But these approaches focus on specialized ephemeral knowledge. Common knowledge, which every single engineer needs to have at his disposal to originate state-of-the-art results, can still be primarily found only in books. Pattern languages are an approach to provide common knowledge in an easily accessible way. Beyond this, pattern languages aim at some further properties which are not objectives of other knowledge management approaches (chapter 2). Pattern languages were originally invented by Christopher Alexander [3] [4] [5] in the 70s. They were first applied in civil and architectural design to capture design experience and to communicate the according solutions with customers. During the last decade the approach has been commonly perceived in the software community. Currently, pattern languages have been applied to many fields within computer science. They have gained a strong influence on those fields, especially software engineering and programming [6] [7] [8] [9] as well as human-computer interaction (HCI) design [10] [11] [12]. Even in pedagogy pattern languages have been applied [13].

In engineering design as well as Product Lifecycle Management (PLM) pattern languages have yet not been applied. The domains described above, in which pattern languages have proven to be expedient, are similar to PLM concerning their design orientation, interdisciplinary collaboration and customer awareness. Thus, pattern languages are supposed to provide a similar benefit, if they are applied within PLM.

3.2 Syntax and Semantics

The central idea behind pattern languages is that, due to complexity, humans have evolved archetypal concepts which solve recurrent problems. These concepts are called patterns. Within a pattern language all patterns have a uniform format and structure. The structure of the original patterns by Alexander is constituted by a set of content types [3], which can be found with only minor amendments in other patterns languages:

- The unique and descriptive *name* of the pattern.
- A *ranking* of its quality (omitted in some other pattern languages).
- A *picture* illustrating an example of the pattern.
- The *context* in which the pattern can be applied. The context consists of the patterns which are supported by the actual pattern.
- A short *statement* delineating the recurring problem which is referred by the pattern.
- A detailed description of the *problem* comprising a comment on the conflicting forces which cause the problem. In case of PLM most of these forces are of technical (e.g. an engine should be powerful and ecological), economical (e.g. a product has to be cheaply producible and competitive) or organizational nature (e.g. short time-to-market and lean value chain). The solution must describe how the forces can be balanced or resolved.
- Situations in which the described problem occurs together with a description of the solution are delineated in the e*xamples* section. The Examples should refer to widely known application and explain how those applications solve the problem. Examples are important on the one hand to lead novice readers towards the general solution of the pattern via a comprehensible set of instantiations of this solution. On the other hand, they give professional readers empirical verifiable evidence of the validity of the pattern.
- An archetypal *solution* of the problem illustrated by a diagram.
- References to *supporting patterns*. These references point to other patterns, which “unfold” the solution of the current pattern, for example the pattern “Road Crossing” is supported by the pattern “Raised Wall”.

Patterns do not stand for themselves. Like described above, they comprise references to “supporting patterns”. This results in a hierarchical structure leading from a most general top-level pattern over larger-scale patterns to elementary ones (Figure 1). Each elementary pattern can be reached via one or even more ways from the top level pattern. Thus, the set of all patterns belonging to the same language constitutes a semilattice (a partially ordered set closed under either supremum or infimum) with the “supporting pattern”-references as ordering relation.

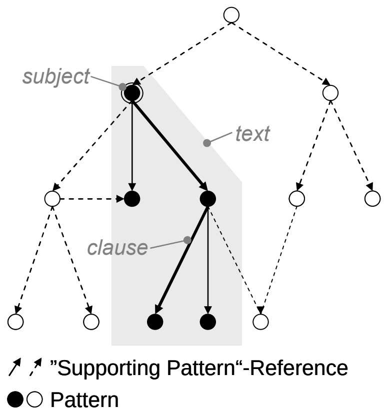


Figure 1 : The structure of a pattern language.

This concept can be compared to a spoken language. A spoken language comprises words and grammatical rules which describe how the words can be related to each other resulting in a clause. In case of patterns the “supporting pattern”-references can be seen as the grammar of the pattern language. The clauses generated by this grammar are sequences of patterns describing a set of constitutive solutions. If a problem corresponding to a certain pattern occurs, a subset of supporting patterns which is subject to his intentions is chosen by the user (architect, software developer, designer …). The other supporting patterns are discarded. Each chosen pattern in turn entails a further subset of chosen supporting patterns. As a result, a sublattice evolves with the original problem as the join. The paths down from the join constitute a set of clauses with the original problem as the subject. This set can be seen as a text, which is written in the pattern language, expressing the user’s ideas of solving the problem.

3.3 Philosophical Considerations

Behind the idea of pattern languages, there is a certain philosophical theory which delineates the intention of this approach: Because patterns are supposed to refer to recurring problems and archetypal solutions, a pattern language describes a timeless way of the application domain (cp. [4]). Thus, pattern languages persist over decades and are applicable regardless ephemeral realisation aspects. Many outstanding archetype concepts which are intended to be described by patterns imply a certain hardly describable quality like an inner beauty. Alexander names it the quality without a name [4]. This quality cannot be reduced to a single dimension [10] but is to be captured in a pattern. A living pattern language is considered to be the gate to be passed to reach the quality without a name [4]. The usage of a pattern language constitutes the timeless way mentioned above leading through the gate.

4 PLM PATTERNS

4.1 Potentials of PLM Patterns

PLM is a strategical approach to manage the entire lifecycle of a product and its components to ensure sustainable benefit. It can be seen as a meta-theory integrating theories and methods from discrete subareas within the product lifecycle like marketing, industrial design, engineering design, production planning, production, sales, maintenance and disposal. Currently, a bunch of methods has been developed in the context of PLM [14] [15] [16]. These methods on the one hand and the methods and theories of the subareas within the lifecycle on the other hand are only loosely connected and lack of integration so far. The aim of applying pattern languages to PLM is to develop a cohesive PLM-theory which relates current PLM-methods to each other, integrates them with the methods and theories of the subareas and makes the evolving comprehensive set of methods continuously applicable during the whole product lifecycle as an interdisciplinary lingua franca.

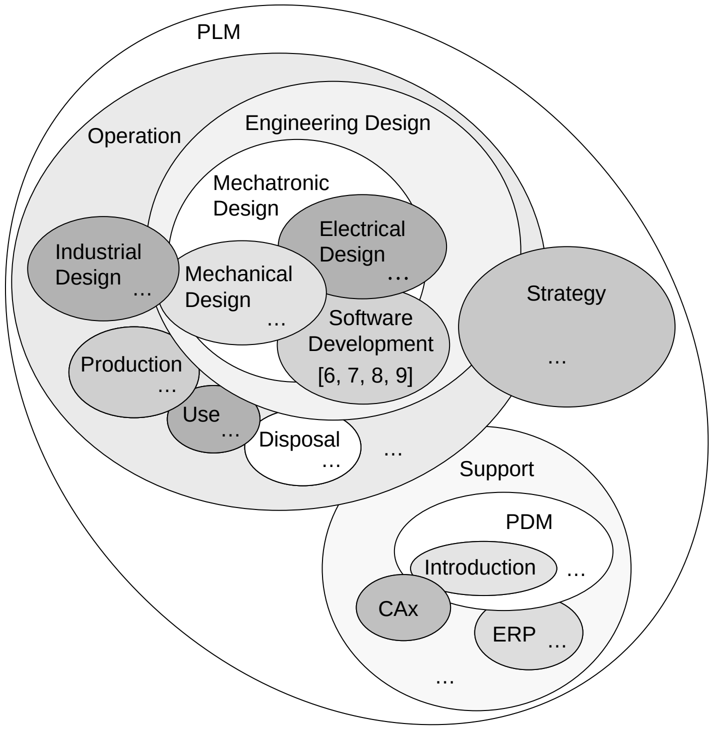


Figure 2 : A framework for a PLM pattern language.

A common motivation for the application of pattern languages throughout the various disciplines, which is also expedient for PLM, is to capture archetypal knowledge and initiate a generative problem solution process based on this knowledge. A major objective of Alexander's work is to share the knowledge incorporated by the pattern language with the inhabitants (customers) and facilitate them to participate in the design process [4]. For similar reasons, pattern languages are applied to HCI design [1]. Users on the one hand do not understand the technical jargon of software engineers and software engineers on the other hand have only a vague cognition of the application domain. Pattern languages are applied to establish communication between both parties. In general, the language-like concept of pattern languages described in section 3.2 makes this approach capable to become a common lingo which facilitates collaborative work between experts from different disciplines as well as laymen like customers.

4.2 A Framework for PLM Pattern Languages

Current pattern languages for software development only cover a single area and one user group (software developer). Even the pattern language of Alexander covers one area (architecture) but addresses two user groups (architects and inhabitants). HCI-Design patterns span three areas (application domain, HCI, software development [10]) and are related to three user groups (user from application domain, HCI-designer, software developers). PLM comprises even more subareas to be integrated as well as user groups to be addressed.

Figure 2 depicts a framework for a PLM pattern language comprising these subareas. Dependencies between different areas are represented by overlapping circles. For example, strategies determine the operational methods to be applied. Operational methods in turn determine how PLM-supporting systems have to be arranged and configured. The framework divides the area of PLM into three major segments: super ordinate strategic approaches, operational approaches to realise value-added chains according to the strategies and approaches to support the effective and efficient progress of value chains. A strategy is constituted by a bunch of goals to be reached [17]. Thus, in the strategy-section the desired goals can be seen as the objects to be designed. The design objects in the operation-section are the products and components, whilst in the support-section the PLM-supporting systems and the design tools are the design objects.

To develop a complete pattern language for PLM, the grammar of the language has to be developed as well as the structure of a pattern and the content. The grammar of Alexander's language structures pattern according to the spatial structure of the addressed design objects, i.e. patterns addressing large-scale objects refer to patterns addressing comprised small-scale objects. PLM is more complex than architecture because it integrates different kinds of design objects with various levels of details, different lifecycles and various engineering disciplines. Thus, an approach with time as a primary structuring criterion supplemented by the spatial size like proposed in [10] as a secondary one (cp. [10]) seems to be appropriate. Additionally, the design object is required as third structuring criterion. A structuring criterion regarding the involved engineering disciplines is not expedient because one aim of the PLM pattern language is to create a common interdisciplinary lingua franca. The inner structure of a pattern proposed by Alexander (section 3.2) seems to be largely appropriate to be transferred to PLM patterns.

The framework depicted in Figure 2 gives an overview of the content covered by the PLM pattern language. As an integration approach it comprises not only PLM-strategies and supporting tools, but also content from various subareas within industrial design, engineering design and production planning. The integration of this content makes the development of PLM pattern languages a challenging, but very rewarding mission. Especially the development of sub-languages describing the following topics seems to be particularly interesting: PLM-strategies and their dependencies on the operational level, integration of customers into the design process, collaboration between industrial design and engineering design, mechatronic design (collaboration between mechanical design, electrical design and software development), integrated representation of current approaches in mechanical engineering, collaboration between engineering design and production planning, arrangement and configuration of PLM-supporting systems according to operational approaches, interconnection of PDM- and ERP-Systems and introduction of PDM-systems.

4.3 Example: The Complexity Pattern

Complexity is a central element to be considered in PLM and a key success factor of manufacturing companies. Thus, the complexity pattern, which is part of the PLM pattern language, will be delineated in this section to illustrate the pattern concept. The structure of the PLM pattern language follows the structure proposed by Alexander [3] and described in section 3.2: *Name*, *ranking* (omitted here), *picture*, *context* (directly followed by) *statement* +++ *problem*, *examples,* therefore: *solution* (represented textually and graphically) +++ *supporting patterns*. Like the pattern language of Alexander, the PLM pattern language comprises no explicit labelling. Instead, a consistent layout helps to identify the content types. This Alexandrian style makes the pattern language more readable.

COMPLEXITY

… a marketing strategy has already been elaborated – MARKETING STRATEGY. This can be seen as one strategical dimension. Another strategical dimension is the product portfolio – PRODUCT STRATEGY. In line with the product strategy the complexity has to be adjusted.

+++

The market requires a product portfolio with a preferably huge variety and dynamically changes its requirements (high external complexity). Unfortunately, external complexity and internal complexity correlate with each other, so a high external complexity leads to a high internal complexity. The internal variety causes costs and efforts

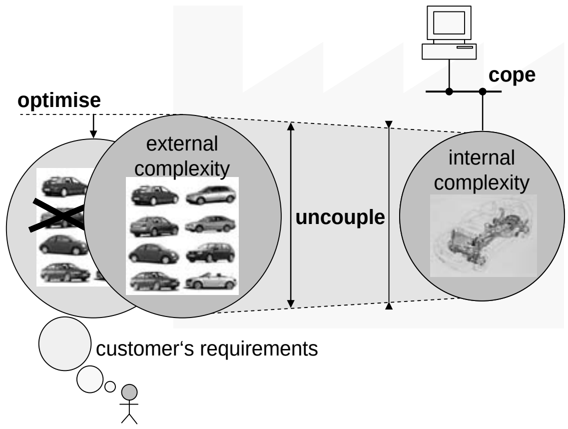
A manufacturer of semitrailers, for example, offers customised products. Several customised features originate high costs. A market analysis yields that the customer value decreases, if these features are discarded. But at the same time the customer satisfaction increases because even the cost price decreases.

An automotive company (Volkswagen) holds three brands (VW, Audi, Seat) producing a total of seven compact cars (Seat Leon, Audi A3, WV Bora, Sat Toledo, VW Beatle, VW Golf, Skoda Octavia). This adds up to a high external complexity. To decrease the internal complexity, the seven cars have been built upon a common platform. Additionally, a sports car has been developed using this platform (Audi TT).

A company produces high-quality fans sold on a high price. It embarks on the strategy to offer mass customised products, so the external and internal complexity is very high. The company decides to introduce a PDM (Product Data Management) system to make the huge amount of product data manageable.

Therefore:

Optimise the external complexity, uncouple the external complexity from the internal complexity and take measures to cope with the remaining internal complexity.



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The offered product features have to be balanced with the demands of the market to optimise the external complexity – OFFERING VS. DEMANDS. To uncouple the external from the internal complexity, resources (product data, production resources, suppliers …) can be adopted for several product components at the same time – MULTIPLE USE – or can be reused for new product components – REUSE. Several IT systems like PDM or ERP systems are expedient to cope with the internal complexity – PLM SUPPORTING SYSTEMS. …

Table 1: The complexity pattern.

4.4 Application of PLM Patterns in Industry

PLM has evolved to optimise the lifecycle of products and the related information in industrial environments. Thus, in order to be expedient any PLM-supplementing approach has to provide an added value to industrial application scenarios. In case of PLM patterns, a huge benefit is already gained by applying the original concept of pattern languages. This provides archetypal knowledge comprising exclusively com-

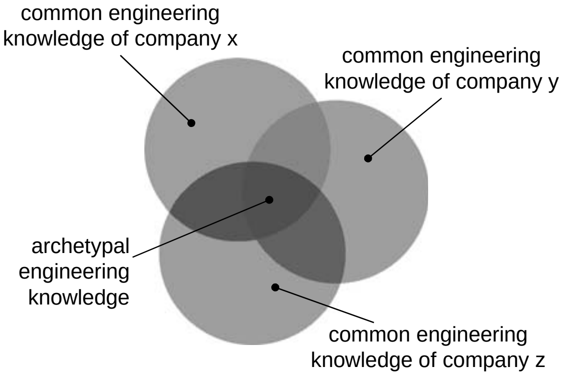

Figure 3 : Common engineering knowledge from a company's point of view.

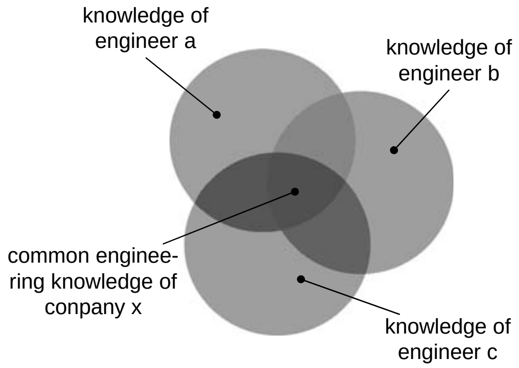

Figure 5 : Common engineering knowledge from an engineer's point of view.

pany spanning content, which can be seen as the basic knowledge every engineer needs to design competitive products. But beyond that, outstanding products require specific knowledge which the competitors do not have at their disposal. Although the pattern approach was originally intended to provide archetypal knowledge, due to its hierarchical structure it can be amended by a layer concept to combine archetypal with company-specific as well as employee-specific knowledge.

The meaning of archetypal engineering knowledge implies that it can be seen at the same time as common knowledge of the engineers working for a competitive company (Figure 3). Engineers of an outstanding company additionally have common knowledge about recurring problems which is specific to the company and therefore not part of the archetypal engineering knowledge. Similarly, the common engineering knowledge of a company is (resp. should be) at the same time individual knowledge of each engineer, but in general each engineer additionally has some individual knowledge about recurring problems which other engineers do not have (Figure 5).

The common and individual engineering knowledge from a company's point of view as well as the common and individual knowledge from an engineer's point of view can be combined using several layers like depicted in Figure 4. The common layer on the top comprises archetypal patterns and thus represents the actual PLM pattern language. This layer can be amended by sub-layers to manage individual knowledge. On a first sub-layer company specific knowledge, which all engineers of a certain company have in common, is located. The patterns on the company layer are interconnected to each other and connected in both directions to the patterns on the common layer. This constitutes a semilattice. Thus, from a company's point of view the construct can be seen as a pattern language comprising company-specific engineering knowledge which each engineer should have at his disposal.

Even specific knowledge of an engineer for solving recurring problems can be described by patterns. These are located on the employee layer (Figure 4). The patterns of the employee layer are interconnected to each other and connected in both directions to the patterns of the company layer. Together with the semilattice of the company's pattern language, this constitutes again a semilattice which can be seen as a pattern language from an engineer's point of view. This language covers the specific knowledge of a certain engineer about proven solutions of recurring problems.

The layer construct described above should be created in a top-down way initially and may be completed in a bottom-up way afterwards: The common layer is a prerequisite to create the company layer as well as the employee layer. Thus, it should be completed before the creation of the other layers starts. Although the common layer is very expedient for many companies, it will hardly be provided by a company to its competitors. So, it is up to the scientific community to develop the common layer, whilst the specific layers have to be created by the companies. To facilitate the detection of common knowledge, the creation process might start with the employee layer. Patterns occurring in many employee languages are candidates to constitute the company layer. If a pattern shifts from an employee layer to the company layer, the connections to other patterns do not change. Only the scope of persons who can access the pattern will be extended.

To realise that concept, a dynamic pattern language which provides user identification and a personalised employee layer is required. Not only for this reason, web technologies rather than plain paper are recommended for the implementation.

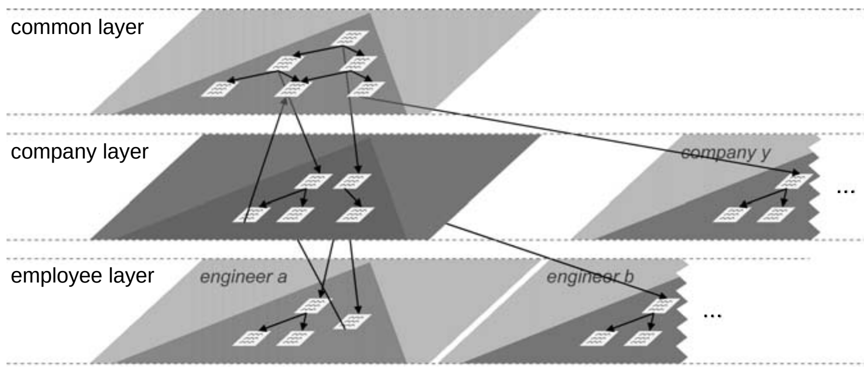

Figure 4 : A layer concept to combine archetypal and company-specific as well as employee-specific engineering knowledge.

5 BACKGROUND PATTERNS

The structure of pattern languages primarily aims at making knowledge easily applicable. It comprises only empirical, week evidence given by the examples for the validity of each pattern. Nevertheless, the *context* and *supporting patterns* -links establish a network which assembles peaces of knowledge to a coherent whole.

Background patterns are an approach proposed by the authors to amend each pattern by background knowledge comprising theoretical evidence corroborating the statements of the pattern. By this background knowledge a pattern language is turned into a holistic theory covering the application area of the pattern language. A background pattern is assigned to a single PLM pattern and has no further links to other patterns. It comprises the scientific theory underlying the PLM pattern. Similar to the structure of conventional patterns, which has proven to be of value, the background patterns are to be structured consistently. Therefore, two alternative pairs of content types seem to be expedient: *These* with *evidence* and *actuality* with *explanation* respectively. Each background pattern may consist of an arbitrary amount of such pairs depending on the statements to be corroborated. At the end of each background pattern, the referenced literature should be listed.

Background patterns make the pattern concept just as expedient for engineering education. Conventional education media like books, scripts or lecture slides present the subject matter in a purely sequential way. References between content elements which constitute each other would improve the comprehensibility. Such references are provided by the *context* and *supporting patterns* -links of a pattern language. The pattern language provides an overview of the subject matter, the content of teaching is comprised by the background patterns. Thus, the pattern concept amended by background patterns constitutes an approach to give a subject matter an intuitive structure and increases the pedagogic efficiency as well as effectiveness. Furthermore, the “context” and “supporting patterns”-links support the lecturer in proving whether the subject matter is covered completely.

6 SUMMARY AND OUTLOOK

In architecture, the pattern approach has not been received well, because Alexander’s concept enabled the inhabitants (customers) to influence the design process and take some influence away from the professionals [10]. Obviously, architects were not inspired to apply pattern languages. In contrast, in PLM and engineering design professionals are encouraged by the management to cooperate with customers. Thus, there is some potential for pattern languages to be commonly applied in these areas. The example of software development, where pattern languages are already very popular, endorses this assumption.

This paper has accounted for the applicability of pattern languages in PLM and engineering design. Some approaches to develop a PLM pattern language as an interdisciplinary lingua franca were proposed. Further research has to be done to refine these approaches and complete the PLM pattern language. These ongoing efforts will be published at *www.plmpatterns.org*.

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About the integration between KBE and PLM

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Abstract

This article is focused on the integration between KBE (Knowledge Based Engineering) applications for Design Automation (DA) and companies' data repositories managed by PLM (Product Lifecycle Management), and PDM (Product Data Management) systems. In particular, the authors conducted their research proposing a method to retrieve data or documents of pre-existing components from a document repository, before proceeding to design products. As result of that, designers save time spent in design, verifying loops and documents producing, thanks to the reuse of existing components or product. In order to illustrate their approach, the authors developed an application where the KBE system checks the availability of existing components or products before let the designer proceed to design. New produced documents are stored into the data repository for next design activities.

The paper is organized as following: first, it starts with the description of some relevant aspects in engineering design: product and process representation, knowledge reuse and sharing, PDM and KBE functionalities; then, the paper continues analyzing the functionalities of KBE and PDM system in order to introduce the issue of the integration; third, it goes on describing the approach followed by the authors; next, it describes the application above mentioned and performed by the authors on these topics; finally, the results of the work are reported.

Keywords:
PLM; KBE; Design Automation.

1 INTRODUCTION

This paper deals with the integration of KBE (Knowledge Based Engineering) systems with PLM (Product Lifecycle Management). In particular, the research focuses on methods by which KBE applications developed for Design Automation (DA) can automatically retrieve parts stored in a repository. The problem of retrieving parts in a data-base is a neglected topic in Design Automation; in fact, several works have been written on the capability of KBE of retrieve knowledge, data and documents from repositories, but very few efforts have been completed successfully on the investigation of methods by which do that.

Noel and Brissaud, [1], in their paper, state that "shared aspects are only about geometry. Technical data are duplicated because they are mostly considered as specific to the tool. Very useful concepts such as a graphic user interface and the usual tricks of the discipline of collecting data in an acceptable format and avoiding computer process corruption are not unified and are therefore unable to be used efficiently. Levels of concept abstraction are adapted to the task and so only experts may understand tools". The authors go on affirming that PDM systems are suitable to store CAD files because of many reasons described in their paper. Moreover, they assert that files stored in the PDM can be considered as "the atom of knowledge" for Product description. But, they also state that because of the hundreds of parameters used to define the shapes of the parts, it is very difficult to retrieve a particular file. In fact, no information is provided in a PDM to highlight specific design parameters and justify their use. They observe also that "a model update must to be performed by hand", because the only extra information offered by a PDM system is given, in most cases, as unstructured annotations in textual or image format.

Szykman, Sriram and Regli [2], affirm that although PDM can represent some kinds of non-geometric knowledge such as information about manufacturing process or bills of materials, representation of the artifact itself is still generally limited to geometry. The lack of a formal product representation that includes function, behavior, and structure has been identified as a shortcoming of existing PDM systems. Similar considerations are also reported in [3]. In conclusion, we can state that one of the most relevant issues of knowledge and data retrieving from a PDM is to investigate the methods to do that. Starting from these observations, the authors have developed a methodology to retrieve documents using a particular coding and they tested their approach in a real industrial case.

2 TOPICS IN KBE APPROACH TO DESIGN AUTOMATION

The capability to search and retrieve parts directly from a repository can be considered a new and not well defined topic in Design Automation. Up to now, traditional issues concern knowledge representation, knowledge reuse and sharing. In particular, the first one is structured in terms of products and processes representation. Before realizing the knowledge reuse and sharing, with implementing the application, the formalization of the gained knowledge is highly recommended. The following sections highlight the state of the art related to this aspects and define the new topic.

2.1 Product and Process Representations

In traditional design process some activities are overlapped, in particular in some situations it is not well defined when an engineer works to define product architecture or when he/she executes a step of a procedural process to dimensioning, choosing and so on. In a computer application this fact is not satisfactory; "the design research literature reflects this by exhibiting a dichotomy between process representation and product design" [4]. Therefore, the problem about knowledge representation within a computer program can be subdivided in two sub-problems: the product architecture and the design process representation. In a CAD approach the main issue is the representation of the product architecture. Gorti et al. [4], Colombo et al. [5][6] indicate Object – Oriented approach as the most suitable and adopted technique to represent the product architecture, structured as a tree.

Most of the commercial KBE systems adopt this approach that permits to represent with a logic order the functional structure of the product and allows easily modifying, adding or deleting parts and subparts without heavily modify relations among the parts themselves. A not object – oriented approach (like the algorithmic languages) constrains the user modify all the code in case of variations of product structures [6]. Moreover, every part or component is independent each other; so, it's possible to consider them as small application, able to be applied in different level of a tree structure of the same or other products, inheriting parents characteristics.

The second topic in KBE approach to DA is the representation of the Design Process; whereas the logic approach to define the product architecture is "bottom up", typical of CAD product modeling, in the case of the process an engineer follows preferably the "top down" logic, that is he/she goes from high level specifics and functions to detailed ones. Different approaches can be used to represent design process; in the following two of these are highlighted:

1. In a totally object-oriented approach, we must represent process by using properly variables and methods of each object and characteristics such as inheritance mechanism. A lot of commercial KBE kernel, the more famous also, ICAD from KTI Inc, implement such a solution; but this procedure of knowledge representation is not familiar to engineers and this fact limited the diffusion of KBE applications in industrial domain, especially in SME (Small Medium Enterprises). An extension to traditional object-oriented representation is proposed by Gorti et al. in [4]; new elements such as explicit relationship entities, constraints and mechanisms for comparing interchangeable objects were introduced. But also in this case, the design process is embedded in the product structure and not independently represented;
2. An approach that permits a partially independent representation of the design process is proposed by new KBE commercial kernel. As an example, RuleStream (by homonymous software house) permits to create the design procedure as consequent steps, which recall user interfaces including all the operations to be performed, in order to complete the design tasks. In this case, a design procedure can be represented also without being related to a product structure. In other words, first, you have to create the product tree; then, you have to represent the design process unlinked from the product structure representation; finally, you can link the process steps with the properties included in the product tree.

2.2 Knowledge formalization

In order to develop a DA application able to dialog with knowledge repositories, the developer has to take into consideration different aspects, as well explained in [7]:

1. Knowledge acquisition;
2. Knowledge collection;
3. Knowledge formalization.

Knowledge formalization is a crucial aspect and a lot of efforts have been spent to study this problem. We cite several projects dedicated to this issue, particularly the MOKA, the DEKLARE and the KOMPRESSA projects.

The MOKA (Methodology for Knowledge Based Engineering Application) [7][8], addressed to aeronautical companies, has delineated the guide lines for the implementation of a well built application; in particular, it consists of different tools and methods to acquire, collect and formalize the domain and the strategic knowledge. This methodology considers, after the activity of knowledge collection by a specific form called ICARE (Illustration, Constraints, Activities, Rules and Entities), the use of UML language (indeed, modified to better represent a KBE application and called MML – Moka Modeling Language) to describe the dependencies among objects, parameters and methods to be implemented in the application. That permits to make explicit the domain knowledge and the strategic knowledge involved in the application. The realization of a specific tool, the MOKA Framework, help developers in translating the knowledge acquired with ICARE forms to MML representation.

The DEKLARE (Design Knowledge Acquisition and Redesign Environment) Project [9][10] furnishes similar tools of the MOKA project and it is addressed also to SME. It consists of three main tools: the DEKLARE Design Analysis Methodology (D-DAM), to acquire company knowledge in the specific domain of the product; the Design Description Language (DDL), to formalize the knowledge acquired with D-DAM; Design Advisory System (DAS), a framework to develop applications using the D-DAM application results. The DEKLARE methodology is different from the MOKA one by the target. In fact, DEKLARE is addressed to SME, and it is underlined also by the gradual way by which the application can built.

The KOMPRESSA (Knowledge-Oriented Methodology for the Planning and Rapid Engineering of Small-Scale Applications) methodology, addressed to SME, too, focuses on the phases to cover out in order to capture and formalize company knowledge and to build a KBE application. The main aims are to provide guide lines to products and design activities analysis, to provide methods to apply the best practices and to furnish techniques to realize the knowledge reuse and sharing and maintain applications. Principal phases are nine, but, in according with the special needs of the company, something may be skipped, in order to not impact too much in the design process of the company.

Other projects in the same field are REFIT [11] (Revitalisation of expertise in foundries using information technology), or CommonKADS [12], which was the base of newer projects like MOKA or DEKLARE.

3 THE PROBLEM OF KBE AND PLM-PDM INTEGRATION

The projects presented in 2.2 are very suitable for the companies they addressed to; however, they do not consider the specific issue of this paper we will describe in the following. An engineer can solve some design problem by choosing standard, commercial or existing parts; in this situation his/her work consists in retrieving parts from data-base or repository. If we want to develop DA applications able to do automatically the work done by the human expert, we must implement mechanisms that permit to perform specific search on company's data-base.

The data-base can not be "ad hoc" implemented for the specific DA application but it must be the company's PDM-PLM repository. In this context, the main functionalities considered for PDM-PLM are data repository and workflow management.

There are a lot of problems in defining a general procedure to automatically search parts on a repository; in this work we propose an approach based on a specific coding of parts and assemblies. The code should represent the main information on the specific component; in other words, code should not give information only on geometrical aspects, as well explained also in [1]. On the contrary, it should give information on other aspects related to the component and how and why the component is created in a particular manner. For example, a shaft should be coded using numbers for the dimensions, but also alphanumerical characters, which provide information on the morphology, assembly procedures, adaptability for a specific use, and so on. A similar approach was developed in Group Technology to identify families of parts; following sections explain our implementation by using a case study.

4 TEST CASE

The authors developed a KBE application to test their approach. In particular, they covered out the main phases indicated by the methodologies presented in 2.2. Main phases are: Knowledge acquisition (product and process), formalization, definition of the integration specification between KBE and company archive manager (in this case, a PDM), implementation.

The presented application is addressed to the automatic design of an industrial mixer and it was developed using the software RuleStream. The aim of this application is to enable designers to share their knowledge and reuse their applications or part of them in other applications and perform the integration between the application and the company PDM. In order to do that, the authors developed a system to retrieve data and documents stored into the PDM to reuse documents already produced.

4.1 Knowledge Acquisition

Figure 1 shows a schematic description of the machine.

As it is possible to see, there are three functional groups: the Engine Group, the Rotor, the Stator. Each of them includes sub – groups and elementary components.

In the next Figure 2 is the hierarchical representation of the product. In order to let the application search in the company PDM system, the authors created a way to index all the parts, properties, CAD files and drawings using queries referring the information included in tables stored in the PDM. For example, the part "Shaft" (both engine and rotor ones) has attributes (such as properties or CAD files, and so on) which values can be calculated or searched into the tables stored into PDM. If the value matches correctly with the correspondent one present in any PDM table, the system skips the design and verifying tasks and uses the values characterizing the part present in the PDM. In the next sections, the querying system is explained.

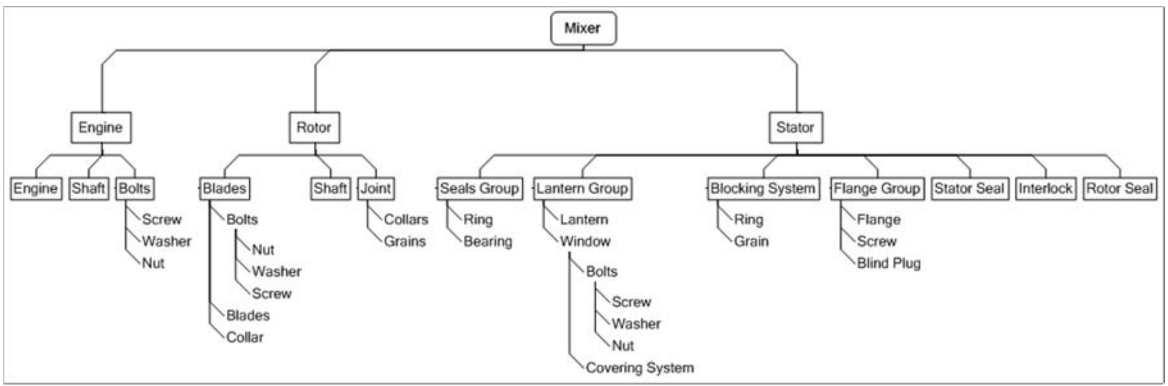


Figure 1: Architecture of the mixer.

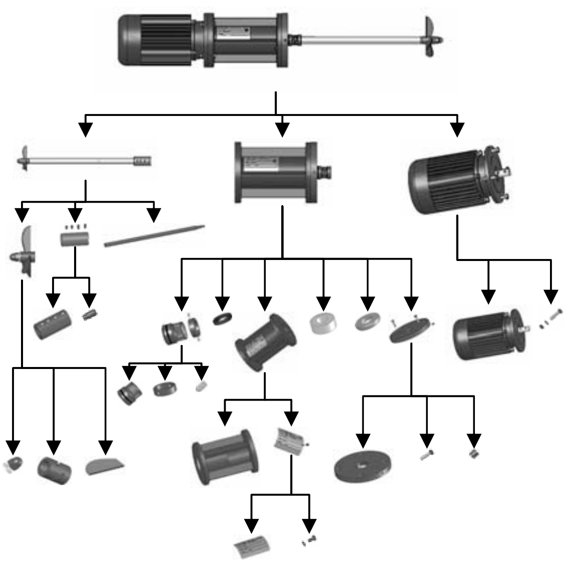


Figure 2: Hierarchical representation of the mixer

4.2 Knowledge formalization

Before implementing the application with the KBE software, a schematic representation of the application, using UML language, is needed in order to understand relationships among parts and properties. In Figure 3, the UML blocks representation of the application is shown.

As it is possible to see from the first figure, there are three main groups called “Stator”, “Rotor” and “Engine”. The following figure represents the rotor group more in detail and in relation with the engine and the properties of the top block.

In the Figure 4, the simplified design process representation is showed using IDEF0 language. In figure (a), it is illustrated that the general process is addressed to produce drawings and BOM, with updating of PDM. The system searches in the PDM documents already realized in past projects and tries to reuse it, in order to avoid the re – designing of existing components or products. As result of that, the system skips several steps, such as the designing and verifying of the most of components.

In figure (b), the A2 step block is exposed. In particular, it is underlined how designers proceed to the retrieving of past projects before designing new components. New and existing components, taken from the PDM, are used to configure the final product.

4.3 Implementation

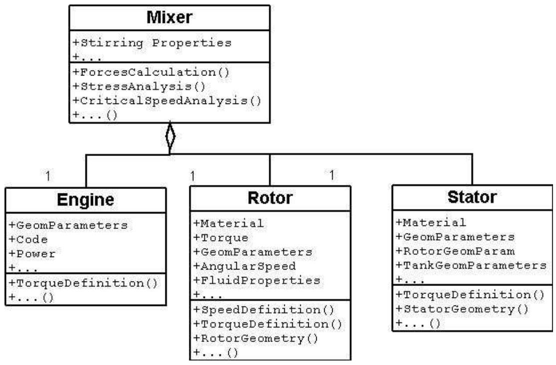
The authors used RuleStream to develop the application. First, they created the so-called product control model (PCM), that is, the hierarchic object oriented tree representing all the possible configuration of the product. Then, they fill the PCM with all the proper parts and properties, in according to the UML schema showed in Figure 3. Third, the authors defined the process to cover out by the user, creating proper user – interfaces for every step of the process. Next, they simulated the PDM functionalities of archiving of documents and data and created the tables and folders for each component useful to configure the product. Fifth, the authors created the indexing system to relate the parts present in the PCM with data present in the PDM, in order to let the user search existing parts before proceed to design new components. Final, they created the procedures to generate BOM, drawings and to store them in the PDM, with the generated 3D CAD files.

4.4 Use of the application

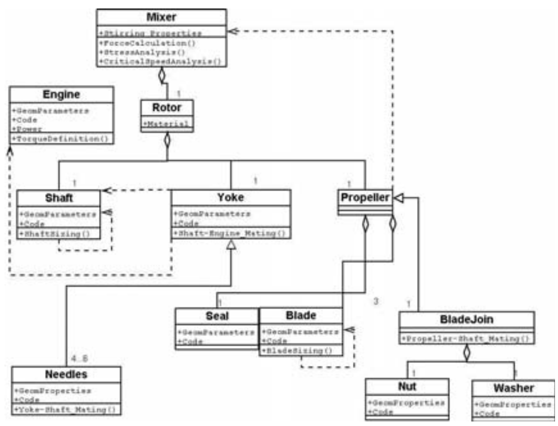
Once developed the application, RuleStream displays user - interfaces that permit the designer to automatically configure the final products, be them new or a retrieving of a past project, in according with the process modeled. In the next Figure 5, a snapshot of the application.

The UML schema in Figure 6 represents the sequence of the phases a designer has to cover out in order to complete the configuration and archive new components.

In this schema, it is possible to notice how the designer dialogs with the PDM through the use of the KBE application. For example, in the step “Part Configuration”, other than letting the user design new components, the application retrieves from the PDM all the designed component (“Parts Existence Check”) for each part and gives to the designer the possibility to select one of them (“Selection of the Part to be used”). Then, the system proceeds to assembly the selected component with the other ones.



(a)

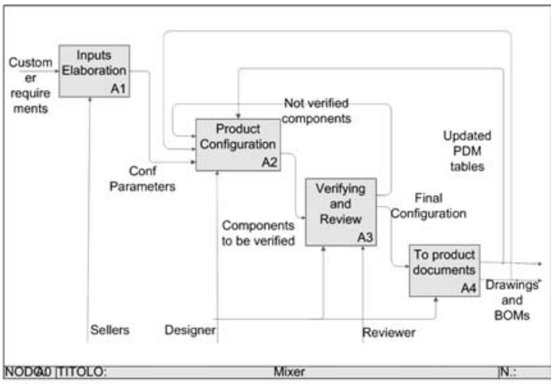


(b)

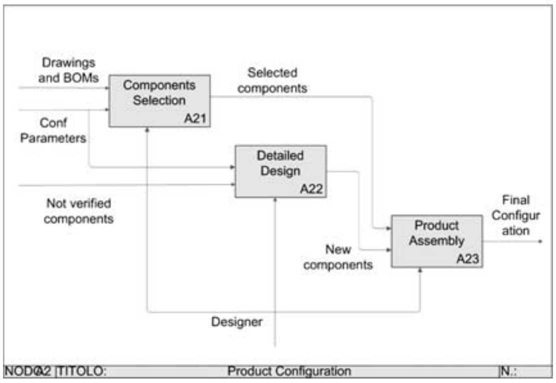
Figure 3: UML blocks. (a) Top part; (b) Rotor.

In other words, the application reproduces the design phases above mentioned. In particular, it enables designers automatically design the industrial mixer and it can be used in two different ways. The first method permits to configure a new product, following all the normal steps defined to design the mixer, such as the calculation of the forces or the sizing of the shaft, as the design process is. The second way enables the designer to query the PDM to let it return all the components already designed, using their drawings, codes, and data in general.

By using the second way, the application generates a code for every component by which it can investigate into the PDM and verify if a part with the same code already exists. On the positive case, it returns that component and its drawing and avoids the next design and review steps. On the negative case, it lets the designer decides weather to proceed to design a new component with that code, or to investigate into the PDM if a similar component exists, with the rules described in the next sections.



(a)



(b)

Figure 4 (a): The general design process; (b): The phase of design and configuration of product

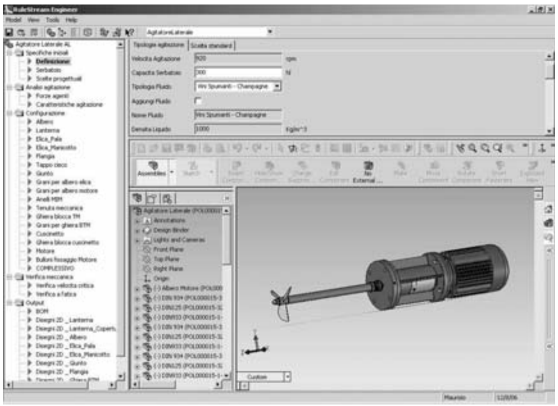


Figure 5: User interface

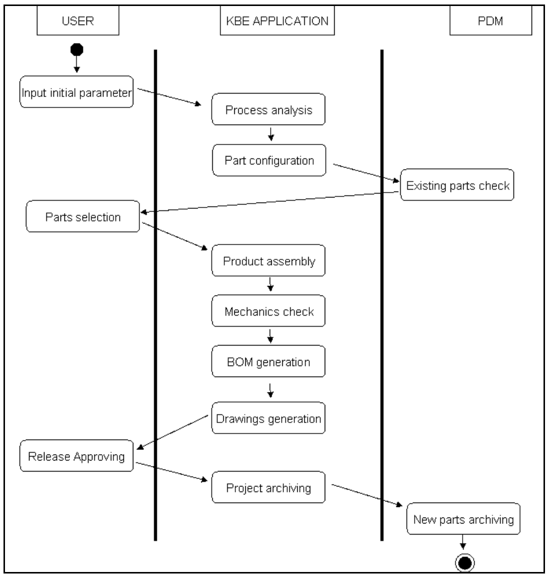


Figure 6: Sequence of operations to configure the final product, with archiving of new parts.

4.5 Description of the querying to the PDM

In order to search stored projects and documents, the authors defined a specific coding system.

As an example, in (1) is the coding used to define the shaft:

SHAFT 25/572 CON1 (1)

25/572 means that the diameter is 25 mm and the length is 572 mm and CON1 give direction about the taper ratio to adopt.

The system generates a code in according to the sizing rules and compares it with the existent in the PDM system.

As an example, in (2) it is reported the formula for the automatic calculation of the code:

result = "*SHAFT* " & *this!CalculedDiameter**1000 & "/" & *this!ShaftLenght**1000 & " " & *this!TaperType* (2)

If the shaft with that code already exists in one of the tables included in the PDM, the system uses the related data and skips all the steps to design and verify it. If it does not, the system proposes two ways to proceed. The designer can create the shaft *ex-novo*, giving it the new generated code, or he/she can select a shaft among a set of codes existent in the PDM, through specific queries to the tables stored in the PDM. The next section shows how the querying method works.

The authors simulated the functionality of storing of the PDM, creating a set of folders and subfolders and a set of tables in a database server. In particular, the tables contain the data needed to design, or select or configure a specific component, such as shafts or joints or screws. The folders contain the configured products, BOMs, CAD files and drawings. All files are coded, in order to be discovered during the configuration of new products.

In order to select a component stored into the PDM, also generated in a previous configuration, the application searches in the corresponding table where the component data are stored and returns all the codes matching with the one calculated by the computer and give a suggestion about the most suitable component to use. The designer can keep it or select another one. The system returns only the possible configurations, eliminating the wrong solutions. For example, in the design step of the shaft, the system first generates a code that is the result of its calculation and it relates the values of a set of properties to the values included in the generated code; then, the system checks the presence of the generated code in the PDM tables. If the code exists, the system retrieves all the data related to the selected shaft and uses its drawings, CAD files and related documents, during the final configuration; otherwise, it lets the designer chooses if generate new documents such as drawings or use another existing shaft selecting it among the most suitable ones.

In order to choose which component is good to be selected, the system enters the shafts table with the property “diameter” and returns all shaft with that diameter or greater. The calculation of the diameter is covered out considering the common engineering design rules, such as the calculation of the torque or the instability.

5 CONCLUSIONS

This paper deals with the integration of KBE and repository systems in a PLM environment. In particular, it investigates the methods by which a KBE system can inquire a knowledge repository (usually PDM) in order to retrieve suitable components for the configuration of a product. First, the paper starts with a discussion on the necessity to generate a specific code also for not geometrical data, but also for other information. Then, the paper focuses the attention to some relevant topics in engineering design, such as the representation and the management of the knowledge. Third, it goes on examining the specific aspect of the integration of a KER and a PDM system. Next, a test case is presented, and, finally, the conclusions are reported.

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Integrated Product and Service Engineering *versus* Design for Environment – A Comparison and Evaluation of Advantages and Disadvantages

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The objective with this paper is to, from several perspectives including those found in the traditional Design for Environment (DfE) literature, compare and evaluate advantages and disadvantages between the concepts of DfE and Integrated Product and Service Engineering (IPSE). Lessons learned from the use of DfE have been integrated into the IPSE methodology.

One conclusion is that IPSE is a promising approach to take the environmental related requirements that DfE tries to promote one step further, i.e. to be better integrated with other types of offering-related requirements. In short, IPSE opens up for a more balanced development of offerings.

Keywords

Integrated Product Service Offerings, Integrated Product Service Engineering, Service Engineering, Design for Environment

1 INTRODUCTION

"Competing in time" reflects a growing pressure on firms not just to introduce new products but to do so faster than competitors [1]. The rate of market and technological changes has accelerated in the past decade. Central to competitive success in the present highly turbulent environment is the firm's capability to develop new [2] and to improve and further develop and optimize old products i.e. an increased emphasis has been put on time efficiencies in the product development process. Developers within the company must develop and proceed faster and faster - and at the same time satisfy an increasing number of customer product demands.

In traditional product development a multitude of requirements must be considered. Ullman [3] has categorized some major customer requirements into eight types: functional-performance, human-facto, physical-factor, reliability, life-cycle, resource and manufacturing requirements. The aim in the design process is to optimize the product in relation to those requirements. This can be illustrated with a geometric form, e.g. as a box, where the box represents the product and its sides represent different perspectives/views, e.g. economic and quality, from which the product can be optimized from (see Figure 1). The volume of the box can be seen as the total cost of generating the product or offering. The aim is to out of existing requirements create as good a product as possible. *The focus in the optimization is in general focused on producing products for as low a cost as possible, but at the same time with as high a price as possible. An example of this would be to get a box's total volume, i.e. cost, as low as possible*.

When focusing on only one perspective, there is a risk that one tends to "push" down costs, a push that if done incorrectly implies that one could get higher costs for other issues. It is important to try to reduce the life cycle cost of the entire offering, i.e. avoid costs that give a "net" cost reduction in relation to the functionality.

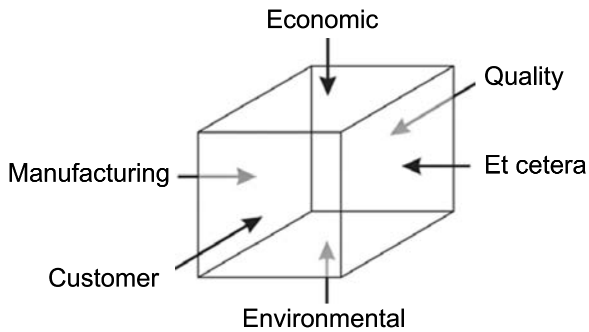

Figure 1: Some different perspectives to use when evaluating and optimizing a product.

As Blessing, Chakrabatri *et al.* [4] have stated "*the aim of engineering design research is to support industry with aids that can improve the chances of producing a successful product"*. In the literature, there are numerous of methodologies to guide and support product developers in this process, e.g. QFD, FMEA, and LCA. The aim of the companies is to produce successful products that enable them to provide benefits.

One problem with many existing support tools is that they tend to be solely focused on one issue, e.g. quality or the environment. Today, a more overarching perspective is seldom found in the literature, e.g. as the notation by Blessing [5], Baumann, Boons *et al.* [6] and Bylund, Grante *et al.* [7] indicate. The restricted perspective of many design method and tool developers has resulted in many stand alone methods and tools - tools that are aimed at solving one problem or issue in the industry and most likely do, but with a result that does not fit in with the rest of the company's modus operandi [7]. The conclusion after a literature review is that design methods and tools are almost always lacking from an overarching and holistic perspective - even if some of them claim to have one.

The single focus opens up a possibility for sub-optimization. When focusing on e.g. design for production in order to cut down costs, e.g. by using more integrated parts, this may result in increased costs for service and end-of-life treatment, instead of reducing the overall cost for the product, i.e. the total life cycle cost increase. This cost could in this case be both environmental and or monetary in nature.

2 OBJECTIVE AND METHODOLOGY

The objective with this paper is to, from several perspectives including those found in the traditional Design for Environment literature[1], compare and evaluate advantages and disadvantages between the concepts of *Design for Environment (DfE)* and *Integrated Product and Service Engineering (IPSE)*.

To do so, we have analysed existing literature and also reviewed how some companies, mainly in the mechanical industry, are working with issues like DfE and IPSE.

3 DESIGN FOR ENVIRONMENT METHODS

During the past years, there has been a trend towards a rapid development of DfE methods and tools to employ in the area of product development. According to Mathieux *et al.* [8], extensive research on DfE, mainly in the areas of strategy, methodology, and tools, has been carried out by research organizations and industrial companies. The result is a considerable number of DfE methods and tools [9, 10] that fall into a wide range of categories, from relatively simple checklists or general guidelines to more complex software-based decision-making methods [10, 11].

Despite the many existing DfE methods and tools, their use is still limited. When they are used, these methods and tools are often not integrated in the product development process. This is a point highlighted by e.g. Baumann *et al.* [6, 12] and Tukker *et al.* [13].

NUTEK, the Swedish Business Development Agency [14], had a similar conclusion in its final report on a three-year-long DfE project. According to the report, some large multinational companies (particularly in the fields of electrical and electronic goods, motor vehicles and packaging) are addressing the issue in a rather comprehensive way, and the study concludes that DfE plays a small role in many companies (particularly small and medium-sized enterprises).

Some small and medium-sized enterprises (SMEs) have experience with DfE (demonstration) projects, but they rarely lead to the use of DfE in ordinary product development [13, 15]. Further, most companies do not treat DfE as a management issue see e.g. [16]. Finally, it is common that when a company does practice DfE, the focus is on environmental redesign of products instead of the development of new products. Given this, the potential benefits of DfE have not been realized. The general experience and conclusion of Lenox *et al.* [17] is that if a company uses DfE, it is usually carried out by those working in specialist functions (i.e. those not involved in the ordinary product development, but those working at the company's environmental division). The results of the DfE work are often not carried back to the rest of the product development process in an efficient way. In many cases, the methods and work with DfE are executed separately from the rest of the product development. This may be a result of the isolation that many methods and tools have been developed in, as described by both Blessing [5] and Baumann *et al.* [6].

4 INTEGRATED PRODUCT AND SERVICE ENGINEERING

Manufacturing companies, which have traditionally focused mainly on their physical products in the development phase, need to change and widen their working procedures in their offering development. Integrated Product and Service Offerings have been promoted from several perspectives, e.g. economic, social, and environmental, and research in this area has emerged in several disciplines. The methodology is closely related to the area of DfE, but has a wider scope including Life Cycle Engineering (LCE) [18].

IPSE is a methodological approach for creating Integrated Product and Service Offerings. *The aim with IPSE is, from a lifecycle perspective, to generate and optimize offerings with a combination of products and services that satisfies an identified customer need, and at the same time increases the competitiveness of suppliers.* IPSE focuses not only on the production phase, but also incorporates the use and the end-of-life treatment phases, enabling great potential for environmental improvements. In addition, it creates new ways for the supplying company to profit from environmental improvement during the use and end-of-life phases, especially if the offering's products are still owned and controlled by the supplier. Example improvements include a reduced need for spare parts, energy and other products during use, which translates into savings from an environmental perspective as well.

The IPSE-model, illustrated in Figure 2, highlights and illustrates vital and crucial activities in the generation of the offering (see also Lindahl *et al.* [19]). The two-way arrows in the method symbolize the important communication needed between the different stakeholders within the lifecycle activities.

4.1 Step 1 – Need and requirement analysis

The main issue is to start from the customer's needs and requirements in order to generate efficient and effective business offerings in conformance with the value constellation concept by Normann and Ramírez [20]. *The identified requirements should primarily be seen as requirements on the requested function and not as product or service-related.* In this activity, it is important to have in mind that it is also critical to determine needs and requirements for other stakeholders, e.g. the managing board, authorities and suppliers. The environment is, in this view, not a stakeholder, but environmental-related requirements are stated by different stakeholders, e.g. legislation.

4.2 Step 2 – Concept generation

The concept generation differs from traditional concept generation since it better highlights the need to generate concepts in an integrated way, concepts that from the beginning and in a parallel processes comprise both the offerings for service and product content. The focus is on finding the best combination of products and services based on the validation of the different requirements stated for the requested function.

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[1] In this paper, the concept Design for Environment is used but the literature review also incorporates literature of similar concepts, e.g. Eco-design and Green Design.

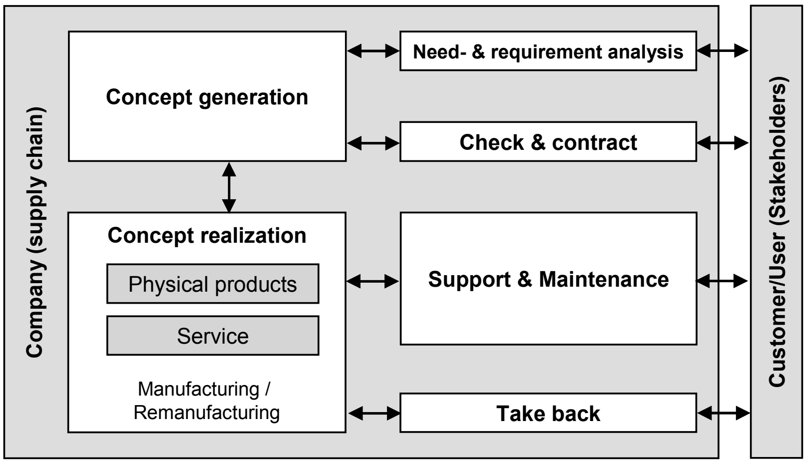

Figure 2: An Interactive design model for IPSE.

The combination can be based on standard products and services, but also on customized ones. The previously developed IPSE methodology provides good support for this activity [21].

4.3 Step 3 – Check and contract

In this activity, it is not only important to verify that customers understand what they will gain from the offering; it is also important to verify that the customer is satisfied with the offering. To do so, the determining factor is that the offering can be transcribed for the customer in an understandable format, e.g. with parameters and description that the customer is familiar with and can interpret. One way to convince the customer of the gain is to use the "need and requirement analysis" activity-identified parameters, and compare the values from the use of the offerings with the original values.

4.4 Step 4 – Concept realization

When there is an agreement/contract of the offerings, e.g. the function, the next step is to go from concept to realization of the offering, i.e. produce the different services and products needed for the offering. The existing IPSE methodologies support an improved dialogue between different stakeholders in this realization process.

4.5 Step 5 – Support and Maintenance

During this activity the offerings function is used and during this phase that the service and maintenance is delivered. Active communication with the customer during this activity is a good opportunity for companies to learn more about their customers' needs for service and how to better identify and fulfil customer requirements. Since the customer focuses on utilizing the offering and therefore has direct experience with the combination of products and services, it becomes easier to obtain an understanding of his/her experience with the offering.

4.6 Step 6 – Take-back

It is quite common for Integrated Product Service Offerings that the products' ownership is not transferred to the user, and that the products are therefore taken back when the user no longer needs the offering. The IPSE approach can successfully be integrated with a remanufacturing system [22].

5 DISCUSSION

This section compares and evaluates IPSE and DfE from different perspectives. Other perspectives exist, but the number of pages has limited us to only discuss a selected few. Note that the listed perspectives are not presented in any sort of ranking, and they are all more or less related to each other.

DfE methods and tools like e.g. LCA, which emphasise a holistic view from a life cycle perspective, are often promoted as holistic to enlarge their focus from not only regarding the production phase but also incorporating the use and end-of-life treatment phases. However, according to Lindahl [23] and Lenox and Ehrenfeld [24], one of the problems with several DfE methods and tools is that they tend to focus on the single objective of minimizing environmental impact. It is therefore a bit paradoxical that DfE methods and tools in fact are in general very "unholistic" in the fact that they only focus on environmental issues.

The advantage with IPSE is that the method does not focus on a single issue but instead incorporates a wide range of issues, e.g. environmental, quality and economic [18]. Of course, this is also the case for many traditional product development methods such as QFD. The IPSE method has a structured approach, e.g. including scope and flow models to cover the entire offering's life cycle and different stakeholders' requirements (see Figure 3).

5.1 Product perspective

DfE methods and tools, like many other traditional design methods and tools such as e.g. various CAD tools, are in general not designed to deal with offerings, i.e. combinations of products and service that require a simultaneous focus on the product and service as a whole.

Existing DfE methods and tools are primarily focused on dealing with physical artefacts and their evaluation. One reason for this is that many of them are based on quantitative data from the entire life cycle, e.g. that concerning material content, emissions and energy consumption. This data are in general quite tricky to gather for physical products, not to mention for services. For practical reasons, there has therefore been a focus on DfE on products.

Another reason for this distorted focus has been that the offerings' service content has often been added on after the products have been designed [25]. One major obstacle with this is that it implies a need to develop the service based on an existing product, since it is very expensive an often unrealistic to change the existing product. This implies less cost-efficient offerings than could be the case if one could design them simultaneously, e.g. a small change in the product that could make the service much easier and increase the customer's satisfaction.

The difference with the IPSE methodology is that the basic idea is to develop the offering's service and product content simultaneously and in an integrated way.

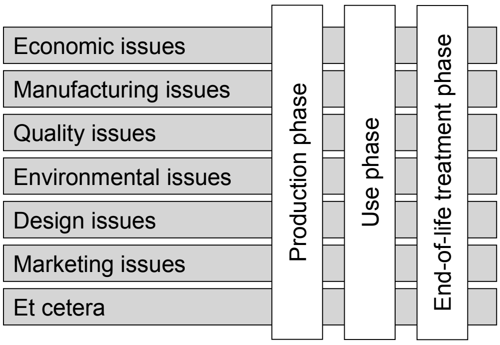

Figure 3: How different issues relate to different product phases. DfE methods tend to focus only on environmental issues, implying a risk for sub-optimization. The advantage with IPSE is that that method does not focus on a single issue, but instead incorporates a wide range of issues/perspectives in its view. Scope and flow models cover the entire product life cycle as well as different stakeholders' requirements.

5.2 Use-phase perspective

The IPSE methodology has taken DfE methodologies' focus on a life cycle perspective one step further. Instead of only analysing and optimizing the product from a life cycle perspective, the IPSE methodology aims to cover and support the offering company in all steps in an offering's life cycle, and especially during the use-phase. The IPSE methodology focus on the use-phase is related to the fact that it is during this phase the offering generates its customer value. It is also during this phase that the service is generated, and at the same time consumed. In many cases, it is also during this phase that most costs related to the offering occurs, e.g. from energy consumption and service. To help customers to reduce this cost and to get paid for this is not only good for the company and customer, but also in general from an environmental point-of-view. Studies show that a major part of an offering's environmental impact occurs during this phase [26].

In addition, DfE tends to place great focus on this phase, but the problem is that stakeholders in general tend to have difficulties in judging and understanding the environmental data output from DfE methods and tools, e.g. those expressed in CO_2 equivalents.

As McAloone and Andreasen [18] state, IPSO has a wider scope than DfE. One example of IPSO's sharp focus on the use-phase is e.g. its focus on making the use-phase more efficient and effective. These types of improvements tend to reduce the environmental impact, e.g. by reducing energy consumption.

5.3 Customer / Stakeholder perspective

In most DfE methods, environmentally-related requirements tend to be treated as the most important or other types of requirements are not even handled, e.g. LCA. The important issue - whether the customer will and can accept the offering after changes based on environmental considerations - are not in focus. There is a risk that the product for example: a) is very good from an environmental point of view, but b) that the changes made may imply that no customer wants to buy the product, since their requirements are neglected.

The lesson learned and implemented in the IPSE methodology is that *it does not matter that the product is excellent from one perspective, e.g. an environmental one, if the customer does not buy it*. There must be a sensitive and balanced handling and prioritization of different stakeholders' requirements. In the IPSE methodology, this is done in a structured way in the concept generation phase.

Finally, the IPSE methodology advocates a close dialogue with customers / stakeholders. This is especially important in the use phase, since it is here a great part of an offering's environmental impact occurs. By being proactive and having well-developed systems of e.g. education and maintenance, the environmental impact in relation to customer-perceived value can be controlled and reduced.

5.4 Design perspective

When integrating products and services into combined offerings, the identification and handling of requirements becomes more complicated and requires a more holistic view also incorporating the use phase, since the service is produced and used during the use phase. In many cases, the end-of-life treatment also becomes very important since the products might be used several times. If the company maintains control over the offering's products, this is even more important.

IPSE focuses on this part of the design process. This is natural in order to implement changes in a cost-effective and efficient manner. It is also important to make such changes as early as possible in the design process.

Even though the name Design for Environment indicates a great focus on design, many DfE methods and tools have little support for designers. When it comes to dealing with the outcome from many DfE methods and tools, there is a lack of practical support concerning what to do and how to make the improvements. Existing DfE methods and tools are mainly focused on pointing out environmental problems with an existing product, not on how to manage and reduce such problems. Of course, there are some exceptions, but of these, some are tricky to use since they tend not to support the identification of what to focus on first.

The background to this may be that these methods and tools have, in general, been developed with a scientific and theoretical background, sometimes with little regard for their application in practice [27]. The lesson learned when developing IPSE methodology is to have a continuously and parallel interaction with industry in order to get immediate feedback [28].

5.5 Improvement perspective

The improvement issue is important in order to find new solutions that are more e.g. environmentally friendly. It is important that methods and tools stimulate a focus on improvement rather than conservative thinking. One way to generate new ideas is to view a product from a different perspective, and DfE methods and tools with their environmental perspective have such a point-of-view, and have in many cases been an efficient and effective way for companies to find new improvements. Also, the life cycle thinking in these methods and tools has stimulated new improvements, since those working in different parts of the product life cycle have begun to talk to each other.

In addition, the IPSE methodology aims to support improvement-focused thinking, and to help the user to step out of their traditional thinking/focus, e.g. not just focus on the product but instead focus on the context the product or service is used in order to make it as good as possible.

The more perspectives a developer is aware of, the more options he or she will have, and the more likely he or she will be able to produce a successful product. However, the more perspectives there are the more complex the evaluation process becomes. Crucial for success is that the optimization is done with as many different perspectives in mind as possible, e.g. economic, quality and environment. The ISPE tool, Service Explorer [29] is a powerful tool to support such management of different perspectives, as it supports the judgement of different requirements and the innovation process.

Finally, our research and that of others has shown that the supplier's focus on offering integrated products and services can be a driving force for developing new and innovative technical solutions, and has proven to be a successful marketing channel for companies aiming to spread new technology to their customers.

6 CONCLUSIONS AND FURTHER RESEARCH

The conclusion so far is that IPSE is a promising approach, not to take DfE one step further, but to take the environmentally-related requirements that DfE tries to promote one step further, i.e. to be better integrated with other offering-related requirements. Valuable lessons learned from the use of DfE have been integrated into the IPSE methodology.

Since the scope of IPSE is wider and not solely focused on environmental issues, it clears the way for a more balanced and objective development of offerings. IPSE has a strong advantage in that the method includes the analysis of both the mix of products and services within the offering, but is also related to the life cycle of the offering. At the same time, there is a focus on balancing various types of requirements, where environmentally-related requirements are just one of many that a developer needs to pay attention to.

Related to this, there are indications that it is preferable to analyse a product, service or an integrated product and service offering from several perspectives, and to put different perspectives in relation to other perspectives in order to see what consequences might occur.

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Service CAD System to Support Servicification of Manufactures

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Abstract
Servicification is a key toward environmental conscious business in the secondary industry. This paper aims at demonstrating the ability of a CAD system, which has been developed with the name Service Explorer, to represent services by manufacturers. To do so, services of renting and cleaning home appliances, which a manufacturer recently provide in Japan, were applied as an example. As a result, the system has been proved to provide the environment for a designer, for instance, to describe effectively the value for a service receiver and its realization medium.

Keywords:
value, product, service activity, design, modelling, representation

1 INTRODUCTION

Addressing services is a key issue in Life Cycle Engineering (LCE). Such services include maintenance, repair, upgrade, take-back, and remanufacturing. A variety of research dealing with a set of products and services already exist in the LCE research community as well (e.g. [1-6]). Among them, the discipline that our group attempts to establish is called Service/Product Engineering (SPE). The motivations of SPE research include the importance of service activities that have been getting more critical in manufacturing industries. One of our goals is to develop a CAD (computer-aided design) system that designers can effectively utilize upon designing services with the SPE discipline. To do so, capability to model services and computability of the model is among the features of such a CAD system. This CAD system is expected to contribute to servicification of manufacturers, which means increasing service intensiveness of the business toward dematerialization. This paper specifically aims at demonstrating the capability of the CAD system [3, 7], which have been developed so far, to model how, what, and why to deliver services by manufacturers.

The rest of the paper consists of the followings. Section 2 explains the importance of services and existing related research. After Section 3 briefly presents the service CAD system, Section 4 demonstrates their application to a service case. Section 5 verifies the capability and Section 6 concludes the paper.

2 RESEARCH OF ENGINEERING SERVICES

2.1 Importance of service

It goes without saying that in the tertiary industry service activities are the source of core value and are regarded crucial. This paragraph describes a recent situation in the secondary industry. Manufacturers today encounter quietly but steadily growing trends. One is servicification of consumers' behaviours, which means a shift from customers' consumption of physical products to their consumption of softer or solution-based services (e.g. [8]). The other is, as widely recognized in this research community, environmental problems, which have been quite serious in some areas over a couple of decades. According to such trends, the importance of services has been rising in manufacturing industries as well.

2.2 Existing research

Motivated partially by the above-mentioned trends, industries have been increasingly focusing on services. As a result, new concepts such as Product- Service Systems (PSS) [9, 4, 10, 11] Functional Sales [1, 12], and Functional Products [13] have been developed so far. PSS can be defined as consisting of 'tangible products and intangible services designed and combined so that they jointly are capable of fulfilling specific customer needs' [14]. The business concept of Functional Sales can be defined as "…to offer a functional solution that fulfils a defined customer need. The focus is, with reference to the customer value, to optimize the functional solution from a life-cycle perspective. The functional solution can consist of combinations of systems, physical products and services" (modified from [1]). Functional Products, also known as "total care products" are products that comprise combinations of "hard" and "soft" elements [13]. Our research group captures services in such a slightly different way from others that receivers' transition of status, not the providers' activities, is the core of the service. We do not regard physical products as prerequisite in provided offers, while most of the other existing research (e.g. PSS) does. Thus, our definition of service is "an activity that a provider causes a receiver, usually with consideration, to change from an existing state to a new state that the receiver desires, where both contents and a channel are means to realize the service" [2]. As is clear, our concern is not only the environmental issues.

In common to these three concepts, a service is trying to be incorporated into the design space, which has traditionally been dominated by physical products in manufacturing industries. The research ranges from identifying engineers' mindsets and new engineering models, to developing design procedures. Our development of the service CAD system named Service Explorer [3] is among very few research of constructing computer support tools for designers.

3 SERVICE CAD SYSTEM

3.1 Service/Product Engineering (SPE)

The term “service” has been defined above; however, what is Service/Product Engineering (SPE)? It is a discipline to increase the value of artifacts and to decrease the load on the environment by focusing on service [3]. Importantly, it is value, not service itself, that counts. Service or product is a measure to realize value. That is meant by the name SPE. Note that SPE has both analytical and synthetic aspects. SPE aims at intensifying, improving, and automating this whole framework of service creation, service delivery, and service consumption. To increase the total satisfaction of receivers, we can improve functions and/or quality of both channels and contents. Traditionally, engineering design has aimed to improve only functions. A better function of a new product, we have believed, makes consumers satisfied. In SPE, however, not only the functions of artifacts but also the meaning of contents must be matched to the specifications given by receivers. Then the satisfaction level of receivers increases.

3.2 Modelling method

A service model in SPE consists of several sub-models; “flow model”, “scope model”, “view model”, and “scenario model” [6]. The rest of this section those sub models after describing an important concept called “receiver state parameter”. The reason for modelling “receiver state parameter” is as follows. Conventional design regards mainly the performance of physical products; it does not consider the state change of the receiver. Designing a service must be based on the degree of satisfaction with the state change of a receiver. Therefore, it is necessary to express receiver’s state changes.

Receiver’s state parameter

Receiver state parameters (RSPs) are classified into value and cost depending on whether the customers like them or not. The term “value” here is different from that in Value Engineering [15], where it is defined as function over economic cost. In SPE, value is defined as change of a receiver’s state that he/she prefers, so that function is just a realization method to provide the value in SPE.

Change of a receiver is represented by a set of receiver state parameters (RSPs). Since an RSP consists of quantitative value, including Boolean logic and multi-value logic, we can compute any comparison between two RSPs. In addition, we introduced a new assumption that all RSPs are observable and controllable. This assumption has been unproven with human receivers because we have not had a reliable method to measure the consumer behaviour.

RSPs change by received contents. Hence, in this paper, we assume that contents consist of various functions, whose name is Function Name (FN), whose operating objects are Function Parameters (FPs) and whose effect is represented by Function Influences (FIs).

As the receiver's states may change with respect to supply of contents, RSPs can be written as functions of contents. Parameters expressing contents are called content parameters (CoPs). In the same way, the parameters of channel, which make the flow of CoPs change and thus influence RSPs indirectly, are called channel parameters (ChPs). Hence, we assume that both contents and channels consist of various functions, and both CoPs and ChPs belong to FPs.

It should be mentioned that RSPs are selected from “state parameters” representing a receiver’s state but not getting targeted in the design.

Flow model

When we focus on the relationship between a receiver and a provider, many intermediate agents exist among them. We call the sequential chain of agents “a flow model” of a service. This model is needed because in SPE designers are supposed to consider how organizations participating in a concerned service can be successful in their business.

Scope model

It is necessary to specify the effective range of the service from an initial provider to a final receiver. In comparison to the view model in which a single RSP is expressed, the scope model deals with all the RSPs within the provider and the receiver. In other words, a scope model handles multiple view models, namely multiple RSPs. Thus, it helps designers to understand the activities between the provider and the receiver.

View model

A view model expresses the relationships among the elements of the service; i.e., the mutual relationships among the RSPs and FPs (CoPs and ChPs). It should be emphasized that not only products but also service activities are modelled as measures to realize the service. Physical structures are represented using functions. It should be emphasized that view model works as a bridge between value represented in the form of RSP and physical structures and service activities.

Scenario model

This model represents receivers themselves using the concept of Persona [16] and their behaviours in receiving the service. This is necessary because the grounds behind RSPs of service receivers should be understood. In other words, scenario model serves as a direct source for producing a variety of RSP sets depending on customers’ properties. Therefore, this will be a key element for understanding customers’ needs and wants.

3.3 Design procedures

The authors have already proposed generic procedures for designing services, and verified it through application to an industrial case in industry [6]. The procedures adopt the model of service explained above. Designers are able to design the target service efficiently by following these procedures.

3.4 Service Explorer

The authors have been developing Service Explorer with Java SDK 1.4.1 and XML version 1.0. MVC (Model View Controller) model [17], which has been used widely in general GUI applications, was adopted as basic architecture of Service Explorer. By applying MVC model, high flexibility and reusability of Service Explorer, and robustness of the service model data are realized. Figure 1 depicts the system configuration of Service Explorer. The current version of Service Explorer was developed using Java (Java2 SDK, Standard Edition 1.4.1) and XML version1.0 in the Microsoft Windows XP Home Edition environment. Figure 2 is a screen dump of a window for designers to identify what and why a receiver of a specific Persona consider important. Figure 3 shows a window for displaying the results of semi-quantitative evaluation.

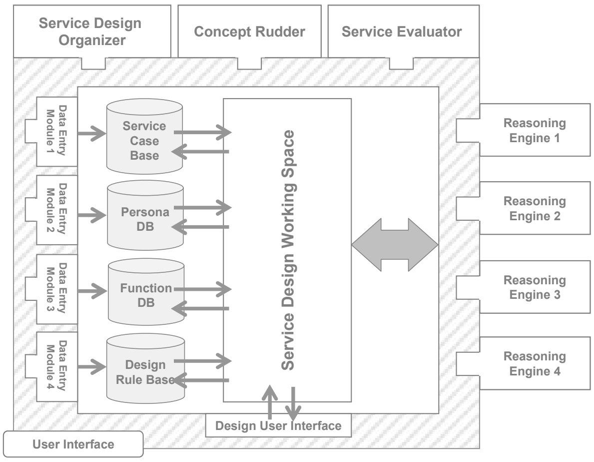


Figure 1. System configuration of Service Explorer

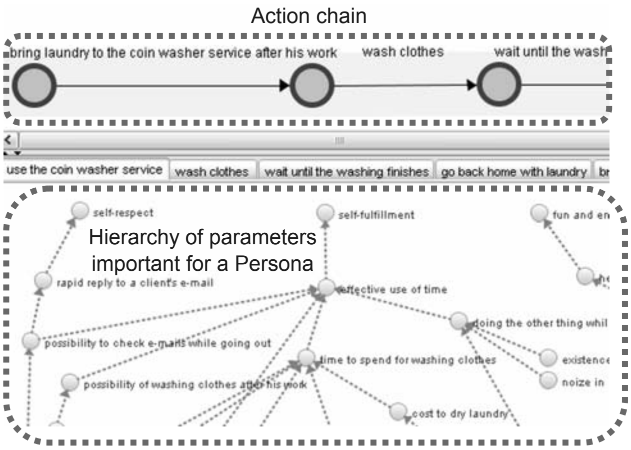


Figure 2. A screen dump for identifying receivers' needs

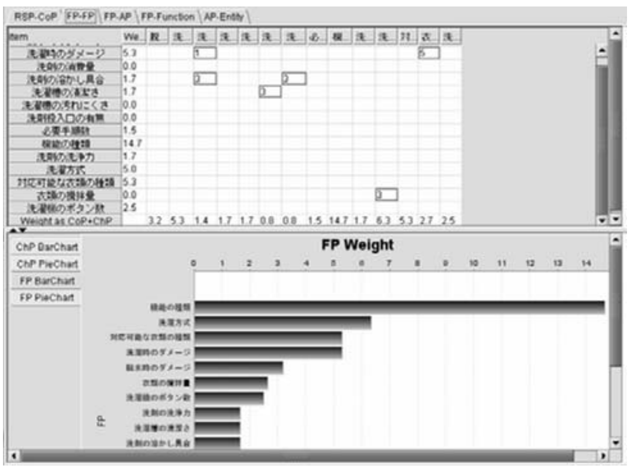


Figure 3. A window for showing the results of semi-quantitative evaluation of services

4 DESCRIBING SERVICES USING HOME APPLIANCES

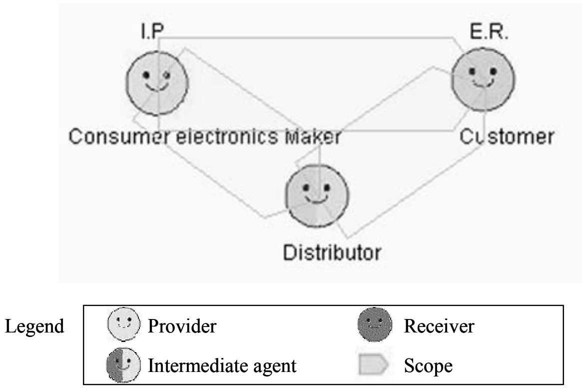
Section 4 aims at verifying the ability of Service Explorer to describe the critical factors of services. The examples taken here all utilize home appliances.

4.1 Providing Home Appliances

This paragraph presents the results of modelling services of providing home appliances on Service Explorer. One is from the traditional service where the provider sells the products to the customers, while the other is from a rental service where the provider owns the products. A refrigerator was taken as an example.

Selling Home Appliances

The Flow Model on Service Explorer includes the home-appliance manufacturer (described as "Consumer electronics Maker"), the retailer, ("Distributor"), and the end receiver ("Customer") (see Figure 4).



Note: I.P. and E.R. mean the initial provider and the end receiver, respectively.

Figure 4. A screenshot of the Flow Model

The RSPs described in each Scope Models and their View Models representing the realization structures are as follows.

- From the manufacturer to the end receiver

Value of the end receiver was described by an RSP named "availability of fresh food", while the economic cost upon purchase was by a cost RSP. The realization structure to affect the "availability of fresh food" was described by the View Model in Figure 5. Namely, this RSP was associated with the function of "keep fresh food available", which was deployed into "extend the storage period of much food" and then into "keep much food cold". The functions in the lowest level are "keep much air" and "keep the air around food cold". The FPs (Function Parameters) describing those two functions are "volume of the air" and "temperature of the air around food". In addition, the entity whose attributes include these FPs is named "refrigerator".

- From the manufacturer to the retailer

Value of the retailer is the refrigerator, while the spatial space for displaying refrigerators was described as cost RSP, which is described to have a proportional relation to an FP for the refrigerator size.

- From the retailer to the end receiver

The information that the end receiver receives from sales persons at the retailer upon buying decision was modelled as value, while the transport of the purchased product was described as a cost RSP.

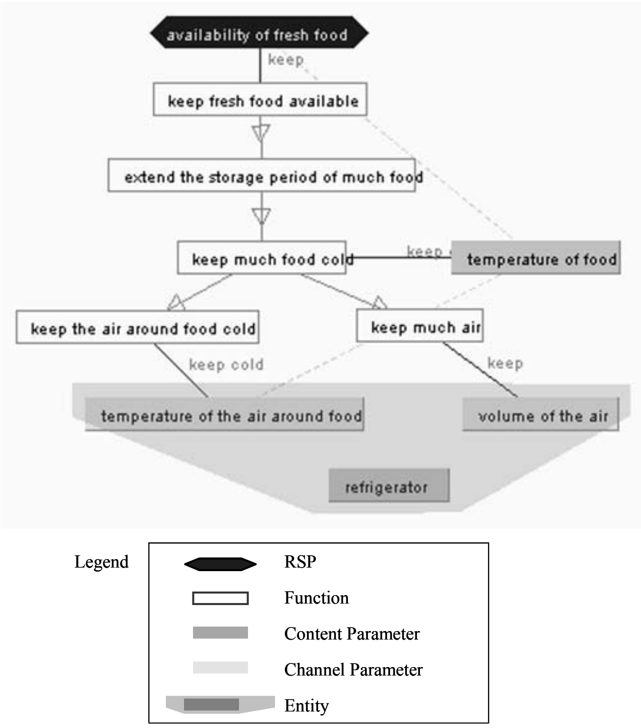


Figure 5. The View Model for the availability of fresh food

Renting Home Appliances

In this service, an end receiver rents a home appliance in a certain contracted period of time and pays a monthly fee. The provider carries out maintenance when the machine malfunctions. This is actually available at present on the Japanese market [18]. The main benefits for the end receiver include reduction of costs and risk when compared to the selling service described in the previous paragraph. For instance, the end receiver has no risk from machine faults and is not obliged to bear the EOL (end of life) cost when the machine is disposed. Furthermore, the economic cost can be lower if the rental period is relatively short.

The Flow Model described on Service Explorer includes the home-appliance manufacturer, the contracting agent, and the end receiver. The end receiver's value of extending the period of keeping the food fresh is described in the same manner as the previous paragraph. In addition, the Scope Model between the contracting agent and the end receiver includes the cost RSP representing the troublesome task upon EOL, which is described as shown in Figure 6. Namely, reducing the trouble for disposal is deployed into the function of taking back products, which removes the FP named "existence of products". On the other hand, in the selling service shown in the previous paragraph, this RSP is described without any realization structure of the provider.

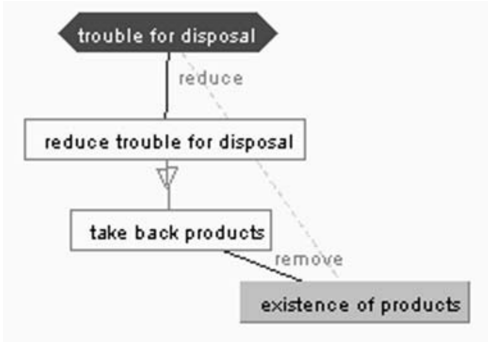


Figure 6. The View Model for the trouble for disposal

4.2 Cleaning Home Appliances

In this service, a maintenance base of a manufacturer clean home appliances that end receivers own and operate. This service is also currently available in Japan [18]. A washing machine is taken as an example, here. This is effective because a kind of fungus often grows inside a washing machine due to the high humid climate in Japan. It is critical that the inside is cleaned up by disassembling the machine. Note that end receivers cannot disassemble it because they lack the knowledge about the product and the machine is not easy to disassemble. Then a manufacturer's knowledge about its own products as well as the type of products in general is adopted as a source of the value created for this service.

The Flow Model described two agents, the manufacturer and the end receiver. The Scope Model between them includes an RSP of cleanliness of the machine whose realization structure is described as in Figure 7. Namely, the top function of "keep appliances clean" is deployed into "do washing machine-cleaning", which is then deployed into "clean outer parts", "disassemble washing machine", "clean inner parts", and "assemble inner parts". Furthermore, "disassemble washing machine" and "assemble inner parts" are concretized into "apply disassemble knowledge" and "apply assemble knowledge", respectively. The described FPs include the attributes of the washing machine, which are all described as ChPs (channel parameters). This allows us to recognize that the washing machine functions as a channel. The model represents that the cleanness of the appliance is provided as value, the professional knowledge about the product is employed, and the machine plays as a channel.

5 DISCUSSIONS

5.1 Verifying the Capability of Description

Application explained above in Section 4 proved that Service Explorer is able to describe the followings.

(1) Provided value

Service Explorer allows designers to describe the value of a receiver in a concerned service in the form of RSP. Thus, it explicitly represents a goal which is more abstract than functionality which designers conventionally aimed at. For instance, the model suggested that the value of selling refrigerator is not cooling the food, rather the availability of the fresh food as explained in Paragraph 4.1.1(1). This allows

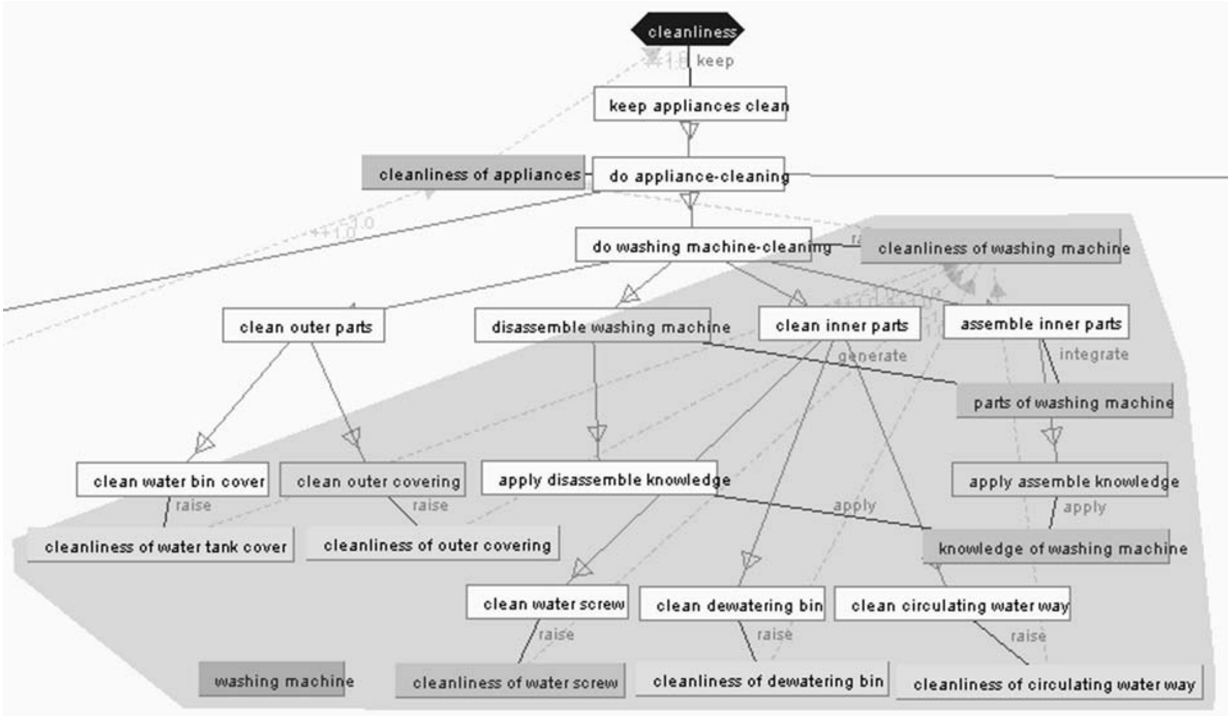


Figure 7. The View Model for the cleanness of the machine (portion)

designers to search a solution within a wider space. In addition, even the value of a service that is not related to physical properties or functionality of a product can be described; e.g. the reduced cost of EOL through taking back products as shown in 4.1. Conventional CAD systems have not addressed such a state change of a receiver which is one level more abstract than the value of a product itself. This is one innovative characteristic of Service Explorer.

As RSP refers to a receiver's state change, any change (e.g. economic state change and immaterial one such as information) can be described in the form of RSP if the change can be measured and controlled. Such description may be verified in the future works.

(2) Measures to provide value

Service Explorer allows designers to describe measures to realize the value of a receiver in the form of functions, which are generally used to understand the roles of products and service activities. For instance, designers understood that the function to keep the food cool is a measure to provide the value of the service, “availability of fresh food”, as explained in Paragraph 4.1.

Furthermore, a physical product adopted in a service is described as an entity on such functions that are deployed enough as explained in 4.1. This allows designers to describe explicitly how a product as an entity functions so as to provide the intended value.

(3) Relations among agents

Service Explorer enables us to describe the relations among agents participating in the service in the form of value/costs and their realization structures in a Scope Model. Thus, represented is the fundamental information: Who transports what to whom. In addition to that, the relations of agents in the service are qualitatively described. Using this information, an initial provider, who designs the service, can optimize the whole service. For example, the capacity of a refrigerator is in proportion to the value of an end receiver from the manufacturer, however, is proportional to the cost of a retailer from the manufacturer as well in the service of selling home appliances. This suggests designers that a trade-off relationship should be considered to optimize the satisfaction of the two receivers from the viewpoint of the manufacturer. Such relationship in a service has been out of the boundary of traditional product design.

5.2 Servicification of manufacturing business

As explained in Paragraph 5.1, service activities can be modelled with Service Explorer as a measure to deliver the concerned service. Furthermore, these activities are described as a component in a model which is used for describing product functions as well. Thus, this implies Service Explorer provides the model for investigating the opportunity of servicification. In addition, value, which represents the deliverable of a service against the measures (products' functions and service activities), has potential of describing softer offer than products' functions, and this may be also an important issue in servicification.

6 CONCLUSION

This paper demonstrated the effectiveness of the ability of the CAD system, Service Explorer, to represent their services by manufacturers. To do so, Service Explorer was verified through application to some business cases. It was proved to represent such properties that are crucial to achieve SPE effectively such as value, costs, and functions either of products or of service activities.

Our future research works include, first, to demonstrate the computability of the model on Service Explorer such as quantitative evaluation and analogical reasoning. Second, the operation of the model that is embedded in the design procedures of services will be established.

7 ACKNOWLEDGMENTS

We would like to express our gratitude to Mr. Tatsunori Hara, Mr. Kentaro Watanabe and Mr. Hiroki Doi from the Univ. of Tokyo for their cooperating implementation of and practice on Service Explorer. This research was also partially supported by a Research Fellowship Program by Alexander von Humboldt Foundation in Germany. The application presented in Section 4 is based on the discussion with Toshiba Service & Engineering Co., Ltd.

Notation list

CAD: Computer-Aided Design
ChP: Channel Parameter
CoP: Content Parameter
EOL: end of life
FI: Function Influence
FN: Function Name
FP: Function Parameter
LCE: Life Cycle Engineering
MVC: Model View Controller
PSS: Product/Service-System
RSP: Receiver State Parameter
SPE: Service/Product Engineering

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Design for Integrated Product-Service Offerings

– A case study of Soil Compactors

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Abstract
Integrated product-service offerings put new requirements on products in comparison to traditional selling. To reduce costs, products need to e.g. be easy to perform repairs on. The aim of this paper was to elucidate how Swepac International has worked with adapting their soil compactors for these offerings. In several cases Swepac has reduced the need of repair and remanufacturing efforts. Furthermore, the aim was also to evaluate the design of a specific soil compactor (FB-200H). Several design improvements were elucidated e.g. introduce snap-fits for a cover, standardise screws, and introduce a drainage hole on a hydraulic oil tank.

Keywords:
Product Service-Systems (PSS); Functional Sales; Remanufacturing; Soil compactors

1 INTRODUCTION

Manufacturing companies around the world are striving to increase their revenues and profitability through, for example, obtaining a larger share of the market and controlling a larger share of the product value chain. This can potentially be achieved, in concert with environmental benefits, by a change or at least a move towards a higher degree of offering integrated product-services instead of only physical products [1, 2].

Furthermore, there are good economic opportunities in the aftermarket of the products, as exemplified in the automobile industry. Because of this, many manufacturing companies are changing their production philosophies from a traditional focus on the manufacturing of the physical product towards a focus of the life cycle of the physical product. As a result, more focus is now put on the use and end-of-life phases, including maintenance and remanufacturing [3].

The phenomenon of integrated product-service offerings has become more prevalent in current consumer patterns, and its emergence is primarily market-driven. In these offerings, a very strong focus is placed on how to fulfil customer needs and create customer value [1]. Although the idea is also named in practise and literature as "functional sales/economy", "product service combinations", "product-to-service", "product service systems (PSS)" and "servicizing", the authors most often mean the same thing [4].

An example of integrated product-service offerings is when a company provides the function of washing clothes instead of the actual washing machine. The customer, in this example, only pays for the number of laundry loads used, instead of purchasing the washing machine itself. Integrated product-service offerings has the potential to be environmentally benign, as it addresses current levels of material consumption while seeking options that may provide functions to the consumer, and without minimizing their level of welfare [5]. In the previously mentioned laundry case, the machines could be filled more efficiently since there was an economic incentive for the user, which also decreased the overall water and power usage.

Integrated product-service offerings are also inline with what the Japanese market demands. Matsuda and Shimomura [6] discuss that the Japanese market is saturated with physical products, and its customers are increasingly demanding more functions and services in combination with the physical products.

The business concept of integrated product-service offerings is still emerging and there is a lack of empirical data concerning its practical application. More data is needed in order to analyze how companies are approaching the concept in order to make it as successful as possible. This means that, for example, the service provider could put more focus on the use and end-of-life phases for the physical products included in the product-service combinations. When the service provider has control over the physical products during the use phase, the incitement for cost reduction increases. For example, integrated product-service offering approach will turn revenues from spare parts and maintenance into costs for the provider.

Related research concerning integrated product-service offerings has been previously conducted by e.g. Ölundh [7], Mont [8], Brännström [9] and Windahl [10]. Issues concerning the organization surrounding integrated product-service offerings are presented and discussed by other researchers in e.g. Hermansson and Sundin [11] and Östlin et al. [12]. This paper focuses on the adaptation of the physical products included in the integrated product-service offerings.

This business strategy of integrated product-service offerings has increased lately among manufacturers in Sweden, and especially so for the soil compactor manufacturer Swepac International AB in Ljungby, Sweden. Swepac is also conducting maintenance and for some compactors even remanufacturing in order to prolong the physical lifetime of the compactors. However, the designers at the company are aiming at decreasing the needs of maintenance and remanufacturing since this allocates costs for Swepac. Furthermore, the customers of Swepac are selecting the level of service agreement in their contracts.

1.1 Aim

The aim of this paper is to elucidate how Swepac International has worked with adapting their soil compactor design for integrated product service offerings. Furthermore, to evaluate and analyse the design of a compactor manufactured and remanufactured by Swepac from the perspective of having it sold through an integrated product-service offering.

1.2 Methodology

The company was visited several times in order to find out how they work with design issues. Semi-structured interviews with managers, designers and operators were conducted. The analysis was conducted by product dismantling and following some guidelines to design for integrated product-service offerings. Swepac provided us with a soil compactor (FB-200H), which was dismantled and analysed at an university laboratory. Furthermore, semi-structured interviews were performed with maintenance staff, manufacturing/ remanufacturing staff and executives at Swepac. The interviews concerned the manner they worked with the compactors during the life-cycle phases. Furthermore, we let the staff comment our design suggestions in order to find out their true potential of improvement.

2 INTEGRATED PRODUCT-SERVICE OFFERINGS

Today, value is added to products by technological improvements, but also through immaterial aspects such as intellectual property, product image and brand names, aesthetic design and styling. These aspects help producers to differentiate and diversify their products to better respond to customer's demands. According to Mont [5], this means a change from mass production to mass customization. Kimura [13] states that a paradigm shift is needed to change from traditional product selling to more service-oriented product sales. In addition, the traditional boundary between manufacturing and services is becoming increasingly blurred [5]. In integrated product-service offerings, the service-providing company decides how to fulfil the function that the customer is buying, whereas in leasing the physical product used for the function is known or specified by the customer. Renting a product is even more linked to a specific physical product. These different forms of providing the customer with their desired demands are illustrated in Figure 1.

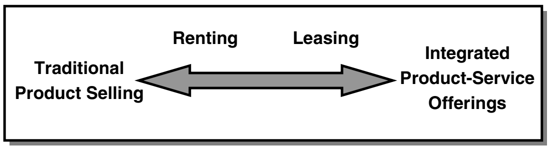

Figure 1: The continuum of traditional product selling to integrated product-service offerings [14].

Within integrated product-service offerings, the function-providing company decides how to fulfil the function that the customer is buying, whereas in leasing the physical product used for the function is known by the customer (see Figure 1). In the cases of renting, leasing and integrated product-service offerings, the product is not sold, and a contract is written between user and provider. This contract is more advanced for the integrated product-service offerings concept. Leasing is a contract form that often is used for financial reasons, as products are often sold to the customers who leased them when the contract has run out. In any case, the overall goal of integrated product-service offerings is to find the most suitable product for the customer [15].

3 DESIGN FOR INTEGRATED PRODUCT-SERVICE OFFERINGS

When designing for integrated product-service offerings, a broad perspective over the product life cycle is needed. This includes, for example, the stages of manufacturing, maintenance, logistics and remanufacturing. In a survey conducted at Swedish and Japanese companies, which use the integrated product-service offerings approach, it was found that they seldom adapted their products for integrated product-service offerings [16]. Previously conducted research by e.g. Kerr & Ryan [17] and Sundin & Bras [18] has also shown that there are several benefits to earn by adapting integrated product-service offerings for remanufacturing.

When adapting products for the remanufacturing process, all of the steps should be considered. For example, if one step such as reassembly is very difficult to perform on a product, it does not matter, in respect to remanufacturing, how much effort has been put into adapting the product for disassembly. This research has identified many properties to consider when designing a product for remanufacturing. The circumstances, e.g. product type, volume, remanufacturing system etc., must be considered since they are important factors when determining a remanufacturing sequence and which properties to prioritize [19].

It is important to have the whole remanufacturing process in mind when designing products for remanufacturing. For example, single focus on one step could make the other remanufacturing steps too difficult or expensive to carry out. One must remember that the essential goal in remanufacturing is part reuse. If a part cannot be reused as is or after refurbishment, the ease of cleaning or reassembly will not be a factor [20]. This means that much effort can be made in product design without obtaining any expected benefits. As Shu and Flowers [20] also contend, the reliability of the part is very important since it has to go through at least one life-cycle, including all remanufacturing steps, and still work satisfactorily.

Sundin [19] has studied which product properties are important for products to have in order to facilitate re-manufacturing. By looking at what properties that are suitable for the different remanufacturing steps (inspection, cleaning, disassembly, storage, reprocess, reassembly and testing) a matrix called RemPro was drawn, see Figure 2. In case studies performed at remanufacturing companies in Sweden, Canada and Japan it was shown that the remanufacturing process steps of inspection, cleaning, and reprocessing were most crucial [19].

To facilitate these steps, the RemPro-matrix presented below shows that designers should focus on giving the products the properties of ease-of-access and wear resistance, since these are important for both the cleaning and reprocessing steps. Following this, the designer should prioritize the properties of ease-of-identification, ease-of-verification, ease-of-handling and ease-of-separation, since these properties are also included as preferable for the crucial steps, but not to the same extent.

Remanufacturing Step / Product Property	Inspection	Cleaning	Disassembly	Storage	Reprocess	Reassembly	Testing
Ease of Identification	x		x	x			x
Ease of Verification	x						
Ease of Access	x	x	x		x		x
Ease of Handling			x	x	x	x	
Ease of Separation			x		x		
Ease of Securing						x	
Ease of Alignment						x	
Ease of Stacking				x			
Wear Resistance		x	x		x	x	

Figure 2. The RemPro-matrix showing the relationship between the preferable product properties and the generic remanufacturing process steps [19].

The remanufacturing company should first investigate which steps are crucial for its specific remanufacturing business area and thereafter try to facilitate this according to the RemPro-matrix, as well as place effort in making the crucial steps in the remanufacturing process as efficient as possible. By doing so, many obstacles could be reduced, and the remanufacturer would have an advantage over its competitors [19].

4 RESULTS

The interviews showed that Swepac have made many improvements of their soil compactor design already. In order to avoid unnecessary remanufacturing the company has introduced new materials instead of the traditional selection. For example, the bottom plate working against the soil is made of special steel in every compactor made by Swepac. This prolongs the physical lifetime of their products. Another example is the hood of the compactor (FB-455) is made of coloured-through polyethylene plastic instead of painted metal. This means that scratches are not easily spotted and if there are severe damages on the hood it can be changed with a new one without going through a repainting process. Furthermore, Swepac decided to attach a rubber bellow along the lower parts of the compactor in order to avoid damages on the steel holding the product together. The soil compactor (FB-455) that has been adapted for offerings is shown in Figure 3.

Figure 3: The FB-455 soil compactor manufactured and remanufactured by Swepac International with e.g. plastic hood and rubber bellow adapted for offerings.

Another example on avoiding damages during use is that the metal hook usually used for transporting is replaced with a strap including a chain, see Figure 4. This reduces the damage occurring from transports much since it is easier, with e.g. a forklift truck, to position the grabbing device in the strap instead of the hook (see Figure 5). Also the friction in the strap is larger than in the metal hook, which could make the compactor slide off the grabbing device (especially if a forklift truck is used). Hence, both the insertion of the moving device and the actual transport of the soil compactor will be safer and less damaging on the soil compactor. One can also see a large difference in hole area for the insertion of the moving device.

Figure 4: The transport strap erected for transport usage on the FB-455 soil compactor.

Figure 5. The FB-450 soil compactor with traditional design manufactured and remanufactured by Swepac.

A third example that became clear during the investigation of the FB-455 product analysis was that the filter for the air inlet to the engine was specially adapted. First of all it was placed at a spot were fewer particles were flying around in the air. Secondly, the filter was adapted for the soil compactor in a manner that it captured more particles than an ordinary filter would do. Since the compactors are used in a very particle filled environment, this kind of filter prolonged the technical lifetime of the engine much. Since Swepac not are experts on motors and how to make service to them, this was a good option for them to reduce maintenance and repairs efforts. The adapted air filter is shown in Figure 6.

Figure 6. The adapted air filter in Swepac's soil compactor FB-455.

In comparison to the traditional product design of soil compactors (see e.g. the FB-450 in Figure 5) many improvements have been achieved. Examples of improvements of the new design are:

- Less visible damages
- Less need of re-painting
- Easier change of cover
- Less wear-out at transports
- Safer transports

The adaptation of the FB-455 compactor has shown good results for Swepac International, however, as a second task another soil compactor was investigated more thoroughly at a Linköping University laboratory. This analysis was performed on the FB-200H during spring 2006. The compactor was disassembled and reassembled several times in order to identify areas where the design could be improved.

During the product analysis several design improvements were elucidated. Some of these improvements will be presented in the paper while the rest is presented in a technical report; see Murremäki et al. [21]. The improvements are, for example; introducing snap-fits at the strap cover for the strap between the motor and the revolving vibration cylinders. The snap-fit introduction would eliminate the use of tools and hence make the assembly and disassembly of the cover faster. The snap-fits would be preferable if it would provide the same quality as for the four screws that usually are used as fastener.

Another improvement would be to standardise the screws used in the entire compactor design. This would reduce the number of tools used for the assembly and disassembly of the compactor parts. Furthermore, costs would be reduced due to less number of articles to keep track on in databases and in storages. Most of the screws used in the compactor are shown in Figure 7a and 7b.

Figure 7a. Screws used in soil compactor FB-200H.

Figure 7b. Screws used in soil compactor FB-200H.

Another improvement concerns the positioning of screws for the lid to the revolving cylinders chamber. In Figure 8 one can see how the screws currently are positioned.

Assembly and disassembly of the lid is in present design obstructed by an adjacent part. If the screws can be positioned according to the suggestion in Figure 9 this obstruction would be less problematic. Changing the positioning of screws will make the assembly and disassembly of the lid go much faster.

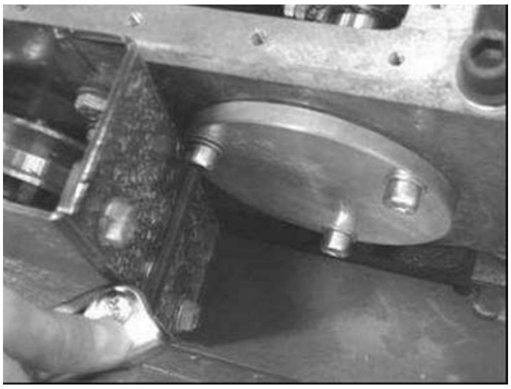

Figure 8. Present positioning of screws for the lid to the revolving cylinders chamber in FB-200H.

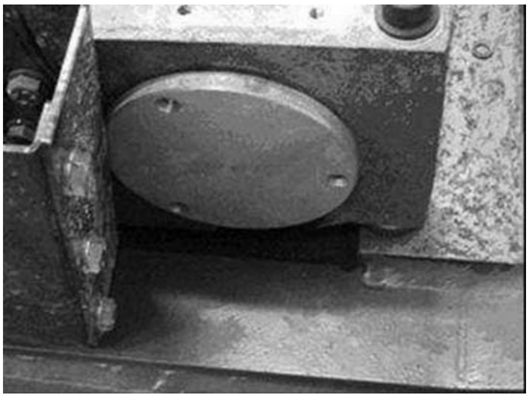

Figure 9. Suggested positioning of screws for the lid to the revolving cylinders chamber in FB-200H.

Finally, one of the most important improvements that were suggested was to introduce a drainage hole for the hydraulic oil. Currently, when emptying the revolving cylinders chamber from hydraulic oil it needs to be sucked up from the hole made for oil fill. This was one of the trickiest parts of the compactor disassembly. The suggested drainage hole would provide for easier changes of hydraulic oil and disassembly of the interior parts in the revolving cylinders chamber. Figure 10 shows where the suggested drainage hole should be placed.

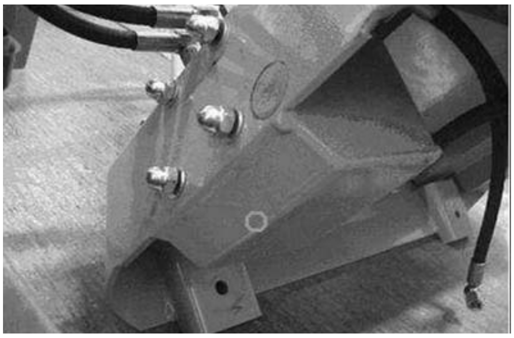

Figure 10. The circle shows the suggested placement of a drainage hole on the soil compactor FB-200H.

5 DISCUSSION

Many of the performed and suggested design changes on the soil compactors are fairly easy to conduct. The company is currently considering the implementations of them. Many of the adaptations concern disassembly and/or reassembly of product parts. These steps are conducted during manufacturing, maintenance and remanufacturing so in cases where the products are remanufactured several times, these efforts have higher impact. In order to identify these kinds of improvements one can use the RemPro matrix (Figure 2) and/or conduct a product analysis. In other case studies of e.g. forklift trucks [3] and household appliances [22] similar improvements were found. In another study performed by Kerr and Ryan [17] photocopiers it was found that energy was needed for remanufacturing if the products were adapted.

From a business perspective, the adaptations have been proven good for Swepac International AB since they achieve a win-win situation with the customer. For example, having the product adapted for maintenance the customer can performed the repairs themselves (i.e. faster -> saves money) and Swepac does not need to send out a maintenance technician (saves money). Also much of the adaptations and product education by Swepac is considered as goodwill and strengthen of the customer relations.

6 CONCLUSIONS

Integrated product-service offerings put new requirements on the products in comparison to traditional selling. The product needs to be easy to perform maintenance and do repairs on in order to reduce costs.

This paper concludes that designers can conduct many changes in order to facilitate integrated product-service offerings. Swepac International who manufacturers soil compactors are also offering them to their customers as integrated product-services. Presently, the designers at Swepac have facilitated their compactors rather well although there are some new design improvements suggested in this paper.

7 ACKNOWLEDGEMENTS

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Service Analysis for Service Design Process Formalization based on Service Engineering

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Abstract

Previous research has proposed a novel approach in dealing with services; we have called this new field service engineering. But difficulties in converting actual service activities into service engineering models have been encountered. These difficulties were caused by the absence of concrete and detailed method in analyzing service operations. Thus, a detailed method of analyzing service activities is proposed to formalize the framework necessary to make analyzing service activities easier. The framework for analyzing service activities is based on the phases of the service encounter as well as the method of hierarchical task analysis.

Keywords:

Task Analysis, Service Encounter, Service Engineering, Service Design Process

1 INTRODUCTION

In the field of Service Engineering (SE), a computer- aided-design system called Service Explorer has been developed [1]. This system has been developed based on the design methodology for service outlined in Service Engineering [2]. However, translating actual service cases into Service Explorer (Service CAD) models have encountered some difficulties. In this paper, a method for the analysis of service is proposed and clarified. The result of this clarification is a set of guidelines on how to describe and structure service activities. Upon implementation of the proposed guidelines, actual service cases will be translated into Service Explorer models easily.

This paper is divided into 5 parts. This section begins with a statement of the need for a formalized method for service activity analysis. Next is a discussion on the current state of research in Service Engineering. This is followed by a discussion about an actual service case application and the difficulties encountered in using the different service engineering models to describe a service. The next section is a discussion on the proposal of a method for the analysis of service activities based on hierarchical task analysis and the phases of service encounter. This is then followed by a discussion and conclusion.

2 CURRENT RESEARCH IN SE

Service Engineering was begun to respond to the need to create a sustainable model of designing artifacts or man-made goods. SE aims to makes it possible to transfer the value of an artifact from the physical aspect to the amount of service it has. Current research in Service Engineering has focused on the development of a modeling methodology for service. Service is defined as an activity that changes the state of the service receiver. This change in state is expressed within a framework involving service providers, service receivers, service contents, and service channels. A set of parameters called Receiver State Parameters (RSPs) is the representation of a receiver's state and this set of parameters are directly influenced by contents parameters (CoP) and indirectly by channel parameters, (ChP). The complex structure of service is represented as a multi-agent network consisting of providers, receivers and intermediate agents. This network relationship is called the Flow Model. The functional relationship between RSPs, CoPs, ChPs are expressed in the View Model. Changes in the RSPs which results from the subjective evaluation of a receiver of a received service are also expressed in this model [1]. A Scenario Model is also used to represent a chain of receiver's actions to describe the receiver's intentions and demands for service.

A model for service design process for improvement was proposed by Watanabe [3]. This model is a step-by-step sequence on how to proceed with designing services into Service Explorer models. However, this model did not present concrete steps on how to implement the design process in a real world case. The modeling of service activities is not detailed and structured enough to systematically translate actual cases into parameters used in modeling in SE framework. The next section further discusses this service design process taking into account the necessary information needed in order to make applying it into real life cases easier.

3 SERVICE DESIGN MODELING

3.1 Service design case study

The researchers used a building elevator/escalator company as an actual case for service modelling. The case involves a service on developing a maintenance tool for maintenance engineers of the company. This case was an exploratory activity that was conducted as a venue for observing the actual modelling of service using SE framework. The goal of this case study is to observe existing problems and difficulties when implementing the current service design process. Opportunities for improvement in the service design process were noted as the subject of further research [4].

The flow of the case study followed the service design process for improvement design [3]. The flow of the case analysis is presented in Figure 1 below.

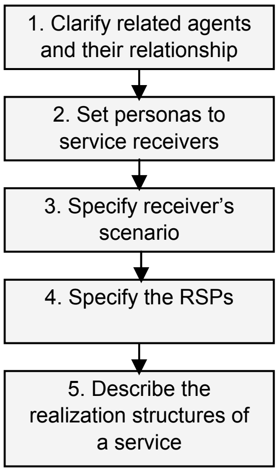

Figure 1: Service Design Process

3.2 Case study observations

The modelling of the maintenance tool development service operation began by determining the potential stakeholders and agents. This was done through interviews and the analysis of documents provided by the company. Documents that were collected and analyzed composed of ISO 9001 certification documents, which included the Quality Manual and the process flow charts for the maintenance tool development service.

After selecting the potential agents of the service, the relationships between them were determined a Flow Model was created. Without creating a Scenario mode the RSPs were then selected l and its root function decomposed into a View Model.

Important observations in the case analysis include (1) the difficulty in determining agent's scenario in the service and (2) the absence method in extracting modeling elements that will initialize the structure of the view model. The modelling activity took much time as there was still no definite procedure in how to analyze real life case scenario and extract necessary information as input to service engineering models.

4 METHOD FOR SERVICE ACTIVITY ANALYSIS

In order to increase the usability of the Service Explorer platform for service modelling, a formalized methodology in analyzing service activities is needed. Up to now, the use of service engineering models is difficult and dependent on the skill and familiarity of the designer. There has been no implemented method in how to set-up the service activity information in such a way that these information can be readily extracted and inputted into a service engineering model

This proposed method is based on the hierarchical task analysis originally proposed by Annett et. al. [5] and on the phases of service encounters proposed by Bitran et. Al. [6].

Hierarchical task analysis is a popular method in Human Factors Engineering, it originated as a means determining training/activity requirement for human operations. It is based on the theory of human performance. On the other hand, the phases of service encounter is a classification of service activities reflecting the different stages that take place in order to deliver a service to a receiver. These two together, the proposed service analysis methodology will take a top-down approach. Meaning analysis will begin from the overall objectives of the service breaking them down systematically to hierarchical levels of sub-goals that will create a detailed picture of the service activity using the phases of service encounter as a guiding framework to begin the analysis.

The following subsections are the detailed steps in the methodology for the analysis of service activities that will be a support for usability in using service engineering models.

4.1 Definition of the goals and objectives [7]

The first step is to define the overall goals and objectives of a service activity. In defining the goals and objectives, the designers will have a guideline on what to include in the scope of the analysis. This will help focus the analysis to what is relevant in the service activity. All subsequent steps will be based on its relevance and inclusion to the originally stated goals and objectives.

The statement of goals and objectives is a generalized statement of the reason why a receiver subscribes to a service. Both the service provider and the receiver aim to realize these goals and objectives in the course of the service activity. In the case of a coffee shop that also offers a place for customers to relax and unwind, the statement of the goal and objective for the customer is stated as follows:

To provide good coffee and pastries at a reasonable cost in a comfortable environment

The statement above is in accordance to the first principle governing hierarchical task analysis, which states that at the highest level of the hierarchy, a task consisting of an operation defined by its goals is chosen. The goals of the task summarize the objectives of the system in some real terms like production units, quality or other criteria.

4.2 Defining the basic service flow

Based on the phases of service encounter, a basic flow of the service is defined. It should be noted that not all services include all phases of the service encounter and some may include some phases not defined in this framework. Bitran [6] proposed this framework of phases to formalize the pervasive aspects of service that is common across all kinds of services. This framework is shown in Figure 2.

Access is the first interaction phase between service provider and receiver. There are numerous ways a service receiver can access service providers: by telephone, fax, computer or personal visits. Included in the access phase of the service encounter is the provision of easy access to service locations through guides or signs. An example of this is the provision of a visible signboard in front of a coffee shop making potential customers aware of its existence.

Check-in is the phase where the service receiver informs the provider of its existence. This is where a provider acknowledges the presence of the receiver through greetings and initial contact.

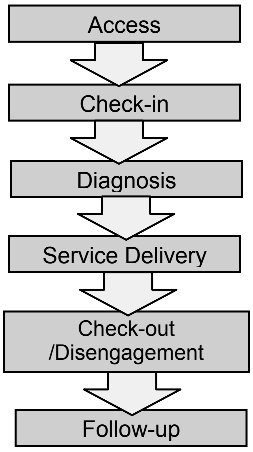

Figure 2: Phases of service encounter

Diagnosis is when the receiver communicates its needs to the provider. This is the time the provider gets to know about the expectations and demands of the receiver. In the case of a coffee shop, this is the phase where the customer selects his desired coffee.

Service delivery is the phase is where the receiver's primary objectives are met. This is the heart of the total service encounter and the overall satisfaction of the receiver is mostly dependent on this phase of the encounter. This is the phase when a customer in a coffee shop gets to enjoy his coffee in a relaxed and comfortable atmosphere.

The *check-out or disengagement* phase is the point where a service activity comes to closure. This is important because the last impression on the side of the receiver is very critical in order to have a repeat of the service.

Follow-up allows the provider to assess the delivery of the service. This is the time when receivers give complaints or commendations on the service they have received.

Take note that all these phases build on each other. All of these phases work together to realize the goal and objective of the service.

It should also be noted that these phases represent the next level hierarchy after the overall goals and objectives of the service. These phases should be defined in terms of its sub-goals in order to contribute to the success of the service.

4.3 Defining the Receiver sub-goals and Provider's means

The second principle in hierarchical analysis of service activities is the breaking down of the main phases of the service encounter into detailed activities by the service receiver. These activities could be a decomposition of an activity into a sequential order of sub-activities or a choice of actions that could be undertaken. The activities are numbered following the numbering of their super-ordinate activities. In this manner an orderly decomposition of the service phases is done. The terminal activities are then translated into sub-goals of the service activities. These sub-goals should be measurable in terms of performance or criteria [7]. Table 1 below is an example of this step in the methodology.

Phases of Service encounter	Decomposed service activities
1.	Access a coffee shop
	1.1 Get relevant information about coffee shop
	1.2 Determine location of coffee shop
	1.3 Locate coffee shop
	1.1 Get relevant information about coffee shop
	1.1.1 Get to know through internet
	1.1.2 Get to know through print materials
	1.1.3 Get to know through posters

Table 1: Example of defining sub-goals

The rule with decomposing the activity is that there should be at least 3 up to 10 subordinates for each decomposed phase of service encounter. Decomposition could either be of the sequential or branching type. The termination of decomposition is based on the judgement by the analyst. This judgement is done when the activity can already be expressed as a receiver sub-goal that can be measured in a sufficient manner.

In each of the receiver sub-goals, the service provider matches it with a means to accomplish this goal. The provider's means are series of operations undertaken by the provider in order to realize the goals of the receiver in the service activity.

4.4 Determining resource requirement

After defining and decomposing the service activities into sub-goals and its corresponding provider's means, the resource requirement for each of the defined provider's

Super-ordinate	Receivers Sub-goals	Provider's Means	Manpower	Materials	Machines	Information	Agents
1.1	Get relevant info. about coffee shop						
1.1.1	To know existence of shop easily	Create a website for shop	Marketing department	Magazine		Info. about coffee shop	Coffee shop, customer
1.1.2	To know existence of shop easily	Advertise in magazines/newsp aper	Programmer		Computer	Info. about coffee shop	Coffee shop, Customer
1.1.3	To know existence of shop easily	Print and post posters around the community	Marketing department	Posters		Info. about coffee shop	Coffee shop, customer

Table 2: Determining resource requirement and agents

means is determined. The resource requirements defined here include Manpower, Materials, Machines, and Information. The provider uses these resources as necessary means in order to satisfy the individual sub-goals of the receiver

4.5 Determining agents

The agents involved in each of the decomposed service activities are then listed down. These agents may include the manpower necessary to realize the service as well as the intended receiver of the service activity. Agents could be individuals, departments in organizations or whole organizations. For each of the terminal decomposed activity, a corresponding active agent is listed down. These agents are the main actors in realizing the corresponding receiver sub-goal. Table 2 shows the completed table of the hierarchical analysis of service activity for the coffee shop example.

4.6 Determining agent relationships

After determining the resource requirements of each terminal sub-goal and listing down the agents involved in each sub-goal, we now define the relationships of the agents in terms of the usage and movement of information, materials, machines and manpower. The existence of any movement or use of these resources indicates a potential service relationship between two agents. The information of these possible relationships are then listed down per sub goal of the service activity.

5 DISCUSSION

The methodology for service activity analysis is a means to make easier the modelling of service using the service engineering framework. In applying the for service activity analysis we will be able to organize information in such a way that it will be easy to use as inputs to service models.

5.1 Input to the flow model

After completing the hierarchical analysis of the service activity we can extract a list of candidate agents and stakeholders for our service model. We can see systematically their contributions as well as relationships with other agents. The list of agents and their relationships is a good basis for creating the provider-intermediate-receiver chain in the flow model.

5.2 Relationship to scenario model

The scenario modeling elements could be extracted from the table by considering the decomposed activities of the receiver. Each of the phases of service encounter corresponds to the action chain of the receiver. These activities correspond to the receiver's scenario and action chain of the scenario model. Since state parameters include the goal type, the state parameters can be extracted from the list of the receiver's sub-goals defined for each of the terminal decomposed service activity. In this way, the column listing the receiver's sub-goal in the main table corresponds to the candidates of state parameters of the receiver.

5.3 Input to the view model

The RSP is selected from the set of state parameters extracted from the Receiver's sub-goal for the decomposed service activities. This RSP is then related to a root function that corresponds to the means of the provider to realize the delivery of the service. The provider's means is a set of operations undertaken by the provider of the service to realize the sub-goals of the receiver. From the Provider's Means column of the completed hierarchical analysis table, the functions that compose the function label structure of the view model can be extracted. These functions are related to the realization structure of a service since these are actions that realize the goals of the receiver. The provider's means can be extracted as function labels of the view model which is a part of the some of the higher function structure of the realization of the service.

6 CONCLUSION

In this paper we have proposed a formalized method in analyzing service activities. This methodology is important in setting up the necessary information needed to create service engineering models. In this way usability of the Service Explorer software will increase because of the availability of definite steps in how to structure available information form an existing service activity.

7 ACKNOWLEDGMENTS

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Leadership - From Technology to Use

Operation Fields and Solution Approaches for the Automation of Service Processes of Industrial Product-Service-Systems

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Abstract

This article describes the paradigm change from the separated view of product and services to a new product understanding consisting of integrated industrial product-service-systems (IPS^2) which establish innovation potentials to increase the competitiveness of mechanical engineering and plant construction. Thus allowing business models where the customer use, e.g. in the form of highly available machines and plants, and not the selling of the machine is of central interest. This article describes the field of operation and solution approaches for the method-supported design and automated execution of the service proportion of IPS^2.

Keywords:

Industrial Product-Service-Systems; Integrated Engineering; Service Automation

1 INTRODUCTION

In mechanical engineering and plant construction, product-related services are usually seen as add-ons to the actual product [1]. The claim of most companies to fulfill all customer requirements and the employee's lack of experience in focusing their activities efficiently on the customer's use led to an unclear number of individual solutions for customers and special solutions with a clear increase of costs. Therefore, the product accompanying approach is no target for mechanical engineering and plant construction and will be replaced by an integrated view, focusing on the customer's use. This paradigm change from the separated view of product and services to a new product understanding consisting of industrial integrated product-service-systems (IPS^2) which establish innovation potential to increase the competitiveness of mechanical engineering and plant construction. Thus allowing business models where the customer use, e.g. in the form of highly available machines and not the selling of the machine is of central interest.

2 LEADERSHIP – FROM TECHNOLOGY TO USE

Driven by the globalization of the world markets and the relocation of production sites of mass products to countries with lower wages, mechanical engineering and plant construction specialized on the production of complex high-technology products and has now a leading role in this field [2]. In order to retain this advantage in the competition, respectively develop it even further, it is necessary to achieve a permanent development of the existing product and process knowledge. In the field of highly complex tool machines, this continuous development requires the control of these high-service processes and assumes a comprehensive knowledge of the process by the supplier. It is only possible if there is a constant contact to the machines and plants in the operating process.

The requirements of the mechanical engineering and plant construction suppliers are linked to the demands of the customers for a comprehensive service offer [3]. This however, results from the effects of the turbulent, global markets, afflicting the increasing requirements concerning flexibility, quality, delivery dates and prices. The customers, as users of the tool machines, react with a concentration on their core competences and strive for a spin-off of secondary tasks.

Both the changes on the supplier's side and the customer's side can be aligned with the supplier's development of the leadership from technology to use. The use orientation as a system solution in the sense of an integrated offer of product-service-systems enables the supplier a life-cycle-spanning contact to his machines and thus the option to optimize the product-service-systems. In the context of innovative business models, the suppliers accept more and more responsibility for individual process steps up to the responsibility for the complete operation of a plant. The customers are therefore free of the control of the highly-complex processes and are able to focus on their actual core competences.

3 PRODUCT-SERVICE-SYSTEMS AND INNOVATIVE BUSINESS MODELS

Industrial product-service-systems are individualized, customer-oriented configurations of products and services, which affect each other due to their integrated development and provision [4]. The structure of IPS^2 is shown in figure 1.

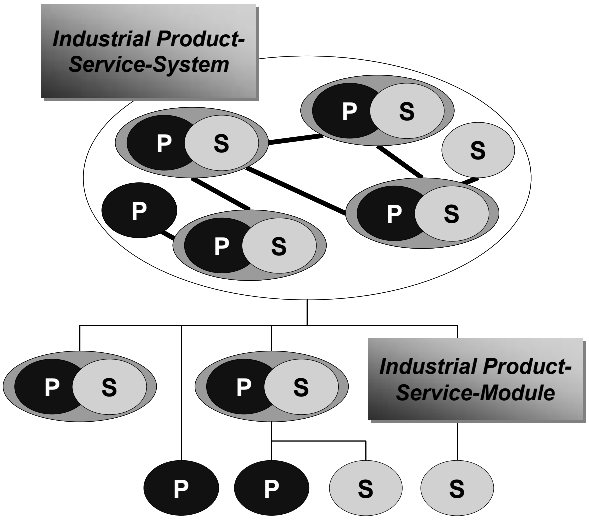

Figure 1: Structure of IPS^2

Innovative and flexible business models, which describe the design of the customer-supplier relation in form of service bonds and settlement modalities, are based on these dynamic systems. One differs between function-, availability- and result-oriented business models. The different types of business models are based on varying configurations of IPS^2, which are placed in the range between products and services (figure2).

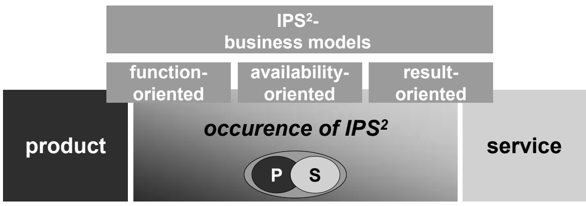

Figure 2: Occurrence of IPS^2 according to [5]

A function-oriented business model includes, e.g. a maintenance contract in order to guarantee the functionality for an agreed period of time. In an availability-oriented business model, the utilizability of the means of production is also guaranteed. For the first time, the supplier takes over business processes of the customer as his own responsibility, e.g. maintenance or repair and thus bears a part of the production risk. In a result-oriented business model, the complete responsibility of the production result is transferred to the supplier, as the customers settle the faultlessly produced parts only. The individual business model can be differentiated by the following criteria:

- **Revenue model**, i.e. the difference between a classic purchase of a machine combined with the signing of an additional service contracts (e.g. maintenance contract), respectively the purchase of services, which are invoiced separately and a rotational fee payment, depending on defined service results (e.g. availability, produced parts) of the machine. Depending on the selected business model with the appropriate pay model, the machine is either owned by the customer or the supplier.
- **Allocation of operating personnel**, the operating personnel for the machines is provided by the supplier in case of a result-oriented business model. Otherwise, the customer is responsible for the operating of the machine and thus for the operating personnel.
- **Production responsibility**, in case of a result-oriented business model, the supplier bears the responsibility for the production processes of the customer. In a function-, respectively result-oriented business model, the customer has the sole responsibility.
- **Allocation of maintenance personnel**, the maintenance personnel for the product-service-systems is provided by the supplier, both for the availability- and result-oriented business model. In case of a function-oriented business model, the maintenance of the machine and therefore the allocation of the appropriate personnel is the responsibility of the customer. The supplier will only provide maintenance personnel on a special additional service order by the customer for an agreed fee.
- **Service request**, i.e. specification if a service process is concluded at the request of the customer or of the supplier.

The different occurrence of the criteria are shown in figure 3.

	function-oriented	availability-oriented	result-oriented
revenue model	selling of the machine	pay on availability	pay on production
allocation of operating personnel	customer	customer	supplier
production responsibility	customer	customer	supplier
allocation of maintenance personnel	customer	supplier	supplier
service request	customer	supplier	supplier

Figure 3: Characteristics of innovative business models

The change of leadership from technology to use, which is implemented by innovative service offers in form of product-service-systems, requires a comprehensive observation of all methods, proceedings and tools, which are currently used during the complete life-cycle of a product.

4 SYSTEMATIC DEVELOPMENT OF PRODUCT-SERVICE-SYSTEMS

An essential condition for an economically successful offer of product-service-systems is their systematic development. A systematic development process has been established with the proceeding model according to the product design. A large number of models to approach the service creation exist in the field of Service Engineering, where the target is the systematic development of services [6]. They serve as the basis for the concrete design of service provision processes. These models of approach are by far not sufficient, as only rudimentary methods, which support the development of service provision processes within these methods, are available for engineering questions. The currently existing Service Engineering approach models, e.g. DIN technical report 75 [7], support the concrete planning and design of service processes only insufficiently due to their low degree of details.

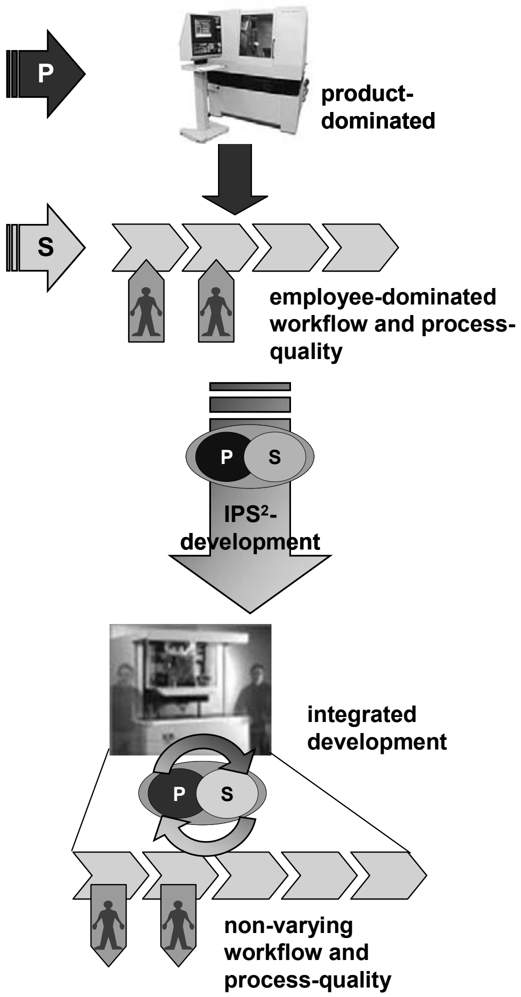

Figure 4: Integrated development of IPS^2

Service Engineering methods, which have already been developed, e.g. Service Blueprinting, respectively GAP-analysis [8], are mainly concerned with the visualization and notation of well-known service processes, respectively with their analysis. It is therefore not only the methods and tools for the integrated observation of industrial product-service-systems with their product and service components which are missing [9] [10], but there is also only a limited access to the basics of Service Engineering.

The industrial product-service-system approach and the integrated development of product and service components result in concrete options for the IT-supported generation [11] and lead to an automated execution of combined provisional processes, which need to be supported by appropriate methods. Therefore there is a need for action. Methods, approaches and tools for the IT-supported generation of provisional processes of industrial product-service-systems need to be developed.

This generation is either initiated by a customer or is a reaction to current data, e.g. in the context of a state initiated maintenance of the industrial product-service-system, which requires the execution of service processes. Furthermore, an automated, respectively semi-automated execution of the provisional processes, e.g. optimization or process monitoring is possible. Both the automated generation and the automated execution of the service provisional process justify the need for a formal, computer-interpretable form of notation.

The following scientific questions arise from the systematic design of the provisional processes of product-service-systems:

- Which methods and tools support the concrete design of service provisional processes?
- How can service provisional processes be designed which unite the stabilization which is required for the economic and cooperative provision and the necessary flexibility and variability for the capacity-depending real-time planning?
- Which service provisional processes can be generated automatically? Which algorithms support the automated generation?
- To what extend can service provisional processes be executed automated by industrial product-service-systems? How can these processes be supported by a formal description?

5 FIELDS OF ACTION

Process Description

The systematic development of provisional processes of industrial product-service-systems requires a defined description of the individual process elements, in order to enable a pre-definition of the individual process steps. These abstract process steps are the basis for the concrete design and can be administered easily by using class structures.

As a result, criteria need to be selected and defined, in order to form IPS^2 classes, which include the standardized service provisional processes.

The purpose of this is the support of a later automated generation of the service provisional processes, as pre-defined models are available for various service provisional processes, which can be designed depending on the concrete requirements of an industrial product-service-system.

The modeling of the IPS^2 classes, which can be described with attributes and operations, can be carried out with the help of object-oriented methods. These IPS^2 classes can be formed by instances, i.e. the specification of concrete parameters for the individual attributes, objects, respectively instances. This type of formal representation and structuring of the service provisional processes allows a clear administration and use of the individual service provisional processes due to aggregation, association and inheritance. A possible criterion for the definition of service classes on a high abstract level is, e.g. the differentiation between cyclic, state-oriented, respectively failure-dependent service provisional processes. The following questions have to be considered in the context of class formation:

- Are there pure IPS^2-classes or is it possible to link product and service components via class attributes, in order to instance IPS^2-objects?
- How can the service process classes be linked to the appropriate product classes? How can the interaction between product and service components be displayed?
- How can the various degrees of automation be considered in the clustering process, both for the automated generation of the processes and the automated execution of the service provisional processes?
- Which class structure support the cooperative provision of industrial product-service-systems?
- How is the detailed design of the operations of the individual IPS^2 classes made? Up to which detail level will the service provisional processes be defined as classes, respectively what is the granularity from which the processes will be displayed in form of operations?
- Are there methods for the IT-supported clustering of provisional processes of industrial product-service-systems?

The attributes and operations for the description of the particular IPS^2 classes, respectively the service provisional processes will be specified based on the definition of various classes. First of all, possible attributes will be derived, which result in particular from the product understanding of the industrial product-service-system. Such attributes can be, e.g. rights, knowledge access, costs, quality, execution time and required resources. When identifying and selecting appropriate attributes and operators, an optimum needs to be determined concerning the competing targets standardization of the service provisional processes, respectively flexibility and variability. At the same time it is necessary to specify the input and output of the particular service provisional processes in order to support the standardization. Furthermore, the exchange of individual process steps has to be enabled in order to support the flexibility and variability of the process and the resource requirements.

The determination of the optimum degree of standardization enables a control of the target competition (standardization, respectively variability) in the description of the service provisional processes. Another point to be examined is which attributes can be changed after the IT-supported generation of the service provisional processes for the support of planning flexibility, in particular when selecting the appropriate resources. Safety-relevant processes cannot be modified if, e.g. an employee with a specific certificate is required, whereas attributes of non-critical service provisional processes can be changed, in order to guarantee an optimum resource available provision of industrial product-service-systems in the supplier consortium. A particular consequence of the product understanding in form of industrial product-service-systems is, e.g. in special cases the option of partial substitution between the particular product and service components. For example, the data collection for the planning of prophylactic maintenance can be product-dominated by using tele-service, linked to a fully automatic data evaluation. The assignment of an employee, who will determine and evaluate the necessary data at the customer's, is also possible. This is useful in particular if no appropriate sensors/actuators are available, respectively if their use is not economical. The use, which is identical from the customer's point of view, will be implemented within the industrial product-service-systems either with a product or service dominance. Changes in the attribute values, in this case the "Resource Use" attribute, can support an optimum provision of industrial product-service-systems. One has to keep in mind that the modifications of the attribute values can have an effect on the sequence of working steps within the service provisional processes.

Formal, Computer-interpretable Form of Notation

Due to the integration of product and service components in form of industrial product-service-systems it is possible, with an appropriate design of the industrial product-service-system, to implement an automated, respectively semi-automated execution of the service provisional processes in certain cases [12]. This automated execution is enabled by an industrial product-service-system, as the product components (control, sensors and actuators) take over the execution of service processes. The object-oriented formulated class structures are designed in a computer-interpretable way with the help of a formalized notation of the service provisional processes. The execution-specific aspects and requirements of the object-oriented description of the service provisional processes have to be identified. Such requirements are, e.g. the consideration of synchronization mechanisms or the design of process steps for the knowledge generation from the operation of industrial product-service-systems. Suitable for the automated provision, which is enabled by a computer-interpretable form of notation, are, among others, processes for the determination of characteristic figures, simulation, optimization, knowledge generation, user support and securing the learning aptitude.

The following questions have to be considered when developing a computer-interpretable form of notation:

- Which service provision classes are suitable for the automated provision?
- In which form and with what means can manual service provisional processes be substituted by automated processes?

Methods and Tools for the IT-supported Generation of Cooperative Service Processes

The methods and proceedings for the automated generation of service provisional processes need to implement the selection of required process elements, the planning of the sequence of these process steps and the automated assigning of attribute values and will be transferred to an IT-based query, which provides for, in the context of an assistance system, the automated generation of the service provisional processes, considering the interaction between product and service components. This assistance system allows the concrete design of industrial product-service-systems according to the requirements of the customer.

The planning method for service provisional processes needs to cover both automated IPS^2-internal processes and semi-automated processes, integrating the customer and the supplier consortium-internal back-office processes. Furthermore, the influence of the attribute values on the design and selection of the individual process steps needs to be considered. For example, an employee with a high qualification requires a process description with a lower detail level than an employee with a lower level of qualification. If the attributes of a process step are changed in such a way that the type of execution is changed from manual, respectively semi-automated to fully automated, the complete process chain of the service provisional processes will have to be changed. The generation of the service provisional processes needs to be feasible for various optimization criteria. In a first planning step, the generation is carried out according to the parameters cost, time and quality so that an optimum service provision process can be generated. Utilization peaks may lead to straits of the intended resources. In this case, the method of the IT-supported generation of the service provisional processes has to be able to generate a process with different basic conditions and thus varying optimization targets, which is now based on the available resources of a concrete case and may vary considerably from the originally planned process.

6 CONCLUSION

In mechanical engineering and plant design, product-related services are usually considered as an add-on to the actual product. This paper describes the solution approaches to develop new concepts and methods which enable the machine producers to design the potential services in an optimal way, already due the development of the machine. This paradigm shift from the separated consideration of products and services to a new product understanding consisting of integrated products and services creates innovation potential to increase the competitiveness of mechanical engineering and plant design. The latter allows business models which do not focus the machine sales but the use for the customer e.g. in form of continuously available machines.

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Implications for Engineering Information Systems Design in the Product-service Paradigm

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Abstract
In an evolving business environment, many organizations are changing their product offering from the supply of predominantly physical goods to the delivery of product-service systems. The resulting need to support both physical goods and associated services throughout their lifecycles has a number of implications. This paper focuses on the changing requirements of engineering information systems caused by the need to represent both physical goods and associated services. Key characteristics that differentiate service offerings from physical goods are surveyed. The impact of these characteristics on the design of the engineering information systems that facilitate the delivery of product-service systems are outlined. The research reported in this paper draws together theories from engineering product definition and service blueprinting approaches that have traditionally been used to capture service products in the hospitality and financial sectors. Early results from the use of the service blueprinting method in defining technical services are presented and approaches to integrating product and service definitions are explored.

Keywords:
Engineering Information Systems; Product-Service Paradigm; Service Modelling; Service Blueprinting

1 INTRODUCTION

A product's life can be viewed to span from its conceptualization to its retirement or decommissioning phase. In its lifecycle, a product typically passes through a number of phases, such as, design and development, manufacturing plan and sourcing, manufacturing and assembly, logistics and distribution, sales, use, after sales support and maintenance, refurbishment and finally retirement of the product.

As increasing numbers of companies move from product delivery to the provision of through-life support services, the need to be able to access reliable product definition data, both from design and reflecting how the product has changed over its life, increase. In many products, especially large complex products, the product definition includes relationships to the organisations and processes involved in the creation of both the product definition and the product itself. The move to through-life support services is increasing the required scope of engineering information systems beyond design and manufacturing to cover the use, maintenance, support, refurbishment and retirement of products.

This paper focuses on how requirements for the design of engineering information systems are changing as the transition from product to product-service delivery progresses. Key features of service products, that distinguish them from physical products, are outlined in Section 2. Theories that underpin, or can be used to explain, current product definition schemes are discussed in Section 3. Section 4 introduces the service blueprinting method and Section 5 presents a case study in its use for the definition of a technical service provided by a company that offers maintenance services. Finally, in Section 6, research findings are presented.

2 KEY CHARACTERISTICS OF SERVICE PRODUCTS

Johne and Storey [1] provide a review of literature related to new service development. New service development includes the definition and delivery of services; the literature relates largely to traditional service products such as financial and hospitality services. Five key characteristics that distinguish service products from physical products are identified: intangibility, perishability, non-ownership, inseparability of production and consumption, and variability.

- ***Intangibility:*** Services are predominantly performances of actions rather than objects that can be perceived using any of the physical senses.
- ***Perishability:*** Services must be consumed as they are provided. In general, they cannot be saved, stored, returned or carried forward for later use or sale.
- ***Non-ownership:*** Largely as a result of their intangibility and perishability, customers do not obtain ownership of services; rather, they experience the delivery of the service.
- ***Inseparability of production and consumption:*** Service products are typically produced and consumed at the same time - consumption cannot be separated from the means of production.
- ***Variability:*** Service product quality is subject to variability because services are delivered by people to people. Two dimensions of variability have been identified [2], [3]
    - o the extent to which delivery standards vary from a norm, and
    - o the extent to which a service can be deliberately varied to meet the specific needs of individual customers.

Parallels between these variabilities and those of physical products can be drawn. The extent to which a delivered service varies from a norm is akin to the extent to which a dimension on a physical product varies with respect to its nominal dimension and tolerance band. On the other hand, the variation of a service to meet the needs of individual customers has parallels with mass customisation and the delivery of customised products.

Engineering information systems to support the lifecycles of product-service systems need to accommodate these distinctions without compromising the need to preserve commonalities between physical and service products.

3 THE DEFINITION OF PHYSICAL PRODUCTS

A recent research programme in the Netherlands focused on the dual nature of technical artefacts and provided insights on the definition of physical products. A key tenet of the dual nature of technical artefacts is that technical artefacts have both designed physical structures and intended functional structures.

On intended functional structures, Vermaas & Houkes, in their ICE (**I**ntentionalist,**C**ausal-role,**E**volutionist) theory [4], assert that when engineers ascribe functions to artefacts they have to consider explicitly the goals for which agents use artefacts and the actions that constitute their use; the agents' actions are captured in a "use plan". A number of papers resulting from this project [5] include discussions on the distinction between function, behaviour and capacity of physical artefacts. Mumford [6] provides the following definitions for function and capacity:

- capacity is a property of an artefact that is understood according to what it can do or what function it can play in relation to other properties;
- function is a capacity plus the use plan that exploits it for an intended purpose.

Design rationale, as captured using tools such as the D-Red software tool [7], is a means by which designed physical structures might be related to intended functional structures. Design intent, for example as captured using advanced requirements management techniques [8], enables intended functional structures to be related to stakeholder intent and so aspects of what Vermaas & Houkes refer to as use plans.

On designed physical structures, Simons [9] uses mereology to provide a theoretical basis for the definition of physical product structures, of which Bills of Materials are the most common manifestation. McKay et al [10] propose a collection of relationships needed to support the definition of physical products. Three groups of relationships needed for the definition of a product are identified:

- those needed to describe a product at a point in its life-cycle and time;
- those needed to support configuration management; and
- those needed to support product realisation.

If services are regarded as products, or parts of product-service products, then the following of questions arise given the discussion in this section.

- What are the intended functional structures of service products and how might they be represented?
- How might product definitions for service products be formulated and how might they be represented in an engineering information system?
- For through life support, are additional kinds of relationship needed to support lifecycle processes after product realisation?

4 TOWARDS THE DEFINITION OF PRODUCT-SERVICE SYSTEMS

Product-service systems are themselves products. As such, engineering information systems to support the lifecycles of product-service systems need to reflect this fact.

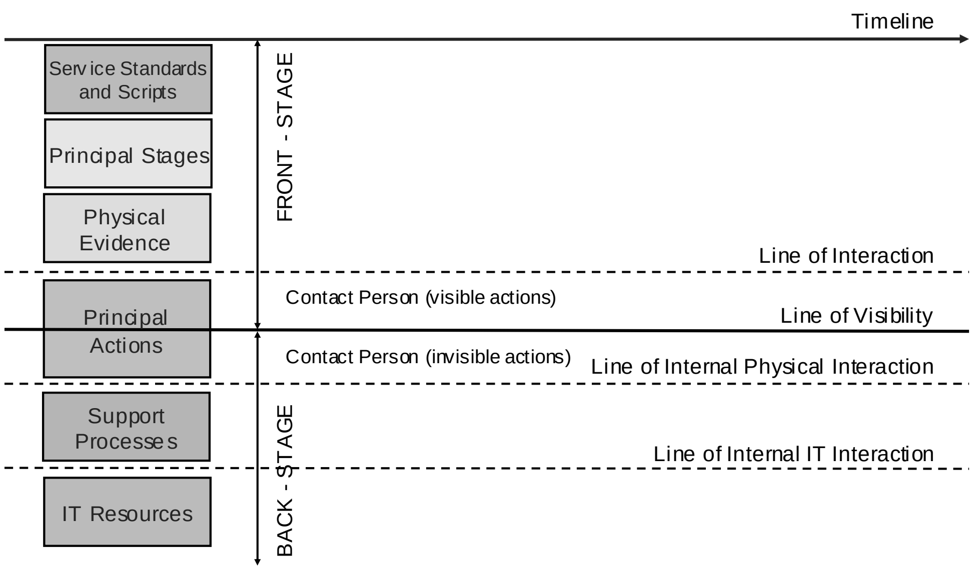

Figure 1: Key elements of a service blueprint (adapted from Lovelock and Wirtz [11])

The STEP standard (**S**tandard for **T**he **E**xchange of **P**roduct model data) is the most recent product data exchange standard and is the product data specification norm to which many engineering system vendors are working towards.

Product lifecycle issues are addressed through the STEP application protocols for particular application contexts [12]. In many, if not all, application contexts, key elements in the definition of physical products are shape and material specification – inherence and constitution relationships respectively. A key question in the definition of services lies in the nature of their properties.

Service blueprinting approaches have traditionally been used to capture service products in the hospitality and financial sectors. The research reported in this paper applied service blueprinting to technical services associated with the maintenance of production plants. Key aspects of the service blueprinting technique are summarised in figure 1.

A service blueprint is built around the principal stages of the service; these are the key process steps as seen by the customer. Each principal stage has its own service standards and scripts which relate to the target performance levels of the service. The association of physical evidence with principal stages of the service addresses the intangibility of the service itself. Two kinds of process are associated with the principal stages: principal actions and support processes. Support processes interact with IT resources. For technical services these could include engineering information systems. The visibility of the sub-processes that form processes in the service definition is governed by their positioning on the blueprint relative to a number of visibility and interaction lines. If the enactment of a service blueprint is seen as a simultaneous production and consumption of the service then these lines govern who sees which parts of the delivery of the service.

5 CASE STUDY – APPLICABILITY OF SERVICE BLUEPRINTING TO ABB FULL SERVICE ®

This research used ABB's Full service process as a case study. This section, courtesy of ABB Limited, provides a brief introduction to ABB and their Full Service process. The appropriateness of the service blueprinting techniques to highly technical service offerings is being explored. Section 5.1 and 5.2 are adapted and reproduced from the 'ABB Full Service ® – Executive Briefing' [13].

5.1 Introduction to ABB and their Full Service ®

ABB (www.abb.com) is a leader in power and automation technologies that enable utility and industry customers to improve performance while lowering environmental impact. The ABB Group of companies operates in around 100 countries and employs about 107,000 people.

ABB Full Service is a maintenance and reliability outsourcing program that has turned routine maintenance activities into a profit source for over 150 clients worldwide. Bringing together world-class maintenance and reliability methodologies, parts and logistics management, online tools, and domain expertise, ABB Full Service increases asset effectiveness while keeping tight control of costs.

5.2 Full Service ® methodology

Developing a Full Service agreement is a collaborative effort between ABB and the client. During the process, a core team of ABB and client resources follows a proven methodology to collect and analyze information in a stage-gate process that balances investments in time and resources against the data needed to make sound business decisions. At the conclusion of each stage, there is a review where ABB and the client discuss progress and reach agreement on how to proceed. Key steps of the ABB Full Service process are summarised in figure 2. Following are the principal stages in this process:

Screening – Scope and boundaries, desired outcomes, resource requirements, executive sponsorship, and schedule are evaluated and documented in this step to guide the team through the engagement. A letter of authorization is signed to approve the feasibility study.

Feasibility study – Functional requirements are developed, benchmarking and gap analysis is completed, current / future states are identified, expected benefits and costs (value proposition) are identified, and a preliminary decision and risk analysis is conducted. A letter of intent is signed to proceed to Partnership Development.

Partnership development – The Maintenance Management Master Plan is developed to set the strategy for maintenance and reliability at the site. Due diligence is performed for human resource, legal, health and safety, and technical issues. Key performance indicators are defined and the mobilization and transition plan is created. A Maintenance Alliance Agreement is signed to initiate mobilization.

Mobilization – Systems and networks are installed, the new maintenance organization is announced, implementation plans are finalized for HR, facilities, supply management, and accounting. A communication plan is developed to facilitate change management and identify issues early in the program.

Implementation –Program execution begins with start-up and training occurs, new processes are introduced.

Contract management and development – The alliance management process governs the relationship and continuous improvement programs are introduced to increase performance at the site.

ABB Full Service provides a structured program to improve and sustain the performance of production assets. The best of these arrangements occurs when the client and ABB work together as team to jointly develop a business model that supports the client's top-level strategy by providing world-class reliability and maintenance services. A risk / reward performance mechanism ensures that continuous improvement opportunities are identified and captured over the life of the contract and reinforces the strategic intent of the Full Service agreement.

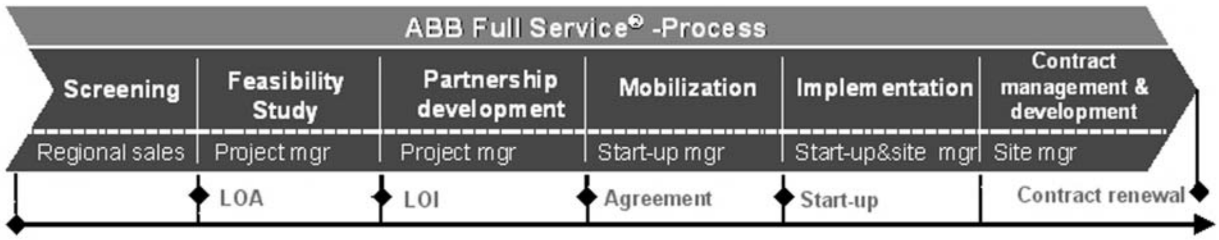

Figure 2: Key steps of ABB Full Service ® process (courtesy: ABB Ltd.)

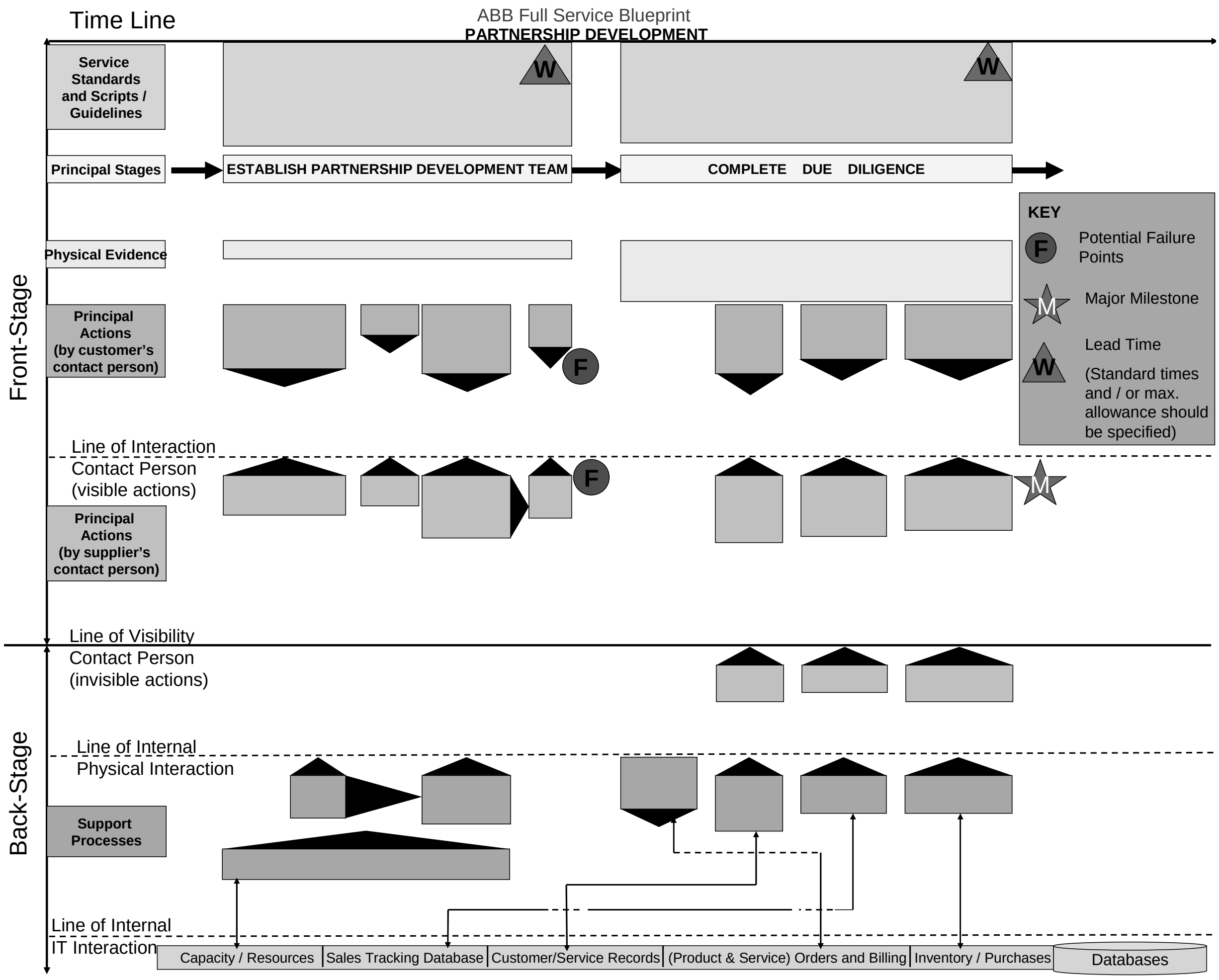

Figure 3: Key elements of the blueprinting technique used to define part of the partnership development phase of ABB Full Service ® process

5.3 Example blueprint

In this research, the ABB Full Service process was recorded using the service blueprinting technique. A snapshot of the key elements of the blueprinting technique used to define part of the partnership development phase is shown in figure 3.

From left to right, the blueprint depicts a sequence of actions over time (represented by a time line). Along the time line, the principal stages involved in the partnership development phase of the ABB Full Service process are mapped in sequence. For each principal stage, its own service standards which relate to the target performance levels are included. Service standards may include lead time, scripts/guidelines for technically correct performance. Two kinds of process are associated with the principal stages: principal actions and support processes. These are represented by arrow-headed rectangles and positioned on the blueprint relative to a number of visibility and interaction lines. The line of visibility separates the front-stage activities (i.e. *visible* to the customers) from the back-stage activities (i.e. *invisible* to the customers) for each principal stage. The line of interaction (in the front-stage) represents the interface between the (visible) principal actions performed by the customer's contact person and the (visible) principal actions performed by the supplier's contact person. Likewise, the line of internal physical interaction (in the back-stage) represents the interface between the (invisible) principal actions performed by the supplier's contact person and the support processes involving other service personnel and information technology. Interactions between support processes and IT resources (represented by a number of databases) are captured by double headed arrows. Physical evidence for each of the front-stage activities are specified in the blueprint. Points having high risk of service failure and points of major milestone reached in the service creation and delivery process are also captured in the blueprint.

6 IMPLICATIONS FOR ENGINEERING INFORMATION SYSTEMS DESIGN

The research reported in this paper has explored the use of service blueprinting, traditionally applied in sectors (such as finance and hospitality) whose products are the services themselves, in the definition of services associated with tangible products that are emerging as a part of the product-service paradigm being adopted in engineering industries.

A number of variants of service blueprints are described in the literature, Lovelock and Wirtz [11], Kingman-Brundage [14-16], and Shostack [17, 18]. All can be regarded as two-dimensional frameworks for the definition of service processes with a horizontal axis representing a chronology of actions and a vertical axis that distinguishes between different kinds of actions. Given the assertion in Section 1 that product definition data includes links to organizations and processes, it can be argued that service blueprints capture engineering information in the form of "as-defined" process maps for aspects of lifecycle support. This aligns with the framework for product data proposed by McKay et al [19] which also includes product data related to product specification and actual products. Effective lifecycle support requires that actual service data is also collected: that is, there is a need to capture what actually happened to individual products through their lives in addition to the definition of what should or might have happened. If the service blueprints are regarded as process maps then support for the definition of pathways through the blueprints are one way in which actual process data might be captured. In the short term, the use of Wiki technology is being considered to capture information relating to service delivery.

When the services are related to technical products, there is a need to establish relationships between technical product data and the blueprints, and pathways through them, of the services that use and create this data. Presently, this technical product data is hidden within the IT resources at the bottom of the process maps.

In defining ABB's Full Service process using the blueprinting technique, it was felt the need to capture actions or processes conducted by the customer or service recipient in the process of receiving the service. This issue was addressed by introducing an additional element termed 'Principal Actions (by customer's contact person)'. The 'Principal Actions (by customer's contact person)' captures actions or processes conducted by the contact person of the customer or service recipient (and visible to the service provider) in the process of receiving the service. The 'Line of Interaction' acts as an interface between customer's activities and activities of the service provider. The modified blueprint framework is depicted in figure 3.

A key characteristic of such services, which may well distinguish them from service-only products, is that they are between companies rather than a person in a company and a consumer and within the context of an enterprise network. Traditionally in service blueprints, although both customer-induced and customer independent activities or processes (performed by the service provider) are captured, they are not separated. An important limitation, that has been noted elsewhere (Fließ and Kleinaltenkamp [20]), lies in the inability to capture dependencies between actions of the customer and supplier, for example, identifying which party in the service delivery process carries out which actions and highlighting alternative courses of action that depend upon what occurs at these interface points. In fact, in enterprise networks, the relationships may not be customer-supplier relationships; for example, in the blueprints reported in this paper, they were nearer to risk and revenue sharing partnerships. Fließ and Kleinaltenkamp [20] proposed separating customer-induced and customer-independent activities or processes (performed by the service provider) in service blueprints. However, none of their blueprints mapped customer's participation in the form of actions or processes performed by the customer. Previous research, on the definition and operation of enterprise networks, indicates that a key to understanding lies in treating the relationships between enterprises as being as important as the enterprises themselves. In blueprinting services that span such relationships, it may well be that there are three interconnected blueprints – one for each partner and one for the relationship itself.

Some service processes require the participation of the customer during all or some service operations. In that case the customer is viewed as a co-producer of the service. As mentioned by Fließ and Kleinaltenkamp [20], the efficiency of such service processes heavily depends on the degree and quality of a customer's participation. For these reasons, it is important to capture customer's actions in defining service processes using the blueprinting technique.

In its present form, the service blueprint does not appear to have a robust underlying formalism (i.e. ontology). Formal ontologies that underpin today's knowledge management systems provide a more structured way of capturing knowledge which could be used, for example, to produce repeatable service delivery and avoid the ambiguities of human interpretation.

7 FUTURE RESEARCH DIRECTION

Early research results indicate that, like physical products, service products have both intended functional and designed (but not physical) structures. Current research is exploring the use of product, process and enterprise network structuring techniques [21] to establish a detailed understanding of relationships that occur in service-artefact relationships.

Today, potentially valuable lifecycle information is typically created and owned by a range of organisations and stored in ways that renders it inaccessible to potential beneficiaries. A real opportunity, in moving to the product-service paradigm, lies in the ability to capture lifecycle information as it is created through the delivery of lifecycle services.

Understanding of the nature of the relationships between products and services is a key to unlocking this potential and enabling sharing of more information across a wider range of lifecycle stages.

8 ACKNOWLEDGMENTS

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Life Cycle Management of Industrial Product-Service Systems

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Abstract
Technical services aim at enhancing the economical and ecological performance of industrial products. To systematically exploit their potentials for both manufacturers and their industrial customers, products and services need to be integrated. Thereby, Life Cycle Management (LCM) provides a promising starting point. On the basis of corresponding methods, important fields of action, regarding the implementation of the resulting industrial Product-Service Systems (PSS) in the investment goods industry, can be identified with respect to customer-oriented PSS planning, integrated PSS development, knowledge based PSS control and life cycle-oriented process management. This article therefore introduces a novel concept for PSS-LCM and describes important elements thereof.

Keywords:
Life Cycle Management; Product-Service Systems; Design

1 INTRODUCTION

While in the past, investment goods manufacturers have largely focused on design, realization and distribution of high quality products, their industrial customers are increasingly expecting to be provided with services such as maintenance, upgrading, user trainings or process improvement. These services do not only contribute to keeping up existing product functionalities [1] but also provide additional ones along the whole life cycle [2].

In light of this, a gradual change of traditional manufacturing companies to producing service providers [3] that focus on customer solutions becomes necessary. To support this change and to provide the basis for realizing customer solutions in terms of customer life cycle-oriented Product-Service Systems (PSS), processes for product and service planning, design and realization need to be integrated. Therefore, a novel concept for PSS life cycle management is introduced in this article. As necessary prerequisites, the main characteristics of PSS as well as the basics of Life Cycle Management are discussed in the following.

2 INDUSTRIAL PRODUCT-SERVICE SYSTEMS

Product-Service Systems are defined as customer life cycle-oriented combinations of products and services, realized in an extended value creation network, comprising a manufacturer as well as suppliers and service partners [4], [5]. In the investment goods industry, industrial PSS are made up of a complex physical product core dynamically enhanced along its life cycle by mainly non-physical services.

Thereby, a distinction between two life cycle perspectives needs to be drawn [2]. From the point of view of the product manufacturer, the product life cycle starts with product design, followed by product manufacturing, product servicing and product remanufacturing whereas from the point of view of the industrial customers it consists of product purchasing, usage and disposal. Taking these perspectives into consideration, the manufacturer has to design physical products, optimized for manufacturing, servicing and remanufacturing as well as non-physical services that support his customers during product purchasing, usage and disposal. Following PSS design, the product core is produced at a limited number of production locations of the manufacturer and the services are provided at the place of product usage by the manufacturer's service branches or his independent partners in close cooperation with the customers. Thereby, the low capital commitment of the non physical services allows for the flexible improvement of the product core as necessary.

It thus becomes apparent that industrial Product-Service Systems comprise customer and manufacturer related sub-systems with multiple interrelations (Figure 1).

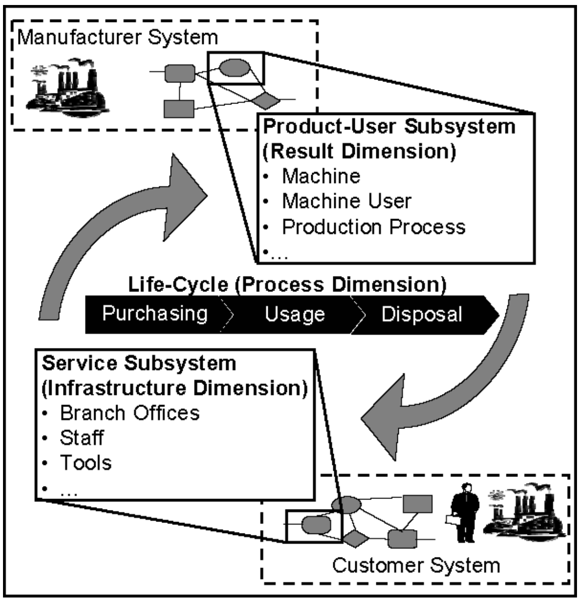

Figure 1: Product-Service Systems

The aim of the product-user sub-system, comprising the physical product core as well as the staff of the customer responsible for its operation, is to provide an expected set of functions during a production process. For example, a road milling machine and its operator are to manufacture a specific road texture during a road construction process.

The second sub-system is represented by the service network with its elements: branches, service partners, personnel, technical equipment etc. By means of services its main functions are on the one hand to keep up and enhance the above functionalities in a customer individual way and on the other hand to continuously provide the manufacturer with customer feedback [6]. For example, maintenance services contribute to the preservation of the functional level of a road milling machine, while trainings provide the user with the competencies, necessary for conducting different milling applications such as complete surface removal or improvement of its texture. Besides, due to their realization implying direct product and customer contact, information on e.g. product reliability and usability can be obtained.

With respect to designing and realizing industrial Product-Service Systems, three dimensions need to be distinguished.

- The physical and non-physical product and service components together provide the customer with a certain set of expected functionalities that represent the result or product dimension of the PSS.
- PSS realization is based on different processes such as product maintenance and training that continuously change the state of the product-user and service sub-systems along the life cycle, e.g. in terms of improved machine or service components. They represent the process dimension of the PSS.
- Finally, the service network provides the resources for executing the state changes as well as for providing the manufacturer with continuous product and customer feedback. It thus represents the information dimension.

3 LIFE CYCLE MANAGEMENT

In order to maximize product performance as well as to promote the implementation of industrial Product-Service Systems in practice, Product Life Cycle Management (LCM) can be taken as a promising starting point.

3.1 Product Life Cycle Management

LCM aims at organizing the interactions between the different life cycle partners by a set of methods and processes for the design and realization of physical products. Thus, maximum product benefit in terms of supporting the customer at using his product in an effective as well as economically and ecologically efficient way, while contributing to the business objectives of the manufacturer can be achieved [7].

Current LCM concepts [7], [8] distinguish between life cycle phase-oriented and -spanning methods. Their main ideas and deficits can be summarized as follows:

Life Cycle phase-oriented methods

- Life Cycle Engineering (LCE) comprises a multitude of function- and target-oriented rules and methods for life cycle-oriented product planning and design. Service planning and design are usually not considered therein.
- Life Time Management (LTM) aims at enhancing the life cycle performance of products by means of services. In absence of systematic life cycle-oriented service planning and design, LTM frequently remains focused on single life cycle events (e.g. product failures).
- Product Cycle Management (PCM) is targeted on closed loop systems for material and information flow. Insufficient contact between manufacturers and their industrial customers resulting from discontinuous LTM hampers the establishment of PCM.

Life Cycle spanning methods

- Life cycle information and knowledge management tools provide powerful means for consistent product data and information management. However, information gathered during product servicing is only seldom included therein.
- For evaluating the overall economic and ecologic effects of products, Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) can be applied. Though they can also be used for assessing specific product benefits of individual customers, the necessary life cycle information is often not gathered systematically, i.e. not available.
- Life cycle-oriented process management aims at standardizing and controlling the interfaces between the product planning, design and realization processes, carried out along the life cycle [8]. This does usually include neither service design nor realization processes.

3.2 Towards PSS Life Cycle Management

Based on the described deficits, important fields of action for PSS LCM can now be identified as follows:

- Based on the identification of new PSS, methods for PSS-planning are required that support the proactive specification of LTM measures in terms of services that contribute to the targets resulting from both the manufacturer's and the customer's life cycle perspective.
- Taking existing approaches from LCE as a starting point, integrated processes and methods for PSS design have to be provided. They must allow the specification of the different models, necessary for describing the product, process and information dimensions of the PSS.
- Upon manufacturing of the physical product core, its usage is to be supported by the defined LTM measures in terms of continuous service providing, taking product purchasing, product usage and product disposal respectively take-back (i.e. PCM) into account.
- By means of exploiting the potentials of services for procuring product- and usage-specific information from the product-user sub-system, a PSS knowledge base needs to be built. It must provide a solid basis for customer individual Life Cycle Evaluation as well as definition of consequential PSS improvements.
- PSS design and realization require all partners in the extended value creation network to have a common understanding of the necessary design, production and servicing processes. Therefore, a life cycle-oriented process management based on standardized process descriptions is needed.

4 FRAMEWORK FOR PSS LIFE CYCLE MANAGEMENT

In order to meet the above mentioned requirements, a novel framework concept for PSS LCM is introduced subsequently.

4.1 Overview

Building up on the manufacturer life cycle perspective, the concept covers four phases, namely Organizational Implementation, PSS-Planning, PSS-Design and PSS-Realization (Figure 2).

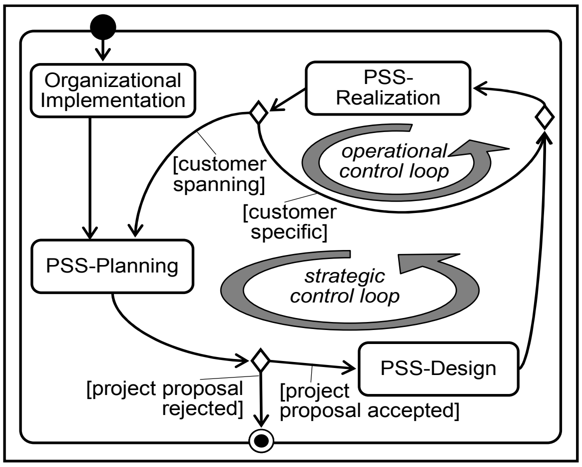

Figure 2: Control Loop Model for PSS LCM.

In the implementation phase, the basis for PSS LCM is laid in terms of building up the necessary design and realization processes as well as implementing the required organizational prerequisites within the extended value creation network. The PSS-Planning phase pertains to the identification and definition of physical and non-physical PSS components contributing to the aims of the manufacturer and customer. For their model based description, the PSS-Design phase covers the subsequent planning and execution of a PSS development project. Thereby, focus is put on managing the integration of product and service design by means of modular design processes.

Finally, PSS-Realization is addressed with respect to procuring and processing customer information that supports continuous PSS improvement and planning. Thus, the operational and strategic control loops shown in Figure 2 can be established in the extended value creation network.

4.2 Preparation

Establishing PSS LCM in manufacturing companies of the investment goods industry requires corresponding organizational prerequisites to be implemented, in terms of standardized processes as well as well defined responsibilities and organizational units. Systematic service design processes only sporadically being at all present in industrial practice, their specification represents a main focus. Together with underlying product design processes they provide the basis for building up an organizational process library as a common standard for process modelling.

In order to guarantee compatibility between product and service design, existing product design processes and corresponding methods are taken as the starting point. A common service product model can be defined by analyzing existing services with respect to their result specifications (e.g. marketing catalogues), process descriptions (e.g. working plans) as well as required resources (e.g. spare parts, tools). Furthermore, existing information exchange processes between the manufacturer, the service partners and the customers have to be documented.

Based on the analysis results, the aspired service design process is specified through analogy building. Therefore, the existing product design process is decomposed, i.e. interrelated activities and their specific input- and output-information are separately documented in table form. The inputs and outputs of the resulting process modules represent standardized interfaces that allow their mutual linkage if the output of one process module matches the input of another one [9]. For each product design process module the corresponding potentials for describing the defined service product model are then evaluated and the activities and input / output information are altered and documented as necessary. The composition of the resulting process modules for service design leads to the required service design process (Figure 3).

The modularized product and service design processes represent the core of the above mentioned organizational process library for life cycle-oriented process management.

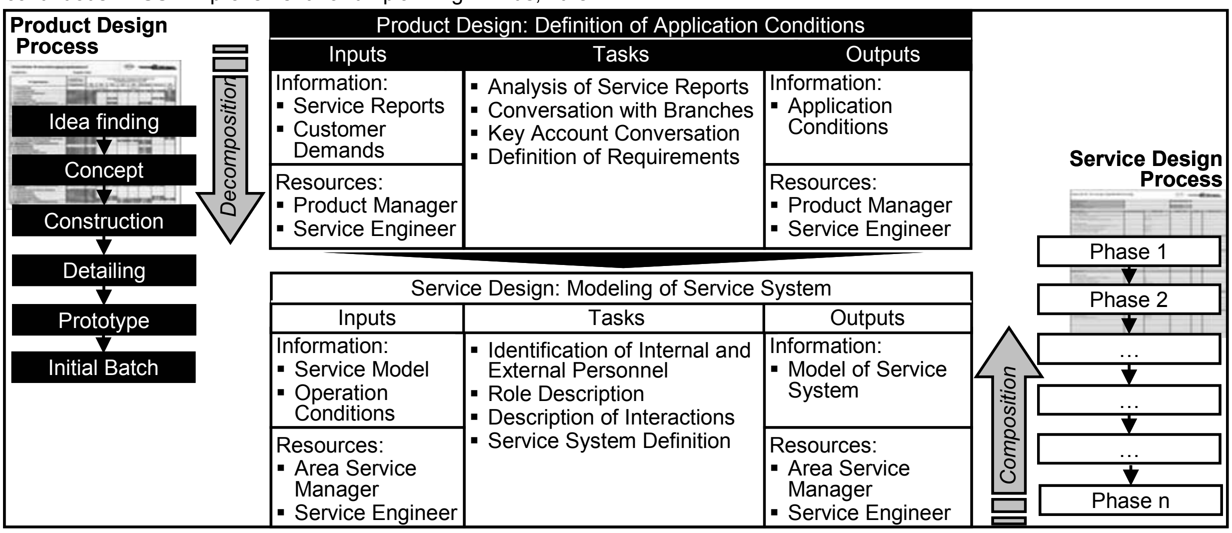

Figure 3: Implementation of Systematic Service Design Processes.

According to its envisaged scope of application, further manufacturing and servicing processes can be added.

Finally, a hierarchically organized PSS-Management needs to be installed as an organizational unit in the manufacturing company as well as in its partners in the extended value creation network. On a strategic level it is responsible for planning new Product-Service Systems, for coordinating their design as well as for their customer spanning improvement. Furthermore the continuous updating of the organizational process library is part of its responsibilities. Actual customer support is provided by the operational PSS-Management in the branch offices. Corresponding tasks pertain to customer order taking, servicing and most importantly to continuous procurement of life cycle information, by means of which the life cycle performance can be evaluated and improvement measures can be carried out.

As the result of the preparation phase, the organizational prerequisites for PSS LCM in terms of implementing the organizational process library as well as institutionalizing PSS-Management and thus the PSS information dimension are laid.

4.3 Customer-oriented PSS-Planning

PSS-Planning aims at identifying, evaluating and selecting ideas for new Product-Service Systems to be subsequently developed and put on the market.

The first step covers the creation of ideas for new PSS, based on external or internal impulses. Therefore, clearly defined targets, resulting on the one hand from the manufacturer's strategies and on the other hand from specific customer and market requirements are needed. For defining the latter, information from the realization of comparable PSS in terms of e.g. customer suggestions, complaints or failure descriptions can be used. Thus, it can be assured that the resulting target system represents the life cycle perspective of the customer.

The following idea finding is twofold. Firstly, the physical product core is defined, applying e.g. creativity techniques. Then, service ideas are attributed along its life cycle as seen from the customer's point of view. A distinction between services addressing the product-user sub-system in terms of product-oriented (technical), user-oriented (qualifying) and process-oriented services can be drawn. Supporting logistical, information-providing and financial services that address the customer system can be additionally assigned. The planning matrix shown in Figure 4 supports systematic service idea finding.

		Customer life-cycle		
		Purchasing	Usage	Disposal
Service Ideas	Technical		*Maintenance*	
	Qualifying	*User Training*		
	Process-oriented		*Application improvement*	
	Logistical			*Take-back*
	Information-providing		*Telematics*	
	Financial	*Leasing*		

Figure 4: PSS Planning Matrix

In the second step, the developed ideas are evaluated against the specified external customer and internal manufacturer targets. Then, the expected influence of the service ideas on the life cycle performance of the physical product core is assessed. Life cycle costs thereby represent a good indicator because they allow both the measurement of the possible customer benefits as well as profit potentials of the manufacturer.

Finally, in the third step promising service ideas are selected and the results from the planning phase are documented in a proposal for a new development project, subject to evaluation by the executive management.

Summarizing, a preliminary description of the product dimension in terms of the physical and non-physical PSS-components, to be subsequently elaborated, represents the main outcome of the planning phase.

4.4 Integrated PSS-Development

Based on the approved development proposal, the PSS-Development phase covers the model based description of the corresponding product and service components during a distributed PSS development project, to be executed in the extended value creation network.

In the first step, the development project is defined, regarding separate work packages for the physical product core on the one hand and the different services on the other hand. Upon determination of the project's milestones, the workplan is refined in a stepwise manner by means of the above process modules. In detail, the workpackages are decomposed into separate tasks. Then, process modules for product and service design are selected from the organizational process library in order to assure their standardized description. This is followed by an analysis of the interrelation existing between the different process modules. Supported by the Design Structure Matrix [10] method, the aim is to identify which outputs from one process module represent an input for another. Measures for bridging the resulting process interfaces between product and service design can then be specified in a pinpointed way. As a consequence, independent process modules are parallelized, unidirectionally dependent ones sequenced and bidirectionally dependent ones integrated. Figure 5 summarizes the described PSS design cycle.

Upon definition of the interrelations between product and service design, the execution of the corresponding tasks represents the second step in the development phase. Since the definition of manufacturing processes for the physical as well as servicing processes for the non-physical PSS components, i.e. the design of the PSS's process dimension thereby represents a major task, the organizational process library can again be applied in case the corresponding process module have be specified beforehand.

During the execution of the PSS development project, the strategic PSS-Management, as an organizational unit installed during the preparation phase within the manufacturing company, is responsible for project coordination and for documenting the findings resulting from each design task in the corresponding process module descriptions. Thus, the organizational process library is continuously updated and extended, so to facilitate future development projects.

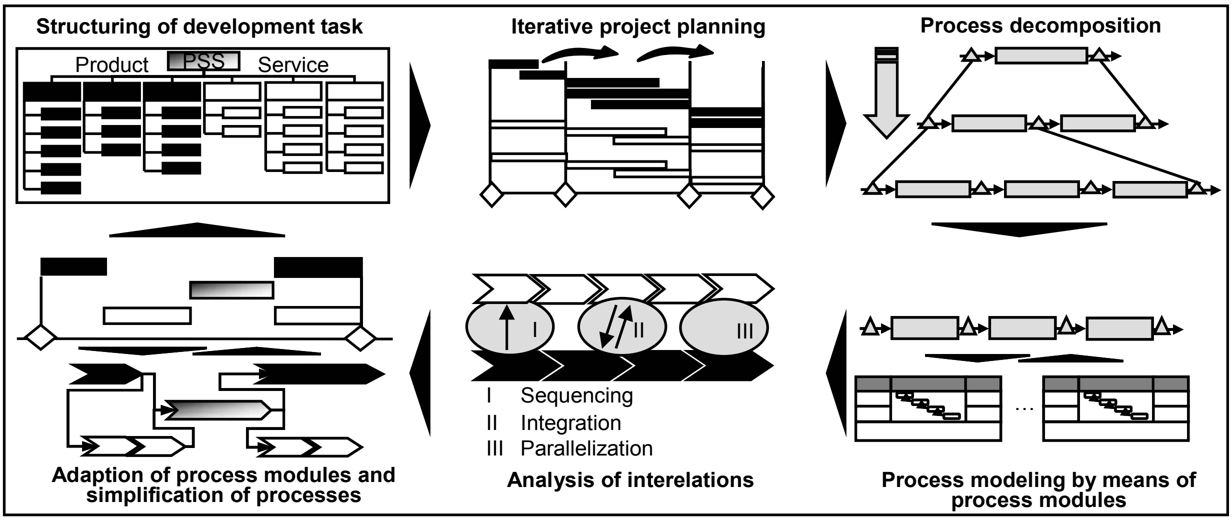

Figure 5: PSS Design Cycle.

In the third step, the designed product and service components are adapted to the requirements of the local markets. While the adaptation of the former is performed centrally by the manufacturer, it is the task of the service branches and partners, i.e. the operational PSS-Management, to adapt the latter in terms of specifying their scopes, processes, resources and modes for continuous information feedback. The PSS-Development phase ends with the worldwide market rollout.

Summarizing, the PSS-Development phase leads to a complete description of the PSS-product and -process dimensions.

4.5 Knowledge based PSS-Realization

Focus in the PSS-Realization phase lies both on providing the customers with a desired benefit through a specific configuration of products and services as well as on the establishment of the described operational and strategic control loops for their continuous customer-specific and customer-spanning improvement.

In the first step, the physical and non-physical PSS-components are configured according to the local customer demands, specified in terms of the targets pursued by the PSS. Then, individual key figures for performance measurement such as guaranteed up-times or maximum spare parts costs are defined by means of which the fulfilment of the specified targets along the life cycle can be evaluated.

The second step refers to the manufacture and delivery of the product components as well as the provision of the corresponding, e.g. product-, user- or process-oriented services. By exploiting their information procurement function, a knowledge base for evaluating the life cycle performance of industrial PSS as well as for defining corresponding improvement measures can be built up. It is thereby necessary for the branch offices or service partners to define individual information requirements for each customer PSS, depending on the input information necessary for calculating the defined key figures. This can e.g. pertain to the service technicians reading out autonomously generated machine-data. Upon retrieval of this information and subsequent calculation of the key figures, it has to be decided whether product- or service-related improvement measures need to be initiated. Workshops with the customers provide a useful means for supporting their definition. Thus, the identification and implementation of customer-specific improvement potentials (e.g. operating errors / operator trainings) results in the establishment of operational control-loops.

Furthermore, taking all Product-Service Systems on the market into account, identification and implementation of customer-spanning improvement potentials (e.g. product errors / product redesigns) results in the establishment of strategic control loops, in terms of the numerous improvement potentials identified in a cross-customer manner providing a substantial basis for new PSS-Planning.

5 CASE STUDY FROM THE COMMERCIAL VEHICLE INDUSTRY

The presented concept has been developed and tested together with a medium size enterprise with core competencies in the design and manufacturing of heavy road construction machines. Being the market and technology leader in road milling machines, it relies on a service network comprising branch offices as well as independent partners.

The enterprise relies on systematic processes for designing and developing products and services to be customer-individually configured. Both processes have been standardized with the aim of building up an organizational process library according to the above implementation phase. Furthermore, by means of extending the scope of the existing service organization in headquarters as well as the service network, the described organizational units, namely strategic and operational PSS management, have been implemented.

As one of its main tasks, the strategic PSS-Management is responsible for continuous planning of new PSS ideas, based on a set of internal and external targets, among others resulting from information, obtained during the servicing of existing machines. As an example, it has been stated by the customers that the flexibility of the road milling machines has to be enhanced concerning the possibility to manufacture different road surface textures. Thus, the PSS-Planning phase resulted in the specification of a flexible cutter system (FCS), i.e. a milling drum that can be task-specifically (e.g. deep milling, surface removal or increase of surface roughness) exchanged. To enhance this physical product core, corresponding technical, qualifying, process-oriented and logistical services were defined. Thereby, technical services referred to upgrading already existing machines with the FCS. Qualifying services aimed at instructing the machine users concerning the correct exchange of the milling drum. Process-oriented services were defined for optimizing milling processes in the field (e.g. cutting specific road materials with minimum wear picks). Logistical services finally pertained to supplying the customers in the field, i.e. on the construction sites with required spare parts (e.g. picks, tool holders).

Upon approval of these ideas by the executive management, a development project was initiated as the first step of the PSS-Development phase. The project plan contained workpackages for designing the FCS as well as the corresponding services. According to the above development phase the workpackages were decomposed into separate tasks and described in a standardized way by means of the process modules stored in the organizational process library. The following interrelation analysis e.g. resulted in a joint definition of assembly instructions for the manufacturing as well as the service staff as shown in Figure 6. This was accompanied by the planning of the required resources such as the equipment needed for upgrading and the logistical processes for worldwide spare parts supply. Furthermore, the modes and processes for continuous information feedback, especially concerning the information to be gathered by the service technicians on wear of the milling drum, toolholders and picks were defined. As the last step of the development phase, the new PSS was rolled out in the service network. Here, a major task referred to adapting the service process descriptions to the local markets.

Figure 6: Flexible Cutter System for road milling machines.

During the currently running PSS-Realization phase, performance measurement figures such as process time per square meter, up-time or average tool costs have been specified for specific pilot customers. Upon servicing of the machines, the required input information for their calculating is procured continuously. Thus, operational and strategic improvement measures such as additional user trainings or minor FCS design changes could be initiated and the customer and manufacturer benefit increased systematically.

6 CONCLUSIONS

The integrated planning, development and realization of industrial PSS within the extended value creation network requires a systematic approach spanning the whole product life cycle. Therefore, in this paper a novel concept for PSS life cycle management has been introduced. Starting with an introduction of both the specific characteristics of PSS and the basics of product-oriented LCM, requirements for PSS LCM have been pointed out. On this basis, a novel concept for PSS LCM has been introduced.

The concept is characterized by taking into account the specific characteristics of industrial PSS to be realized in an extended value creation network. Thereby, systematic planning, development and realization of industrial PSS with respect to enhancing both manufacturer and customer benefits represent the main activities. First applications such as described in a case study show its potentials in the investment goods industry.

7 ACKNOWLEDGEMENTS

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Development of International Integrated Resource Recycling System

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Abstract
It is expected to establish International Resource Recycling System (IRRS) for dealing appropriately with environment concern. Because, Asian countries have been rapidly growing economically in recent years, whereas environmental problems have become more serious. They have become global, complicated and beyond control of a single country. Fuji Xerox established the “Recycling-Site” in Thailand as an integrated recycling center over the Asia-Pacific region and built the worlds’ first full-fledged “IRRS” of its own accord In December 2004. It overcame numerous barriers, including the differences in organizational and social values among nations. We reviewed and analyzed direction, factors, structures and essences of this system for its success.

Keywords:
CIRP International Conference; Life Cycle Engineering; Recycling

1 INTRODUCTION

The Asia Integrated Resource Recycling System of Fuji Xerox (FX) is the first manufacturer-initiated, full-fledged recycling system in Asia. This case represents a new system that was built to transcend national boundaries and traditional custom, based upon a broad partnership of many interested parties as EPR (Extended Producer Responsibility) to cover countries/regions in the Asia-Pacific region. This study is to analyze the realization of this particular case in terms of the system elements with an eye on the subsequent investigation into the ideal establishment of an international integrated resource recycling system (IIRRS) model in the future. In addition, we conducted a technological study into prospects for the construction of a waste electrical and electronic equipment (WEEE) recycling system based on the examination of recycling technology existing in Thailand. We are certain that it could be an example for deployment of future Resource Recycling System internationally within and without office equipment industry.

2 ANALYSIS OF ASIA INTEGRATED RESOURCE RECYCLING SYSTEM MODEL

System concept: IIRRS is understood from the following five perspectives.

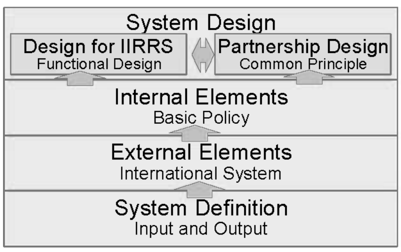


Figure 1: Modeling Framework.

1. **System Definition**: Basic differences from the conventional system.
2. **External Element**: Overcoming of external barriers and construction of a new system.
3. **Internal Element**: Basic deployment policy for construction of a new system.
4. **Design for IIRRS**: Key components of basic design.
5. **Partnership Design**: Key components of partnership development design.

2.1 System definition

With regard to treatment of used machines, subsidiaries of each country have independently contracted with local industrial waste disposal companies to handle industrial discharge, resulting in recycling quality variation. The system introduced this time is to discontinue the independent treatment of used machines in nine countries and region in Asia, and to deliver those to a recycling center in Thailand beyond national borders; furthermore, establishment of the integrated recycling system enables disassembly at FX’s captive recycling plant according to FX recycling quality criteria with an aim at implementing 100% recycling to the extent possible, and eliminating waste across Asia.

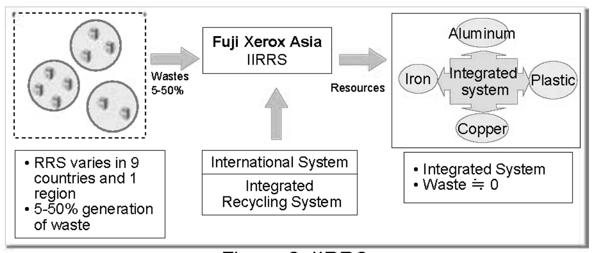


Figure 2: IIRRS.

2.2 External elements

Construction of a resource recycling system in Japan is feasible in a closed-loop framework, based on national laws and regulations, Japanese recyclers with high recycling capabilities, and a central management system for domestic supply/reverse logistic channels. The Asian resource recycling system, however, cannot be executed in an identical manner. It constitutes a regional or interregional recycling system that transcends national boundaries.

The overcoming of external elements is first required, including intentions of different national governments, and surpasses business requirements, such as restrictions, regulations, and customs, before internal can be addressed. Therefore, such external elements as the second layer of a modeling framework are viewed as separate. Our aim is to centralize waste treatment functions in one country across borders, in other words, the development of an integrated recycling base for the Asian region. Removal of restrictions on imports and exports for the base country, formation of high-level recycling partnership (network) primarily in the base country, construction of interregional distribution logistics channels, and ensuring feasibility are prerequisites for realization of the system. FX selected Thailand from the viewpoint of government assistance for relaxation of regulations, and the advantage of recycling infrastructure building.

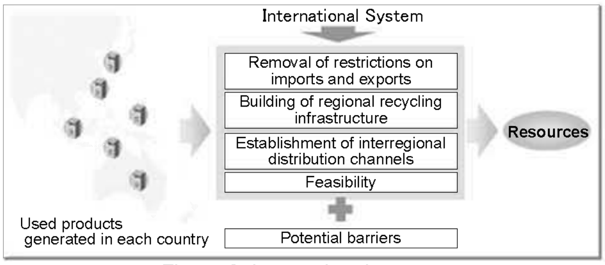


Figure 3: International system.

2.3 Internal element: Basic policy

Foremost, we internally share the FX general policy: **"Promote the reuse of resources for Infinite Zero Landfill"** [corporate social responsibility (CSR)], and the establishment of manufacturer/distributor roles and responsibilities. Next, we promote proliferation of the idea that used products should be collected and recycled at the cost of distributors (a responsibility of waste generators), and that manufacturers should be responsible for waste treatment [extended producer responsibility (EPR)]. Finally, it will be necessary to establish a basic policy from a global perspective to realize the IIRRS scheme.

1. We will not change processes and goals that have been established and highly regarded in Japan

   Many recycling partners agreed on our concept, and participated by a sense of the desire to contribute to Thailand and other Asian nations. Double standards must be prevented.

2. We will gain the trust of our partners, namely stakeholders, and achieve mutual understanding

   It took from 1.5 to 2 years to obtain approval from the governments of Thailand and Australia. What they asked of us were the four basic principles of trust.

3. Four basic principles of "zero burden" of an international system

   If a neighbor disposes garbage in your garden, of course you will get angry. Thinking along the same line with respect to crossing the border, four basic principles were derived. Establishment of these basic policies constituted a major contributing factor in overcoming potential barriers as indicated in Figure 4.

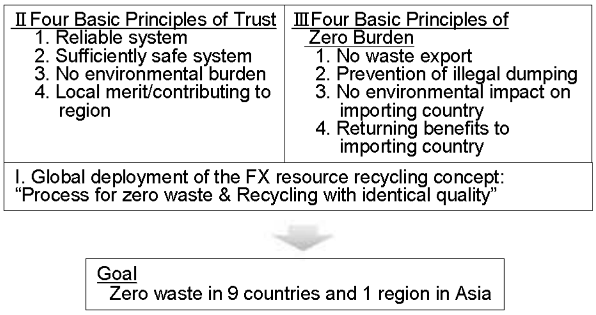


Figure 4: Basic policy.

2.4 Design for IIRRS

Thailand was selected as an integrated recycling base for securing collected volumes. To ensure the same recycling quality, we decided to operate our captive plant and formed our own operational control framework. Furthermore, for risk management, we newly added a manifest and environmental audit system, introducing a mechanism that allows FX to fulfill responsibility for management of all of operations in a closed loop.

The plan for realization of the four basic principles of trust under the cross-border resource recycling system ensures no environmental burden in a tracking system that avoids risks including illegal abandonment and in the handling process, and transparent implementation. In the future, international standardization of these two systems will be a key element of IIRRS progress.

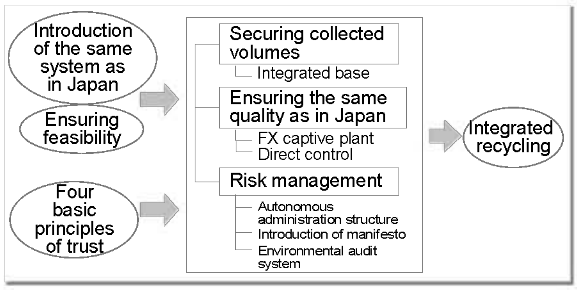


Figure 5: Integrated recycling system.

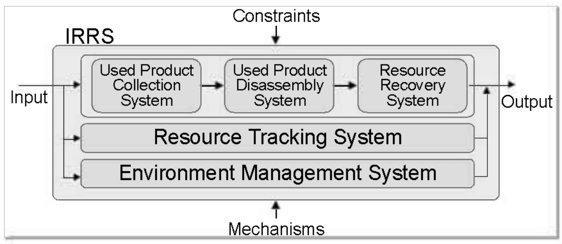


Figure 6: Function design.

2.5 Partnership design

"Recycling and distribution logistics operations" under this system can only be realized through the cooperation of reliable partners. Sharing of a lofty philosophy and aim that transcends different partnership positions will be required.

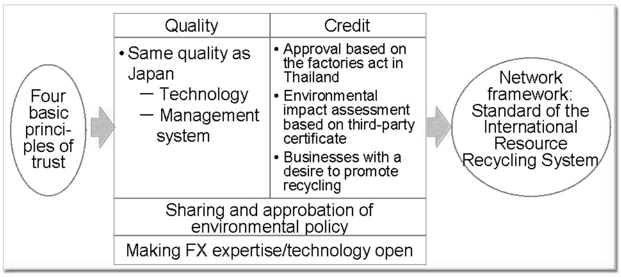


Figure 7: Common Principle—partnership design.

3 VERIFICATION

3.1 WIN-WIN relationship

The FX IIRRS went into full-scale operation in December 2004 and has been running successfully. Assessment obtained from FX and the governments are given below. We confirmed a WIN-WIN relationship by conducting interviews for stakeholders who support the System, i.e. recycling providers and logistics companies.

1. All of the partners made it clear that they enjoyed a WIN-WIN relationship.
2. What they have obtained through IIRRS.

   Improvement of corporate image that efforts for recycling are being made, and raising of environmental awareness of employees.

   Contributing to Thailand by utilizing resources, preventing illegal waste dumping, thanks to FX's provision of recycling procedure in line with the environmental policy etc.
3. Strengths of and requests for the IIRRS.

   It is the manufacturer-led system that has gained governmental recognition and allows easy control of scrap quality and stable supplies.

   It has the advantage of being able to expand into other industry sectors. We want FX to increase visibility and enlarge the IIRRS trunk. We will be pleased to become a designated IIRRS plant; et al.

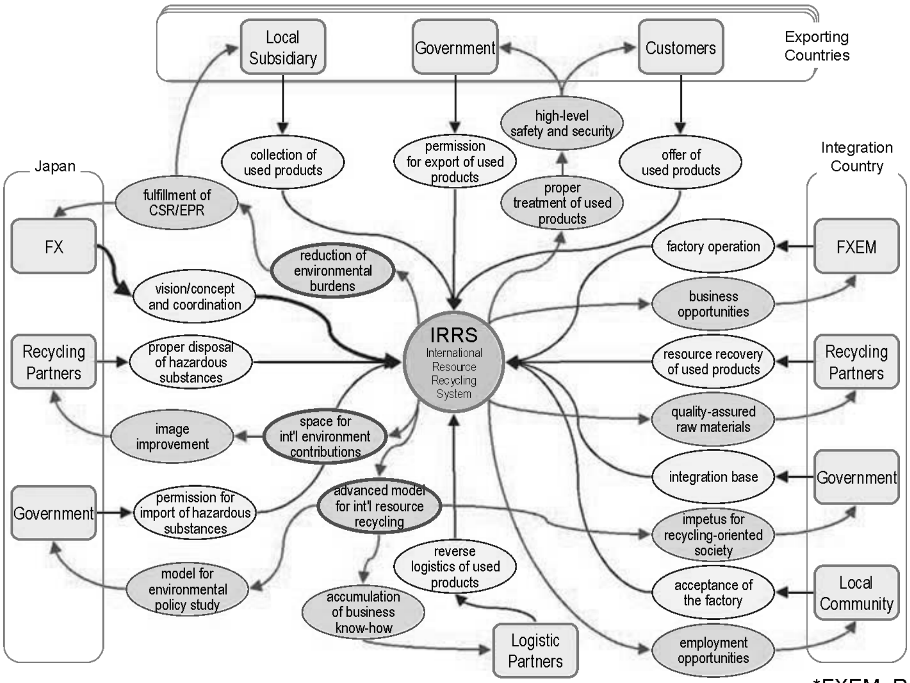
Figure 8 is a WIN-WIN relationship diagram.

For future studies, we plan on implementing the following:

1. Analysis of system factors contributing to a WIN-WIN relationship.
2. Delving deeper into a WIN-WIN relationship with government officials.

Table 1: Effect of IIRRS construction (FX case).

	Fuji Xerox	Thailand/All of Asia
Development of international system	･Immediate achievement of zero landfill throughout nine countries and regions in Asia ･Externally appreciated CSR	･Model center in Thailand (WEEE, EPR, zero landfill) ･New employment, investment ･Utilization of recycled material resources
Reduction of environmental burden	･Landfill volume 1,000 t (Processed before integration: Estimated) --> 104 t ･Complete recycling of hazardous substances	･Improvement of working environment ･Reduction of environmental risks



*FXEM: Recycling-site in Thailand

Figure 8: WIN-WIN Relationship of Stakeholders. [1]

3.2 Advantages of EPR (business involvement)

This study focuses on an EPR (company-initiated) system model, which is built upon the following advantages. In the future, there will be a need to make a comparison between government- and private sector-initiated practice models with the aim of promoting optimization.

1. Hazardous wastes

   Businesses have extensive knowledge on toxic contents and are capable of responsible separation and treatment.

2. Collection

   Development of a venous logistics network is easy by use of return route of arterial logistics network.

3. Technology

   Businesses are very familiar with the parts material and ease of disassembly of their own products, and are able to introduce and expand technologies based on their experience in Japan.

   On-site problems are reflected in next generation product design for improvement.

4. Management skills

   Recycling quality management with the help of corporate management ensures high reliability.

   - High recycling criteria.
   - Central management of a tracking system.
   - Transparency by disclosure of information.
   - High degree of trust in international transfer led by manufacturers.

5. Business cooperation

   Recycling network based on high degree of trust by stable quality, led by manufacturers.

4 TECHNOLOGICAL CONSIDERATION FOR CONSTRUCTION OF WEEE RECYCLING SYSTEM IN THAILAND

Presently, recycling treatment with a low environmental impact is required to WEEE on a global scale. Given such trends, it is contemplated that a proper recycling technology will be necessary for Asia in the future. This time, we analyze the recycling technology of the Asia Integrated Resource Recycling System and Japan's home appliances recycling technology for the consideration of recycling technology needed for WEEE recycling in Thailand.

4.1 Recycling Technology of FX Asia Integrated Resource Recycling System

The main features of recycling process of the Asia Integrated Resource Recycling System are as follows:

1. Thorough manual disassembly and meticulous separation, ensuring a high recycling rate.
   - Manual disassembly does not generate shredder residues to be landfilled.
   - Separation process is conducted under 64 categories; a recycling rate of 99.6% can be achieved (estimation per representative model unit) by selecting recycling partners suited to these categories.
2. Ensuring thorough safety management for treatment of parts containing hazardous substances.
   - In the case where there is not an appropriate treatment process in Thailand, recycling processing is performed in the proven Japanese recycling infrastructure.
3. As for mixed plastics that are difficult to execute material recycling processing, thermal recycling is realized through the use of auxiliary fuels of cement Kiln so as to avoid landfill disposal and simple incineration, ensuring zero waste.

4.2 Home Appliance Recycling Technology in Japan

We examine proven Japanese home appliance recycling technology with respect to typical WEEE products such as TVs, washing machines, refrigerators, air-conditioners.

1. Recycling process of home appliances in Japan

   The recycling process of Japan's typical home appliance plant consists of three operations as the diagram in Figure 9: 1) manual disassembly pre-treatment, 2) automatic shredder and separation process, and 3) recycling of materials sorted.

   - Manual disassembly pre-treatment.

   Set up disassembly lines by product category: refrigerators, washing machines, air-conditioners, and TVs.

   Prior to the automatic shredder and separation, hazardous objects and parts which cannot be treated by automated machines are disassembled and separated by hand.

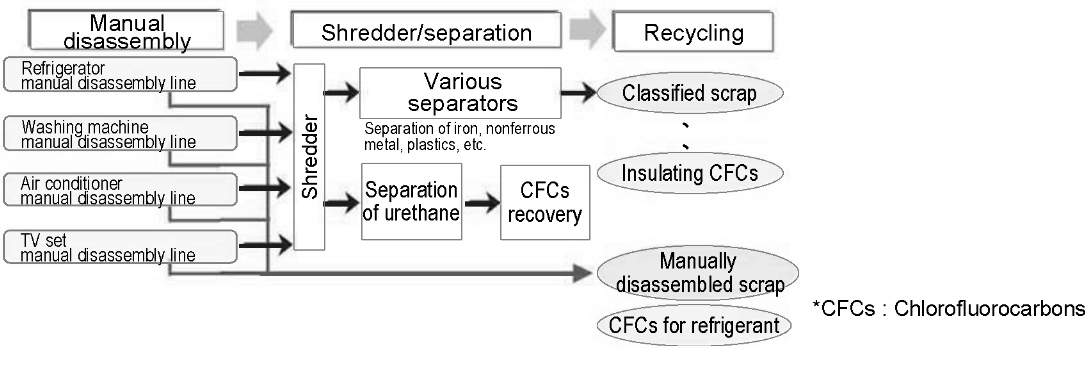


Figure 9: Recycling Process of Home Appliance Plant.

- Automatic shredder & separation.

  Main case other than parts disassembled and separated manually are put in a large size common shredder machine for crushing; metals such as iron, copper and aluminum, and plastics are retrieved by magnetic separator/eddy-current separator/gravity separator.

  In ordinary practice, shredder dust often winds up in a landfill.

  Since heat insulating urethane materials of refrigerators contain CFCs, they are separated after treatment by shredder; and additionally, fine grinding is conducted to retrieve CFCs.

- Recycling of items sorted.

  Metals such as iron, copper and aluminum, and parts such as boards, motors, and compressors which have been disassembled and sorted are treated for recycling by recycling manufactures.

2. Characteristics of home appliance recycling technology.

   Techniques necessary for the above-stated home appliance recycling technology are as follows:

   - Manual disassembly pre-treatment.

     Prior to the automatic shredder and separation process, parts needed for preliminary separation are to be disassembled by hand; for that purpose, operational know-how is required, including classification of parts and the efficient performance of disassembly procedure.

   - Automatic shredder & separator.

     In order to break down large quantity of home appliances into materials and parts appropriate for recycling, it is necessary to ensure consistency with manual disassembly pre-treatment, and an automatic unit capable of efficient disassembly and separation is required, for which the device design technique is needed.

   - Technique for recycling treatment of items sorted.

     In order to ensure a recycling process for a wide variety of sorted items without fail, it is necessary to select recycling partners suited to such sorted items.

4.3 Comparison of Items to be Disassembled and Sorted: Used Office Equipment vs. WEEE

As the data is arranged in Table 2, scrap sorted from office equipment such as copiers and printers is mostly common to that of WEEE; such as home appliances and PCs. It can be said that a scrap item unique to WEEE is CFCs. Accordingly, it is contemplated that it will be possible to utilize the recycling technology of office equipment for the recycling of items to be disassembled and sorted from WEEE.

Table 2: Comparison of items to be disassembled and sorted.

Scrap produced	Office equip-ment	WEEE equipment	
		HA	PC
Ferrous metal	○	○	○
Aluminum metal	○	○	○
Copper metal	○	○	○
Rigid resin	○	○	○
Flexible resin	○	○	○
Expanded polystyrene	○	○	○
Toner	○	X	X
Rubber material	○	○	△
Combined electric and mechanical parts（motor, transformer, etc.）	○	○	○
PWBA	○	○	○
Electric and cable wire	○	○	○
Sheet glass	○	○	○
Mirror/lens	○	X	X
Cathode-ray tube	○	○	○
Fluorescent lamp/LCD backlight	○	○	○
NiCd battery	○	X	△
Se-Drum	○	X	X
CFCs/Cyclopentane	X	○	X
Paper products（cardboard/manual）	○	○	○

4.4 Challenges in the Development of WEEE Recycling Technology in Thailand

In the case where we establish WEEE recycling technology in Thailand based on the above-mentioned technical knowledge, the following case is envisaged as a potential model:

1. Construction of disassembly and separation process by utilizing Japan's home appliance recycling technology.

   In order to execute efficient disassembly and separation for WEEE recycling, it is contemplated that the same unit as those in Japanese home appliance plants will basically be necessary. Also, when transferring Japan's technological know-how on home appliance recycling, the following points are to be noted for implementation. It will be necessary for Thailand to acquire the know-how, including classification of parts to be separated prior to the automatic disassembly and separation process, and establishment of appropriate procedures and selection of facilities for efficient disassembly.

   - Optimization of manual disassembly lines taking advantage of Thailand's characteristics.
   - Design optimization of a shredder device consistent with manual disassembly lines, and of magnetic separator/eddy-current separator/gravity separator.

2. Construction of a technical infrastructure for recycling by making the maximum use of the recycling network in the Asia Integrated Resource Recycling System.

   Since scrap sorted from WEEE is mostly common to that of office equipment, it will be possible to utilize the recycling infrastructure of the Asia Integrated Resource Recycling System that is currently in operation. Additionally, for utilization of the recycling infrastructure, Thailand involves the introduction of technologies that are lacking in this country; main technologies to be transferred are as follows:

- Technology to recycle PWBA or shredder residues into materials for copper smelting.
- Recycling technology for fluorescent lamp.
- Technology to render CFCs harmless.

As mentioned above, we examined a potential model for construction of the WEEE recycling system from a technical point of view, although it simply is a feasibility study in the sphere of the past primary research activity. In the future, we will require further considerations regarding the transfer of Japan's home appliance recycling technology, coordination with the recycling network of the Asia Integrated Resource Recycling System, and introduction of scarce technologies into Thailand.

Meanwhile, from the point of view of considering construction of the whole of WEEE recycling system, there will be more significant challenges, including the preparation of legislation such as Japan's Home Appliance Recycling Law, and improvement of a collection system, which we believe requires discussions primarily by the Thai government and the consumer-electronics industry in Thailand.

5 CONCLUSION

5.1 This study on the IIRRS is an analysis of elements for the establishment of the FX Asia Integrated Resource Recycling System as an EPR-based model case, "aiming at zero landfill through companies' efforts for collection of their own products and for recycling".

Overarching point: The independent EPR-based system constitutes an interregional scheme that transcends national borders from the perspective of securing collected volumes.

(X) Construction of an international framework is required.

(O) Immediate achievement of the goal is feasible by integrating nine countries.

(O) Closed-loop system is established; FX undertake all of the responsibilities.

- Ensuring high-quality and low-risk system.
- Consequently, WIN-WIN relationships of stakeholders are realized.

5.2 The concept for the IIRRS varies according to the following structures:

- Company-initiated vs. Government-initiated vs. Government-Business complex.
- Treatment in each country vs. Interregional collaboration.

As the second step, based on the system model analyzed in this study, we would like to explore a WIN-WIN relationship in more depth, including the viewpoints of stakeholders, and to make efforts toward generalizing the system.

5.3 Regarding establishment of WEEE recycling technology in Thailand

As a model case of development of an efficient, safe recycling system, we considered transfer of Japan's home appliance recycling technology and coordination with the recycling network of the Asia Integrated Resource Recycling System from a technological standpoint. In the future, we will continue investigation on concrete technical-infrastructure-building, including the introduction of scarce technologies into Thailand.

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As the first step, we compiled modelling of this Fuji Xerox's pioneering recycling system to understand it as a whole by clarifying framework, elements in this system that was set out at International Conference on Eco-Balance in November, 2006.

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New Financial Approaches for the Economic Sustainability in Manufacturing Industry

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Abstract
Equipment finance is becoming a crucial task in the manufacturing sector, where the value of production systems can be considerable and the appropriate financing choice can impact on company competitiveness for years. Several variables, requiring new interdisciplinary competencies and approaches, have to be evaluated by companies while taking financial decisions. A survey realised in "Next - Next Generation Production Systems" FP6 European project revealed that a new financial culture and adequate instruments are needed to sustain European manufacturing competitiveness. This paper proposes a structured approach for the selection of suitable financial methods supporting the acquisition of production capacity in the frame of innovative manufacturing business models.

Keywords:
Equipment finance; Financing models; New Business Models

1 INTRODUCTION

Equipment finance is the process of selection and adoption of proper financial methods for the acquisition of production capacity. This process is crucial for industrial companies, especially in sectors where machinery value is considerable and the choice of the appropriate financial instrument can have consequences on company competitiveness in the medium-long period.

The choice of a financial method, which defines buyer-seller relationships in terms of repayment way and supply responsibilities, is very complicated because of the availability of several options (such as loan, leasing, renting, forfaiting, project financing, etc.) on the one hand, and because of the need to evaluate many variables at the same time on the other. Such variables are determined by globalisation factors, technology level, hard competition, market turbulence and the diffusion of innovative business models.

Besides economic and financial impacts, suitable financial decisions can influence production paradigms which respect the environment. An example is when an acquisition contract implies the return of machinery to the producer, who is equipped for its re-use or ecological disposal at low costs.

For all these reasons, effective equipment finance decisions require nowadays multidisciplinary competencies and adequate supporting tools. Results of a survey conducted in the frame of "Next - Next Generation Production Systems" IP FP6 European Project showed that, because of the increasing demand from end-user customers for wide-ranging services from their suppliers, and the conservative culture of this specific industrial sector, European manufacturing companies are generally not prepared to manage equipment finance decisions as a fundamental pillar for their future competitiveness and innovation.

This paper proposes a structured approach to support financial and industrial actors in the selection of a set of suitable financial models supporting the production systems acquisition process. The methodology followed for the definition of such an approach consisted of a preliminary state of the art analysis which enabled an understanding of the main existing barriers for the diffusion of innovative financial practices in manufacturing. Then, financial guidelines were developed and tested involving both financial and manufacturing actors.

2 REQUIREMENTS FOR A DIFFUSION OF INNOVATIVE FINANCE PRACTICES INTO THE MACHINE TOOL BUILDER INDUSTRY

A wide analysis of the available literature about equipment finance was initially assessed [1] [2] [3], even outside manufacturing sector [4] [5] [6] [7], in order to understand the barriers which limit the evolution of financial practices in manufacturing. In fact, management innovations are already common in other business fields where the competitive situation has pushed companies to develop earlier response mechanisms, like in the Engineering and Contracting [8] or Information and Communication Technology industry [9]. The study of such experiences is a valid starting point to transfer successful experiences in other fields.

All existing financial instruments have been identified [5] [10] [11], their application and use mechanisms have been assessed, together with the conditions which make their application suitable. As a general example, project financing is indicated for big investments where several stakeholders having advanced management and financial skills are involved, and when investments related to the project are well declined and programmed. Similarly, forfaiting [12] can be an option for import/export transactions (typically up to 500,000 Euros) and when a bank guarantee for the importer is available. In total, 26 financial instruments have been identified, analysed and classified.

Having this knowledge as background, a case studies campaign was conducted involving financial institutions and manufacturing companies (machine builders and industrial end-users) in Europe, with the scope to assess the real state of the art about equipment finance in manufacturing. In particular, case studies were meant to understand:

- What are really the most used equipment financing methods in manufacturing.
- What are the main difficulties in the relationship between industrial and financial companies.
- What are the improvement opportunities in equipment finance.
- What are the actual barriers to be overtaken in order to introduce new financing methods. These barriers have to represent the starting point for the definition of requirements that new instruments and tools will have to satisfy to support innovation in equipment finance.

In order to consider all actors involved in financial decisions and not only "single side positions", interviews have been addressed to different types of business subjects:

- Financial actors (banks, leasing companies, forfaiting companies, financial service companies), which are the offering party in the relationship system.
- Industrial manufacturers, that represent the customers who need financial services to support the acquisition of machinery or production services.
- Machine builders, which are the suppliers of industrial goods and that, depending on the situation, can offer their own financial services to end users, can cooperate with financial actors for a combined offer of products and services to industrial manufacturers, or can remain outside of the decision ring.

In total, 19 case studies have been conducted in Italy and in Spain, 9 with financial actors, 6 with industrial manufacturers and 4 with machine builders. Results elaboration suggested the following main conclusions:

- There is a general lack in the financial culture of European manufacturing companies: interviewees remarked that they have, in general, a partial knowledge of all the available financial methods to be used and they need support while taking financial decisions. This lack in financial culture leads companies to consider financial subjects as a complicated "black box", and makes them worried about possible opportunistic behaviours of financial partners. This situation does not permit them to benefit from the potential advantages coming from an open relationship and cooperation.
- Financial actors are not generally able to interpret industrial customer needs because they lack the specific technical competencies to understand technology and industrial markets. As a consequence, they request high guarantees in order to grant financing, which make financing conditions often hard for their customers.
- The use of financing methods by industrial companies is restricted to a very few number of traditional standard options, mainly bank loan, leasing (for fiscal benefits it offers), and renting. This aspect is linked to the detected general lack in companies' financial culture that makes them unaware of all the possible financial options at their disposal. This does not enable them to evaluate the advantages and disadvantages that arise from the adoption of different financing methods. In addition, a general conservative approach of companies operating in machine tool builders industry can be detected.
- Requests made by industrial companies to financial actors are, in general, standard and very basic: they ask for low costs, positive fiscal impacts, low time of implementation, possibility of payment deferment and no guarantees. Advanced requests, such as assistance in exportation or financial risk mitigating instruments, are very rarely requested.
- The involvement of external third parties is potentially convenient for all the parties: external actors with multidisciplinary competences (financial and technical) and playing a system integration role, could create advantages at system level. In fact, every party could focus on its core competencies and rely on these external integrators for the necessary know-how they do not own: financial institutions have not often the necessary knowledge to manage capital goods in terms of technical and re-use aspects, end users often need support in the financial decision process, machine tool builders are not able to manage the selling process from the financial point of view and to correctly assess the risk of some models they propose. The involvement of external parties is judged by all interviewed companies to be more feasible than acquiring the missing competencies, especially because of the difficulty in acquiring competencies far away from their core business.

Literature analysis and survey results lead to the definition of the following requirements that should be fulfilled for the innovation of equipment finance management in manufacturing industry:

1) The use of all existing financial instruments has to be promoted through their contextualization in the manufacturing sector, in order to enlarge the range of options that companies can have at their disposal for a better management of financial issues when acquiring production systems.
2) New flexible financial instruments, considering the direct involvement of machine builders in the financial process and allowing the ownership of the production system to shift from the end user to the machine tool builder, have to be better defined with respect to the actual state of the art and customised to the sector.
3) Simple but effective financial guidelines have to be developed with a dual scope:
    - To support end users in the preliminary selection of financial instruments suitable for their specific situation, before the involvement of a financial partner. In this way, they could be better aware of their needs and possible options.
    - To support financial actors and machine tool builders in their offer processes, in order to use an interdisciplinary approach that considers all the relevant variables for the customer (technology, finance, market, organisational situation, etc.) and not only the ones directly managed by the offering party (typically, finance for financial entities and technology for machine tool builders).

3 FINANCIAL GUIDELINES

With the scope of supporting the diffusion of innovative forms of financing in machine tool builders industry, helpful Financial Guidelines have been developed in the frame of

"Next" European Project. Financial Guidelines are particularly useful when companies decide to sell their products using innovative business models, oriented to the offer of a functionality (obtained through a mix of high customised products and services), rather than a physical product.

Purposes of Financial Guidelines are:

- To propose to equipment end users a wide range of adoptable financial instruments, both already used and innovative ones, which are not currently well known nor clearly defined in the literature.
- To support machine tool builders in their proposal processes, in order to make them able to offer high value financial assistance related to equipment they produce.
- To help financial actors to better understand technological and industrial needs while proposing financial products to their customers.
- To allow a preliminary fast selection of financial instruments suitable for a specific business scenario, whilst considering variables related to company, market and technology.

Financial Guidelines consist of three main elements:

- A catalogue of financial instruments applicable in manufacturing sector: main financial instruments, already used in manufacturing and in other sectors and potentially adoptable in machine builder sector, have been selected from the wide range of available options and on the basis of the survey results on the one hand; more innovative instruments have been better characterised on the other.
- A restricted number of drivers for financial decisions in manufacturing sector: decision drivers related to heterogeneous aspects of the business have been considered in order to support the preliminary selection of adoptable financial instruments.
- An algorithm supporting the selection of financial instruments suitable for a specific business situation.

3.1 Catalogue of financial instruments applicable in manufacturing sector

The catalogue represents a list of financing possibilities that manufacturing companies and machine builders have at their disposal when they decide to acquire production capacity.

The catalogue has been defined contextualising in the manufacturing sector the instruments already available on financial market on one side (both actually diffused and not diffused), and better defining some innovative financial method based on the use payment criteria rather than on machines payment criteria on the other.

To select financial methods reasonably applicable for equipment finance among the existing ones, an initial list has been elaborated on the basis of the knowledge acquired from state of the art and interviews, and has been submitted to financial actors in order to have some expert opinions. The methods available in the financial market and judged potentially useful in manufacturing sector are:

- bank loan;
- trade credit;
- overdraft;
- leasing (financial and operative);
- factoring;
- forfaiting;
- stand-by lines of credit;
- commercial paper;
- syndicated lending;
- bank advances;
- project financing;
- bonds;
- venture leasing;
- equity (available internal funds or capital call);
- countertrade.

Besides the list of already diffused financing methods, three innovative forms of financing to acquire production capacity, specifically aimed to the implementation of New Business Models, have been better defined with respect to the actual state of the art [13] and have been added to the catalogue:

- Pay Per Part (PPP): end users acquire production capacity as a service, paying the owner of the machines (machine builder or financial actor) on the basis of production volumes (i.e. the number of parts produced).
- Pay Per Use (PPU): the payment is based on the time the manufacturer uses machines (comprehending stops for maintenance, repairs, etc.).
- Pay For Availability (PFA): the payment is based on the total time of machines' functioning correctly (without considering time spent for maintenance or breakdown).

For these three financing instruments, the general variables to be considered for their assessment have been outlined. The adoption of innovative financing methods oriented to the use of equipment supported by Financial Guidelines, develops also in the direction of a better lifecycle management and environmental impact of capital goods, since for machine suppliers, which remain the owners, eco-management, continuous maintenance and proper disposal becomes part of the core business.

To facilitate users of the Financial Guidelines in the comprehension of all methods, an introductive sheet has been prepared for each of them, explaining the basic mechanisms of its application and its relevant parameters.

3.2 Drivers for financial decisions in manufacturing sector

According to the survey results and considering peculiarities of manufacturing sector and industrial companies, a set of decision drivers to be taken into account in equipment finance decision processes has been defined. In particular, drivers are related to four different aspects of end users' business and can be divided in:

1) Organisational drivers, referring to End User (EU) company general internal situation:
    - EU firm size: indication of company size through the turnover and the number of employees.
    - EU legal form: type of EU legal form.
    - EU firm age: years of activity on the market.
    - Export: it indicates if the EU is an exporter or not.
    - Financial skills: capacity of the company to manage and deal with financial instruments.
2) Economical/financial drivers, related to financial and economical situation of machine end user company:

- Availability of internal funds: it indicates if the EU has internal funds available for the acquisition of production capacity.
- EU rating: indication of the economical and financial health of EU companies.
- Availability of commercial credits: it indicates if EU has commercial credits that can be sold to get financial resources.
- Investment value: equipment price, according to the traditional model.
- Existence of balance sheet constraints or fiscal benefits that are ownership related: it indicates if EU can take advantage of fiscal benefits coming from the non ownership (like costs deductibility), or if there is any balance sheet reason that makes capital goods ownership not convenient (for example, connected to stock exchange quotation).
- Desired payment time horizon: span of time during which the EU prefers to spread his payments.

3) Market drivers: drivers referring to end user external market:
   - Market predictability: it indicates if the EU is able to reasonably forecast its future market demand.
   - Periodicity: assuming that the time horizon predictability is long, the season will be an additional driver indicating if the EU demand has a seasonal demand peaks or not.
4) Technological drivers: drivers related to technical machine parameters:
   - Machines reconfigurability: possibility to reconfigure machines for different productions or capacities. A qualitative evaluation of reconfigurability has to be considered, intending that a machine is reconfigurable if it is possible to modify its structure to change the products' characteristics that it can realise and/or to improve its production capacity with a reasonable investment.
   - Mono-product or multi-product machines: it indicates if the objective of the financial decision is technically conceived for the production of a single product or if they can be adapted with a change of set-up to the production of different products.

3.3 Algorithm to select suitable financial instruments

The algorithm definition is based on the following criteria:

- Organisational and economic/financial drivers act like a filter that eliminates the financial models contrasting with their values (e.g. young companies with a low rating have difficulty in accessing loans, project financing is not adequate for low investment values, etc.).
- Technological drivers combined with different values of market drivers make the adoption of some specific instruments more convenient than the use of other ones (for example, it is very risky to auto-finance not reconfigurable equipments in an unpredictable market).

According to these assumptions, the decision tree showed in Figure 1 is described below.

After the application of the first filter about the organizational and economic/financial company situation, the assessment of market demand predictability divides the decision tree in two main branches. The first branch evaluates the case in which the end user demand is not predictable or is predictable only in the short term; in these situations, machine reconfigurability is evaluated (step 3): if machine is not reconfigurable, ownership-oriented financing forms could be too risky. So, financial solutions with a "use based payment" or a "time based payment" are suggested in End 1. If, on the contrary, the machine is reconfigurable, being the ownership risk in an unpredictability demand context mitigated by the possibility to reconfigure the machine, the existence of balance sheet and fiscal constraints ownership-related is evaluated (step 6). If there is any reason that makes it convenient not to be the owner of equipment, then "use based payment" is suggested in End 2. If not, the last selection criterion of remaining financial instruments is the desired re-payment time (step 7). As a result, the financial instruments, filtered after the selection process, will be presented at End 3. The multiplicity of the options, which will need a quantitative evaluation before the final decision, will depend on the configuration of value drivers (for example, few financial possibilities can exist for a company with a bad financial rating aiming to acquire expensive not reconfigurable machines in an unpredictable market context).

On the other hand, the second branch considers the cases in which the end user market demand is predictable in the long period; in this situation, the type of demand has to be evaluated (step 4) in terms of periodic peaks. If peaks do not exist, the selection process continues like in the first branch (step 6). If, on the contrary, the predictable demand is characterised by peaks, the second technological driver should be taken into account: the technical possibility to produce a multiplicity of products (step 5). Such possibility, in fact, makes in principle the ownership-oriented instruments still valid, since the convenience to own the machine could be justified by the option to produce other items during low demand periods, reducing its inactivity time. It is obvious that the preliminary verification of production needs for other items should be assessed. The verification of these conditions leads to step 6 of the first branch of the tree. If these conditions are not satisfied, "use based payment" or "time based payment" instruments are suggested at End 4.

The proposed algorithm supporting Financial Guidelines has been implemented in a Microsoft Excel ambient with the following main scopes:

- To create a user-friendly interface so that the selection process of all the possible financial methods can be simple, also for actors not skilled in finance.
- To speed up the selection process through the implementation of an automatic elaboration.
- To make all actors more aware about the relations between the financial instruments and the drivers values, so that they can understand what organisational, financial, technical and market elements should change to access to different types of funds.

An example can be useful in order to understand the algorithm functioning.

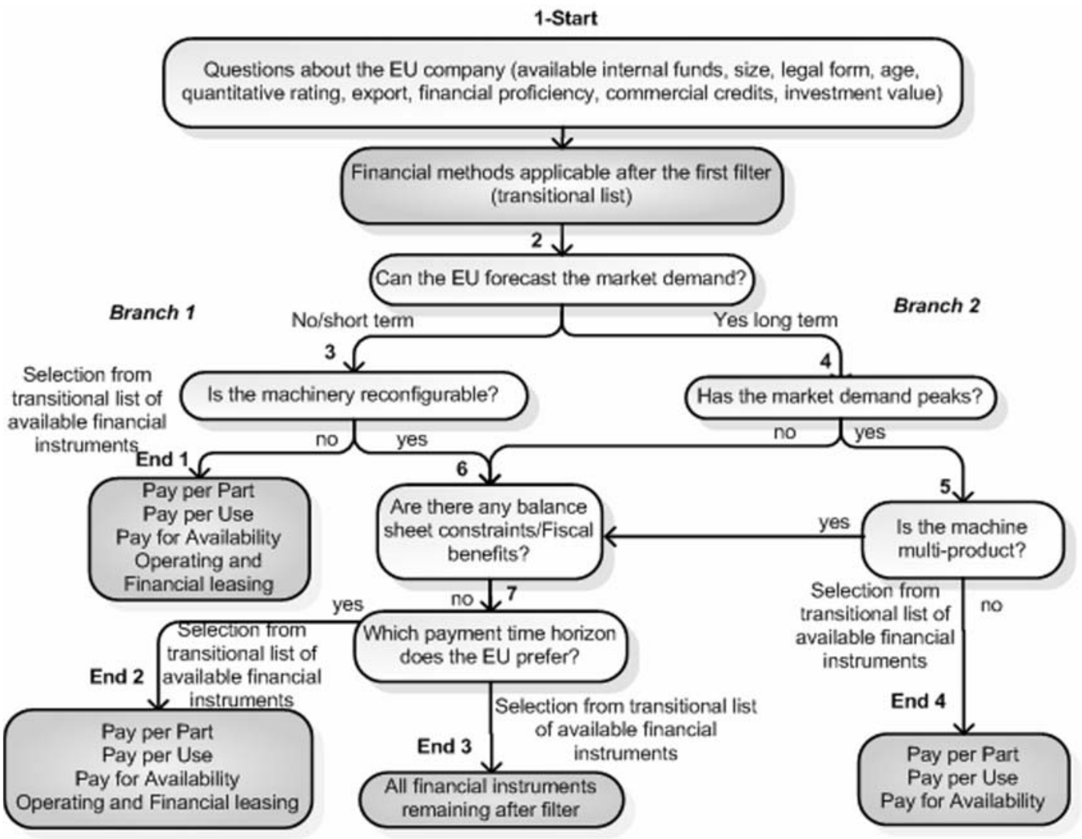

Figure 1: Algorithm supporting equipment finance decisions.

Consider the following scenario: a machine tool end user desires to acquire production capacity but he is not able to assess which are the financial instruments fitting with his specific case. Data related to company situation are the following:

- Availability of internal funds: yes.
- Size: small.
- Legal form: company.
- Firm age: young.
- EU rating: medium.
- Export: yes.
- Financial skills: medium.
- Availability of commercial credits: yes.
- Investment value: high.
- Market predictability: no (long term).
- Periodicity: no.
- Multi-product machine: no.
- Machine reconfigurability: not technologically possible.
- Existence of balance sheet constraints or fiscal benefits ownership related: yes.
- Desired payment time horizon: not important.

Specifying step by step the driver values, the list of available financial instruments is reduced progressively.

Figure 2 represents the Microsoft Excel screenshot implementing the automatic run of Financial Guidelines algorithm. Machine builder can input driver values that describe its situation on the left side, where drop-down window menus give a choice of assumed values and a synthetic help function indicates the meaning of the concepts. On the right side suggested financial methods which fit with the drivers value are showed: the overall list is reduced while entering new inputs, so that the user has an immediate perception of the drivers impact on financial instruments.

At the end, in this example, the following methods are suggested: operating leasing, financial leasing, pay per part; pay per use, pay for availability. Thus, not ownership oriented financial mechanisms are proposed, according to the high risk presented by this business and technological situation. Naturally, the final choice has to be better assessed and further investigations will be needed, but Financial Guidelines restricted the focus to a suitable set of methods suggested for this specific situation.

Easy simulations are also possible in the Excel program changing drivers value. They can show what other financing mechanism could be used if some of the input conditions would be modified, making industrial actors more sensitive with respect to equipment financing methods.

4 SUMMARY

This paper proposes Financial Guidelines supporting the innovation of equipment finance services, offered by financial actors or machine builders to their industrial customers. In order to define the preliminary requirements for Financial Guidelines, the state of the art about financing techniques has

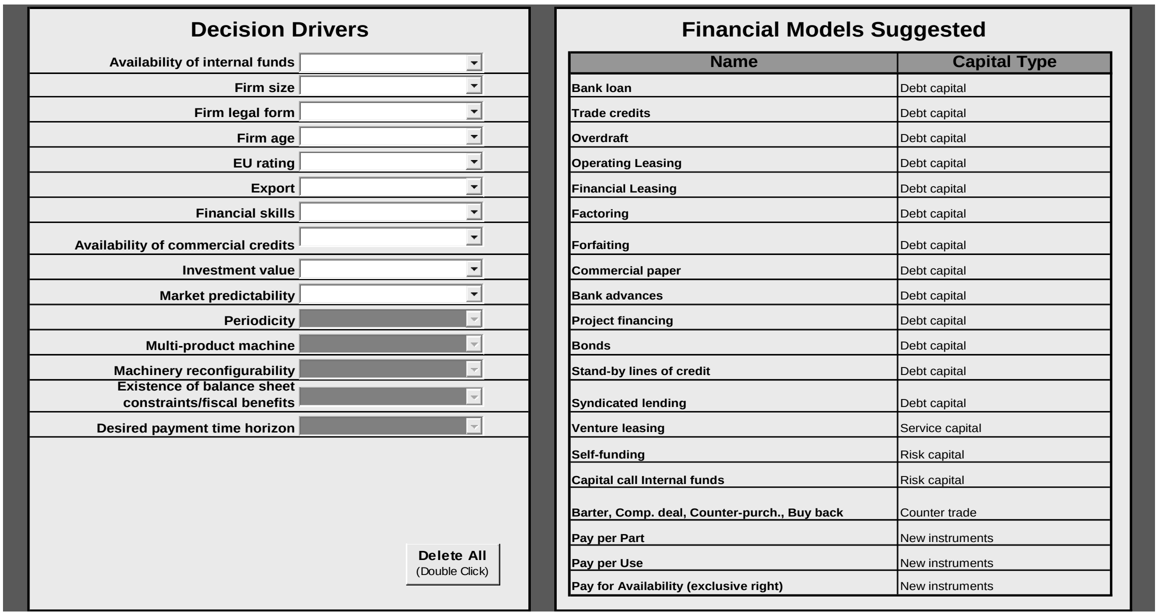

Figure 2: Financial Guidelines screenshot.

been studied and an interview campaign has been conducted in Italy and in Spain. The results suggested the general barriers that Financial Guidelines aim to overcome:

- The general lack of financial culture of industrial companies (end users and equipment suppliers).
- The difficulty of financial companies to understand and meet industrial market needs and technology, which creates a communication barrier between each other.
- The actual use of a very few financial standard options, due to historical reasons and a conservative culture.

The prime value for users of these Financial Guidelines is to offer a catalogue of eighteen financial mechanisms potentially adoptable in the machine builders' industry (both traditional and innovative) which are introduced with explanatory sheets and whose scope is to make familiar all actors with aspects "outside their core business". Secondly, they suggest what are the suitable financing methods for a specific industrial and technological situation, evaluated through a set of consistent drivers that take into account all relevant aspects (financial, technological, market and organisational).

The algorithm upon which the guidelines are based has been implemented in a friendly Microsoft Excel ambient and can be used by end users willing to have a preliminary idea about financial possibilities for their specific case, by machine builders and financial actors aiming at the definition of the best financial service to offer, or by system integrators that have to build a cooperation relationship between industrial companies, equipment suppliers and financial actors.

5 ACKNOWLEDGMENTS

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Energy Use per Worker-Hour: Evaluating the Contribution of Labor to Manufacturing Energy Use

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Abstract

Energy use is an important metric of environmental impact and manufacturing efficiency. However, a major component of energy analysis has yet to permeate life-cycle analysis methodology: the energy use associated with human labor. This paper presents a straightforward method of estimating the energy demands of an hour of industrial labor based on readily available national statistics. In the United States, this estimate yields 30 MJ of primary energy use per worker-hour (EPWH). These results can be applied to inform and expand the application of process-based and hybrid economic input-output life-cycle assessment.

Keywords:
Energy use; Labor; Major Manufacturing Countries

1 INTRODUCTION

Energy is an important metric of environmental impact and manufacturing efficiency. A key parameter of life-cycle assessment (LCA) is energy consumption, as it can dominate environmental impacts such as global warming potential, carcinogenic emissions, and acidification potential. Energy assessment is also effective as an indicator of manufacturing efficiency. As yield, manufacturing cycle efficiency, process capability, and other manufacturing performance metrics improve, energy use per unit output decreases accordingly.

The metric of energy use was popularized largely due to the work of Howard Odum, who has written numerous books on energy and environmental accounting since the 1970's including [1],[2], and [3]. In [4], he presents several methods of quantifying the energy use of labor, in terms of metabolic energy, national fuel share, national emergy share, and as a function of the level of education enjoyed by a worker.

Boustead and Hancock also discuss the energy use of labor in the form of caloric content of food consumed [5]. Calculated as such, they ultimately conclude that the energy contribution of human labor to energy use is negligible.

We argue that the energy associated with human labor must include the energy of infrastructure in addition to that of food, where infrastructure includes housing, transportation, health care, etc. If defined in this way, the energy use of labor can be a significant contributor to manufacturing energy use.

Like economic input-output (EIO) LCA, the methodology presented herein aims to quantify environmental impacts that may not be included in process-based LCA. Because both EIO-LCA and the energy use of labor take a top-down approach, presenting averages for an industry or country, they do so without tremendously increasing the work of LCA practitioners.

Energy use of labor and EIO-LCA should not be applied to the same component of analysis because many sources of energy use would be double counted. However, energy use of labor can be very effective if incorporated into hybrid EIO-LCA, as shown in Figure 1, where EIO-LCA is used to assess activity upstream of the process-based analysis. The energy use of labor enriches the horizontal scope of process-based LCA, while EIO captures vertical supply chain impacts.

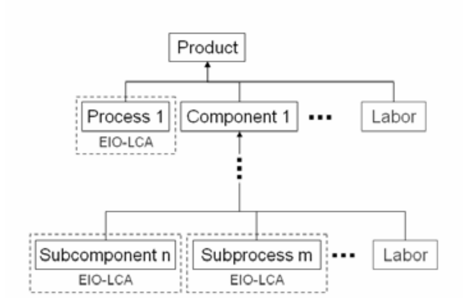

Figure 1: Schematic of process-based LCA and energy use of labor applied in series with economic input-output LCA.

In addition to improving the accuracy of LCA, evaluating the energy use of labor can be applied to extend the decision making capabilities of LCA. The energy use of labor enables us to quantify and inform decisions that introduce or reduce the degree of automation, deal with the location of a plant, or involve labor intensive process steps. Detailed examples of such applications are given in Section 3.

Hannon [6], Kakela [7], Pindyck [8], Welsch [9], and Kemfert [10] thoroughly document the substitutions of energy, labor and/or capital equipment that occur under various scenarios, yet until now, the degree to which these substitutions should occur has not been possible to ascertain.

The energy use of labor consequently helps address the disparities between environmental and economic accounting. Environmental analysis largely ignores labor, while the cost of labor factors very heavily into economic analysis. Evaluating the energy use of labor can help reduce the gap between those who prioritize environment and those who prioritize economics.

Finally, human capital, like environmental capital, has externalities that can be passed from a manufacturing system to society at large. For example, manufacturers who pay workers less than a livable wage rely on social programs to support their workforce. The energy use of labor is a tool with which we can begin to account for the environmental externalities of labor.

2 ESTIMATES OF ENERGY USE PER WORKER-HOUR

Three straightforward methods of estimating energy use per worker-hour (EPWH) are presented to produce a lower bound, an upper bound, and a value appropriate for use in life-cycle assessment. As shown in Table 1, the methods are respectively derived from human metabolic activity, total primary energy supply, and non-industrial energy supply.

Method	EPWH (MJ)
Metabolic Activity – Lower Bound	0.5
Primary Energy Supply – Upper Bound	37
Non-Industrial Energy Supply – Recommended for Life-Cycle Assessment	30

Table 1: US estimates of energy use per worker-hour.

2.1 Metabolic Activity

A lower bound estimate of energy use per worker-hour is given by human metabolic activity. An active individual can expend 2800 kilocalories per day or, on average, 0.5 MJ per hour. However, this method fails to consider the much greater amount of energy embodied in and used in the infrastructure employed to support labor. Nor does this consider efficiency losses from food production to digestion.

2.2 Primary Energy Supply

An upper bound estimate is given by amortizing a country or region's energy supply across its population and over the number of hours in a year.

Odum used the same method to calculate the national fuel share per person [4]. Based on 1993 data, he concluded that 967 MJ are expended per worker-day or 40 MJ per worker-hour. In comparison, 2004 data reveals that 37 MJ of primary energy are expended per worker-hour. This difference indicates rising energy efficiency per capita, possibly as a result of population growth or differences in data collection.

Note that allocating energy use over the entire population gives us a better estimate than allocating energy use over the workforce alone. Just as a machine tool must be manufactured and have an end of life, a worker must have a childhood and an end of life.

This upper bound estimate considers all the infrastructure and services that go into supporting a worker in terms of primary energy. Primary energy is measured in the units of tons of oil equivalent (TOE). Unlike final consumption in the form of refined fuels or electricity, primary energy captures all transformation and distribution losses.

However, energy use per worker-hour calculated based on primary energy cannot be used as a component of process-based life-cycle assessment because this method double counts industrial energy use.

2.3 Non-Industrial Energy Supply

A better estimate of energy use per worker-hour for the industrial sector is derived from non-industrial energy supply, which includes all primary energy except that supplied to industry, as given by Equation 1.

$$EPWH = \frac{TPES - IPES}{population \times hours / year} \tag{1}$$

where *TPES* is a country or region's total primary energy supply and *IPES* is industrial primary energy supply. *IPES* can be replaced with primary energy supply to other sectors of the economy or specific industrial sectors, such as the petrochemical sector, to reflect a particular product or process.

Energy use per worker-hour, in terms of primary energy, captures the energy mix and efficiencies in transformation and distribution for a given region. However, *IPES* is not always readily available, so we approximate it using industrial final consumption (*IFC*) and total final consumption (*TFC*) of energy as follows

$$IPES = TPES \times \frac{IFC}{TFC} \tag{2}$$

This assumes the ratio of final consumption to primary energy supply for industry is representative of the ratio of final consumption to primary energy supply for the country. Countries with industries that consume disproportionately more primary energy than the country at large are penalized by this assumption, resulting in a larger value of EPWH.

The International Energy Agency (IEA) regularly compiles and publishes values for *TPES*, *IFC*, and *TFC* from each country or region in its purview. Though there are disparities in what each country reports, data from the IEA is likely more reliable than data compiled directly from each country. As defined by the IEA, the industrial sector includes mining, smelting and construction but does not include transportation used by industry. The most current data available reflects 2004 activity.

Of the three methods discussed, amortizing non-industrial energy supply yields the most accurate estimate of energy use per industrial worker-hour for use in process-based or hybrid economic input-output life-cycle assessment. This method is applied and discussed in the remainder of this paper.

3 APPLICATIONS

The energy use of labor in the United States is significant relative to the energy use of a machine tool and of labor in other major manufacturing countries and regions. The energy use of labor may also be used to more accurately evaluate labor intensive processes and industries.

3.1 Man vs. Machine

Though there are significant differences between the capabilities of a worker and a machine tool, it is an interesting exercise to compare their relative energy demands. In the US, electricity production from primary energy is approximately 35% efficient [11]. This conversion factor is used to compare primary EPWH with machine tool electricity use.

As shown in Figure 2, the 2.9 kWh of electricity equivalent EPWH that we equate to 30 MJ of primary EPWH is comparable to the power consumption of an automated milling machine but is considerably less than that of a production scale machining center [12].

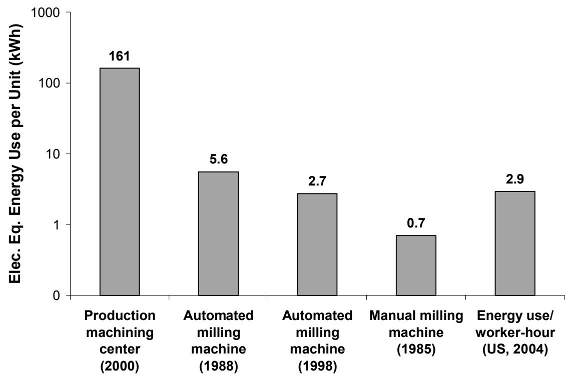

Figure 2: Electricity equivalent energy use per worker-hour in the US based on 2004 data as compared to the hourly electricity requirements of four common milling machines produced in the years indicated, adapted from Dahmus [12]. Note the semi-log scale.

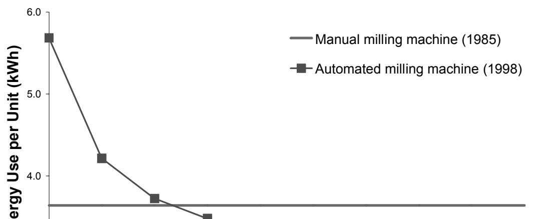

Figure 3: Electricity equivalent energy use, including labor and machine operation, for manual and automated machine configurations.

Dahmus [12] presents a thorough analysis of machining, including material production, cutting fluid preparation, and operation of all components of the milling machine itself. We can obtain an even more complete assessment of total energy use by expanding the analysis to include labor.

Assuming the manual milling machine requires one worker to operate, a worker-hour contributes 2.9 kWh to the 0.7 kWh the machine consumes directly each hour. The actual energy impact of manual milling is therefore five times greater than previously thought. As a component of process-based LCA, this higher energy use may be reflected in a wide range of products and services.

A decision making application of energy use per worker-hour is shown in Figure 3 for Dahmus' milling machines. If a worker is able to operate four or more machines at a time, it is advantageous from an energy point of view to employ the automated milling machine even though it directly uses four times more energy per hour than the manual milling machine. Energy use per part will scale with production rate for each machine.

3.2 Major Manufacturing Countries

The methodology discussed in Section 2.3 can be easily applied to any region with records of *TPES*, *IFC*, and *TFC*, such as those reporting to the International Energy Agency. Major manufacturing countries demonstrate a wide range of energy use per worker-hour values, as shown in Figure 4 and Table 2.

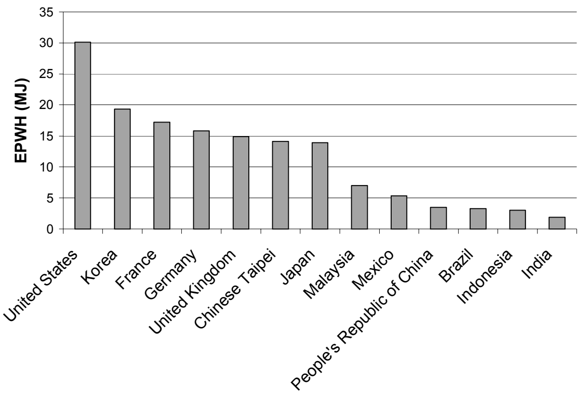

Figure 4: Primary energy use per worker-hour in major manufacturing countries and regions [13],[14].

These differences can be attributed to a complex set of factors. A very important factor is undoubtedly population. With the exception of the United States, the five most populous countries evaluated represent the countries with the lowest values for energy per worker-hour.

There is also an inverse relationship between EPWH and ratio of industrial final consumption to total final consumption. For the countries evaluated, this ratio ranges from 19% for the United States to 41% for China. In general, the more a country expends in manufacturing, the less energy is expended per worker-hour. These trends may suggest relationships between service and manufacturing economies and development, or they may simply be attributed to the calculation of EPWH.

These results do not consider geographic differences in the number of workers employed for any given task, purchasing power and related energy consumption of industry workers compared to the general population, or unemployment rates.

The necessity of excluding industrial energy use from the calculations, as discussed in Section 2.3, is observed when comparing net importers and net exporters. For example,

Country	Total Primary Energy Supply	Industrial Final Consumption	Total Final Consumption	Population (million)	EPWH (MJ)
	(EJ/year)				
Brazil	8.6	2.9	7.2	180	3.3
China, People's Republic of	67	18	44	1300	3.5
Chinese Taipei	4.4	0.93	2.7	23	14
France	12	1.6	7.2	60	17
Germany	15	2.2	11	83	16
India	24	4.0	17	1100	1.9
Indonesia	7.3	1.1	5.5	220	3.0
Japan	22	4.3	15	130	14
Korea	8.9	1.6	6.0	39	19
Malaysia	2.4	0.61	1.6	24	7.0
Mexico	6.9	1.1	4.4	110	5.3
United Kingdom	9.8	1.4	6.9	60	15
United States	97	13	67	300	30

Table 2: Data for Figure 2 [13],[14]. Note that as defined by the IEA, the People's Republic of China does not include Chinese Taipei. Exajoule (EJ) = 10^{12} MJ.

consider the $214 billion trade deficit between the United States and China in 2006. Energy used in China to manufacture goods for sale in the United States does not contribute to the Chinese EPWH. Meanwhile, energy the United States imports in the form of products can be captured by process-based LCA.

3.3 Labor Intensive Processes

Without quantifying the energy use of labor, it is easy to underestimate the environmental impacts of labor intensive processes, such as those used in product installation, maintenance, repair, and recycling.

For example, energy payback time analyses for solar cells often do not consider panel installation, even though it is a major component of their financial cost. Evaluating the energy use of labor is necessary to determine the impact of expensive and labor-intensive solar cell installation on energy payback time.

Labor-intensive sorting processes for recycling are another important application of the energy use of labor. It is important to know the degree to which the energy expended in sorting processes counteracts the energy savings of recycling. There many benefits to recycling outside of energy savings, but the ratio of energy inputs, including that of labor, to energy savings can serve as a measure of efficiency for recycling operations.

3.4 Labor Intensive Industries

The degree of labor required between industries can vary dramatically. Agriculture, handcraft, textile, and service industries are especially labor-intensive. These industries have typically not been the subject of life-cycle analysis, even though their products are consumed in relatively large quantities. Process-based LCA would in fact grossly underreport the environmental costs of a service or an entirely handmade product.

It is also interesting to note that new industries, such as the renewable energy and nanotechnology industries, typically employ more workers per unit output than more established industries [15]. Emerging industries may present problems for LCA practitioners seeking to perform comprehensive assessments. As EIO-LCA data is not yet available for the industry in question, new technologies must be assessed using process-based or hybrid EIO-LCA. Evaluating the energy use of labor is therefore especially valuable to accurately assess the environmental impacts of new technologies and industries.

3.5 Price of Forms of Energy

The prices of various forms of energy are well documented and understood. It is interesting from an economic and social point of view to understand how labor of a given sector is priced with respect to other forms of energy.

4 DISCUSSION

Amortizing non-industrial energy supply produces a simple estimate of energy use per worker-hour. However, there are questions regarding how to apply this information.

At first glance, Figure 2 appears to present a strong argument for the exportation of labor-intensive industries. Yet, energy savings in labor can be easily overturned by energy use in transportation. Intercontinental shipping can consume 1.8 MJ per container-mile, based on industry standard emissions of 85 g CO_2 per container-km [16]. In the United States, a container truck expends 750 MJ per mile [17], in addition to the energy use of the operator. Energy analysis may be a useful tool for siting manufacturing facilities, but the energy requirements of both labor and transportation must be considered.

However, industrial final consumption does not include industrial transportation. This means that the energy use of industrial transport is not subtracted from Equation 1, and is therefore encompassed by energy use per worker-hour. If used in conjunction with process-based LCA, energy use per worker-hour double counts the energy use of industrial transportation. This is a major drawback of this technique that must be addressed to be used with process-based transportation inventories.

It is also not entirely straightforward to decide the number of worker-hours to evaluate in life-cycle assessment. An employee may work eight hours a day, but he or she will continue to expend energy outside of work. Manufacturers reap the rewards of the energy expended during worker-hours in the form of value added to their products and should be responsible for a proportional amount of energy. For the purposes of process-based life-cycle assessment, we recommend calculating the energy corresponding to the number of hours actually worked.

However, one can argue that employers, as a whole, are responsible for the economic activity and corresponding energy consumption employees enjoy outside of work as a result of their hours worked. While the economic activity of both employer and employee are required to sustain manufacturing, consider a factory that employs all workers for only four hours a day. Twice the numbers of workers are needed compared to an identical factory employing workers for eight hours a day. Though these half-time employees would be compensated less and enjoy less economic activity, it is doubtful that their energy demands would be half of that of their full-time colleagues.

Another factor to consider is the effect of feedback. A facility built in a low energy use per worker-hour area may find that its presence spurs economic activity, development, and in turn, increased energy use per worker-hour. It is important to note that energy use, industrial activity, and population can change over time. To be meaningful, energy use per worker-hour should reflect up-to-date statistics.

5 CONCLUSION

Evaluating energy use per worker-hour is a simple and effective way to improve the accuracy and scope of life-cycle energy analysis. This paper makes note of energy use per worker-hour as it compares to a machine tool and to worker-hours in other major manufacturing regions. The potential applications of the energy use of labor in life-cycle assessment are exceedingly broad.

6 ACKNOWLEDGMENTS

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Framework for Integrated Analysis of Production Systems

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Abstract
Production companies act in increasingly complex and dynamic environments. Facing numerous influencing and closely interconnected factors within production systems, companies are forced to cope with economic and to an increasing degree with ecological objective criteria in order to meet market and legal demands. This leads to complex decision situations regarding planning, operation, and optimization efforts of production systems. This paper presents an integrated framework for production system analysis that allows to analyze the interrelations between economic and ecological factors in the context of production system optimization.

Keywords:
Life Cycle Engineering; Production System; Simulation

1 INTRODUCTION

1.1 Environmental and Production Management

Manufacturing processes take raw and auxiliary material inputs and transform them into products and wastes using energy inputs. While a certain part of the energy is used for the value creating transformation and embodied into the form and composition of products, another part is wasted in terms of heat and emission. Thereby, production systems predominantly influence the environmental outcome of a company [1]. In this context, production systems represent the sum of all manufacturing processes, resources, principles, and methods within a production enterprise.

Energy consumption for industrial application will increase up to 5.000 billion kWh in OECD (Organisation for Economic Co-operation and Development) and up to 9.000 billion kWh in non-OECD countries in 2030 [2]. If total energy consumption and energy efficiency of production systems can not be optimized in future, opportunities to create value will be lost due to wasted energy. The forfeiture of missed additional revenues, waste of energy, and waste disposal costs have a threefold negative effect on earnings.

In recent years, environmental questions have become more and more important for production companies. This trend is emphasized by manifold environmental regulations on European and international level and the emergence of a wide diversity of sustainable related research approaches [3] [4]. Recent research findings have revealed that energy efficiency and ecological optimizations become important challenges in the context of production system improvement [5] [6]. Production system design methodologies like lean manufacturing have been extensively studied and a wide diversity of production system design methods (e.g. Jidoka, Poka Yoke, TPM, etc.) for improving quality and costs have been discussed [7] [8]. But there has been little research on the effects of production system design methods and production system configurations on the environmental outcomes (e.g. emissions, waste, etc.) of production systems. Production system represent the major potential to minimize the environmental outcome of a company. The European Commission estimates the overall energy saving potential for manufacturing industry in the EU to be around 25%, where peripheral equipment and standby loss offer important saving potentials [9]. To achieve sustainable production system design results, it is necessary to advantageously integrate rather economic oriented production system design methods with ecological optimization objectives [3] [4] [10].

1.2 Production System Complexity

Integrated economic and ecological optimization of production systems requires to provide information to decision makers and to enable the assessment of consequences of planning and optimization efforts. This entails a verification of production system design methods according to their ecological contribution. Considering the combination of lean manufacturing methods with ecological objectives, economic objective criteria like yield and productivity have to be complemented with ecological objective criteria like minimization and leveling of energy consumption. Therefore, companies are forced to cope with multiplexed objective criteria in order to meet economic and ecological demands.

Production system elements like machines and production lines are assigned to different abstraction levels within a production company. Economic and ecological objective criteria depend on these elements and their interaction. Thus, interdependencies and dynamic behavior of production system elements over different abstraction level have to be considered for production system optimization reasons. This leads to high production system complexity and results in complex decision situations regarding planning, operation, and optimization efforts of production systems. To cope with complexity, an integrated analysis and assessment of ecological and economic objectives of production systems is necessary to provide a comprehensive information basis for sustainable production system improvement.

1.3 Production System Improvement

From a life cycle management perspective, production system design optimization is a comprehensive task related to life cycle spanning activities like process, information, and knowledge management [11]. To support production system design optimization, strategic and operational life cycle management has to pursue the integration of economic and ecological production system evaluations. On the strategic level, life cycle oriented production management has to support the development and assessment of new production systems. The life cycle oriented optimization of existing production systems is subject to the operational level.

Ecological oriented production system improvement requires to analyze the effects of production system design methods on the environmental outcome of a production system. Discrete material flow simulation models can be used to analyze material flows, design configurations, performance, and cost structures of production systems [12]. System dynamics models allow to depict cause-effect loops of production system design methods on a high abstraction level [13]. Ecological balance approaches focus on modeling the rather static input-output relations of processes [14]. These modeling approaches can support the integrated economic and ecological evaluation of production systems to a certain point, but they lack in depicting low abstraction machine states, functional production systems and related design methods, and the emerge of continuous flows like energy emission within one model. Therefore, a framework for integrated production system analysis is presented in this paper. The framework is supposed to:

- Depict the dynamic behavior of discrete and continuous input and output flows and driving process structures of complex production systems.
- Support the analysis of effects of production system design methods (e.g. Jidoka, Poka Yoke, TPM, etc.) and production system configurations on overall performance, quality, energy consumption, and emissions.

In the next chapters, the framework approach and the developed framework model components are presented.

2 FRAMEWORK APPROACH

2.1 Integrated Process Model

To analyze production systems with respect to economic and ecological objectives, a specific set of data is necessary as an informational basis. The definition of input and output flows is a prerequisite to determine required economic and ecological information on production systems [10] [14]. Therefore, ecological and economic process models are combined to an integrated process model (Figure 1). This model serves as the fundamental starting point for an investigation of the input-output structure. The integrated process model represents a description model of production system flows that allows to capture all relevant flows and their quantitatively values. Material and energy related input flows are put in contrast to valuable products, discarded products, and emission flows to enable an integrated economic and ecological evaluation [14]. As the flows can be investigated on different abstraction levels, the next section describes the vertical level of production companies, that inherent the considered input and output flows.

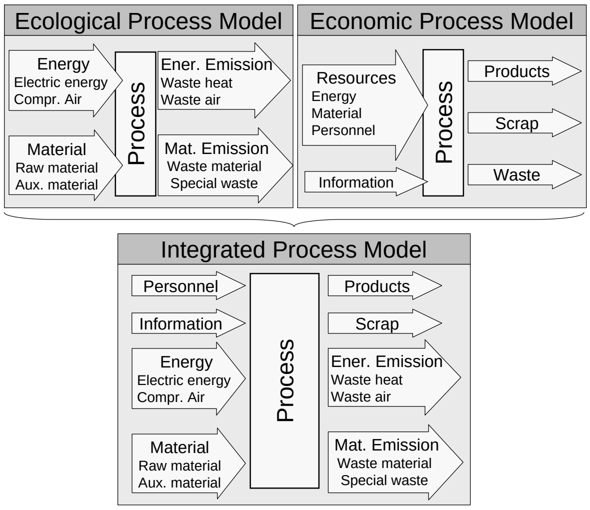

Figure 1: Integrated Process Model [10].

2.2 Hierarchical Decomposition

Economic and ecological optimization efforts have to consider different abstraction levels simultaneously in order to achieve global optima. The decomposition of a production system allows to depict elementary objects, values, and flows on each hierarchical level in more detail and to identify and analyze hidden cause-effect chains across different abstraction levels. Furthermore, the development of hierarchical model levels fosters the deep understanding of the production system behavior and its inherent processes [15]. By integrating the decomposed level into one framework, the flows of lower levels are interconnected and propagated to the upper level while controls and policies are propagated down from upper to lower levels. The framework approach consists of a company level, production line level, and process module level.

The company level of the framework summarizes highly aggregated flows and values of the underlying levels. Thereby, this level can be used to analyze and describe the overall system performance and environmental outcomes in terms of yield, overall profit, energy consumed, etc. Moreover, the company level defines a set of parameters for the definition of the production line configuration, quality gate positions, maintenance policies, and quality standards. These parameters and policies take effect on the production line and process module level. Thereby, the company level allows to set decisions and policies by adjusting parameters that are propagated down to the inherent level. The production line level consists of a configured set of process modules, quality gates, and buffers and thereby depicts the production system design. Policies are decisions taken in the company level are propagated down to this level in order to take effect on the configuration of this level. The process module level represents functional elements like machines, buffers, and quality gates that process parts in discrete events and thereby can be regarded as flow drivers. At the same time, waste and emission flows are created by machines on this level. Production system design methods like Jidoka, Poka Yoke or TPM, determined on higher abstraction level, take effect on this level. Figure 2 depicts the framework decomposition and the related input and output flows.

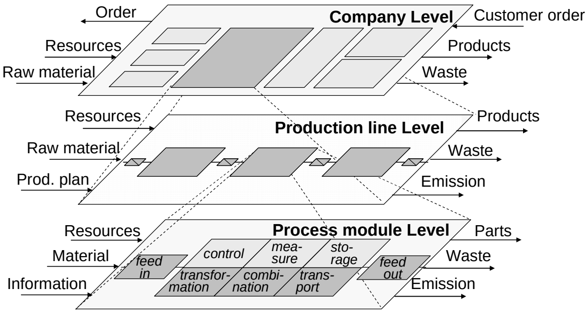

Figure 2: Decomposition of framework and related flows [15].

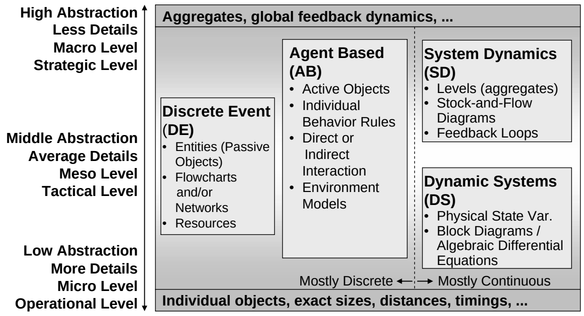

Figure 3: Modeling approaches [16].

2.3 Modeling Techniques

On a very low abstraction level, e.g. motion, chemical reactions, and temperature changes, continuous models are generally used to capture the real physical world (Figure 3) [16]. On a very high abstraction level, e.g. an extended supply chain network or a consumer market, where large amounts of discrete objects and events behave like continuous processes, continuous system dynamics models are generally used for modeling purpose. Discrete event modeling is often used on a middle abstraction level, where only certain important changes in continuous processes are considered. Thereby, discrete event modeling represents an interface between a low and a high abstraction level. Using discrete event modeling, only the “important moments” in a production system lifetime are considered. That means that continuous changes are approximated with events if needed. Events can be the moment when a part arrives at a machine, an amount of raw material reaches the maximum buffer capacity, or a machine finishes processing.

The integrated economic and ecological analysis of production system requires analysis of discrete (e.g. material, parts, etc.) as well as of continuous flows (e.g. emissions, heat, etc.) on different abstraction level. To comprehensively capture these different types of flows, an integration of modeling techniques is required. Therefore, the framework is designed with Anylogic 5.5™, a hybrid simulation software, that integrates continuous and discrete modeling.

Hybrid modeling allows to integrate discrete and continuous modeling. Thereby, the advantages of both techniques can be used. This way, precise low abstraction model components of physical devices and flows, e.g. a machine auxiliary device producing an emission flow of waste coolants, can be combined with discrete event components of manufacturing processes within a production system. A discrete production system model component on the other hand, allows a combination with high abstraction system dynamics models components, e.g. a model representing the dynamic market demand in an extended supply chain. In this case, the discrete event part of the model subscribes to variable values of conditions of a system dynamics model component that changes continuously over time.

The integration of continuous and discrete model components can be realized using the Unified Modeling Language (UML) for real time. UML for Real Time (UML-RT) is an extension to UML that offers the ability to clearly separate structures and behaviors, and to develop complex, event-driven real-time systems of machines and production systems.

To model and simulate production system behavior in real time, statecharts, active object classes, message classes, and lookup tables are used as core modeling elements.

Statecharts are a method to graphically model UML-RT methodology and to capture different states of an object, transitions between them, events that trigger those transitions, timing, and actions that the object makes during its lifetime [16]. Using statechart, discrete logic and continuous time behavior can be integrated in order to integrate low and high abstraction levels in the production system model (Figure 5, d). In statecharts, a set of differential and algebraic equations can be associated with a state on a statechart diagram. When a state transition is taken as a result of, e.g., some discrete event, the system of equation changes. This way, discrete logic affects the continuous time behavior. If a condition over continuously changing variables is specified as a trigger of a transaction, the opposite effect occurs, as the continuous time behavior impacts the discrete part of a system. Using statechart, machine characteristics like performance, quality, energy consumption, and emission can be implemented and defined.

Active objects are used to model active production system elements like machines, quality gates, and production lines. Each active object has a structure diagram to define the interface of the active object, to define the encapsulated objects and their interconnections, and common elements such as ports, variables, timers, and statecharts. Active objects have parameters that can be used to parameterize active objects. Parameters are needed, when active objects, e.g. different types of machines, have the same structure determined in the class structure diagram, but differ in parameter values like cycle time, mean time to repair (MTTR), or mean time to failure (MTTF).

To describe and analyze the behavior of the production system, it is necessary to depict input and output flows. The flows and the data interaction within the framework are established using so called *message classes.* Active objects can pass message class entities via their ports. Message class entities carry specific sets of parameter (e.g. mass, type of material, environmental measures, etc.). Entities parameter can be used for entity flow control and real time evaluation. Different types of messages are used to represent different types of entities. During the flow of messages, their parameter can be accessed and modified by the active objects.

Lookup tables are used to define complex non-linear relationships, which cannot be described as a composition of standard functions. A lookup table is a function defined in the table form. Thus, lookup tables can be used to bring experimental data, defined as a table function, to a continuous mode. Lookup tables can be used, e.g., to qualitatively describe the influence of operator qualification level on the MTTR at a specific machine or the definition of energy consumption profiles of machines (Figure 4).

3 FRAMEWORK MODEL COMPONENTS

3.1 Input and Output Flows

Input and output flows of the integrated process model differ in terms of discrete and continuous flows (Table 1). Input and output flows may have time discrete behavior or time continuous behavior. Discrete flows are modeled using message class entities. Detailed information on economic and ecological entity characteristics are used to specify and analyze the type of entity flow. Based on the attached information, performance, quality, costs, and environmental evaluations can be applied.

		Flow Direction	
		Input	Output
Flow Behavior	Dis-crete	*Raw Material* *Auxiliary Material*	*Products* *Discarded Parts* *Solid Emission* *Auxiliary material*
	Conti-nuous	*Auxiliary Material* *Energy*	*Fluid Emission* *Gas Emission* *Heat*

Table 1: Flow direction and behavior.

Continuous flows are described in terms of stocks, flows, and algebraic equations (Figure 3). Discrete manufacturing process states or discrete entity flow rates, represented by statecharts and message class entity flows, can trigger continuous flow rates. On the other hand the discrete flow or flow control logic may depend on a continuous flow rate.

3.2 Production Line

Production lines are modeled using active object classes comprising of several embedded machines, quality gates, and buffers. The basic production line configuration is a linear system, where unprocessed parts enter the system at machine M1 and move on through the buffer B1 to the next machine until they reach the last machine and leave the system. Figure 5 depicts a linear production line on level b) with three machines, three quality gates, and three buffers. It is assumed that the first machine M1 is never starved and that the last machine M3 is never blocked by downstream buffers. Quality gates may be located after machines at specific positions in the production line. Like machines, quality gates have a specific cycle time.

3.3 Machines

Machine active object classes are modeled to represent the main processing elements within a production system. Figure 5 shows the machine active object M1 in section c). To depict different types of machines, specific machine characteristics (e.g. MTTF, MTTR, etc.), ports and variables can be defined using machine parameters. Parts enter a machine through the machine input ports and wait until personnel resource is available to be seized. When a personal resource is available, the part seizes the personnel resource for processing. Parts are processed according to a defined machine cycle time and release the personnel resource after processing has finished. Finally, the parts leave the machine. It is assumed, that only one part can be instantly handled by the machine. If a processed part cannot leave the machine due to a full downstream buffer, no other part can enter the machine and therefore has to wait in the upstream buffer.

Machines are considered to have multiple operational and down states which are idle, repair, maintenance, high yield, and low yield. These machine states are modeled using statechart diagrams (Figure 5, d). States correspond with real physical and operational aspects of a machine and allow to represent the functional behavior of a machine over time. If a machine is in a down state, the machine entry is blocked and arriving parts cannot enter the machine. When the machine enters a low yield state, parts that being processed are attached with a defective quality attribute. A machine switches it states by following the defined transitions in the statechart. Transitions can be taken depending on time and event based factors. Common time based factors which have been implemented are mean time to failure (MTTF), mean time to repair (MTTR), mean time to quality failure (MTQF), and mean time to detect (MTTD) [8].

A machine is assumed to consume energy like electric energy and compressed air, and to produce waste and emissions depending on the type of machine and the current machine state. Energy consumption is associated with activities which consumes constant power and with energy requesting activities that demand variable power over time [5]. Generally, there is an additional energy requirement while processing parts. This additional energy often correlates with the quantity of parts processed. Figure 4 depicts a normalized lookup table that can be used to represent the variable energy consumption of a machine.

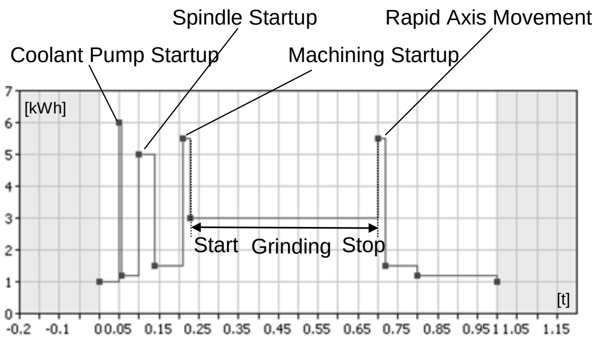

Figure 4: Exemplary lookup table representing the simplified energy consumption profile of a grinding machine.

The emergence of discrete waste generally depends on the number of processes parts, whereas the ratio of waste units per parts can be adjusted via parameters. Continuous emissions are created depending on the time of operations and the duration of certain machine states.

3.4 Quality Gates

Quality gate active object classes are modeled to depict quality inspection stations. Quality gates (QG) can be placed after machines or as final elements of a production line (Figure 5, b). The function of quality gates is to identify defective parts and thereby to prevent further non value adding production steps.

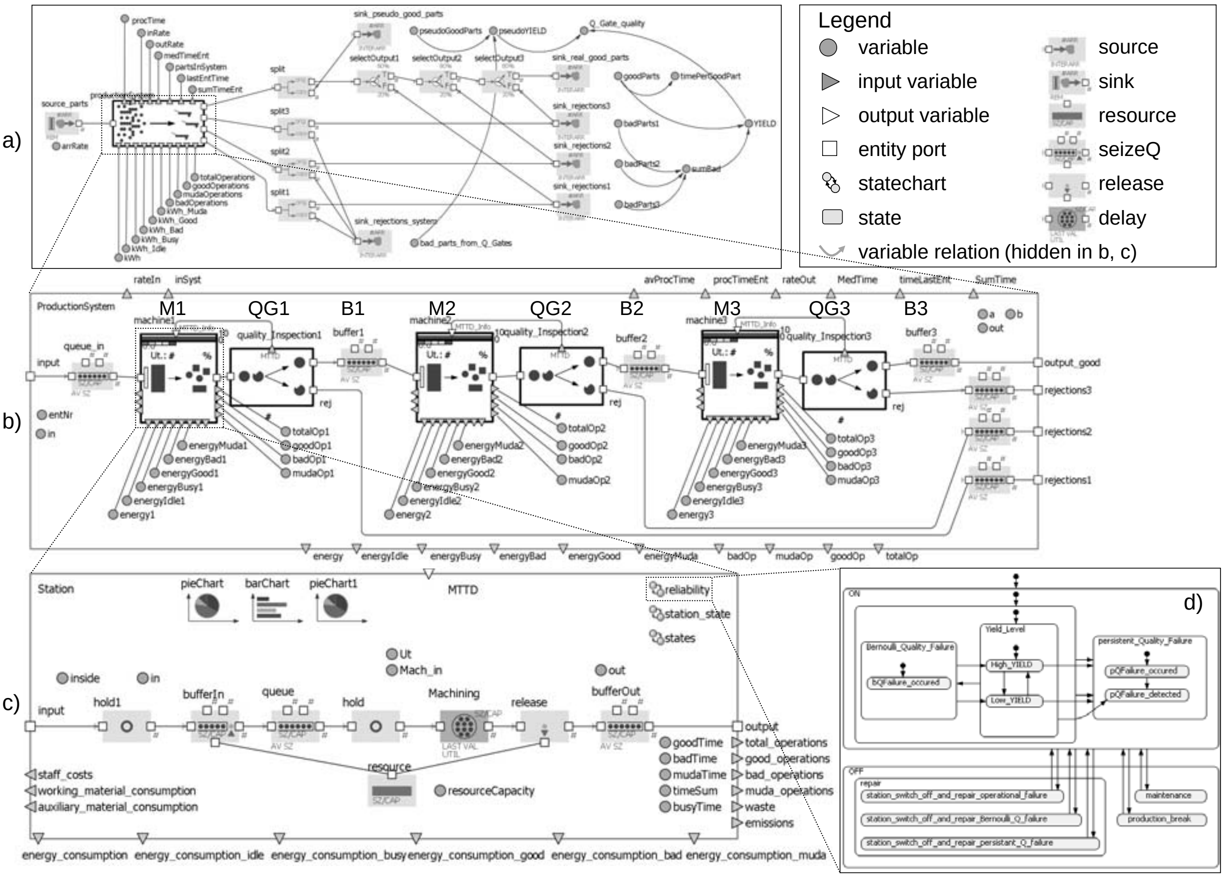

Figure 5: Hierarchical framework model, created with Anylogic 5.5 simulation software.

After a part leaves a machine, the quality gate analyses the parts' quality attribute and removes defective parts from the main process flow according to its correct detection probability. This behavior entails probability rates for two options: either defective parts are declared to be good or good parts are declared to be defective. The nonexistence of quality gates may lead to an ongoing processing of parts that have previously been damaged by upstream machines. These operations are defined as non-value-adding operations. As machines perform different operational steps, every processing step may request an inspection procedure. It is assumed, that quality gates can solely perform machine specific quality checks. Therefore, a specific type of quality gate is necessary for each type of machine.

3.5 Buffers

Buffers elements represent passive storage locations between machines (Figure 5, b). They store incoming entities according to the FIFO (first in, first out) order. An entity may leave the buffer via the output port when the following machine is ready to accept it. As buffers provide space for processed entities produced by upstream machines or unprocessed entities to downstream machines, they can prevent starvation and blocking of machines. Thus, buffers decouple sequences of machines and may increase the total production rate of a production line [8]. The buffer capacity can be increased in order to increase the time span to provide parts for downstream machines if upstream machines are blocked. If a machine without an attached quality gate switches into a low yield state in which it produces defective parts, a high buffer capacity may be harmful as lots of defective parts may be stored in this buffer. The role of buffer capacity on good overall system yield, production rate, and total production performance for different quality policies is one of the matters the framework allows to analyze.

3.6 Personnel Resources

Personnel resources are modeled in terms of discrete resource entities. They are considered as necessary process input as they serve as a resource for machine operations. When parts enter the machine, a personnel resource entity is seized. After the part is processed and leaves the machine, the operator resource entity is released by the part and is thus available to be seized by following parts. As an incoming part waits until it can seize an operator resource entity, the processing can not be started, unless personnel resource is available. On higher abstraction level, the mean utilization rate of personal resources and activity based costs can be calculated. Personnel resource may have specific attributes like age and qualification level. Generally, the process behavior depends on resource attributes. This allows to describe personnel capabilities and characteristics. A qualification level can be mapped to repair time and failure detection time in order to describe the effect of training on production system performance. The specific relation between qualification level and the influenced times is modeled using lookup tables.

4 INTEGRATED ANALYSIS AND OPTIMIZATION

The integrated economic and ecological analysis and optimization of production systems focuses on different aspects that are of particular interest to this approach. These aspects are performance and quality on the economic side, and energy consumption, waste, and emission on the ecological side. The company level of the framework allows to analyze and optimize the dynamic emergence of emissions and energy consumption with a high functional and temporal resolution (Figure 5, a). Thereby, the framework enables to evaluate production system design methods like Jidoka and TPM.

For example, the application of the Jidoka method can be modeled in terms of quality gates which relocate defective parts from the value creating flow directly after the incorrect operation has occurred. As a result, further non-value adding efforts as well as energy consumption for processing of bad parts can be prevented. To find the best possible positions for quality gates and to optimize buffer capacities, parameter optimization experiments can be applied. Anylogic 5.5™ allows to identify optimal system parameters for defined objective functions using the integrated optimization software OptQuest™. Thus, optimal model parameters for buffer capacities and quality gate positions can be identified that give minimum or maximum value of an objective function. In the presented example, the minimization of the overall energy consumption is defined as objective function. During the optimization experiment, the parameters for quality gates (Q1On, Q2On, and Q3On) and buffer capacities (b1, b2, and b3) are optimized by parameter variation experiments using heuristics, neural networks, and mathematical optimization methods. Figure 6 shows a screenshot of the optimization experiment. In this example, the optimization experiment has revealed optimal parameters for buffer capacities and quality gate positions. The resulting parameters minimize idle and low yield machine states and thus reduce the total energy consumption from 158 kWh to 101 kWh.

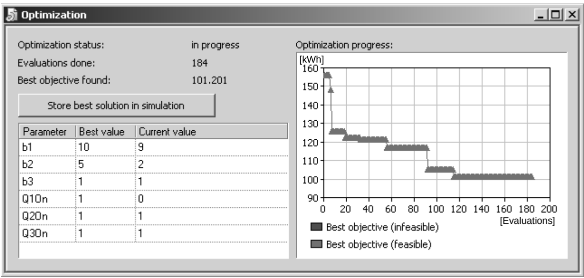

Figure 6: Simulation based optimization experiment.

5 SUMMARY AND OUTLOOK

In this paper, a framework for integrated economic and ecological analysis of production systems is presented. The framework allows to simultaneously analyze the effects of production system design methods and configurations on economic and ecological performance indicators. A wide range of experiment designs can be configured to support the derivation for sustainable production system design solutions. Thereby, the framework enables to gain deep-insights into the emergence of both, economic and environmental related outcomes of production systems with respect to current production system design questions. We conjecture that it should be possible to perform simulation based optimization experiments in order to identify potentials for both, economic and ecological production system design optimizations. The next steps will be further model development, model verification and the assessment of detailed machine data.

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Designing services based on ‘intelligent’ press-die-systems

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Abstract
Forming technologies and deep drawing in particular play a key role in Germany’s industry regarding quality, costs and time. The production system’s efficiency is thereby tremendously influenced both by timed and qualitative availability of press and die. A detectably higher availability resp. service life of the entire press-die-system along with novel services for a condition-oriented press and die maintenance represent a solution to the actual dilemma. Furthermore new service models to optimize the spare parts management as well as business models, e.g. pay-per-piece, are additional options. In a consortium of industry and university within the research project *Smart Stamping*, the Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University is to create the necessary preconditions for such offerings.

Keywords:
Industrial Services; Business Models; Life Cycle Costing

1 PROBLEM STATEMENT

Deep drawing represents a core competency of the German producing industry. This includes both sides of the production process: the parts manufacturer himself (still dominated by the automotive industry) and the suppliers of press and tool. The latter put Germany into a leading position within the global competition. But in today’s manufacturing environment, competition is marked by shorter product life cycles and an increasing demand for product customization [1].

Opening markets in Eastern Europe, increasing supply from Asia and reserved investments in Germany’s domestic market threaten especially the tool and die industry with an above-average fall in prices [2]. One consequence is the consolidation of the branch: big tool makers such as Karmann drastically cut down their workforce, others close down entire tool- and dieshops (like VoestAlpine Matzner, which used to employ 350 workers). As the branch is characterized by small and medium-sized companies, further insolvencies are predictable.

A provable increased availability of the press-die-system is one solution to this difficulty. It lives up the expectations of each participant in the production process of pressed parts: parts manufacturers as well as suppliers of investment goods.

From a technological point of view, German presses and tools are of superior quality and abilities compared to those of most competitors. But so far companies lack the chance to prove this advantage on a cost basis. In addition, they are currently not able to sell these investment goods in terms of a guaranteed availability of the latter. A broad measurement data acquisition and monitoring of press and die, which is also known as Condition Monitoring, is one promising approach to increase the availability of manufacturing systems. Damages can thus be detected earlier or even be avoided.

Speaking of metrological preconditions, appropriate sensors for an adequate monitoring of press and die do already exist, however they have been applied infrequently. But there is a lack of studies on how to combine these various proposed solutions. Only a holistic approach, which involves both press and die, allows drawing conclusions out of the forming process. Interpreting the wearout of the involved components thus becomes possible. Yet these studies face the problem of enormous machine hour rates. Along with the constant workload of plant and machinery, the relevant applications and measurements during the on-going process are after all impossible.

An example for the need of knowledge of the actual condition of press and die is the unexpected downtime of Volkswagen’s Wolfsburg stamping plant in May 2005: Several shifts with over 12,000 employees were affected, 2,000 cars could not be manufactured due to this blackout [3].

2 OBJECTIVES

A solution to this problem is the aim of the German research and development project *Smart Stamping*. Its basic idea consists of two objectives:

- Sensor technology is directly applied to press and die in order to collect process-data and data on the actual condition.
- A data interface between stamping plant, press manufacturer and die maker is defined to enable condition-oriented services.

Combining both objectives leads to a two-loop-system, which needs to be closed (figure 1): the control loop of the deep drawing process itself (machine-oriented loop) and the control loop between the parts manufacturer and its suppliers (service-based loop).

The closed loop of the deep drawing process consists of sensors applied to press and die, the press control and a metrology computer, which provides direct metrological access to the stamping process. Thus, this machine-oriented loop allows early reactions to wearout and anomalies and helps minimizing the risk of downtimes. Each data gathered by sensors in press and die is used to monitor the drawing process. In case of exceeding critical values (e. g. press force), the press is shut down automatically and a cause analysis is initiated before the die is seriously damaged.

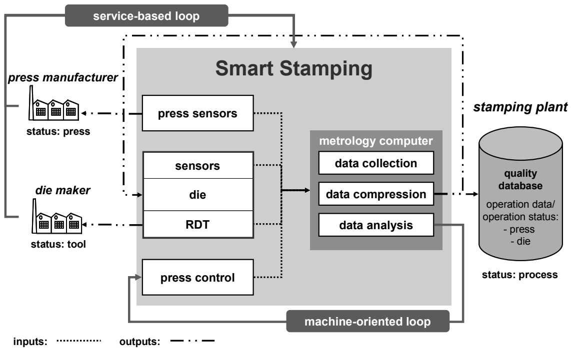

Figure 1: 'Intelligent' press-die systems with both loop systems.

Designing an interface between manufacturer and operator of the press-die-system aims at an intelligent marketing of increased availability as an extra service. Above all, this includes a condition-oriented and preventive maintenance along with an optimization of the deep drawing process, which is achieved with the help of the know-how of press manufacturer, die maker and metrology supplier. Having new 'intelligent' press and die technologies in use at many different production sites of various customers, the manufacturers of press and die benefit from a steeply rising learning curve. The latter can, in hindsight, be offered to the customer as a service. Integrated sensors help to better analyze the reasons for malfunctioning and downtimes of the press-die-system. Further capabilities to improve the system's output and performance can be made accessible. This closes a spanning service-based loop, which allows an optimization of the production facility and therefore an increased availability.

In addition, the process data helps to prove this increased availability and the output of the press-die-system. While negotiating with purchasers that insist on a fixed acquisition price, a premium price can be achieved as suppliers of investment goods are put in the position to plausibly prove the additional value of their products. Thereby cost models, such as pay-per-piece, can be offered to the customer: The operator of the press/die only pays for the parts he really manufactures and indirectly gains a guaranteed availability.

These objectives include the following potentials:

- Avoidance of dead times (e. g. wearout of valves, failure of hydraulic pumps, collisions).
- Exposure of idle resources of press and die.
- Reduction in response times in case of failures, minimizing downtimes.
- Easier-to-schedule efforts in maintenance.
- Scheduling of maintenance-work to non-production times.
- Minimized expenses in diagnoses due to online access.
- Optimized spare parts management (condition-oriented procurement, reduction in costs of having capital tied up).

As a result, nearly 85% of currently unused reserves in terms of availability of the press-die-systems are planned to be made available.

3 STATE OF THE ART

Over the last years, machining technologies such as turning and milling have been more and more substituted by forming technologies, of which deep drawing is one of the most important and widely-used techniques. It comes into operation for the mass-production of consumer goods right up to extremely complex components for the automotive and aircraft industries.

Nowadays increasing demands concerning quality and productivity force companies to focus on complex component geometries. They shall help to reduce the number of production steps and therefore reduce costs. To successfully achieve this aim, technologically superior and capital-intensive production facilities are required to comply with mandatory production-related process parameters. A profitable operation of such machinery makes high productivity and availability at the same time inevitable. Whereas productivity can be increased to some degree 'simply' by technological efforts, a lack of availability is the main reason for insufficient uptimes of production facilities. Figure 2 gives a schematic overview of the service life of machineries based on a survey at Volkswagen [4]:

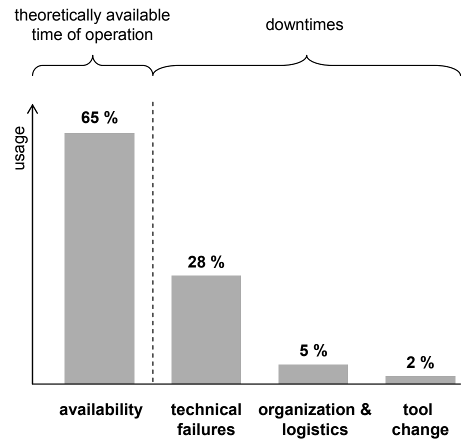

Figure 2: Problems of the availability of presses.

Optimizing press, die and the entire forming process in terms of quality, output and operating costs includes the conception of new business and service models. Business models are subject to changes which are results of constantly changing interests of the customers. Conventional units/ entities of the strategic management (business unit, branch, company) are not adequate to take these changes into consideration. Considering the resource-based-view, Bettis broadens the range of these units as he defines similar competencies instead of substitute units for the observation of the environment [5, 6]. Other opinions extend the analyses to strategic networks [7] or to the 'value net' of the company [8]. Nevertheless Staehler considers these extensions not to be sufficient enough to adequately grasp changes [5]. A business model is therefore chosen as the appropriate unit for analyses.

Numerous academic approaches to business models lead to a variety of different aspects of which a business model could consist. Table 1 summarizes different elements of models according to Mueller-Stewens and Fontin [9], Bieger, Rueegg-Stuerm and von Rohr [10], Knyphausen-Aufsess and Meinhardt [11] as well as Hamel [12]:

Mueller-Stewens/ Fontin	Bieger/ Rueegg-Stuerm/ von Rohr	Knyphausen-Aufsess/ Meinhardt	Hamel
value proposition	incentive system	product/ market combinations, customer value	core strategy
marketing	communication concept, growth concept	product/ market combinations	interface to the customer
production of goods and services	organization, cooperation mechanism, coordination mechanism, configuration of competencies	configuration and execution of the value added	strategic resources, value added network
benefit	benefit concept	profit mechanism	interface to the customer

Table 1: Synthesis of approaches to business models.

Keeping in mind the research project's objective and the industries' needs for action, Staehler's business model [5] supports the organizational design of business models for the marketing of increased availability as a service. His approach to new business models refers to Hamel, who conceived a framework for business models.

This framework is composed of four main components. Its foundation consists of so-called benefit potentials [12].

The **core strategy** describes which role the company plays within the competitive arena. For this purpose the business mission defines the main target of the company's strategy, whereas the range of products and markets indicates which customers are attended to in which markets and in which product segments. The basis of differentiation circumscribes how the company distinguishes itself from the competition.

Strategic resources imply that each competitive advantage is based on company-specific possibilities. The company's core competences describe its unique knowledge. Material and immaterial goods are called **strategic assets**. Accordingly, **core processes** are activities linking knowledge and goods to the benefit of the customer.

Interface to the customer: Implementation and support describe how the customer is reached and how customer service is designed. Gathering and usage of information on the customer are understood as information and insight. The dynamic relation goes into the emotionality of the relationship to the customer. Benefit and profit mechanisms are at the bottom of the price structure.

The **value added network** complements and enhances the company's resources. Vertical relationships with suppliers lead to horizontal relationships to customers. Alliances with competitors may help minimizing risks.

In parallel to Meinhardt, Staehler summarizes these elements to three core objects [5]:

The **value proposition** defines the products and services that supply the certain customer needs.

The **value added** respectively the **architecture of the production of goods and services** answers the question how the output shall be generated. Whereas the internal architecture accounts for resources (e. g. core competencies, assets), mechanisms for communication and coordination and externally sourced activities, the external architecture describes the interface to the company's customers and its value added partners.

The **benefit model** focuses on how to design the profit mechanism.

Successful business models additionally integrate the service sector: It already plays a major role for the economies of numerous countries and its importance for the production industry is increasing steadily [13].

But more important for many companies is the fact that services have become 'mandatory'. They offer new potentials for differentiation and therefore new earnings become accessible. These potentials open up various development perspectives for the company, ranging from a *simple* manufacturer to a service providing manufacturer to a producing service provider [14] – keeping in mind the complexity of a professional service management in regard of cultural, organizational and technical problems and questions [15].

In general, products are responsible for customer loyalty; however differentiation within markets can only be achieved through customer-specific solutions. These solutions are no longer sold as a physical product, but rather as a service. Rendering and performance of services are closely linked to value added processes.

Services offer numerous chances in today's competitive environment: Higher margins in the service sector, positive marketing effects of services or strategic potential are just a few examples [14]. Therefore tool and die makers as well as press manufacturers move away from their old image of being *ordinary manufacturers* and expand their product lines to new services.

Thereby incentive systems tie in with market and performance decisions while offering extensive and efficient problem solutions to the customers. Incentive systems set three objectives:

1. Structuring the core product.
2. Make the customer aware of versatile services.
3. Differentiate oneself from competitors.

Individual partial performances are bundled to customer-specific packages to solve their problems, which offers advantage both for customer and supplier. The more distant the service provision is from the initial product, the more customer-specific it has to be designed. Therefore business models for services are of great importance for companies. The value proposition, the value added and the profit mechanism of service offers in incentive systems have to be designed in a coherent business model. Designing these service models offered can refer to adequate preliminary work, which assists in structuring and guiding the development of solutions to availability-optimized press-die-systems.

In reality, the situation is different and more complicated: The methods described are not sufficiently adapted in order to establish transparent services paid for by the customer. Information exchange between supplier and customer is barely adequate. Therefore maintenance activities are mainly reactive (leading to dead times of presses) or preventive according to fixed intervals. A statement on the actual necessity of maintenance can thus not be made, needless downtimes are assumed. In addition, the services offered at the present time are insufficient in terms of profitably guaranteeing a maximized availability of the press-die-system.

From the customer's point of view, 'back-up' capacities of production facilities are not able to make up for dead times of presses due to high capital costs. In combination with little stock along the supply chain this may lead to an insufficient supply of the customer; further downtimes along the entire supply chain are the result. Assuring the availability of a production facility by storing spare parts is economically impossible, as long-dated spare parts lead to a high capital tie-up as well. Besides, in case of problems service technicians are rarely available on time; preventive instead of condition-oriented maintenance schedules regular inspection intervals to unfavorable time slots. Therefore it can be assumed, that in numerous times maintenance activities are necessary at a later date. This date can be scheduled to a planned downtime of a machine and would not affect its productivity.

Another starting point for improvement is the set-up of press and die. Normally the press-die-system is dimensioned for maximum security needs (along with the cost disadvantages involved) as no detailed process data exists. At this point suppliers have the chance to generate an added value by offering an early and ideal set-up as an extra service.

The press manufacturer however is not able to guarantee such condition-oriented maintenance, as he has a lack of mandatory process data. This is mainly a result of an insufficient exchange of data with the parts manufacturer that operates the press. Today many companies do not provide this data as they fear the loss of guarantee claims in case of abnormal operation conditions. On the other hand they do not want to transfer information on their process know-how to third parties. But this transfer of information would certainly allow a comparison of similar production processes and thus enable an optimization of one's own process know-how.

Although remote processing has been state-of-the-art for a long time by now, process data is not being transmitted yet; customer services today are not able to readout machine-specific process data to optimize the problem diagnosis and, for example, directly bring along the proper spare parts. Probably the biggest deficiency is the lack of feasible approaches on how to define safe and confident dealings with sensitive data. Today there are no existing tools to classify the data or to coordinate how involved participants handle the latter. An improved condition-oriented maintenance is therefore not possible at the moment.

On the other hand an increased availability of a production facility could be achieved through redundant components. But as this technical alternative requires tremendous extra expenses it makes no economic sense. From the press manufacturer's point of view only services, which are rendered anyway and do not come along with additional expenses, can achieve an increased operational availability of his machinery.

The second supplier of the press-die-system, namely the die maker, ensures that his product is in proper shape and condition on the basis of fixed maintenance intervals. To do so, the dies are time-consumingly examined by specialized staff. Typical characteristics of wearout are checked in order to obtain indicators for the risk of maloperation and failure. Besides time and effort for this procedure, the condition assessment is often faulty and not objective.

4 NEED FOR ACTION

Reality shows that existing deficiencies concerning condition-oriented maintenance of press-die-systems are a consequence of the following aspects:

- Parts manufacturers as well as suppliers of press and die possess only insufficient knowledge of the deep drawing process.
- Services rendered by the providers of investment goods are not yet *tailored* to a customer's specific problem.
- Condition-oriented maintenance activities are mostly carried out in fixed intervals.

A main barrier for an efficient condition-oriented maintenance is the lack of availability of life cycle and process data, which is neither adequately gathered nor communicated. Figure 3 shows the life cycle of a deep drawing die including the die maker's dynamic ideal and real learning curves. First, gathering of life cycle data allows the die maker to improve his own processes and to reach an ideal learning curve. Second, life cycle data also delivers information about the point in time at which certain costs thereby incurred. In this way they unveil spots in which service models make good sense and would be generally accepted by the customers.

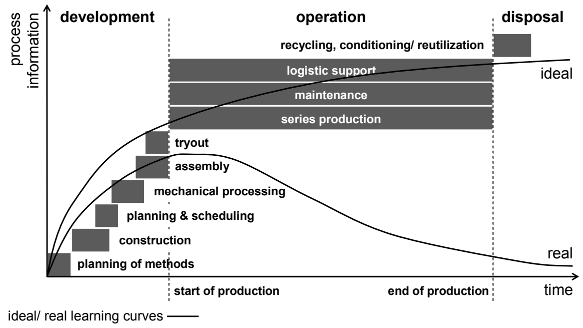

Figure 3: Life cycle of a deep drawing die [16, 17].

Appropriate life cycle costing models for press and die, which are being developed by the Laboratory for Machine Tools and Production Engineering, shall help to close the existing gap of information between supplier and parts manufacturer. Thereby strategies for the gathering of life cycle data by the integration of measurement technology into the press-die-system are developed. Above all, new service models based on condition-oriented and preventive maintenance along with an optimization of the deep drawing process are configured. Resulting new service models represent business models integrating services and the physical product. Being based on life cycle costs, these models may lead to options such as pay-per-piece or pay-per-hour. A growing body of literature has identified business models for capital goods based on the provision of tailored combinations of products and services as high-value integrated solutions to customer needs over the last years [18, 19, 20].

5 ACKNOWLEDGEMENTS

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Business models for technology-supported, production-related services of the tool and die industry

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Abstract

Today's turbulent economic environment confronts German tool and die makers with new challenges. To compete with China and with the new eastern members of the European Union, German companies must come up with innovative products and services to stand out from their competitors. New types of business models shall offer individual solutions to the customers, integrating product and services to a hybrid product. Within the research project *TecPro*, 'intelligent' tools which are to deliver completely new data from the production process will be developed. With their help, business models for technology-based product-service-systems are to be designed.

Keywords:
Tool and die making; Business Models; Product-Service-Systems

1 INTRODUCTION

Tool and die companies take up key positions within the production industries of Germany, Japan, the United States and few other countries as a study by the Michigan Manufacturing Technology Center (MMTC) shows [1, 2, 3]. The role of tool and die makers is a result of their responsibility for the industrial value chain in terms of time, costs and quality (figure 1):

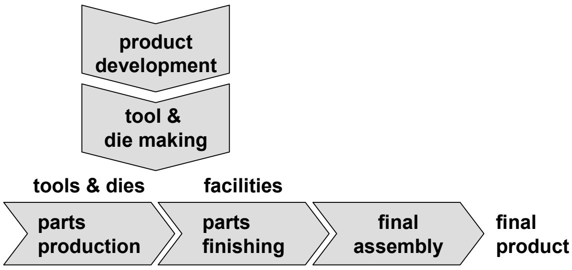

Figure 1: Tool and die making within the industrial value chain.

They decisively determine their customers' productions' adherence to schedules:

- Each start of production depends on the completion of the required tools and their integration into the existing production facilities.
- A tool's technological abilities have significant influence on set-up and cycle times of the machine tools.
- Up to one third of the final product's manufacturing costs can be tooling costs.
- The product's quality is directly linked to the tool's quality.

Purchasing departments of original equipment manufacturers (OEM) use electronic platforms more and more frequently. Already in the year 2000, Ford Motor Co. expected 70 to 80% of all of its purchasing transactions to take place on the World Wide Web within the next two years [4]. Therefore the range to differentiate oneself from the competitor is constantly being made smaller. Online submissions of quotas, mainly known as e-bidding, leave the product price as the only selection-criterion. The quality and abilities of a tool, which vastly influence a facility's productivity, are barely and inadequately considered in such purchases. As these parameters are difficult to be proved to the customers, German tool and die companies are falling more and more behind.

2 COMPETITIVE ARENA

In today's turbulent environment German tool and die companies are threatened by two current developments: At first, over-capacities arise from the eastern enlargement of the European Union as well as from an increasing supply in Asia, which leads to a big drop in prices. This decline is intensified by an advantage in total costs of up to 31% in these regions compared to tool makers in Germany [5]. Secondly, foreign tool and die companies convince through bribing constructive and excellent production know-how. The latter relativizes advantages in both productivity and quality of the German industries.

The machine tool industry, whose forming and molding machines are set up with tools and dies, faces the very same problems. Besides it stands responsible for an efficient manufacturing of products and goods. Export quotas of about 80% of injection molding machines manufactured in Germany are, amongst others, a result of increasing exports to Asia and Eastern Europe. As a consequence, services for injection molding machines have to be provided worldwide. Therefore machine tool companies currently consider building up international service networks to be one priority objective for the next years. But they know from experience that co-operation partners often cannot assure the desired quality of service. For this reason usually highly qualified employees of the company have to be deployed across the world.

Both tool makers and machine tool manufacturers now face the question on how to sell their abilities and capabilities at best in order to remain globally competitive. Industrial services do offer a chance to sustainably improve the positions of German companies in this fierce competitive environment. Ideal solutions to the customer's problems instead of a 'simple' product can meet the customer's challenges [6].

In this context the interface between machine and tool plays an important role: it enables both the machine and the tool manufacturer to answer the question, which process data is required to generate the target output.

3 RESEARCH APPROACH

Within the research project *TecPro*, German tool and die companies are to be given new approaches to cope with the presented problems within the competitive arena.

The basic approach is to define an interface for the exchange of data between tool and machine, which shall assure that there is only one single interface at the customer's side, as figure 2 shows:

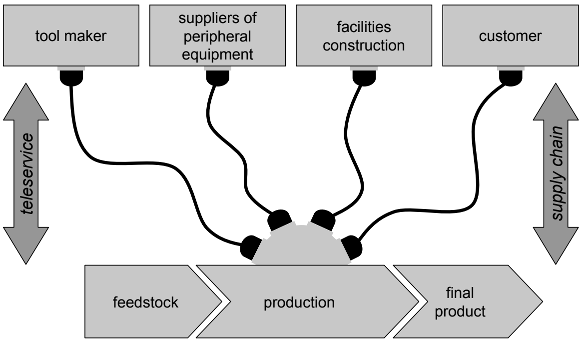

Figure 2: Interface for the exchange of data.

Multiple users, such as the tool and the machine manufacturer, are connected to this interface via remote data transmission (RDT). The research project's aim is to develop new business models for these so-called teleservice-supported product-service-systems. Thereby organizational, commercial, strategic and technological aspects are taken into account.

The main issues of the project are:

- Analysis of the requirements for an integrated approach to business models for technology-supported product-service-systems.
- Conception of business models for product-service-systems based on 'intelligent' tools.
- All interfaces between the processes of the business model and the technical applications are defined.
- The intermediary results are transferred to the injection molding process.

Since the mid 1990's, the development of services has been performed under the name of *Service Engineering* [7, 8] in German speaking countries – parallel to the American *New (Industrial) Service Development* [9, 10]. Today a business model may become a product in and of itself [26]. Within *TecPro,* the approach of new business models for product-service-systems based on state-of-the-art measurement technology therefore goes beyond these long-established definitions.

4 STATE OF THE ART

Stable competitive advantage can only be achieved through sustainably superior products. This means that these products do not only have to meet current customer expectations. Moreover they have to preserve the demanded value of benefit within as many future scenarios as possible [11]. Small and medium tool and die companies have to face the question, which products and services are going to be offered to which markets in the future. By answering that question they need to distinguish themselves from their competitors.

An exclusive differentiation in price has not quite worked out over the last years. Furthermore the initial situation for such a differentiation is not given in Germany. Labor and non-wage labor costs have been a major focus in the political debate on Germany as an investment and industrial location. While the debate means an agonizing concern and increasingly acrimonious public discussion about the future of Germany's economy, social makeup, research, social welfare and international competitiveness, every single German company has to deal with these costs in its own way to remain yet competitive. Foreign competitors from Southern and Eastern Europe as well as from China, that are stunningly boosting their product quality, incite local companies to high-performances. Nevertheless, the question how long the pricing pressure can be beard remains unanswered.

The extension of existing business models provides a chance for German tool and die companies to sustainably improve their competitive position in this fierce environment. Potential values can be exploited on the basis of Porter's three generic competitive strategies: overall cost leadership, (product) differentiation and focus [12]. Within the branch of tool and die making, the latter can be subdivided into cost leadership and differentiation as it achieves one or both of these positions vis-à-vis its narrow market target. Criteria for differentiation over other companies can be: time in terms of adherence to schedule, productivity and life span of the tool – whereof each allows a real differentiation and a price premium, see figure 3:

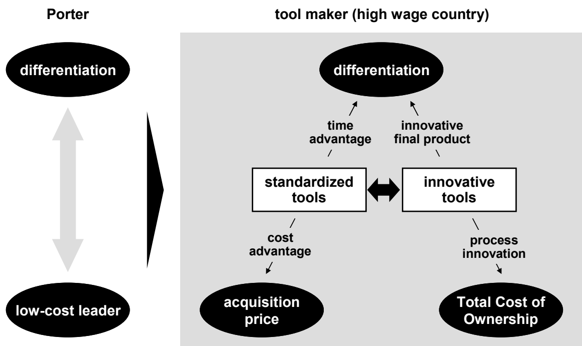

Figure 3: Strategic product placement within tool and die making [16].

The success of a company is founded in its business model. One can speak of a *Strategic Fit*, if all elements of the business model are harmonized with each other [13, 14, 15]. Beyond this, the individual elements are to intensify one another. This fit is of particular importance for the tool and die making industry: the cardinal positions of innovative and standardized tools lead to varying needs and development potentialities (figure 4).

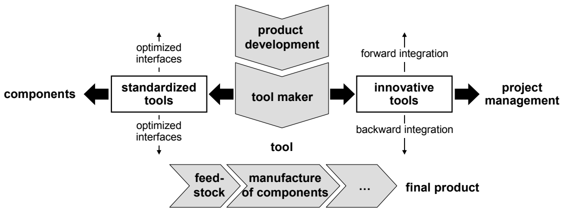

Figure 4: Consequences due to product placement [16].

A concentration on standardized tools makes uniquely defined interfaces to adjoining sectors essential. Innovative tools on the other hand demand a steady learning process as well as a profound involvement into the development process of the customer. Upcoming needs can thus be easily identified and an early contribution to the realization of the innovation can already be made. Thereby taking over of more accountability for projects becomes possible [16].

The Laboratory for Machine Tools and Production Engineering has carried out several case studies on successful business models, as figure 5 shows. A gross distinction can be made into the two dimensions *cooperation* and *benefit*.

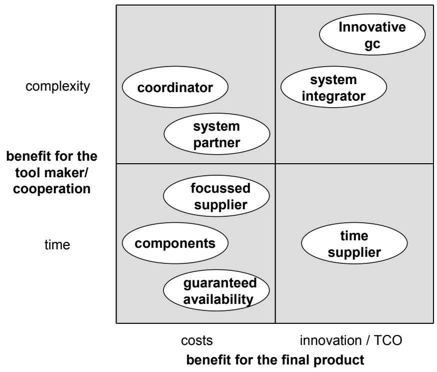

Figure 5: Successful business models of tool and die makers.

A morphological box is the basic element of each model to be generated. It offers several possible specifications for each characteristic. Choosing one specification per characteristic configures the total system. Some definitions of business models are quite abstract and outward looking [17, 19, 20, 18, 21] whilst others are detailed and all encompassing of business functions [22, 23, 24]. According to Mueller-Stewens and Lechner, a business model consists of four sub-models (refer to figure 6):

- Value proposition: which value is offered to the customer?
- Marketing: how can appropriate customers be attracted?
- Benefit: how is the profit mechanism to be designed?
- Production of goods and services: how shall the output be generated? [18]

The value proposition defines the products and services that supply the certain needs of a customer. Thereby services which consist of modular bundles [25] gain in importance: Based on competitive strategies, a new business model has to configure reasonable product- and market-combinations. These combinations allow drawing precise conclusions of how to achieve competitive advantage.

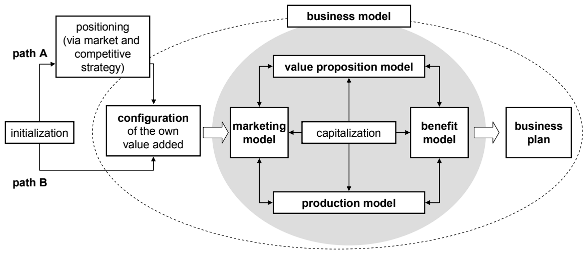

Figure 6: Business model according to Mueller-Stewens and Lechner [18].

A 'strategic triangle' is formed by the customer, the competitors and one's own company. It describes a market in which service offers are exchanged. The dependencies among the three vertices of the strategic triangle are defined by the marketing model. It sets off activities to identify and address the needs of economically attractive customers which are subsequently contacted by the sales department. This process is supported by adequate communication tools and the corporate claim. However, the marketing model needs to define the attitude towards the company's competitors and not just towards its customers.

What matters in the benefit model is the question on the company's profit mechanism:

- Units, usage and output are determined and build up a benefit basis.
- Achievable benefits from transactions are estimated and benefit levers are selected.

According to Frick, a bonus for guaranteed availability plays a decisive role besides the basic principle of differentiation. The benefit basis specifies what is sold and which delivery of goods is accounted for. Hence it characterizes the entire business model [16].

The value proposition model defines the manner of the value proposition itself. Based on the configuration of the value added it defines the discrete phases, resources and skills are allocated, make-or-buy-decisions are made. Beyond this, partner contributions are determined and coordination mechanisms as well as communication channels are installed among the partners and among the defined phases.

In addition to the configuration of the value added, the flexibility of one's own capacities is of outstanding importance for tool and die companies – in terms of both unsteady demands and work tasks. The organizational structure is essential for a complete specification of the model. For this reason, the focus is restricted to the central criteria of business models for tool and die makers.

Configuring individual business models leads to a dilemma, that is described best by Hawkins: "as the (dot com) bubble grew, the market filled up with books and articles about business models, ranging from the vaguely analytic to the quasi instructional – how to construct viable business models and how to avoid lemons. The business model seemed to fill a niche even if no one could explain exactly what it was [26]." Therefore a configurator for business models has been developed at the Chair of Production Engineering at RWTH Aachen University (figure 7). It shows the different elements of a business model [16]. Choosing one element per row leads to specified business models for tool and die makers. In doing so, the competitive conduct does not make any contribution to a differentiation of the individual business models.

value proposition	benefit of co-operation	complexity reduction	timesaving			
	benefit of the product	costs	innovation			
	services "development"	part development & prototyping	consulting part development	part optimization	none	
	services "production"	batch production, refined	batch production	SOP-monitoring	repair/ maintenance	none
marketing	market presence	all-rounder	specialist	problem solver	one-stop-shop	
	market access	service provider	internal or external tool maker	external tool maker		
	range of customers	focus on strategic partners	partners & other customers	spectrum of customers		
	competitive behavior	defensive, internal	defensive, external	offensive, internal	offensive, external	
benefit	responsibility for delivery	tool components	tools	Operating resources	parts	productivity
goods and services	configuration	integrator	layer player	orchestrator	retailer	
	capacities (dimensioning)	workload	availability			
	range of processing	scale	scope			
	organization	dynamic, national	dynamic, international	static, national	static, international	

Figure 7: Configuration of business models.

5 TECHNOLOGICAL ENABLER

Considering the research approach, knowledge of the actual conditions of tool and machine is crucial. This includes information on wearout, operating conditions and operating times. Without the acquisition of this data, neither a profound statement, whether tool and machine are run on mandatory operating conditions, nor a statement on overcharges of tool or machine can be made. For that reason there is a huge need to identify state-of-the-art measurement technology to gather this data. Forecasts for proper service intervals can thereby be made and be scheduled to non-production times. The operational availability of machine and tool can be increased.

To make this data available for the tool maker, the gathered data is stored in so-called transponders, which are directly attached to the particular components [27]. Their small size and the fact that they are directly attached to the tool allow transponders to monitor the operational conditions of tool along its entire life cycle. An appropriate IT-linkage can make this process data available to the manufacturer of the tool. Thus he becomes capable of monitoring the process and of installing a *reactive maintenance* and of integrating the knowledge gained into new product development processes. At the present time, production-related processes with the tool cannot be influenced by its manufacturer as soon as it has been delivered to the customer.

6 PARTICULAR REQUIREMENTS FOR NEW BUSINESS MODELS

As worked out, new measurement technologies help to receive extended process data from a tool within the process of manufacture. This new technology is to individually adjust and customize a preventive maintenance of the tool to the customer. Thus the response time in case of service need can notably be shortened.

Therefore companies have to focus on the development of hybrid products, resp. the integration of products and services, which go beyond established business models. The development of such production-related services follows the customer's wish to reduce his own vertical range of manufacture and to outsource operations of the secondary sector. Additionally, the latter fulfills the general understanding of value added within networks.

Along with five dedicated German companies, the Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University is committed to strengthen the position of German companies of the tool and die sector. Within the research project *TecPro*, new concepts allowing the companies to specifically offer availability and productivity of their tools are to be created.

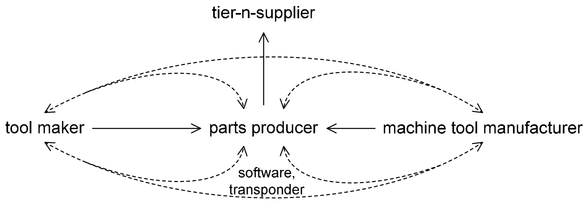

Figure 8: Multi-lateral flow of information between tool maker, machine tool manufacturer and parts producer as objected within the research project *TecPro*.

Realizing such technology-based product-service-systems, the project consists of three essential parts:

- Individual business models need to be designed for the provider of products and services. This includes the necessary concepts of how to design the services offered.
- Excellent technological solutions to enable those business models have to be developed.
- Field test in the injection molding process.

Business models for hybrid products comprise organizational, commercial, strategic and technical aspects. The strategic aspects are vitally important, as in order to obtain success in business with services, a consistent strategic planning and a consequential realization of business models are unalterable [28]. Organizational aspects of a business model include the design of the value proposition offered to the customer, the cross-company division of the creation of value and lastly the design of the benefit model [18].

New technological solutions shall qualify companies to develop such business models. 'Intelligent' tools which are to deliver completely new data from the production process both from tool and machine can represent this solution. Therefore, in a field test new types of sensors are integrated into an injection mold and into a molding machine to measure all relevant data and information of the production process. The data collected is directly linked to the actual state and wearout of tool and machine. Transponders, which are directly applied to the tool and to the machine, are able to retain this information. They provide the information for further processing by the tool maker or the machine manufacturer. Both suppliers are thereby in the position to offer an optimized preventive maintenance and react promptly and adequately. An enhanced availability and productivity of the entire injection molding process is achieved.

Besides a guarantee of availability for their products, the allocated data and information from the injection molding process put both tool maker and machine manufacturer in the position to get to know the performances of mold and machine in operation better. Faulty manufactures and downtimes can directly be assigned to their origin: namely mold, machine or operator. 'Intelligent' tools eliminate the missing proof of maloperation, which is one of the biggest barriers for full service models.

The rules of the prevailing competition can thus be changed for the benefit of the German tool and die and machine tool industries: On the one hand, their ability to compete is strengthened by newly business models; on the other hand, the turnout with superior tools and perfectly matching machine tools becomes more efficient, which compensates the price-advantage of low labor cost countries.

7 ACKNOLEDGEMENTS

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An Empirical Study of how Innovation and the Environment are Considered in Current Engineering Design Practise

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Abstract
This paper reports the findings of a study of the current innovation and environmental considerations of six businesses that design and manufacture products affected by the product-related environmental legislation. Activities undertaken with the businesses provide insights into their New Product Development (NPD) processes, their innovation capabilities and their actions to improve their environmental performance. Several features of their NPD processes are suggested as presenting opportunities for eco-design tools to be integrated into design practises without negatively affecting the current NPD process. Finally, a conceptual framework is proposed which highlights the inter-relations between business, environmental, and customer requirements of a product across its lifecycle.

Keywords: Eco-design; New Product Development; Design tools

1 INTRODUCTION

It has been widely noted that although a wide range of eco-design tools have been developed relatively few of them have been adopted into industrial practices [1]. One response from researchers has been to propose modified NPD models which emphasise the integration of eco-design tools into the process [2]. However, it has been noted that of the relatively few businesses who have adapted their NPD process to improve product environmental performance, most have ignored the models proposed by academic researchers and have instead developed their own models based on real-life practice [3].

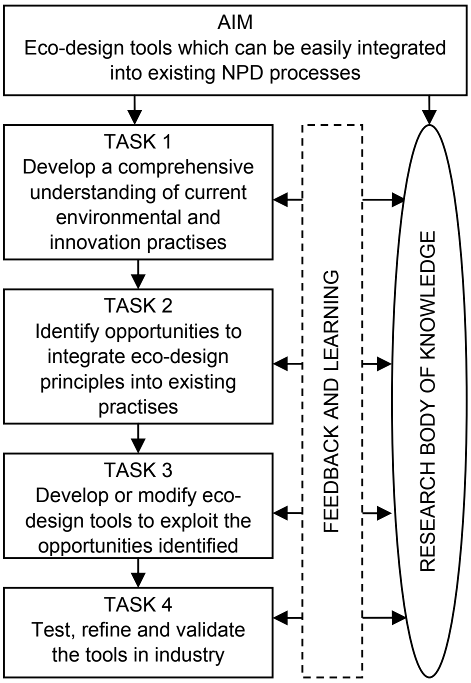

Figure 1: Research aims

This research takes the alternative approach in which the aim is to modify existing eco-design tools or develop new ones such that they fit into the existing NPD process of the business [4]. This paper reports on a study of the innovation and environmental practises within six businesses in the South-West of England. The results of this study along with the subsequent analysis contribute towards the completion of tasks 1 and 2 of the wider research program, as shown in Figure 1.

2 METHODOLOGY

2.1 Selection and recruitment of businesses

The study was conducted with six businesses that design and manufacture products in the South-West of England that are likely to be affected by the Waste Electrical and Electronic Equipment (WEEE) [5], Restriction of Hazardous Substances (RoHS) [6], or Energy Using Products (EuP) Directives [7].

Business	Size	Product Range
A	Medium	Professional audio equipment
B	Medium-Large	Location/inspection equipment, sensors
C	Medium	Water/central heating controls, utilities metering
D	Medium	Heating, ventilation and hot water systems
E	Medium	Vending machines
F	Small	Industrial testing equipment

Table 1. Characteristics of the businesses surveyed

Whilst primarily a study of design activities, there was interest in selecting businesses who also manufacture in the area as this would lead to greater engagement with the manufacturing process and so greater knowledge of the environmental impacts of the product. Also, research literature has suggested that product-related environmental legislation is a strong driver for eco-design [8]. Business characteristics are summarised in Table 1

2.2 Development of research methods

The aim of the research was to gain an understanding of the **real** practises of businesses. It was therefore decided to develop a range of activities which would require the business to demonstrate their environmental and innovation performance by providing evidence and concrete examples.

The visits lasted around three hours and the participants generally included, as a minimum, the Environment Manager (or equivalent) and the Design/Technical Manager. A typical visit programme is shown below with subsequent sections providing details of the key activities.

Visit programme

- Presentation by the researchers on the latest developments in the WEEE, RoHS and EuP Directives followed by discussions on how they affect the business
- Activity to assess the level of environmental 'pro-activity' of the business within its supply chain
- 'Life Cycle Thinking' activity to assess current environmental actions throughout the product life cycle
- Factory tour
- NPD process mapping activity
- Innovation benchmarking questions
- Recording of the business's current 'innovation funnel'

Life cycle thinking activity

A chart listing the six lifecycle phases was presented to the participants who were given a brief explanation of the principles of life cycle thinking. The researcher then went through each lifecycle phase asking for examples of where actions or initiatives had been taken by the business to reduce the environmental impacts associated with that phase. Prompts were given where necessary.

NPD process mapping

This activity was introduced by presenting the participants with examples of both formal and less formal NPD process models and asking which of the examples most closely related to the business' own process. The participants were then asked to talk through and map out their NPD process on a flipchart. This map was further elaborated by asking the participants to add comments to identify general strengths, in green pen, and general weaknesses, in red pen.

Innovation benchmarking questions

An abridged version of the UK Design Council's 'Living Innovation' [9] benchmarking questionnaire was used. Three sets of three questions covered the business' ability to 'inspire' their designers, 'connect' with their customers and suppliers, and successfully 'create' – take good ideas into manufacture. Each question was written on a separate small card with a 4 point Likert-type scale at the bottom where one participant noted the consensus of the group by ticking the appropriate box. This consensus-seeking method was intended to obtain a response which was as representative of 'the business' as possible.

3 RESULTS

In order to facilitate inter-business comparison and benchmarking, a quantitative scoring system was developed for some of the activities. The scoring system for the activities and the business results are presented here:

Supply-chain pressures activity

Businesses who applied more environmental pressures on their suppliers than they received from their customers were deemed to be environmentally 'pro-active' in their supply chain, and vice-versa. Businesses were awarded 0 to 4 points for this activity depending on their level of 'pro-activity' with a score of 2 indicating a neutral balance. According to this criterion, only one business was considered to be 'pro-active' on environmental issues, half of the businesses were found to be 'reactive', and the remainder were 'neutral'.

Life cycle thinking activity

Table 2 shows the number of businesses who have made 'significant' efforts in each of the life cycle phases (indicated by a cross). A business was deemed to have made a 'significant' effort if it was able to provide three or more examples of initiatives or methods they use to reduce the environmental impacts during that particular phase. Four out of six of the businesses were able to demonstrate significant effort in three of the lifecycle phases with the remaining businesses able to demonstrate significant effort in at least one phase.

Life cycle phase	Companies making a 'significant effort'					
	A	B	C	D	E	F
New concepts	X	X				
Selection and use of materials			X			
Production optimisation	X	X	X	X	X	
Distribution system	X		X		X	
Impacts during use				X		
End-of-life strategy		X			X	X

Table 2: Results of life cycle thinking activity

Innovation benchmarking questions

The innovation benchmarking questions were scored by awarding +2 points for a 'strongly agree' response, +1 for an 'agree' response, and conversely -1 and -2 points were awarded for 'disagree' and 'strongly disagree' responses respectively. All businesses scored positively on the benchmarks but the scores varied considerably from +4 to +12 points. In all cases the scores appeared to be consistent with the researchers' views as to the relative innovation 'strength' of the businesses.

4 DISCUSSION

4.1 Environmental performance of businesses

Supply-chain pressures activity

Several of the companies commented that there had been an increase in the dialogue between the business and their supply-chain in recent years. In most cases this dialogue appeared to be limited to issues directly relating to compliance with legislation such as the WEEE and RoHS Directives. The positive effect of this communication was that the majority of businesses appeared to be on course to fully comply with the WEEE and RoHS Directives where necessary. Four businesses had received customer requests for information on wider issues such as if the business had an environmental management system. Only one business could give an example of how such communication had led to an improvement in the environmental performance of the product which was not directly related to legislative compliance.

Life cycle thinking activity

From Table 2 it is noteworthy that five of the manufacturers have made significant efforts to reduce environmental impacts through 'production optimisation'. This is logical given that improvements made to the production phase are likely to lead direct cost-savings for the manufacturer e.g. through reduced energy costs or waste minimisation. The wide-spread interest in 'cleaner production' during the 1990s is another likely explanation of the success seen in this area.

In contrast, just one manufacturer had made significant improvements to the 'impacts during use' of their products. The products of businesses A, D and E clearly have very significant impacts during their use phase and yet only one had made significant improvements in this area. The question therefore presents itself as to why the other two manufacturers had not yet attempted to make improvements in the use phase of their products' lifecycle. In both cases the businesses estimated the use phase as posing the greatest environmental burden, therefore lack of awareness is ruled out. In fact, both businesses explained that energy efficiency was not an important consideration for their customers, which was reflected in their product specification and weightings.

Whilst undertaking the life cycle thinking activity it was occasionally necessary to provide examples so that the participants could identify environmentally beneficial activities from their own business. It is suggested that this is because these activities had originally been framed as 'cost-saving' activities and the participants struggled to view these activities through an 'environmental frame'.

Several businesses commented that they were pleasantly surprised by the number of positive environmental actions that were attributed to the business within the life cycle thinking activity. Furthermore, three out of the five businesses who completed feedback forms after the visit agreed or strongly agreed that due to the visit they planned to improve their environmental actions. This implies that the activities had raised environmental awareness and motivation to some extent.

4.2 Innovation capabilities of businesses

NPD process mapping

The NPD models were analysed with a view to identifying popular tools or methods and similarities or features of the process which might provide suitable 'entry-points' for eco-design. The results of this analysis are presented in Table 3.

One weakness which was mentioned by the majority of the businesses concerned the difficulty in developing an accurate and stable requirements specification. Many businesses mentioned that work progressed even when the requirements specification had not been formally agreed or that changes to the specification were often made after it had been agreed. This was perceived as wasting engineering effort and slowing project progress. Research literature suggests that the formulation of the requirements specification is a key stage for the integration of environmental considerations [15]. This suggests that there are opportunities for methods which can both improve the requirements specification formulation process and integrate environmental considerations.

Innovation funnel

It was observed that businesses found it difficult to discuss 'failed' projects and struggled to provide examples of failed projects. Academic literature [16] suggests that successful innovators have a high number of projects drop out of the NPD process but that these failures are mitigated by failing 'early' i.e. before significant time and resources have been committed to the project. Several businesses commented that they made efforts to learn from their failed projects, but overall it was concluded that the 'fail early and often' culture was not

Common 'Strengths'	Business benefit	Eco-design opportunity
Use of QFD	Ensure that requirements specification accurately represents needs of customer	Promote use of QFD for the Environment [10] which extends existing QFD tools by including the 'Voice of the Environment' to set environmental targets
Regular safety and compliance reviews	Avoid the negative business impacts of non-compliant or unsafe products	Include an environmental review as part of the safety review – check for environmental compliance and ensure environmental targets will be met [11]
Strong emphasis on cost-management and designing to a price point	Ensure that product is price competitive within its market segment	Use of financial methods such as environmental accounting [12], or Eco-Value [13] to emphasis cost benefits to business of eco-design
Customer feedback as an input to the design process	Ensure that customer requirements are understood	Further enhance customer focus by moving from 'eco-efficient' satisfaction of *requirements* to the effective fulfilment of *needs* through 'co-development' methods [14]

Table 3: Opportunities for eco-design within existing NPD process models

present in any of the businesses studied.

A number of differences were noted between the innovation tunnels of the businesses in terms of the number of new projects launched per year, the time taken in development etc. However, it is difficult to draw general conclusions from these results as it is likely that the variations observed are as much due to contextual factors (such as the technology cycle of the industry, the size of the business,) as they are to the innovation strategy or culture of the business.

4.3 Development of a conceptual frame work

It was noted in section 4.1 that the businesses studied in this project struggled to recognise the environmental benefits often associated with their cost-driven actions. It was also noted that many of the businesses placed significant emphasis on trying to capture and understand the customer's requirements, as is reflected in the structure of their NPD processes and the common use of tools such as QFD. Based on these two observations it was suggested that a conceptual framework which clarifies the inter-relationships between the business, environmental, and customer requirements of a product would be useful. In the following section such a framework is developed and applications of the framework are suggested.

The Business-Environment-Customer Synergies Diagram

Reviewing previous literature is it apparent that significant time and effort have been devoted to developing tools and methods to motivate a business to consider the environmental aspects of product development as well as customer and business requirements. One focus has been on methods to link economic and environmental performance such as 'eco-efficiency' [17], 'eco-cost/value ratio' [13] and environmental economics [12]. Other work has considered the stakeholders within the environmental NPD process. This has led to the development of stakeholder maps [18], and an environment orientated Customer Value Chain Analysis tool [19] which models the interactions and transactions between the major stakeholders in the product lifecycle. There are also several tools which help to generate lists of environmental considerations for a product and prioritise them. These include examples which focus on functional aspects, such as QFD for the Environment (QFDE) [10], and non-functional aspects such as legal, cultural, and cost performance [20].

Unfortunately, none of the currently available tools or methods appear able to represent the product requirements from the viewpoint of the business, the environment and the customer **simultaneously**. Recognition of this fact led to the development of the 'Business-Environment-Customer (BEC) Synergies' diagram presented shown in Figure 2.

The BEC Synergies diagram is intended to represent and classify the inter-relations between the key stakeholder requirements of the product throughout its lifecycle (referred to from now on as simply 'product requirements'). Product requirements are positioned on the diagram according to the stakeholders for whom that particular requirement will provide a benefit. Figure 2 uses real examples taken from the six businesses visited. Beyond this segmentation of product requirements, the BEC Synergies diagram can be used to classify the types of business methods or design tools which may be appropriate when attempting to fulfill the requirements within a sector, as shown in Figure 3.

Application of the BEC Synergies Diagram

It is suggested that businesses may use the BEC Synergies diagram in the development of an eco-design projects using the following procedure.

First, list the major product requirements and place them on the BEC Synergies diagram as in Figure 2. Next, decide on which aspects of the design to focus on. The completed diagram should help to identify where previous projects have already made improvements, what aspects have been neglected, and where there remains potential for improvement. These are then reviewed, looking for opportunities to create environmental benefits whilst also benefiting the business, the customer or ideally both. Having selected a focal area for the project the team will need

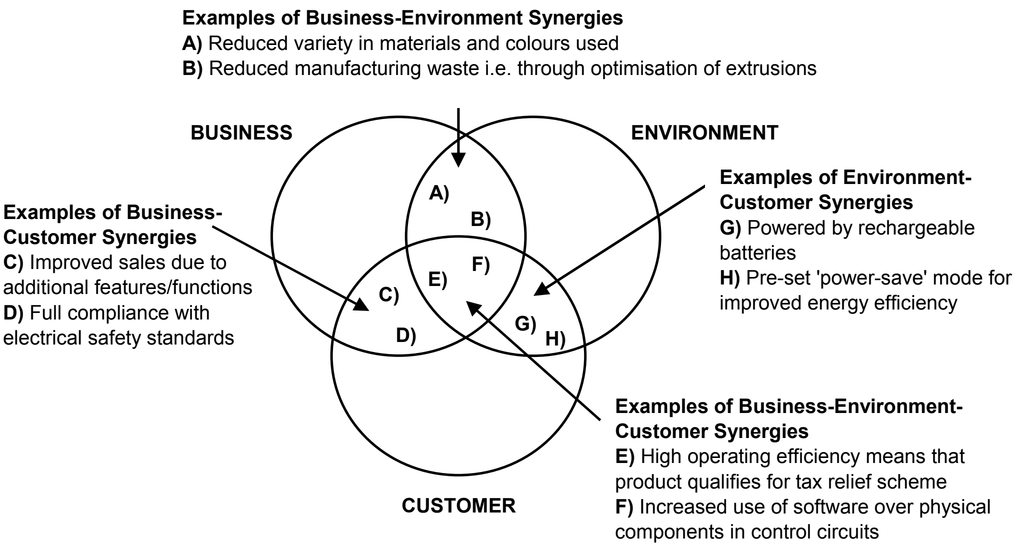

Figure 2: BEC Synergies diagram showing the inter-relations between business, environmental and customer product life cycle requirements

appropriate tools and methods to assist them. These can be selected by listing the business and design methods currently available to them in a separate BEC Synergies diagram, as in Figure 3. By selecting tools and methods from within the segment of the diagram as the focal area an appropriate match should be found. For example when Business A wanted to reduce manufacturing waste they used environmental economics to justify the purchase of a solder recovery machine and Design for Manufacture methods and analysis to optimise the materials usage in their extruded parts. The focal area of this project and the methods selected both came from the business-environment synergy segment of diagram. Where appropriate tools or methods are not available the team should consider investing in new ones or else review their choice of focal areas as attempting such a project without supporting tools is likely to lead to less successful outcomes.

Discussion of the BEC Synergies Diagram

Businesses have historically paid little attention to the environmental loads they engender through their activities and products. Environmental legislation such as the WEEE, RoHS and EuP Directives are forcing businesses to correct this oversight. This process is challenging but brings with it opportunities for fulfilling business and customer requirements in a more sustainable manner. By clearly segregating the product requirements in terms of how they will benefit the major stakeholders, the BEC Synergies diagram is a tool that companies can use to review their current business activities and the focus of their design efforts and identify opportunities for improvement.

One limitation of the BEC Synergies diagram is that the customer is represented as one homogenous entity. Recent work has noted that the marketplace comprises a diverse range of customers with different requirements. With this in mind, it has been suggested that market segmentation principles combined with the concept of the 'eco-cost/value ratio' may help businesses to identify opportunities for creating business value whilst still reducing the overall environmental load of their products [21]. However, this method relies on having data concerning the environmental load of products in the form of an eco-indicator points score. Generally, only large businesses with significant experience of eco-design would have such data available. The BEC Synergies diagram might therefore be appropriate for companies taking their first steps in eco-design, whilst tools such as the eco-cost/value ratio might be reserved for more advanced eco-design practitioners. Further work is required to validate the usefulness of the BEC Synergies diagram and its application.

5 CONCLUSIONS

- Compliance with environmental legislation and a desire to reduce manufacturing costs/overheads were found to be the main drivers for environmental beneficial actions.
- Communication on environmental issues is increasing in most supply-chains but generally remains limited to legislative compliance issues.
- The activities conducted with the businesses appear to have increased awareness of the positive environmental effects of current business processes and have increased motivation to make further improvements.
- There remains significant potential to improve the way in which environmental considerations are integrated into the requirements specification formulation process.
- The BEC Synergies diagram is suggested as an appropriate tool for businesses starting out in eco-design who wish to identify focal areas for eco-design projects and select appropriate tools.

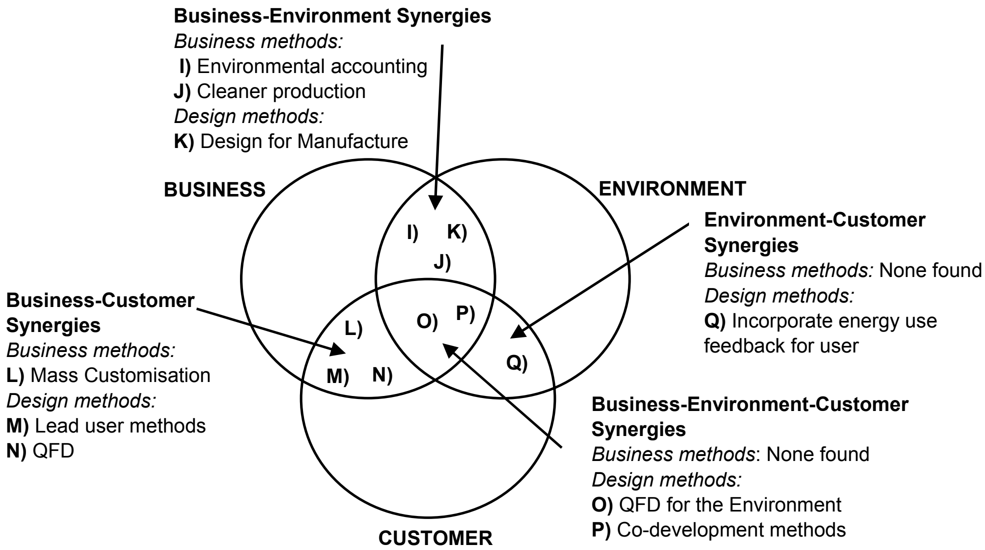

Figure 3: Using the BEC Synergies diagram to identify appropriate business and design methods.

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Using The Delphi Technique To Establish A Robust Research Agenda For Remanufacturing

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Abstract

Remanufacturing is driven by different factors (such as extended economic profits, reduced environmental loading, social inclusion and job creation) and opposed by various barriers (such as reverse logistics, customer perception, product disassembly and component inspection). This paper details the results of two research surveys that have elicited the views of academics from around the world who are involved in remanufacturing research. The studies used the Delphi Technique to calibrate the different views on this broad and "open-ended" topic. The paper explains the Delphi Technique, the development of an online Delphi survey software tool and the STEEP (Social, Technical, Economic, Environmental, and Political) structure used for the surveys. The paper describes the process of using the Delphi Technique with the panel of academics, and shows the main results from each survey along with proposals for the continuing research agenda.

Keywords:

Remanufacturing, Delphi Technique

1. INTRODUCTION

1.1 Remanufacturing

Remanufacturing is the term given to the process of reusing products by returning them to their as-new standard and form. It has become an increasingly popular research topic given its theoretical potential to enable future economic and manufacturing development to be more sustainable - that is "*development that meets the needs of the present without compromising the ability of future generations to meet their own need*" [1].

The principal driver making manufacturing more sustainable is the fact that virgin production uses high levels of energy and raw materials. As this production energy and much of the product material is not recovered, it is not sustainable. Thus, a key concept to true sustainability is identified as "closed loop manufacture" where end of use products are diverted from disposal to become new "raw" material/manufacturing streams [2, 3] as shown in figure 1. There are various factors that make remanufacture the strongest return option [4, 5, 6, 7, 8].

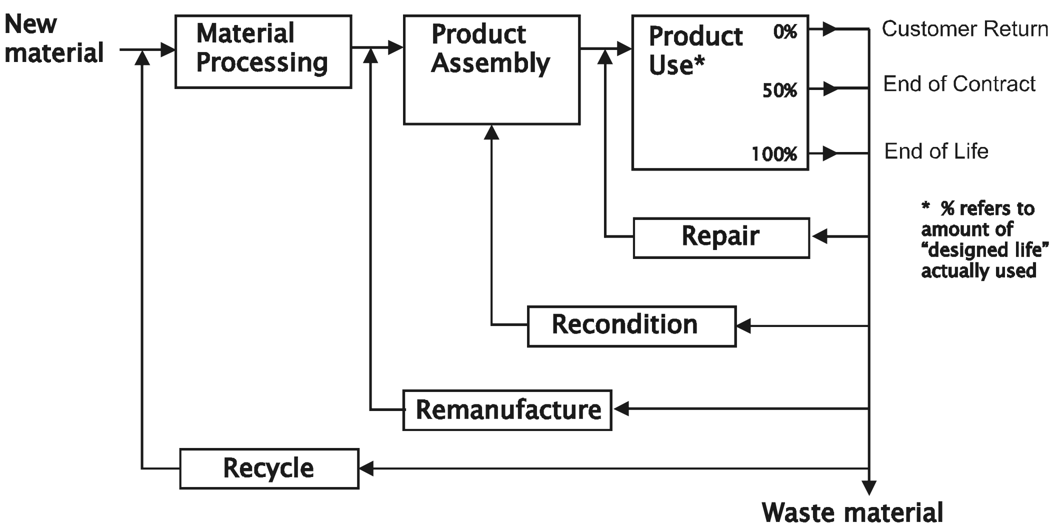

Figure 1: Closing the loop through remanufacturing

Firstly, unlike recycling, it preserves the embodied energy invested in the product's 1st life by maintaining much of the component geometry and material composition. Lund estimates that an *average* remanufactured product only requires 20-25% of the energy used in its initial formation [9]. This requires a lower production cost, thus reducing the price of the remanufactured product. However, both repair and reconditioning preserve embodied energy too.

Secondly, it brings used products to "like-new" functional state with warranty to match. A remanufactured product is quality assured to the same standard that the product had when it was originally sold. This is the most evident distinguishing characteristic of this recovery route as neither repair nor reconditioning provides this. Bras & McIntosh state that, by receiving back old products, manufacturers can obtain feedback on reliability and durability information and can also resell into lower-priced markets, typically costing 60% of the original production cost [10].

Other benefits include the reduced production waste generated as components are already formed. Meadows claims [11] that for every 1 tonne of a typical final product, 10 tonnes of "waste" are generated to produce it.

1.2 A Remanufacturing Research Agenda

However, the quest to increase the remanufacturing of products is presently not without significant barriers. At present most remanufacturing operates within niche markets and at relatively low volumes. If this activity were to grow 10 or 20 times bigger, it would require products to be designed and made differently, to be sold using different business models, to be traced and returned, and - most significantly – to appeal to consumers in such quantities that it would be economically viable. How then is a research agenda for remanufacture to be formed, prioritised and progressed? The traditional methods of a single researcher literature review or questionnaire survey of other researchers have the weaknesses of the bias of that researcher's question setting and subsequent interpretation. In addition, surveys often have poor response rates [12]. A better approach is to hold discussion workshops although these involve logistical problems in getting people together (particularly internationally) and they are not confidential or anonymous, and so direct criticism/disagreement can be difficult [13].

2. THE DELPHI TECHNIQUE

2.1 The Delphi Survey Method

The Delphi technique [14, 15] offers an alternative approach, by asking open questions to an expert group who then respond to each others answers to calibrate the group thinking.

The underlying premises for the approach are firstly that successive estimates will tend to show less dispersion and secondly that the median of the group response will tend to move towards the strongest answer [16]. Its main advantages are that it can be used asynchronously to accommodate practical constraints and can be conducted single or double blind to encourage more objective review and moderation.

The technique comprises four main stages (once the administrator & expert team have been established). These are shown in figure 2.

1.	**Ask members a set of open-ended questions & gather answers.**
2.	**Collate answers & send each member the entire set of answers.**
3.	**Ask members to comment, correct and then rank the answers they read.**
4.	**Collate ranked answers and produce a report on the findings.**

Figure 2: The Delphi Technique's Four Main Stages

Figure 3 shows the way in which one participant (shown in the middle) may provide an answer which the rest of the panel considers strong, and thus follow. However, a particular participant (shown at the bottom) may not follow this reasoning and stay with their original thinking. The benefits of this approach are thus that the leader can be identified and further researched, as can the independent to understand why s/he sees things differently.

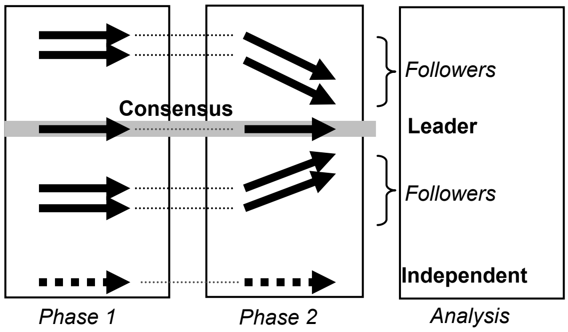

Figure 3: The Convergence of Panel Thinking

2.2 An Online Delphi Tool: www.webdelphi.com

The authors designed a web version of the process to both reduce the participants' and administration time & cost. The software was written by a specialist company [17] and coded using PHP 5.2 and MySQL 5.1. The administrator was able to create and oversee the survey and at the end is able to extract a report of the survey showing the highest ranking answers to each question. All data collected was held on a secure web server in accordance with the UK Data Protection Act 1998. A screen view of the software is shown in figure 4.

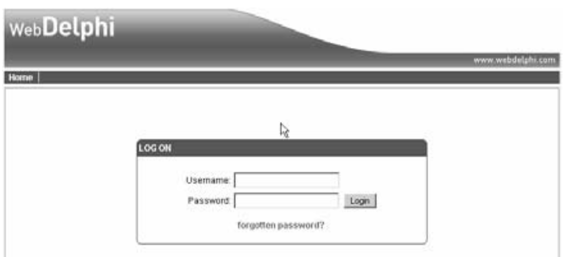

Figure 4: The Webdelphi.com login screen

2.3 The STEEP Structure

STEEP [18] is an acronym for the five areas that have an important impact on remanufacturing strategy. These are:

S – Social
T – Technical
E – Environmental
E – Economic
P – Political

This structure was used as a framework for the survey questions.

3. THE GLOBAL ACADEMICS SURVEY

3.1 Webdelphi Survey Structure

The survey was structured in two distinct parts: part one to establish the strongest questions to ask the panel and part two to establish the strongest answers currently by the panel to strongest questions.

The five aims (in order of priority) of the two-round survey were:

1. To develop a global research community that is willing to periodically share ideas and thinking.
2. To establish what is collectively known by this group and encourage peer review of the evidence.
3. To determine the degree of agreement/disagreement (and associated certainty/uncertainly) to the research questions posed.
4. To identify the strongest/clearest areas of research to pursue
5. To consider the effect of the Delphi Technique on establishing/influencing the research agenda.

The authors invited academic contacts in the remanufacturing research field either to participate themselves and/or to forward/nominate other academics. The "flyer" advertising the survey explained its central aims, what was required of each participant and that user anonymity would be kept. A final grouping of 10 academics was selected from the USA, Europe & Asia. Although no academics responded from Africa this is probably just a reflection on the low number of academic researchers there in this field and the paucity of authors' contacts. A description of the final panel is given in Table 1.

Countries represented	UK, Sweden, Netherlands, Germany, USA, France, Japan
Number of Men	7
Age range of panel	Approx. 30 yrs – 60 yrs
Academic Specialisms	Engineering, Business, Manufacturing, Operations Management

Table 1: 9-Member Expert Panel Characteristics

The process followed the methodology shown in figure 5.

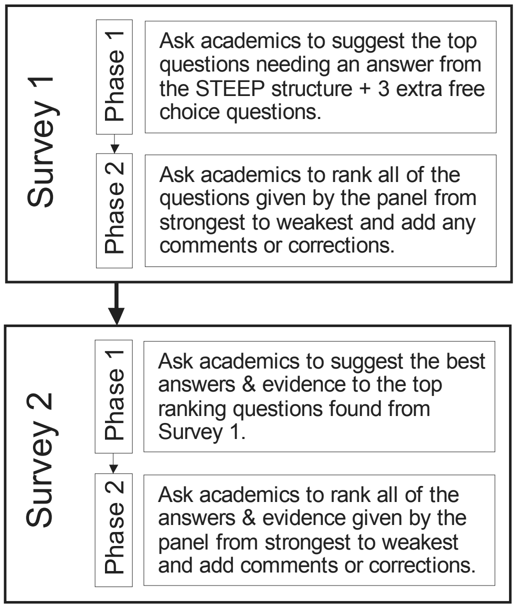

Figure 5: The Two Delphi Remanufacturing Surveys

3.2 Delphi Survey No. 1

The first survey therefore sought to establish the top questions needing to be asked or researched.

In phase 1, each academic logged into the webdelphi.com software, read each of the questions and then gave their personal best answer to each.

In phase 2, each academic logged in again and then read all of the answers to each of the questions (i.e. their own answer together with the answers from all the other academics). Each academic then ranked the answers for each question from 1^{st}, 2^{nd}, 3^{rd} best etc. Answers could be "tied" as equal or rejected.

3.3 Delphi Survey No. 2

Having identified the strongest questions from the academic group, the second survey therefore sought to establish the top answers or evidence to those top questions. In this time 2 academics failed to respond in phase 2, so the panel size reduced to 7 people.

In a similar fashion as the first survey, each academic logged in to give their individual best answers and then logged in again later to rank theirs and all the others from strongest to weakest.

The exact questions and the top ranking answers are given in table 2.

Q	The Question asked of the panel in phase 1…. / The top ranked answer given after phase 2 ….	% given to top rank:
Social	*Which are the main reasons why a user should buy a remanufactured product, i.e. what are the users driving forces to buy a remanufactured product rather than a new product?*	*25%*
	Attractive price-quality relation E.G. Price (cheaper than new product) Quality (as good as new) Other reasons (to a less extent, and more difficult to measure): environmental consciousness	
Technical	*Which products are technological worth to remanufacture?*	*26%*
	The products needs to have a suitable combination of: - high material value after use (e.g. forklift trucks, filling machines) - collectable amount of cores after use (e.g. single use cameras, toner cartridges) - a market demand of remanufactured products (e.g. household appliances, computers) - a design that facilitates remanufacturing (e.g. single use cameras, soil compactors).	
Environmental	Are remanufacturing products more environmental friendly than new product innovations? (e.g. old car for Reman. without catalyst and new car with catalyst... update/upgrade)	23%
	Not always. It depends on if there are technology leaps in the product design. Products that have a big energy use during the user phase might not be environmentally preferable to re-use. This is the case, for example for refrigerators of good energy classes. Mostly, for passive products, remanufacturing is a preferable option.	
Economic	Which novel economic/business model has the greatest potential to capitalise on the revenue potential of remanufacturing?	24%
	Selling use instead of products! If I sell holes and not drilling machines, I want to sell as much holes with one machine as possible - not as much machines as it works right now!	
Political	Do we need "directives on product recovery" to develop remanufacturing?	24%
	Actually, the best would be that voluntary industrial schemes would emerge, so Directives would not be necessary. However, Directives are already in place and unfortunately directives are biased towards recycling and they do not have a life-cycle approach (because it is also not an easy task to do so, it is much easier to write a directive simply setting recycling targets). Thus, given that there are already directives pushing towards recycling, additional directives/regulation towards design-for-remanufacturing could counterbalance the effects.	
Extra 1	How are remanufacturing issues properly included in the product development process?	18%
	The remanufacturing issues should be properly included in the product development process like any other issue that needs to be considered e.g. price, ease of use, quality. This could be facilitated by having remanufacturing staff included in the design teams and/or at design meetings.	
Extra 2	Which design factors are the most influential on making a product suitable for remanufacturing?	18%
	Design for “disassemblability”, for diagnosis and testing.	
Extra 3	Which industrial sector is emerging as the next most popular sector for remanufacturing to automotive, aerospace and defence?	22%
	Products for industries (as opposed to consumer products) of which functionality is the most important; for example, office equipment, manufacturing machines, and factory equipment.	

Table 2: Survey 2 Questions & Top Ranked Answers

4. ANALYSIS OF THE DELPHI ANSWERS

4.1 Analysing the whole group answers

In terms of the overall responses to the 5 main questions, the following analysis has been made by the authors:

Q1: *Which are the main reasons why a user should buy a remanufactured product, i.e. what are the users driving forces to buy a remanufactured product rather than a new product?*

The top 4 ranked answers centred on cost, the remaining 3 centred on environment and quality. The key point of agreement from the panel was that the cost advantage needed to be communicated in connection with equal quality even if at lower functionality to a new product. Thus, economy (saving money) was seen as the main reason.

This prompts the research question: what evidence is there that this is the main reason people currently buy remanufactured products?

Q2: Which products are technological worth to remanufacture?

Despite being a question about technology, many answers still focussed on the economic conditions for worthy remanufacture. This shows how high economic matters feature.

However, a strong theme of technological stability came through the range of answers stating that when a new technology had been established (and was thus likely to remain for some time) then products from these technologies were suitable to remanufacture given that their performance and functionality would not differ significantly from brand new products.

This prompts the research question: how can products be measured for their technological stability so that they can be assessed for remanufacture?

Q3: Are remanufacturing products more environmental friendly than new product innovations? (e.g. old car for Reman. without catalyst and new car with catalyst... update/upgrade)

The strongest answer was “not always” with other answers giving the same sense. However, apart from the evidence cited for the top answer, many of the other answers suggested that the answer to this question was, as yet, unknown to the panel members.

This prompts the research question: what studies already exist in other research domains. If none do, and yet a major claim for remanufacturing is the environmental benefit (as given earlier in this paper), then this is a research priority.

Q4: Which novel economic/business model has the greatest potential to capitalise on the revenue potential of remanufacturing?

Together with the top answer, a number of other answers centred on the change from selling “products” to selling “service” or “function”. The brevity and clarity of the top answer seemed to capture this idea best.

Product Service Systems have been researched for some time and yet have had little impact on how most products are traded. However, there has been more evidence of moves towards rental and leasing schemes.

This prompts the research question: to what extend are OEM remanufacturing operations based on rental/leasing schemes? If this is the main business model for existing operations then this may strengthen the case for policy moves to encourage this in other product (even consumer?) markets?

Q5: Do we need "directives on product recovery" to develop remanufacturing?

Of all the questions in the 2nd Delphi Survey, this one gave the least consensus with two diametrically (yet logically connected) views.

The top answer promoted the wish for voluntary schemes to emerge based on market forces and better corporate social responsibility.

However, although other answers followed this theme, the opposing view was that, given the existence of other Directives, a further one would be needed for product recovery. The reasoning suggested that these current directives may work against product recovery in favour of recycling.

This prompts the research question: what evidence is there that current directives do work against remanufacturing? If connected research on environmental benefits does show remanufacturing to be better, then any opposing directives can be better challenged.

Q6-8

The main findings from these additional questions were that:

Unless the strategic benefit can be seen, remanufacturing will not be embedded in the product development process. The design challenges are then incorporated like any other technical challenges and do not necessarily need widely different tools, except for cost/environmental trade off tools.

In terms of designing, disassembly, diagnostic and testing features were most important.

4.2 The Wider Remanufacturing Research Agenda

From the given analysis of the answers, the following research themes have been found:

1. Understanding why people currently buy remanufactured products.
2. Measuring technology stability (as a potential proxy for remanufacturing suitability)
3. Finding/making better environmental impact studies
4. Establishing what business models are used by current OEM remanufacturing operations.
5. Assessing what impact existing directives have on remanufacturing operations.

The authors consider, from analysis of the full set of answers & rankings, that the agenda item 3 is the priority given that most literature on remanufacturing (excluding the USA) cite the environmental argument as a strong motivation for increased activity. Given the authors’ context within the EU, this research in this area is a priority. This suggests collaboration is needed with environmental scientists.

The authors further consider that agenda item 4 is the next most important area given that this may also, in part, answer agenda items 1 and 2. This suggests collaboration is needed with business schools.

The remaining agenda item 5 is intriguing and yet of long term significance. Collaboration is needed with policy studies groups to progress this research.

5. ANALYSIS OF THE DELPHI PROCESS

Whilst the authors used the Delphi Technique to overcome a number of practical and confidentiality issues, it is interesting to analysis the effect the process may have had on the survey outcomes.

Although 9 academics gave research questions in the 1st Delphi Study, only 7 of these continued onto giving answers to these questions in the 2nd Delphi Study. Technical difficulties with the software no doubt played a part in their departure as did the ensuing delay whilst the remaining bugs (and hardware failures!) were fixed.

However, of the remaining 7, figure 5 shows which academics in the survey had their questions ranked highest overall (in ranking 1st, 2nd or 3rd).

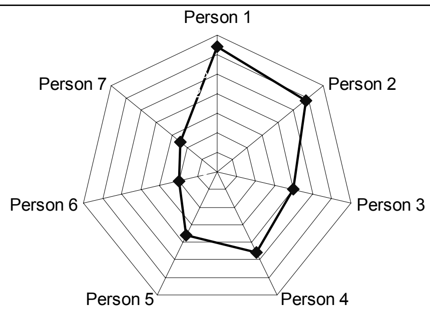

Figure 6: Highest Ranked Answer Distribution

Figure 6 shows that persons 1 & 2 had a high influence on the overall group ranking, persons 3, 4 & 5 and moderate influence and persons 6 & 7 a low influence. Thus, this demonstrates that the academic group, when exposed to alternative answers (whether entirely different or better phrased/argued) did change their minds from their 1st round answers.

Despite the clear strong influence of persons 1, 2 and 3 the top answers for the 8 questions did not all come from these three people. Persons 1 to 5 gave answers that the group considered then considered the strongest. This therefore suggests that the contribution of most of the group was significant and the wider group of available answers helped promote the best answers to the top.

Each of the academics involved in the 2nd round survey has received a full copy of the results report without names and identification made. Thus, as the surveys were conduced double blind, only the administrator (who has agreed to be bound by confidentiality) knows which person is which.

Thus, the wider understanding of the academic community has been increased through the circulation of a significant number of literature citations and case study examples. The degree of consensus between academics has been assessed (a fact borne out in that many of the answers were similar) and yet trends and gaps found too.

6. CONCLUSIONS

This paper has shown that remanufacturing is a complex subject involving a wide number of issues driven by different stakeholders. It has described two Delphi studies undertaken to find the strongest research questions and known answers to these questions.

A number of priority research areas have been suggested by these studies. Of most significance is the need for stronger environmental evidence to establish when remanufacturing is a better strategy and then to determine which products fit these conditions. This is of particular importance within the European Union where environmental considerations have a significant impact strategic decision at governmental levels.

The use of the Delphi Technique appears to have been successful. Evidence has been presented showing that academics did converge on particular answers, yet a wide number of participants had strong answers selected.

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Coherent Design Rationale and its importance to the Remanufacturing Sector

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Abstract
Design Rationale is the combination of the structure that underpins the design of a product, and the reasoning behind it. This paper details the findings of ongoing research into the creation of a Remanufacturing Design Platform Model (RDPM), focusing on understanding the rationale behind Design for Remanufacture (DfR), and investigating alternative design strategies, points in the process at which decisions regarding end of life reuse are made, and criteria and other factors which influence such decisions. Key criteria to be considered in the creation of a design rationale for remanufacturing are suggested. The main challenges for designers of "remanufacturable" products are also considered.

Keywords:
Remanufacturing, Design Rationale, Design For Remanufacturing, Design Criteria

1. INTRODUCTION

Design Rationale is the combination of the structure that underpins the design of a product, and the reasoning behind it. Gomes & Bento (2001) described it as being a mixture of reasoning and knowledge, whilst pointing out that creating a coherent rationale could be difficult given the diversity in (potentially conflicting) design needs and designer knowledge. A design rationale is also a record of design decisions that can aid future generations of design. Myers et al, (2000) described design rationale as being: "a record of the basic structure of a design, codifying how the design satisfies specified requirements, as well as key decisions that were made during the design process". There are many tools that can be utilised in the structuring of design rationale, such as Case Based Reasoning (CBR) (Gomes & Bento, 2001; Rosenman, 2000), the Design Structure Matrix (Steward, 1981; Browning, 2001; Eppinger, 1991), and Axiomatic Design (Suh, 1990). The later techniques enable the structure and layout of the design to be mapped in detail – a important factor according to Suh (1990). Further benefits of a recorded design rationale include the provision of "guidance in exploring alternative designs, whether as part of the natural evolution of a design or in response to changing requirements", and the enabling of "easier maintenance of artifacts over their life cycles and more effective reuse of designs by making it easier for downstream engineers to understand how a design works" (Myers et al, 2000).

The fact that a design rationale records details which enable later generations of designers to understand how a product works is of crucial importance to remanufacturing. Among the fundamental barriers to remanufacturing are product disassembly and component inspection (King & Burgess, 2005). These authors point out that such activities can be both difficult and expensive, and arise because "products are often not designed for disassembly". Moreover, components are often not designed to be easily removed, and can therefore hinder inspection and identification of reusable parts. This history of poorly considered product design needs to be addressed if products are successfully to be remanufactured or reused in line with current legislation (WEEE; Europa, 2003). To that end, this paper outlines the nature of design rationale generally, identifying design characteristics and the benefits of such a structured approach, before suggesting key design criteria for remanufacturing, and how the general rationale can be adapted for the purpose of remanufacturing

2. DESIGN RATIONALE DEFINED

Generally speaking, the design rationale for a given product describes in detail how it has been put together in the way that it has, and why. There are many definitions for a design rationale. Apart from those of Gomes & Bento (2001) and Myers et al (2000) mentioned in the introduction, Donaldson et al (2006) describe it as mapping "the first phase of the product development cycle, (which) encompasses researching what to develop for a successful product and planning appropriate actions for the project team to develop and successfully release their products to market. This phase culminates in a business review in which the product concept, the required investment, and the projected returns are scrutinized to determine whether proceeding to the development phase is the best alternative for the organization", whilst Gomes & Bento (2001) further describe the rationale as encompassing the "functionality of design, required behaviour of product, product structure and implantation". Conversely, Ishii et al (1995) described 'the rationale of developing the product family' as being "a means to achieve economy of scale and standardization of production". Volpentesta et al (2004), meanwhile, described the rationale for distributed management of design data as the enhancement of "design-manufacturing engineering or product data management (PDM) systems for managing product development as a single integrated business process". Donaldson et al (2006) noted that an understanding of "customer needs and values is fundamental to the definition of a product, particularly a new product", whilst Dentsoras (2005) stated the importance of understanding required and actual relationships between product components, and both Wang & Terpenny (2003) and Reich (2005) promoted the necessity of knowledge acquisition and design trade-offs.

As can therefore be seen, there are a great many definitions of the term 'design rationale' and what it should embody. It is also important to address why it is necessary to create such a rationale. There are a number of benefits attached to recording design decisions. Myers et al (2000) note that "information would facilitate collaboration among multiple distributed designers—a tremendous benefit for large scale design efforts." Importantly for remanufacturing, they also suggest that "design rationale would enable … more effective reuse of designs by making it easier for downstream engineers to understand how a design works". Brissaud et al (2003) suggest that design documentation helps to improve "a current product generation when modifications, updating or new versions are needed", whilst significantly, Gomes et al (1998) highlight the help provided when needing to "utilise old solutions".

2. 1 Generic Criteria for Design Rationale

Having discussed the nature of product design rationale and the benefits associated with its good preparation, we can also look at some design criteria or metrics on which rationale can be based. Borg et al (2000) identified cost, time, and quality as being significant factors which affected the design of a product and its rationale. Assessing these factors in the context of 'Design For x – DFx' and product disassembly, Borg et al suggested that the effect during product disassembly of poor design decision-making (and perhaps unclear rationale) could be:

- more time consuming due to difficulties in separating permanent bound parts;
- more costly as cutting or separating machines as well as skilled operators need to be used;
- of a low quality because components are likely damaged during disassembly process, hence, they cannot be reliably reused.

In addition to the effects during disassembly, ill-conceived design tends to be more costly due to an increased number of design revisions, and due to iteration within the design process (Barker & Guenov, 2004).

Gomes & Bento (2001) agreed that quality was of significant importance, but also suggested productivity, maintainability, and portability as being key factors that should be considered by the rationale. Some of these factors are of particular relevance to remanufacturing: for example, Bras & Hammond (1996), when discussing Boothroyd & Dewhurst's earlier (1991) criteria for remanufacturability, consider metrics for a "goodness" of remanufacturability, and cite three criteria to define an ideal part or component from a remanufacturing viewpoint:

1. Only large ranges of motion should be considered (small motions can be accomplished by incorporating elastic elements into the part)
2. The part must be made of a different material, since the properties of that material are required to achieve design requirements
3. The part required to facilitate the process of assembly or disassembly (such as access panels or housing covers)

These criteria revisit the disassembly issue considered earlier, but also stress that thought must be given to the material from which a component is manufactured, and the ranges of motion to which each individual (and group) of components is likely to be subject. Other criteria deemed specific to remanufacturing will be discussed later within the paper.

2.2 Adapting Design Rationale for Remanufacturing

When considering how general design rationale can be adapted to the purpose of remanufacturing, we must first look at the specific needs of remanufacturing. King and Burgess (2005) identified four technical barriers which need to be overcome before remanufacturing can succeed, these being reverse logistics, component disassembly, component inspection, and customer demand/perception. Other authors, such as Sundin (2004), list the following factors, drawn from earlier research by Hammond et al (1998):

- The availability and cost of replacement parts
- Product Diversity
- Cleaning/Corrosion
- Design Related Issues (complexity, fastening methods, means of assembly and disassembly, increased part fragility)
- Employee skills

Moreover, Parlikad et al (2005) suggested that amongst the problems faced by 'demanufacturers' are a high variety of products, and uncertain product condition after usage. As such, a large quantity of information is required about a product before it can enter the remanufacturing process. Parlikad et al (2005) state that this is a major obstacle to the efficient recovery of value from returned products

Many of these factors can be lessened in their influence by taking the needs of remanufacturing into account at the design stage. Finger (1998) stated that the information required from previous design rationale included knowledge to answer specific questions, and ''pattern in the artefact information", a view echoed by Reich (1998) who called for the characterisation of existing knowledge. Gomes et al (1998) reinforced this by stressing the need to reuse existing solutions. Hammond (1986) stressed the importance of identifying failure cases. Brissaud et al (2003) summed up this approach: "the current solution (product data), which addresses both the meeting of functional requirements and the processes involved (manufacturing, assembly, recycling processes, etc.), AND the argumentation (process data), which is a collective building of knowledge about the project, used to evaluate and validate each technical choice". Thus knowledge of the existing system, together with the reasoning or building of knowledge concerning the system, can be used to evaluate a suitable path forward. Wang et al (2003) and Srinivasan & Gadh (2000, 2002) suggested another way of lessening one of the barriers to remanufacturing, when discussing product disassembly. A set of 'steps for disassembly' were proposed:

1. the relative motions of the components are determined without considering the tools, fixtures, or robots required to achieve these motions;
2. assemblies are assumed to be rigid, frictionless, and defined by nominal geometry;
3. components are "1-disassemblable": a single linear motion along the directions of coordinate axes from the assembly; and
4. disassembly sequences are monotonic: the components are totally removed while disassembling and non-destructive.

As we have seen there is much in types of product and also methods of design, which serves to complicate a rationale for remanufacturing Gomes & Bento (2001) suggest that: "One possible way of overcoming this difficulty is to use 'chunks' of solutions or sub-solutions to problems in solving new design problems, thus reusing previous reasoning results". This reuse of previous knowledge and design solution satisfies the need to be environmentally conscious, as expressed by Tomiyama (1997) and Umeda et al (2000) in the work on the Post Mass Production Paradigm (PMPP). Other authors have also commented upon this need for grouping of components. Umeda et al (2005) spoke of the need for "localisation of design structure/modularisation", while Braha (2001) emphasised the need for careful topological mapping of product components. Manfaat et al (1998) took this a step further by propounding the need to 'cluster' components together based on component commonality. This commonality issue was also stressed in 2000 by Jiao et al, who stressed the need to develop detailed measures of product commonality.

Dentsoras (1999) acknowledged the clustering principle when stating that: "In design, a decomposition of the design problem is always required" and that among the ways that a design may be decomposed is into 'sub-problems' (Dym, 2004) – or groups of functional components. Dentsoras also referenced other authors (Cross, 1991; Serrano & Gossard, 1992; Ullman, 1992) to point out: "In every design problem there are always design constraints. There are different types of constraints functional, topological, material, etc. that usually refer to different design issues and may appear during almost all the stages of the design process."

A promising method addressing many of these issues is that proposed by King & Burgess (2005) and Du et al (2003): Platform-based design. As a rationale, it offers the ability to group components together either functionally or in terms of likely component wear/failure, and in so doing enables savings on time and complexity during product assembly/disassembly, and a further cost saving in that components of similar value (or longevity) can be grouped together thus facilitating ease of access and reuse (King & Burgess, 2005; Barker & King, 2006). Several authors have suggested suitable criteria that should be considered in a design rationale for remanufacturing (Design For Remanufacturing –DFR), and these are summarised in table 1 on the following page.

The criteria fall into four separate categories: Activity-based, which suggest the actions needing to be performed during remanufacturing, along with sample metrics; Performance-based criteria such as component obsolescence (which might alternatively be termed wear- or failure-rate), component performance and flexibility, and a measure to identify future performance requirements (enabling component lifespan and performance to be gauged over potential generations of products); Product lifespan metrics are required to monitor an individual product throughout its lifespan, a source of potential information on such factors as failure rates and component longevity; and functionally-based criteria, which defines the physical qualities of the product – e.g. construction material, physical dimension, and cost in terms of price and energy use.

3. THOUGHTS ON POTENTIAL ISSUES FOR DFR

At this stage it is also necessary to pay attention to possible issues regarding Design For Remanufacturing (DFR). In addition to those mentioned in the previous section, Umeda (1999) stated: "In the worst case, encouraging design for recycling results in creating huge amounts of low quality, expensive, and unusable recycled materials." This necessitates careful thought as to how design rationale should be structured, and design criteria selected. Gomes & Bento (2001), discussing software reuse, highlight the difficulty in selecting the right or most suitable component from an extensive array of component options, whilst Myers et al (2000) make the valuable point that: "designers rarely produce detailed rationale in practice because of the substantial time investment required". They also comment that although "efforts to support the acquisition of rationale information have focused on languages and tools for structuring the acquisition process", this still requires substantial involvement in terms of time and effort from the designer.

Meanwhile, Reich (1998) suggests that due to the large amount of design issues and possibilities, there is an inability to learn about all issues, and therefore "no design is 'completely complete'". Du et al (2003) point out that a significant issue in product design is to exploit the shared logic and cohesive architecture underlying a product platform. Finally, Coyne et al (1990) state that "a fixed set of components with a fixed set of properties is often regarded as a defining characteristic of configuration design problems" – a fact refuted by Feldkamp et al (1998).

It can therefore be seen that there are a number of issues surrounding the successful completion of a design rationale generically, and also of one directed specifically at remanufacturing.

DFR Criteria	Author proposed by
Activity criteria	
Replacement (key)	Bras & Hammond (1996)
Assembly (no. of parts, time)	Bras & Hammond (1996)
Disassembly (no. of parts, time)	Bras & Hammond (1996)
Testing (reliability, quality, predefined performance criteria, design limits)	Bras & Hammond (1996)
Inspection (visual)	Bras & Hammond (1996)
Replacement (basic)	Bras & Hammond (1996)
Refurbishing (no. of parts to be refurbished, time, cost)	Bras & Hammond (1996)
Cleaning (time, cost, legislation (legal, environmental))	Bras & Hammond (1996)
Performance criteria	
Obsolescence	Umeda et al (2005)
Functional Upgradeability	Umeda et al (2005)
Performance	Umeda et al (2005)
Component Flexibility	Umeda et al (2005)
Functional insensitivity: absorbing the difference between before and after upgrading without structural changes by adding margins to components. It suggests using components of which functionality and performance are excessive to the first generation but indispensable for subsequent generations	Finger (1988)
Future uncertainty (future performance and reliability requirements)	Umeda et al (2005)
Product Lifecycle phase criteria	
Design, Realisation, Use, Disposal/Renewal	Borg et al (2000)
Functional criteria	
spatial layout of components within product	Manfaat et al (1998), Braha (2001)
Material type	Umeda et al (2000)
Weight	Umeda et al (2000)
Reusability	Umeda et al (2000)
Method of Recycling/reuse	Umeda et al (2000)
Product/Component price	Umeda et al (2000)
Manufacturing cost	Umeda et al (2000)
Manufacturing energy	Umeda et al (2000)

Table 1: Potential Design For Remanufacturing (DFR) criteria

4. CONCLUSIONS

This paper has identified the need for a coherent design rationale to underpin product design. It has identified a number of issues that hinder such work, not least the the overhead of time, and the vast number of issues and opinions that occur within the context of product design.

The paper has examined the potential difficulties in creating a rationale specifically for DFR, notably spatial layouts and poor disassembly planning, but has suggested a method that may overcome some of these issues, using a clustering technique and grouping product components together by wear or failure rate: platform-based design.

The paper has gone on to suggest a number of criteria that may be of relevance to DFR, and has grouped them into the following categories: Activity, Performance, Product Lifecycle phase and Functionality.

The next steps in the evolution of a DFR rationale need to be a validation of the suggested criteria in an academic and also industrial context.

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Survey on Environmentally Conscious Design in the Japanese Industrial Machinery Sector

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Abstract

Product assessment carried out from the viewpoint of environmental aspects is one of the tools which are commonly used for environmentally conscious design (ECD). However, it sometimes becomes little more than a token procedure for some design engineers because there are too many items in the product assessment stage to properly evaluate their products. In addition, the evaluation items might not accurately reflect the environmental requirements for the products. In this paper, we surveyed the current status of ECD in the Japanese industrial machinery sector, and then we proposed several guides for use by manufacturers and/or industrial organizations when writing product standards involved in the preparation of appropriate product assessment guidelines.

Keywords:
Environmentally Conscious Design; Product Assessment; Design Review

1 INTRODUCTION

As the approaches to environmental protection in manufacturers increasingly shift from environmental considerations in the factory to the development of environmentally conscious products, the importance of environmentally conscious design (ECD) increases more and more. ECD activities in the electric and electronics industries are well known, however the objectives of these activities are mainly focused on consumer products. We focused, instead, on improvement of the ECD process for industrial machinery characterized by a long life cycle and multiple users.

Some research surveys on the current status and the spread strategy of ECD in various industries have already been carried out (e.g. [1], [2]). Some of these studies were questionnaire surveys concerning the motivation, ECD tools used, and the environmental aspects considered in the respective enterprises, but they were not investigations of how ECD is simultaneously practiced in the new product development process. Some studies, as shown below, have addressed the direct relationship between product development and ECD. For example, Lindahl et al. focused on ECD methodology and tools, and compiled a list of the features of those ECD tools readily accepted by the designers [3], [4]. Ernzer et al. carried out a survey on manufacturers in Germany, and considered the best strategy for the implementation of ECD in routine design work from the viewpoint of the new product development process and the organization of the company [5]. Further, Masui et al. surveyed the current status of the ECD process and the tools used in the Japanese electric and electronics industry [6].

In this paper, we first surveyed the current status of ECD in the industrial machinery sector. By interviewing several manufacturers in order to understand the current status of ECD, we found that several problems need to be solved to ensure that the products produced by the ECD process are environmentally friendly. As a result, we therefore proposed several guides summarized in Figure 1 to improve the ECD process in this sector.

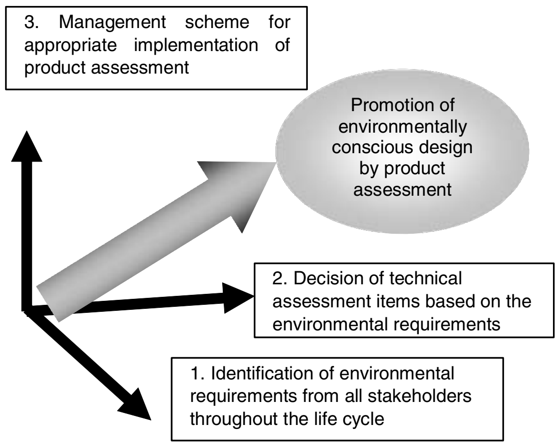

Figure 1: Three important elements in the ECD process to ensure that a new product is environmentally friendly

2 SURVEY ON THE ACTUAL STATUS OF ECD

2.1 Objectives of the interviews

As part of the survey, we visited five industrial machinery manufacturers belonging to four different sectors including construction machinery, agricultural machinery, printing machinery and machine tools. On average, three persons were included in each interview. In many cases, one was the manager of the environmental department, and the others were product design engineers and/or technical staff from the environmental management department.

Table 1: Survey results on ECD obtained through interviews with various manufacturers.

Questions		Construction machinery	Agricultural machinery	Printing machinery	Machine tools
Objective product	Status of life cycle management of major products	· Export ratio is over 60% (Company B) · Half of all hydraulic shovels are rented (Company A) · Design life is about 8,000 hours · Outline of product circulation is surveyed by the industrial group	· Export ratio is up to 70% · Average product life is about 19 years · Status of second-hand users is not understood	· Export ratio is about 60%. Used products are also exported. · Life of a sheet offset press is about 10 years · Manufacturers do not take back used products, but enter into contracts with secondary users for maintenance	· Export ratio is 30% · Product life is up to 20 years · Manufacturers do not take back used products, but enter into contracts with secondary users for maintenance · Tracing used products is very difficult
Implementing scheme of ECD	Companywide policy & structure for ECD	· Product development group handles environmental requirements · Environmental regulations are managed by the standards department	· Environmental department decides companywide policy and surveys environmental regulations	· Environmental department at headquarter is in charge of the management of environmental requirements related to companywide policy	· Product assessment is executed by the design department · Results of product assessment are reviewed in DR where sales, procurement and quality management departments also join in
Implementing scheme of ECD	Flow of new product development	· Execution of product assessment in the design review stage	· Product assessment is executed in three phases	· Flow of product development is described in ISO 9000 · DR is executed in four phases of product development	· Environmental regulations and requirements summarized in the development meeting are referred to product planning · Product assessment is executed in the design and trial manufacture phases
Implementing scheme of ECD	Method used to collect environmental requirements	· Environmental requirements are treated as a part of quality management	· Customer requirements are collected by dealers	· Collection is carried out by the environmental department at headquarters · Environmental criteria used by customers	· Requirements from customers
Contents of ECD	Environmental aspects considered in the ECD process	· Utilization of biodegradable oil, marking different types of plastics (European regulations) · Exhaust gases from diesel engines	· Response to regulations regarding exhaust gas emissions from diesel engines · Marking different types of plastics	· The focus of improvements on the environmental aspects of products is to reduce the environmental burden during the use stage (declared in ISO 14001 certification)	· Improvement of working conditions (Response to CE mark) · Enhancing energy efficiency · Promoting the reuse of parts and easy disassembly at the end-of-life stage
Contents of ECD	Guideline or tools utilized inside the company	· Execution of product assessment (Company A) · Environmental requirements are also included in design standards (Company B) · LCA is executed using BOM data (Company B)	· Execution of product assessment · No execution of LCA · No database of chemical substances	· No execution of product assessment · No execution of a precise LCA, but understanding input/output of electricity, consumables, water and so on by using an "Environmental impact assessment sheet"	· Execution of product assessment (ISO 14001) · The list of assessment items is exhaustive in order to compensate for any lack of care · Checking the items corresponding to actual customer requirements
Contents of ECD	Policy or guideline published by the industry group	· The industrial group developed the disassembly manual · The industrial group developed the standard used to calculate the recyclability indicator	· Utilization of the standard developed by the construction machinery association to calculate recyclability	· Product assessment guideline is being developed by the industrial group	· Criteria used in assessment were based on the guideline of the electric and electronics industry · A standard to estimate the performance of energy saving is being developed

2.2 Questionnaire

To ensure a smooth and efficient discussion, a questionnaire was sent to each company beforehand and the interview was carried out along the lines laid down in the questionnaire. The contents of the questionnaire included the following three main topics:

Product objectives

First of all, we asked about the characteristics of their main products and the status of their life cycle management. The questions regarding life cycle management included

- Percentage exported
- Product lifetime
- Traceability of products (including used products)

Implementing scheme used for ECD

For this topic, we asked about

- Companywide policy & structure for ECD
- Flow of new product development
- Method used to collect environmental requirements

Contents of ECD

The final topic was related to the contents of ECD. The specific questions raised concerned

- Environmental aspects considered in the ECD process
- Guidelines or tools utilized inside the company
- Policies or guidelines published by the industry group

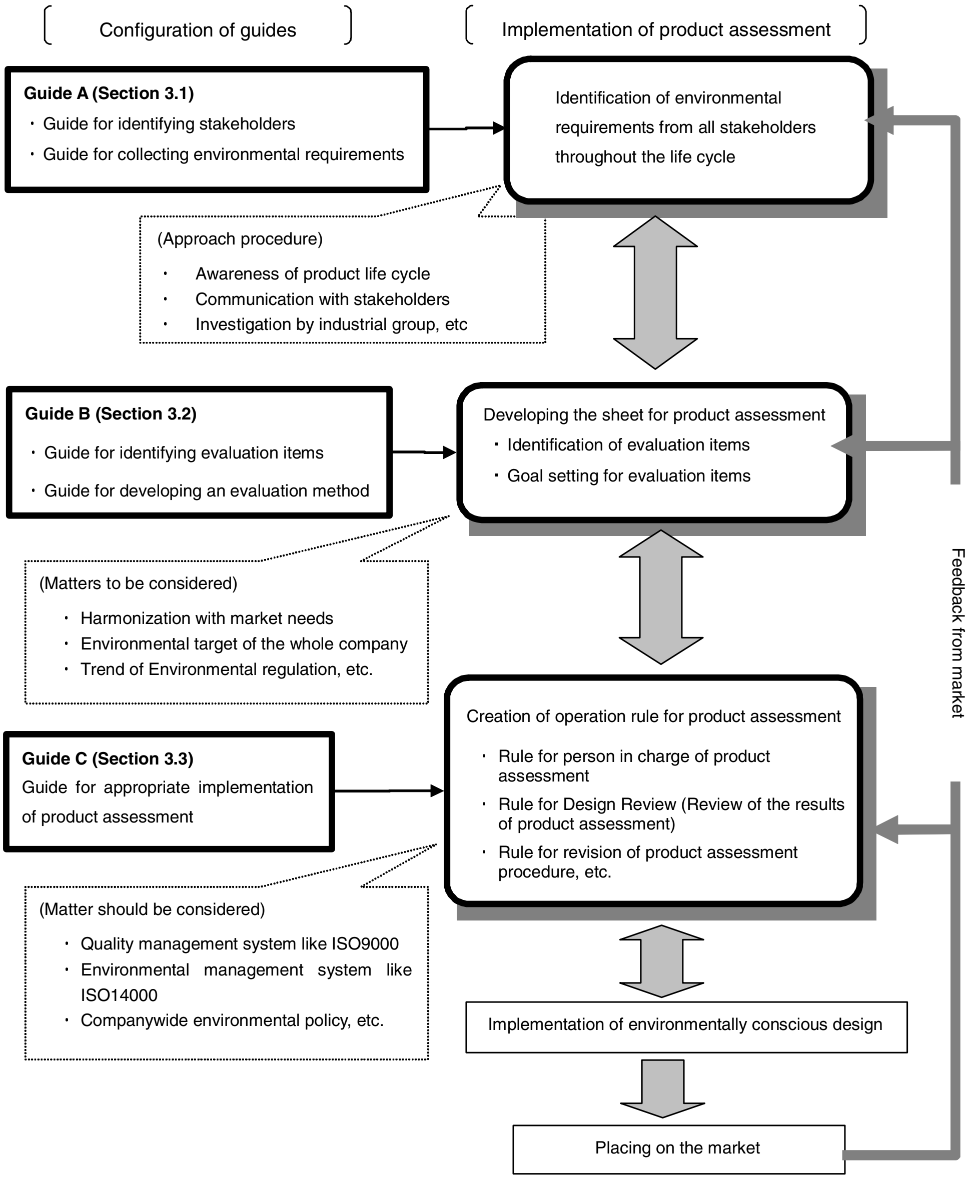

Figure 2: Relationship between the guides and the preparatory activities used for product assessment inside the company.

2.3 Survey results

The results of the survey are shown in Table 1. The lifetime of industrial machinery is very long and, in many cases, secondary and tertiary users therefore exist for used products. It is difficult for manufacturers to manage the whole life cycle of industrial machinery because the export ratio of their products is high and because used products are also exported to foreign countries for second-hand use. As a result, there are many stakeholders involved, including potential ones that manufacturers are not aware of.

In terms of the ECD process, product assessment and similar tools are often used as ECD tools for design review. The environmental aspects and specific criteria of product assessment should be determined on the basis of environmental requirements. However, the environmental requirements considered by the manufacturers derive from environmental regulations and their immediate customers, and do not always correspond to the requirements of all stakeholders, such as overseas recyclers.

In terms of the implementation of product assessment, there are a few companies which have a scheme in place to review the results of assessments carried out by the designers. Every company carried out design review (DR), not only for environmental aspects but for other aspects associated with developing a new product. In order to assure the environmental consciousness of a product, it seems to be necessary to have a third person double-checking the results of environmental assessment carried out at the DR stage.

3 GUIDES FOR THE IMPLEMENTATION OF PRODUCT ASSESSMENT

Based on the survey results described above, we proposed three guides for product assessment. These are shown in Figure 2 and include a “Guide for identifying stakeholders and their environmental requirements (Guide A)”, a “Guide for making a product assessment sheet (Guide B)”, and a “Guide for implementation of product assessment (Guide C).” In the following sections, an outline of each of the guides is introduced.

3.1 Guide A: Guide for identifying stakeholders and their environmental requirements

It is important for manufacturers to investigate the life cycle of their products and to identify all stakeholders, as shown in Figure 3. In general, the life cycle of industrial machinery is complicated because there are multi-generation users spread across many countries.

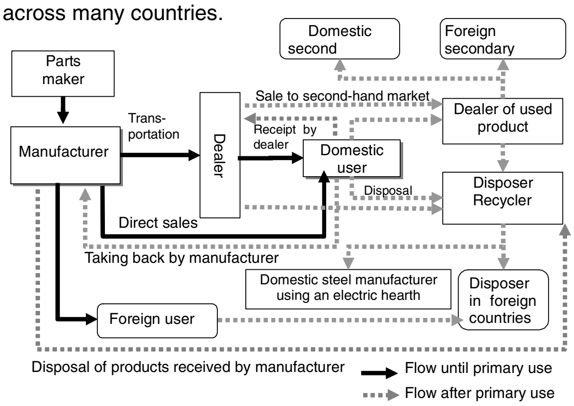

Figure 3: Example of the product life cycle of industrial machinery

Figure 4 shows a simplified decision-making tree for risk management. For instance, the environmental risk is high in Case C because unknown secondary users in a foreign country utilize the used product and because a recycler in a foreign country might not be able to dispose of end-of-life product appropriately due to lack of information regarding toxic materials, disassembly methods and so on.

Table 2 shows an example of stakeholders and their environmental requirements. As described above, potential environmental requirements, like those of foreign recyclers, also have to be considered in some cases.

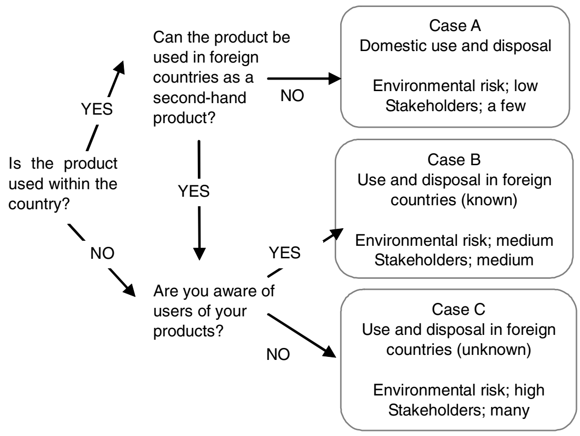

Figure 4: Environmental risk depending on traceability.

Table 2: Example of stakeholders and their environmental requirements throughout the product life cycle

stage	Stakeholder	Environmental requirements	Impor-tance
Manu-facturing	Government (Regulation)	· Low emission of noise and vibration · Air and water emissions must satisfy ambient criteria	+++ +++
Usage	User	· Reduction of running cost by energy saving · Long life/ upgradeable · Prevention of contamination · Less consumable supplies · Low emission of waste	+++ ++ +++ + +
	Maintenance services	· Easy disassembly · Low emission of waste	++ +
	Government (Regulation)	· Compliance with environmental criteria · Management of toxic substances	+++ +++
End-of-liffe	Retailer	· Low disposal cost · Indication of means of disposal and information on toxic materials	+ ++
	Government (Regulation)	· Compliance with standards on the outsourcing of waste disposal	+++
Disposal	Domestic recycler and waste disposer	· Easy disassembly and transport · Prevention of pollution such as oil leaks · Prevention of mixing of copper with ferrous scrap	+ +++ ++
	Foreign recycler and waste disposer	· Easy disassembly with general tools · Information on materials and disassembly method is described in several languages	++ +
	Government (Regulation))	· Compliance with standards on waste disposal	+++

Table 3: An example of a product assessment sheet.

Viewpoint		Approach	Criteria	Target	Degree of achievement		
					DR1	DR2	DR3
Energy saving/ Reduction of CO_2 emissions		Reduction of energy consumption	· Reduction of manufacturing processes · Saving energy for operation				
		Utilization of clean energy	· Utilization of renewable energy · Changing transportation method				
Effective utilization of materials	Reduction of material use	Less material usage	· Reduction of number of parts · Less waste during product use · Utilization of recycled materials				
		Long-term use	· Enhancing the durability of materials and parts				
		Enhancing the ability to maintenance and upgrade	· Utilization of common parts · Utilization of parts that can be easily repaired · Enhancing modularity				
	Reuse of valuables	Reuse of products	· Cleaning surface of product easily · Structure with easy function checkout				
		Reuse of parts	Retrieving useful parts easily				
	Recycling of materials	Enhancing disassemblability	· Selection of joining method that allows easy disassembly · Dismantling and separation with standard tools				
		Enhancing recyclability	Selection of materials that can be recycled easily				
			· Easy separation of different materials · Utilization of common materials				
		Providing information	· Indication of disassembly position · Marking different types and grades of materials · Providing a disassembly manual written in several languages				
Environmental protection		Safety and ease of disposal	· Easy shredding · Easy separation of explosive material				
		Reduction of toxic materials	· Reduction of use in processes · Reduction of toxic substances contained in a product				
		Prevention of contamination	· Reduction of water and soil pollutants · Reduction of air pollutants				
		Reduction of noise, vibration and odor	· Reduction of noise, vibration and odor				
		Promotion of providing environmental information	· Indication of appropriate disposal · Providing information on chemical substances				
				Total			

3.2 Guide B: Guide for making a product assessment sheet

This guide shows the basic procedure for making a product assessment sheet and shows how to identify the evaluation items based on environmental requirements. Table 3 shows an example of a product assessment sheet for industrial machinery. In general, a product assessment sheet has a hierarchy structure. The environmental viewpoint items are matched with the appropriate approach procedures and criteria. The criteria in the table can be changed depending on the product characteristics. They should be selected so as to suit the environmental requirements analysed in Table 2. Next, the environmental goals are set for all criteria. How well the design improvement has achieved the set target will be reviewed at every DR stage in the ECD process (see Figure 5).

3.3 Guide C: Guide for the implementation of product assessment

In order to assure environmental consciousness of the product passing the standardized ECD process, it is necessary to confirm the assessment results carried out by the designers themselves. Figure 5 shows the flow of general product development, the key role at each stage, and an example of the person in charge of each of these roles. Here, it is assumed that the environmental goal is set at the product planning stage, and that the quality manager then reviews the results of design improvement evaluated by the designer.

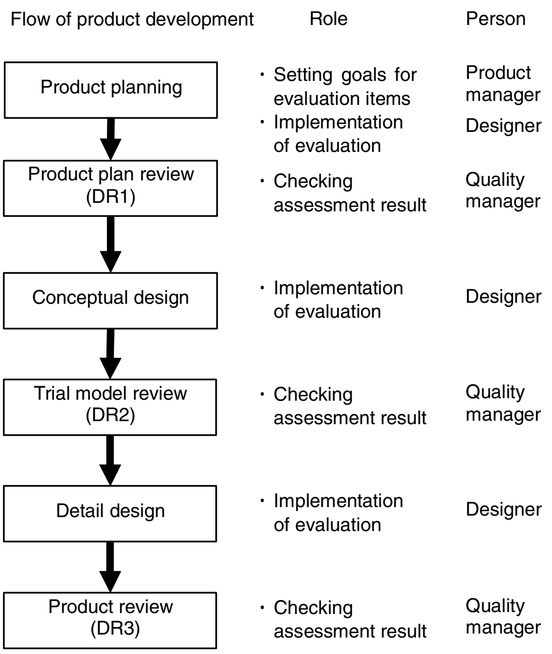

Figure 5: Example of an operation standard for product assessment.

4 CONCLUSIONS

In this paper, we surveyed the current status of ECD in the industrial machinery sector and then proposed several guides to improve the ECD process. These guides include the methodologies used to identify the stakeholders and their environmental requirements (Guide A) and instructions on how to make a product assessment sheet (Guide B). In addition, in Guide C, we summarized the operational scheme of product assessment needed to assure the environmental consciousness of each product developed according to the standardized ECD process.

5 ACKNOWLEDGMENTS

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Survey of Sustainable Life Cycle Design and Management

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Abstract

The impacts of our increasingly unsustainable production and consumption has necessitated a major change in product design and development. This change is embodied in the vision of sustainability, which is attained through Sustainable Life Cycle Design (SLCD). This paper analyses the current practice of SLCD in the UK manufacturing industry by conducting a survey of companies in five major sectors. A case study is also presented to discuss the implementation of SLCD strategies in practice. A critical analysis of the trends obtained from the survey and a comparison of the results are presented. The paper is concluded by summarising the main findings of the survey and proposing a set of guidelines and recommendation for planning and implementing sustainable life cycle design in industry, thus suggesting change of course from conventional product design and manufacture towards sustainable production and consumption.

Keywords:

Sustainable Life Cycle Design; Drivers & Barriers; Strategies; Tools and Techniques; Case Study

1 INTRODUCTION

The vision of sustainability is achieved through Sustainable Development, which has gained widespread attention globally since the Brutland Commission report defined it as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” [1]. Sustainable Development seeks to achieve a balance between equitable economic development, social betterment and environmental responsibility and has been growing in importance due to increasing awareness of the relationships between environmental issues, socio-economic factors and concerns about the future.

In recent years, there have been mounting social, economic and environmental pressures on designers, inventors and product developers to adopt more sustainable approaches in product design and development [2]. Waage [3] suggests a close relationship between design and sustainability, suggesting that it is at the concept stage where over 70% of the costs of development, manufacture, usage and end-of-life treatment are locked-in along with associated social and environmental impacts. The crux of our unsustainable paths have been traced to conventional design and manufacture [4], which does not contemplate sustainability at the design stage and seek corrective strategies through end-of-pipe solutions [5].

In industry, sustainable development approaches in product design and manufacture have evolved from a focus on end-of-pipe strategies in the seventies [6] to a realisation in the eighties that some of these methods (for example, substitution of natural and raw material for synthetic ones), were viewed as un-fit to solve long-term objectives sustainability and Sustainable Development.

In the nineties, the focus shifted to eco-efficiency, as a measure of the integration of economic development and environmental responsibility [6]. Industrial concern has since been shifting towards inclusion of social-related factors [7], to fully integrate the pillars of sustainability, giving rise to a new design approach termed as Sustainable Life Cycle Design (SLCD). This is the main focus of the project reported here which is to examine the strategies, tools, benefits, drivers, as well as the barriers of SLCD by conducting a survey of SLCD and analysing of the results. The paper also presents a case study on the implementation of SLCD to illustrate a successful application of SLCD in practice.

2 IMPACT OF PRODUCT DESIGN AND MANUFACTURE

The production and use of industrially manufactured products make a multitude of undesirable impacts on the environment most of which can be traced back to the design concepts and features embedded in the product life cycle from raw material extraction through to product disposal [8]. Those environmental impacts usually originate from unsustainable design concepts and manufacturing practices with significant social and economic costs which are not wholly accounted for, leading to major environmental issues such as ozone depletion and climate change [9].

These problems are exasperated as a result of inadequate resource eco-efficiency, escalating population in certain regions of the world, over-consumption and heavy dependence on fossil fuel in the developed countries. [10]. Consumers in the developed world are consuming increasingly more than can be replenished, endangering the opportunities of sustenance of future generations and causing irreversible changes to the ecosystem. The major source of anthropogenically-induced climate change has been identified as emissions of greenhouse gases such as carbon dioxide, methane and nitrogen oxides most of which are emitted by transportation systems and industry in the developed world [11]. The burning of fossil fuels on the global scale accounts for the release of about 6.5 billion tons of carbon in the atmosphere per annum [11]. There is also proven scientific evidence that the average temperature of the earth has risen by about 0.6^0C in the last 100 years [12] and will continue to rise in the next few decades to alarmingly higher levels leading to more severe changes in the climate with the real prospects of loss of life and extinction of many species.

3 SUSTAINABLE LIFE CYCLE DESIGN

SLCD is a holistic product design and development approach which seeks to minimise social and environmental burden, over the whole of a product's life cycle [13], whilst achieving economic viability and encouraging Sustainable Development at the local, national and global levels. In broader terms, it is the moral and ethical extension of Life Cycle Design (LCD), which considers all life-cycle stages from concept development to product service and end-of-life treatment, integrating environmental aspects as well as traditional product design criteria such as cost, quality and service [14]. SLCD extends beyond eco-design which focuses only on reducing environmental impacts and seeks to balance economic and environmental aspects [2].

SLCD is managed through Product Lifecycle Management, PLM, a "systematic, controlled method for managing and developing industrially manufactured products and related information, offering management and control of the product development and marketing process, the order-delivery process and the control of product related data throughout the product lifecycle, from the conceptual idea to the scrap yard" [15].

The project reported here investigated the status and practice of SLCD in several key sectors of UK industry in order to identify and analyse the main drivers and barriers as seen by senior managers in industry. Based on the research carried out and the case study conducted, this paper aims to provide practical guidelines and recommendations for successful implementation and management of SLCD.

4 DESIGN OF QUESTIONNAIRE

The objective of the questionnaire was to survey industry's views and attitudes towards SLCD. The survey sought to establish the key drivers and barriers of SLCD as well as the strategies that can be adopted for SLCD. The survey was also designed to find out what the advantages practicing SLCD were. The questionnaire consisted of fundamental questions about SLCD as follows:

1. In what way(s) is your company approaching sustainable manufacturing?
2. Is Life Cycle Design Practiced? What techniques or methodologies are being used?
3. What are the main drivers of Life Cycle Design?
4. Which Life Cycle Design strategies are currently being adopted by your company?
5. What are the important advantages of Life Cycle Design?
6. What are the barriers to implementing Life Cycle Design?
7. What percentage of your company products is landfilled at the end of their life cycle?
8. What actions are being taken towards corporate social responsibility?
9. Is Life Cycle Management practiced in your company?
10. Are training programme and/or knowledge transfer provided for staff?

5 SURVEY OF SLCD AND ANALYSIS OF RESULTS

Senior managers, environmental advisors and product designers from design consultancies, automotive companies, component suppliers, electrical product manufacturers, electronics and packaging Industries operating in the UK were targeted for the survey as they were regarded as the main manufacturing companies having the capability to influence the human-nature relationship in a significant way. Respondents were mainly from large and medium sized companies. The response rate was 50% which was achieved through direct networking and by attending major events. The other method of contacting companies and inviting them to participate in the survey was by phoning the firms and sending the questionnaires by email.

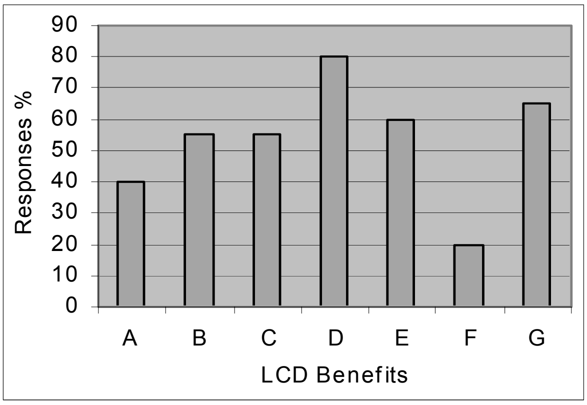
Across the industries responded to the survey, automotive companies were the most participative as 45% of all responses were received from this sector. Significant number of responses was also received from the automotive suppliers (20%), and the electronics industries (15%) as shown in Table 1. As can be seen, 70% of respondents practiced LCD across the industries surveyed. This large figure was mainly due to the high level of participation by the automotive industry, which made up 50% of the 70% practicing LCD.

The most important advantage of LCD according to the survey was shown to be compliance with legislation as depicted in Figure 1. Other important benefits were improvement of environmental performance and anticipation of future legislation. Most companies appeared to be minimising the environmental burden just to enable them comply with legislation through reactive strategies and end-of-pipe actions. However, to attain the long-term goals of SLCD, companies need to be proactive by undertaking more sustainable product design and manufacturing strategies thus discharging their responsibilities more actively towards the environment and the society.

Figure 2 shows that environmental regulation and management commitment were the greatest drivers of LCD according to the companies surveyed.

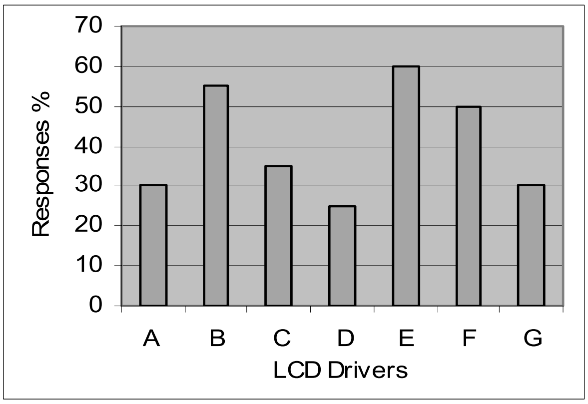
Industry Sector	Percentage of Responses Across Industry Sectors			
	Responses %	**LCD Practice %**	**PLM Practice %**	**Training & Knowledge Transfer %**
Design Consultancies	10	14	17	9
Automotive Companies	45	50	50	27
Automotive Suppliers	20	21	17	27
Electrical Products	5	0	0	0
Electronic Industry	15	7	17	27
Packaging Industries	5	7	0	9
Overall	100	70	60	55

Table 1: Percentage of respondents across industry sectors.



A - Reduced Costs	
B - Competitive Advantage	
C - Supply Chain / Customer Demand	
D - Compliance with Legislation	
E - Anticipation of Future Legislation	
F - Motivation of Employees	
G - Improved Environmental Performance	

Figure 1: LCD benefits.

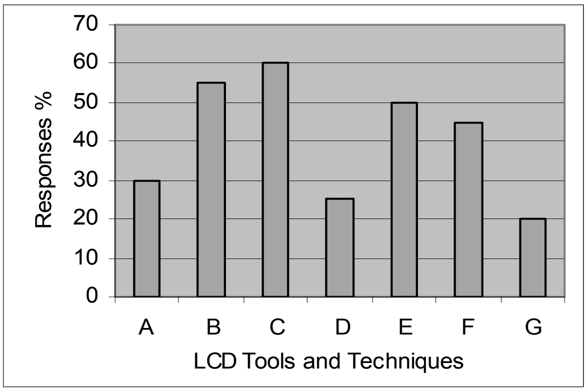


A - Regulations-WEEE	
B - Regulation-ELV	
C - Regulation-RoHS	
D - Employees' Concerns	
E - Management Commitment	
F - Increased Competitiveness	
G - Cost Reduction	

Figure 2: LCD drivers.

Regulation is an important driver of LCD as compliance is necessary for company's survival [16]. Legislative bodies are increasingly aiming for higher rates of material recovery and recycling. Most respondents that participated in the survey were affected by the directive on waste electronic and electrical equipment (WEEE), the directive of end-of-life of vehicles (ELV), and the directive on restriction of hazardous substances (RoHS). ELV is a very important driver for all automotive companies; the electrical and electronic products' industries are bound by the WEEE directive and the RoHS affects most industries using hazardous substances. To date, environmental legislation has largely concentrated on the end-of-life of manufactured products and has thus not led to fundamental changes in the design and development of new products [17]. For example, cars cause the greatest amount of impact during the service phase of their life cycle and although all cars manufactured in Europe will be 100% recyclable in near future, the greatest amount of damage to the environment will still be caused during the service stage if exhaust emissions are not cut more drastically through future legislation.
Management commitment and competitive pressures were also seen as important drivers for LCD according to the survey results; while the least important driver of LCD was acting on employees' concerns. However, as employees are the main source of creativity and eco-innovative ideas, their views and ideas should be encouraged to help companies change course towards more sustainable product design technologies and manufacturing processes.

Figure 3 shows that 60% of the respondents indicated that the most popular tool was Life Cycle Assessment (LCA).



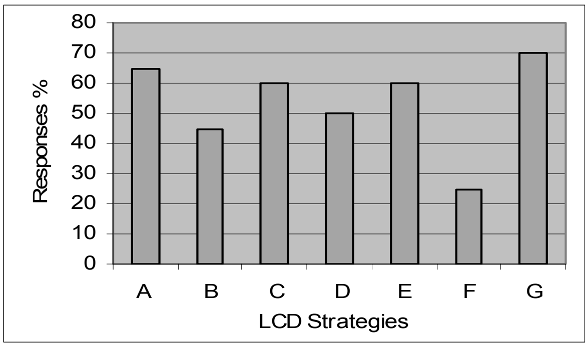
A - Checklists	
B - Environmental Impact Assessment (EIA)	
C - Life Cycle Analysis (LCA)	
D - Life Cycle Costing (LCC)	
E - Cost Benefit Analysis (CBA)	
F - Engaging Stakeholders	
G - Social Impact Assessment (SIA)	

Figure 3: LCD tools and techniques.

Social Impact Assessment was the least used tool as only 20% of the firms reported using such tools. This is attributed to the fact that the social aspect of sustainability is the least developed and has not been given enough attention and importance compared to LCD tools.

As can be seen in Figure 4, 70% of the companies surveyed used the minimisation of hazardous materials as the most popular LCD strategy; followed by design for recyclability. It should however be noted that as consumers become more aware of the life cycle impacts of products, they would increasingly favour products without any hazardous materials.

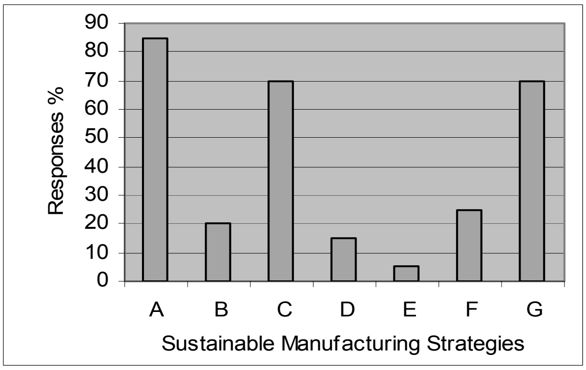
Figure 4 also shows that other LCD strategies adopted by the companies participated in the survey were Design for Recyclability (65%) and Design for Environment (60%). There was a high level adoption (100%) for Design for Recyclability (DfR) within the automotive companies as this sector of industry is highly affected by the ELV Directive. Design for Upgradeability (DfU) and Design for Disassembly were the least favourable LCD strategies according to the survey. This may be explained by short life cycle of products by the packaging industry and the modular design of electronic products. The electrical products' industry is more amenable to upgrading products due to the high energy and material consumption during the production of such products.



A - Design for Recyclability	
B - Design for Disassembly	
C - Design for Environment	
D - Design for Extended Life	
E - Design for Service	
F - Design for Upgradeability	
G - Minimisation of Hazardous Materials	

Figure 4: LCD strategies.

The main barrier to LCD is costs according to the survey. The results showed that for 60% of respondents, cost was the main barrier to adopting and practicing LCD. Life Cycle Design may be costly due to the amount of time and resources usually needed to collect relevant life cycle data and also due to lack of relevant expertise. The survey showed that 30% of respondents felt that there was little pressure from their customers to practice Life Cycle Design. Overall, these barriers as identified by the respondents showed that there is still considerable lack of awareness of sustainability and sustainable LCD and management.



A - Waste Management	
B - Reuse	
C - Recycling	
D - Green Suppliers	
E - Reverse Logistics	
F - Remanufacturing	
G - Life Cycle Design	

Figure 5: Sustainable manufacturing strategies.

Figure 5 shows that 85% of respondents approached sustainable manufacturing by waste management while 70% adopted recycling. Although 70% of the respondents practiced LCD, 30% (excluding the automotive industry) sent over 70% of their products / components to landfill sites. While legislation is getting tighter and the costs are going up, industry such as the automotive industry is encouraged to avoid landfill sites altogether and instead engage in recycling; nevertheless, much of the waste from manufacturing companies in the UK is still being sent to landfill sites [19].

As regards social responsibilities, the survey showed that 80% of respondents gave community contributions and 65% had flexible working practices. These social responsibilities are regarded important for the welfare of employees and the local community. Companies are increasingly expected to show socially responsible behaviour towards their stakeholders. Despite the fact that the majority of the respondents were large to medium sized organisations, only 55% provided environmental training or had any LCD knowledge transfer programmes for their staff. Without appropriate training, employees may lack the motivation and technical know how to change towards sustainable life cycle thinking and therefore enable their organisations to change course towards more sustainable product development.

The survey also showed that 60% of respondents practiced PLM to improve design and process reuse. Other benefits were reduced development costs (35%) and shorter time-to-market (25%). This shows the importance of managing new product development process from a life-cycle perspective.

6 CASE STUDY: SUSTAINABLE PRODUCT LIFE CYCLE DESIGN IN PRACTICE

A case study was conducted on Ecover, a pioneering Belgian company, and its products to study and illustrate the successful application of SLCD in industry. The product of focus is an ecologically sound cleansing detergent. On a strategic level, Ecover is committed to ecological responsibility and optimisation of economic value. Its environmental policy covers cleaning effectiveness and sustainable quality. The ecological initiative was driven from the conviction of company management to take proactive responsibility for the company's actions and ensure that their activities can continue perpetually without threatening the natural ecological balance. From its very onset, Ecover marketed a phosphate-free washing powder, long before phosphates were labelled as a problem causing eutrophication. Driven by its ethical values, Ecover considers the earth as having boundaries and exists by the principle of "doing more with less". Ecover's implementation plan for Sustainable Life Cycle Design (SLCD) began by defining business vision and strategy, defining environmental objectives and drafting the principles of sustainable product design. The principles of product design included: respect for mankind and the environment, competitive pricing with conventional brands, convenient application and efficient performance. Product design and development process was undertaken by adopting a cradle-to-grave approach which considers process design (i.e. production) as well as product design aspects (e.g. reuse, recycling). To analyse and optimise the flow of material and energy, life cycle inventory tools are employed. Ecover also uses sophisticated equipment to check the performance and quality of its products as well as the quality of materials supplied by its supply chain. All product design and development is done in-house and innovative ideas and sustainable thinking are encouraged throughout the company.

6.1 Implementing Sustainable Life Cycle Design (SLCD)

The relevance and need for products are questioned and products are designed at Ecover to meet relevant needs. Raw materials are chosen on the basis of originating from plants or infinite minerals and having strong cleaning properties, together with the ability to achieve greatest biodegradability and minimised aquatic toxicity. Ingredients do not include toxic chemicals or camouflaging additives such as optical brighteners found in conventional brands. However, minimised quantities of petrochemicals are still used, thus indicating barriers to complete ‘greenness’. Ecover practices most aspects of green marketing and is careful about the terminologies they use in their advertising campaigns. Ecover does not claim their products are environmentally-friendly but rather claims that they are ecologically-sound as they truly are.

Products are manufactured in an ecological factory where the main buildings / structures have been designed based on innovative and eco-friendly ideas inspired by the company’s staff. A green roof keeps factory room temperature between 4^0C-26^0C. The factory buildings have been constructed such that they maximise the use of sunlight by taking advantage of the sun’s daily movement from east to west. An onsite water treatment facility purifies wastewater. The best available and most energy-efficient production techniques are used in the manufacture of Ecover products. Low energy consuming machinery and equipment are used throughout the factory. All Ecover products are designed to have high skin compatibility and due to the perishable nature of detergents, all products are designed for complete biodegradability, going beyond the current legislative requirements of 60% biodegradability.

Although a systematic PLM is not actively practiced, product information is well organised and managed based on Ecover concept principles. Suppliers are screened by a stakeholder management system. Ecover complies with ISO 14001 and finished products are labelled with dosing instructions and Vegan Society labels (except the washing-up liquid containing milk whey) and award labels. Packaging boxes are marked with SPI markings for recycling / reuse purposes. To ensure adherence to its principles, Ecover has an animal testing policy to ensure that no animal tests are carried out before supply; and a stakeholder management system to confirm that materials supplied adhere to Ecover’s principles.

Ecover suppliers are encouraged to minimise packaging and supply in recyclable materials. Ecover have examined recycling pathways and have a recycling facility in place to enable plastic bottles used for packaging bottles to be recycled together with the cap and labels. Bags, barrels and boxes are reused in-house or returned to suppliers. Packaging boxes are reused after being tested about ten times before being recycled. Customers can purchase refill packs and refill pumps with a cost incentive to avoid cost of packaging and transport.

For successful implementation of SLCD, all staff are given environmental training and there is a company-wide involvement in decision-making. Monotony is avoided by job rotation. Ecover also engages in dialogue with other stakeholders and is in membership with wider-societal organisations such as ISO. To provide transparency in their product development, Ecover released the formula of its detergent in 2002.

6.2 The Business Case for SLCD

Ecover’s success has shown that that business cannot go wrong with sustainability as a strategic vision. The company engages in risk management as it considers all impacts at the product concept stage. Products are designed to meet relevant needs and are therefore designed to avoid waste through reuse and refilling. Renewable materials are used to ensure sustainability in the long run. Ecover enjoys increasing growth and profitability, wider societal support and recognition for its product design and business practices and, therefore, can invest in R&D while building social capital such as creativity, innovation leading to continuous improvement.

7 CONCLUSIONS

The range of industries chosen for the survey allowed a diverse range of views to be collected on the current practice of SLCD in design and manufacturing companies. Although 70% of respondents stated that they practiced LCD, most did not seem to have a genuine business interest in the social aspects of SLCD. The automotive companies accounted for 45% of responses and therefore results are skewed towards that industry. Management commitment and regulation were identified as the main drivers of SLCD. The survey also showed that green procurement and reverse logistics were not appropriate strategies. Green suppliers will further advance sustainable development and create economies of scale to decrease costs in the long run. Cost and time were seen to be the greatest barriers to implementing LCD as respondents suggested they may hinder time-to-market.

Ecover case study showed that companies practicing SLCD depend heavily on innovation and employees’ creativity. Ecover products are a good illustration of products designed according to the principles of SLCD as they promote sustainable use of resources, are in harmony with nature, promote ecological and human health, and advance economic sustainability whilst meeting relevant needs of today’s consumers without compromising needs of future generations. The case study also verified the findings of the questionnaire as it showed that the implementation of SLCD can result in a profitable and sustainable business. At Ecover, the main driver of SLCD was management commitment and not compliance with regulation. Business strategy and product life cycle strategy were well integrated at Ecover as the case study revealed that it was easier and more cost-effective to the entire life cycle of the product at the concept stage. Implemented SLCD strategies covered social issues such as satisfaction of real needs and stakeholder engagement; environmental issues covered waste prevention and minimisation and economic concerns covered both short and long term profitability. Implemented strategies included using renewable energy, restorative material cycles, design for reuse, recycling, minimising aquatic toxicity and maximising biodegradability.

Regarding sustainable manufacturing strategies, the case study revealed that companies practicing SLCD focused on waste prevention rather than on waste management whilst actively designing for recycling and reuse. The case study highlighted the difficulty in greening the supply chain, revealing that room for improvement exists in finding green suppliers for raw materials. Lastly, the Ecover case study suggested that important techniques or tools for assessing LCD included engaging stakeholders to ensure that corporate goals are well aligned to stakeholder expectations. As product systems are kept simple, there is less need for sophisticated or complicated tools such as the Life Cycle Analysis (LCA). It is concluded that the adoption and implementation of SLCD is the right product strategy for gearing towards sustainable production and consumption.

8 RECOMMENDATIONS

Conventional designers and product developers should recognise that there are limits to our growth and therefore they should align their business goals with the principles of sustainability to address the sustainability challenge. Industry needs to be more proactive and take responsibility without legislative enforcement. Designers need to question the impact of the decisions they make when designing products and take a long-term view by focusing on eco-innovation rather than being market-led. Product design teams must be multi-disciplinary and play a role in educating consumers on sustainable consumption. In future, SLCD could aim to design products that promote and reflect sustainable lifestyles.

Companies practicing SLCD flourish on eco-innovative ideas which may come from suppliers, employees, contractors, consultants and networking with companies. Strategic partnership and collaboration are necessary for gaining knowledge and competitive advantage in developing sustainable products. To avoid unsustainable and end-of-pipe solutions, all aspects of product design, manufacture, service and disposal should be addressed at the concept development stage. Through training and knowledge transfer and working closely with suppliers and other stakeholders, product designers should become more aware of the social, economic and environmental impacts of the products they develop. Careful development and adoption of SLCD strategies is necessary as trade-offs may exist between various sustainability and product design and manufacturing criteria. In the long term, manufacturing industry should move towards dematerialisation of the production-consumption cycle and change course from selling the ownership of products to providing services customers need or require.

The research work on SLCD reported here is to be continued at the University of Warwick by extending the scope of the study to cover a wider range of organisations involved in design, development and manufacturing of products. Further work is also planned to investigate the social dimension of sustainability in greater depth and its closer integration with product design and development process. It is hoped that through collaborative research programmes and knowledge transfer, manufacturing industry can take further proactive steps in adopting SLCD and moving towards a more sustainable future.

9 ACKNOWLEDGEMENT

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11 CONTACTS

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An approach of home appliances recycling by collaboration between the manufacturer and the recycling plant

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Abstract

Law for the Recycling of Specified Kinds of Home Appliances (Home appliances recycling law) has been enforced since April 2001 in Japan. Four kinds of used appliances (refrigerators/freezers, air-conditioners, television sets, and washing machines) are specified to be recycled by law, and are transported to the recycling plants which are designated by manufactures, and are recycled properly at the plants.

The product recycling through out the cycle of manufacturing, use and mechanical recycling has steadily been implemented over five years since the law had been enforced.

Recycling plants are recycling useful materials as much as possible, and treating the environmental risky material properly. And they have been providing the necessary design information for productivity of product recycling to the manufacturers. As the result, some materials recovered from used appliances in recycling plants have already been used as a part of the products.

We introduce the current status of home appliances recycling in Japan that has been popular and took root in the society, and we also introduce an approach by the collaboration between our company and our recycling subsidiary.

Keywords:

Recycling, Home appliances, Manufacturer, Recycling plant, Mechanical recycle Horizontal self-recycling

1 INTRODUCTION

Law for the Recycling of Specified Kinds of Home Appliances (Home appliances recycling law) has been enforced since 2001, and the cyclical products' recycling scheme such as producing, using, and resource recycling has been established. Recycling plants recycle valuable materials as much as possible and recover the environmental risky material and treat them properly. Also they advise disassembling information collected from recycling process to home appliances manufacturers, so they play an important role of DFE (Design For Environment).

Now five years have passed since recycling law was enforced. The recycling law has been taking root in Japanese society. We will introduce the current situation of home appliances recycling through the activities of Mitsubishi Electric and its recycling plant Hyper Cycle Systems.

2 CURRENT SITUATION OF HOME APPLIANCES RECYCLING

Home appliances recycling law was enforced in April of 2001 in order to save landfill space. The landfill space has been going short by mass production, mass use and mass waste. Home appliance recycling law is also for the purpose of reducing waste volume and recycling valuable materials as much as possible. After recycling law was enforced, used home appliances were transported to the recycling plants, and recycling system is operated. The system transforms "waste" into "valuable resource". The engineers of home appliances manufacturers have applied the recycling technologies and treatment data collected in the recycling plants. Therefore, DFE has developed and the recycling oriented products' circulation has established (Figure1).

Four kinds of appliances include air-conditioners, TV sets, refrigerators/freezers and washing machines, and were regulated as scope of home appliances recycling law.

11.6 million appliances in total were recycled in 2005 at the 46 recycling plants in Japan. 3.85 million of air-conditioners, 1.99 million of TV sets, 2.8 million of refrigerators/freezers and 2.95 millions of washing machines were recycled as a detail of above treatment volume. "Sold material ratios" must be higher than the criteria regulated by recycling law. "Sold material ratio" is the value of which the weight of valuable and zero cost materials is divided by products' weight when the recovered materials transported from the recycling plants to contractors. (These regulated standards of air-conditioners, TV sets, refrigerators/freezers and washing machines were each regulated as 60%, 55% 50% and 50%, respectively.) These actual result values were from 66 to 84% in fiscal year of 2005. We utilize the resources as much as possible and treat environmentally risky material properly as mentioned above.

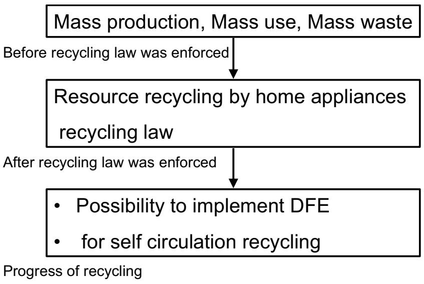

Figure 1: Effect by Home appliances recycling law.

3 OVERVIEW OF HYPER CYCLE SYSTEMS CORPORATION

3.1 Basic policy

Hyper Cycle Systems Corporation (HCS) started operating, as a recycling plant managed by Mitsubishi Electric Corporation, in May of 1999. It was before the enforcement of home appliances recycling law. It is located in Ichikawa city, Chiba prefecture in Japan. It recycles office automation (OA) equipments and home appliances collected from whole Chiba prefecture, the parts of Tokyo, Saitama, and Ibaragi prefectures. It recycled a total of about 50,000 ton of all kinds of appliances and equipment in FY2005. It also aims to perform high quality recycling and takes the best care to prevent to diffuse environmentally risky material in contractors as well as recycling plant.

It focuses not only on compliance, but also on its philosophy, it implements followings: a) Minimizing the emission of environmentally risky material, b) Recovering the maximum volume of resource, c) Feedback recycling information for DFE, not as just “a home appliances recycling plant” but “a resource production manufacturer” that produces new resources.

3.2 Home appliances Recycling treatment process

Specified parts are manually removed from home appliances at first, because they are composed of complex and various parts. These parts are categorized following parts; a) Parts containing valuable material, b) Environmentally risky material and parts, c) Parts affect badly to the shredding and separation process.

Parts containing a lot of metals such as motors are disassembled and recycled at contractors that are entrusted from recycling plants.

Homogeneous plastics, that have a heavy weight and have easiness to removed foreign materials in the disassembling process, for instance vegetable cases of refrigerators, washing tubs of washing machines etc., are sent to plastic shredding process and recycled. Environmentally risky material such as Freon-gas are recovered and treated properly.

The remaining parts after removed some parts in the disassembling process are sent to shredder. Metals are separated and recovered from shredded materials by magnetic separators, eddy-current separators and other separators that separate and recover metals. Recycling process of HCS is shown in Figure 2. There are some metals remaining in the “first” residue after the first process, so other materials are recovered from this residue by wind separators, strong magnetic separators, and other separators in the second process. This “second” residue that mainly consists of plastics is tried to recycle as high quality of plastics by micro-shredding technology described below.

Refrigerators and freezers are shredded by the special facilities in order to recover CFC (Chloro-Fluoro-Carbon) in heat insulators. Released CFC is recovered into the liquefaction recover equipment. Manufacturers have an obligation to recover Freon-gas in heat insulators by home appliances recycling law from April of 2004. HCS has installed this equipment and has been recovered CFC since the start of business.

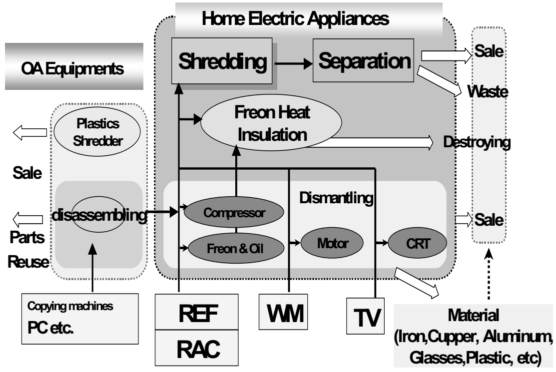

Figure 2: Recycling process of HCS.

4 RECYCLING CONCEPT OF MITSUBISHI ELECTRIC

Our recycling concept is shown in Figure 3. We focus on the high quality of recycling, so we have developed to recycle plastic that appears hard to recycle, salt water used as a balancer of washing machine and Freon-gas, etc. Also we have developed to use these materials for our own products and utilize the information from recycling plants for DFE.

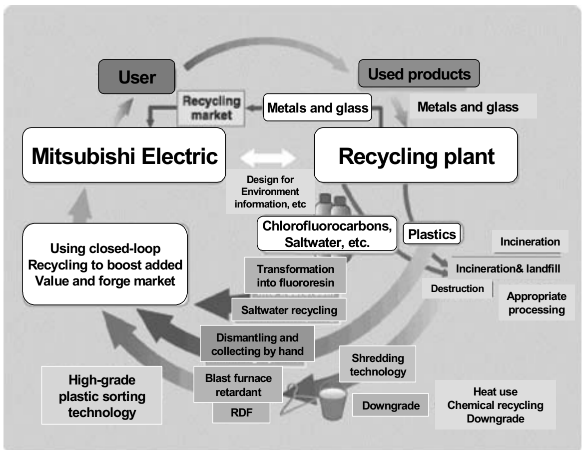

Figure 3 : Recycling concept of Mitsubishi Electric.

HCS gives us DFE information such as material kind indicating method, assembly method for easier disassembly, plastic kinds reduction or change, and impediment to recycling. We consider ways and means to improve material kind method, and change material kind and assembly from this DFE information.

Especially we have aggressively developed the plastic recycling technology since our start of home appliances recycling business. We classify the plastic recycling process by the term "LEVEL", according to the characteristics and the purity of recovered plastics, and the difficulty of plastic recycling technologies (Figure 4).

We have developed the plastic recycling defined as "LEVEL 2" and also developed to develop the technology plastic recycling defined as "LEVEL 4" which technological level is much higher than "LEVEL 2". We introduce some examples of the development of technology in the next section.

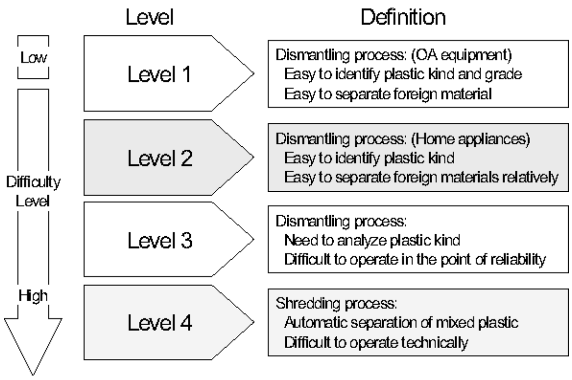

Figure 4 : Category of plastic recycling level.

5 DISASSEMBLING PLASTIC RECYCLING (LEVEL 2)

Vegetable cases of refrigerators are easy to be removed from refrigerators and contain little extraneous foreign materials. These are mostly made of Poly-Propylene (PP), although some few cases are Poly-Styrene (PS). We distinguish by slapping sound and separate these two kinds of plastic cases. Recovered vegetable cases made by PP are shredded into mm-size pieces that are called "flakes" and then after that they are shipped to contractors. Flakes are washed, mixed, re-pelletized, and reused as the plastic parts of our own air-conditioners. In this case, we realized to implement 100% material recycling to our products by removing foreign materials and adding the most appropriate mixture. Vegetable cases are recycled to the service panel of air-conditioners outdoor unit shown in Figure 5.

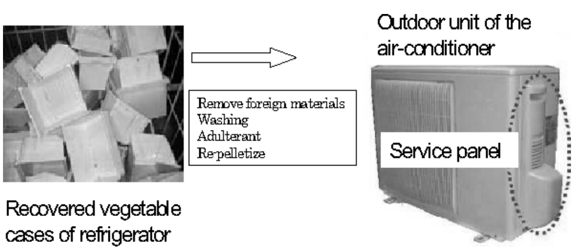

Figure 5: Level2-plastic recycling of vegitable cases.

6 MIXED PLASTIC RECYCLING (LEVEL 4)

Plastics recovering on manual disassembling process are limited. Current maximum volume of this type of plastics at HCS is estimated approximately 1,000 ton per year. On the other hand, total volume of plastic residue exhausted from shredding and separation process is approximately 7,000 ton per year.

HCS has developed the micro-shredding technology subsidized by "New Energy and industrial technology Development Organization" (NEDO) that is one of the independent administrative institutions. We established the new technology that separates more kinds of plastics based on the micro-shredding technology subsidized by NEDO.

In this section, we introduce the outline of micro shredding and the high-grade separation process as shown Figure 6.

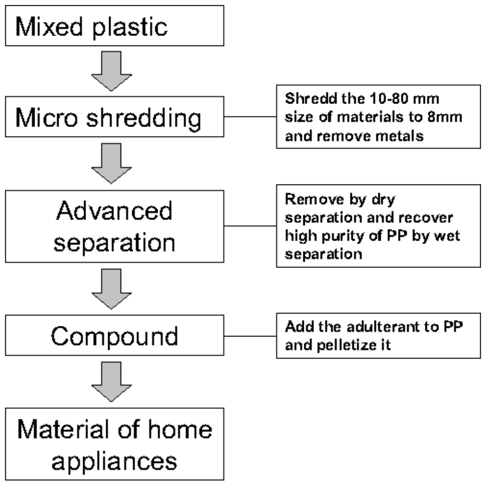

Figure 6: High level of wet mixed plastic separation.

6.1 Micro shredding technology

As described in chapter 5, vegetable cases of refrigerators are easy to be removed and contain little extraneous foreign materials. However approximately 50mm size of plastic residue after mechanical process contains small wires and small pieces of metals that cannot be recovered by metal recovering separators. We shred this plastic residue into approximately 8mm size of pieces and separate these small pieces by dry specific gravity separation and electrostatic separation. And we can get the high quality mixed plastic which metal concentration and PVC (Poly-Vinyl Chloride) one are well below 0.5% by this process.

This plastic residue is used be incinerated or landfilled. But if we use this technology, we can use it as blast furnace retardant or Refuse Derived Fuel (RDF), or downgraded materials.

6.2 High-grade separation technology

These recyclable mixed plastic pieces have about 30% of PP. This is the technology that separates and recovers PP from these plastic pieces by wet separation process. At first, we wash and separate roughly those pieces by hydro-cyclone. Next, we separate those by sink-float separator.

Finally, we can recover much higher purity of PP by the rubber and Poly-Urethane (PUR) removing process. As a result, we have established the high-precision separation process we can get the high purity of recovered PP regardless of wide variation of piece size.

6.3 The development of plastic self-recycling

PP recovered by “LEVEL 4” technology is mixed with various grades of PP, but we have confirmed that there is little physical fluctuation through the year and that we can use it as well as virgin material by adulteration technique. We have now developed self-circulation of our products through the quality verification. On the other hand, recovered PP of “LEVEL 2” described in chapter 5 is composed of specified grade of PP. So we have to choose application how to use PP of “LEVEL 2” and PP of “LEVEL 4” flexibly. We could not perform the high quality of recycling to apply to the parts of home appliances in such case as the chassis of refrigerators until now, because it is bonded to the expanded PUR and it cannot be recovered in disassembling process. But we have possibility to realize the high quality of recycling in such case as low purity of plastics by the “LEVEL 4” technology.

7 FUTURE DEVELOPMENT

Balance of environmental impact reduction (ecology) and cost (economy) by the technologies is necessary to establish the sustainable society. It is important to promote DFE for this purpose.

“ Law of acceleration of recyclable materials utilization” was regulated in 1999 in Japan. Many of Japanese industries including home appliances industry set up “Products assessment guideline” and each industry has made “Internal rule of products assessment” which is promoting DFE.

DFE has been shifted from “First generation” that is considered on the desk to “Second generation” that is the approach of a harmonization between design section and recycling plant (shown in Table1). HCS provides verification and implementing data of recycling plant to the engineers of Mitsubishi Electric. Also HCS have been developing to “Third generation” of DFE that uses Life Cycle Assessment (LCA).

We have developed unique Design For Disassembly (DFD) method that can evaluate the products recycle ability from the viewpoint of not only LCA but also actual recycling process adopted in our plant. This DFD can be used for product design. We are working on a standardization of DFE. And we have made efforts through in-house technical seminar named “Environmental Conscious Design course” for design engineers, so that DFE becomes one of the factors of product design.

Manufacturers collect and recycle the specified four kinds appliances by each treatment process in Japan, although over 90 kinds of equipments are treated together in EU. We invested in some of recycling plants and dispatched our engineers from our factories. These engineers improve recovered material quality by each appliance and get the DFE information from products manufacturers’ viewpoints. These activities make easy closed loop recycling such as horizontal self-recycling.

We Mitsubishi Electric and HCS will contribute to advancement of 3R technology for “high quality of recycling” and “Comprehensive DFE” in the future as well.

Development stage	Detail	Case
First generation	Execution of product assessment (Paper plan)	Products assessment manual
Second generation	Verification by recycling plant Utilization of measurement data	Guideline of design Feedback to design
Third generation	Application of the evaluation techniques	Selections of materials and production process by LCA, etc.

Table 1: DFE development.

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Product Individual Sorting and Identification Systems to organize WEEE obligations

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Abstract

With the implementation of the Waste Electrical and Electronic Equipment directive (WEEE) manufacturers of electrical equipment are obliged to take responsibility for their appliances. At the moment different configuration of recycling systems are discussed in Germany which have in common that the recycling costs are distributed among the manufacturers by their respective market share. The developed concept allows an automated identification of electrical waste by means of RFID technology. A product individual signature of products has not only the potential to identify products but can also be useful for the entire product life cycle in terms of production control, documentation of the production process and after sales services.

Keywords:
Reverse Logistics, RFID

1 INTRODUCTION

A product and producer specific identifier is a prerequisite for unambiguous identification; this is especially necessary for the goals of the WEEE directive to be taken into account to a sufficient extent. The basis for this is that each individual product must be labelled with a number and the product's producer. Such an identifier should be effected so that it is generated automatically and cannot be forged. The identifier should also be permanently affixed to the product and be as insensitive as possible to external influences. A suitable approach for this could be the application of RFID technology. Therefore, products placed in circulation in the future could be equipped with a transponder.

In addition to the advantages of the identification's being automated, the producer also enjoys significant advantages in production control and after sales services. Given the large quantities of electric and electronic products, an unforgeable marking would be of considerable significance for cause related computation of disposal expenditures. Therefore, the implementation of an expenditures related coding system is a significant success criterion for a lasting disposal concept.

2 REALIZATION

The central component of the disposal system is a database to which all producers have access through the world wide web and in which they can enter data which is relevant to disposal. With that, every product is registered in this database with its product specific data and its own unique number and can therefore be identified. At the same time, all producers are recorded with their products. In this manner, incidents of fraud can be largely avoided. This database can also be used as a tool for documentation and controlling.

Thus identifcation technolgies like RFID are becoming a key factor of a sustainable circulation economy. With RFID technology, RFID tags of up to 32 kB can be written and automatically read out without physical contact. Authentification, authenticity and confidentiality are warranted by the principle of asymmetric encoding.

2.1 Transposition Alternatives

The alternative concepts for transposition of the WEEE directive can be classified by certain criteria. The charge for disposal can be paid either by the producer/ distributor/ importer or by the purchaser. The directive's requirement that the producer be held responsible corresponds to payment by the producer. Further differentiating characteristics are the time of this payment (at purchase time or at disposal time) and the type of disposal charge (individual or blanket charge). The design of the system for the return of waste goods also depends on who adminstrates the registration. Many possibilities are conceivable here, starting with the operator of the database or a central register. Decisions are also required for the form of financing, for which both the assessment and coverage principles are candidates.

At least this would fulfil the requirement that the producer be made reponsible. In this concept, registration is administrated by a central register. As in Switzerland, the system is financed in accordance with the assessment procedure.

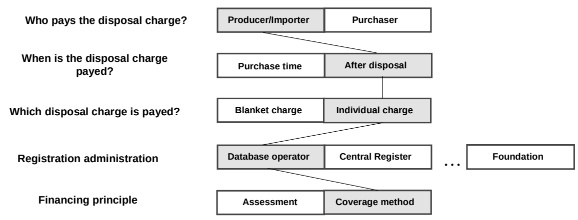

Figure 1: Concept of the IDENT Research Project

In Germany alternatives for transposition of the WEEE directive are currently under discussion (see figure 1). These are based on assignment of disposal costs in accordance with market share. However, such models are not suitable for determining the responsibility of individual producers (as is required by EU Directive 2002/96/EC) because this would place producers of ecologically superior, long live products at a disadvantage. Producers of top quality products have a relatively large market share in the area of electric and electronic devices; that is, with this model they would pay a correspondingly higher proportion of the disposal costs and today they would already assume responsibility for recycling, when in fact their products had not yet reached the end of their life cycle. The logical result is that producers of inferior, short live products would pay a relatively smaller portion of the total disposal costs and thus be treated to a free ride! The resulting behaviour of these producers would not be desirable because production of their goods would result in high consumption of resources. If this model were implemented, the producers of the inferior products could produce at lower cost in comparison to the producers of the top quality products. Increased demand for the inferior products and the associated higher production volumes, which would also be supported by the necessity to replace the devices after a short time, would lead to greater consuption of resources. The bottom line is that the fundamental idea of the directive would not be realized.

The concept of the Systems for Identification and Sorting for life cycle management of household appliances (IDENT) at the Berlin University of Technology research project provides that every producer or distributor***/*** importer of products pays the disposal charge for the products which it itself places in circulation so that the fundamental basis of the responsibility of the producer is implemented. However, in this system the individual disposal charge is not levied when the device is produced or sold; rather, it is only levied when the product is presented for disposal. For the producer of each old device to be identified at this point in time, the products must have been labelled unambiguously. Product identification has to take place automatically so that all processing costs are kept low. That is why the IDENT project proposes the use of RFID tags to mark products in the sense of Article 11 of the WEEE directive, by which the producer is identified unambiguously.

The task of registering the products is assumed by the operator of the database. In contrast to the other methods presented, financing takes place in accordance with the princple of coverage. The concept of the IDENT research project fulfils all the WEEE directive's requirements for a disposal system for old electric devices.

2.2 Identification Technologies

Identification technologies form the interface between the physical world of value added processes and the virtual world of informatics. In this connection ubiquitous computing is regarded as a next step of innovation.

The Auto-ID technologies specified in this connection have, in particular, a high potential for efficiency and effectivness increases achieved through networking between physical objects of the real world and external information systems. In the ideal case, human beings, which were previously mediators, can be replaced by direct machine to machine communication. With the help of RFID systems, information interfaces which are primarily automated are created in physical value added processes. Both increases in physical efficiency of processes and improvements of their information dependent value added portions are major aspects because there are no media breaks in the digital information chain. Discontinuities in media form a significant restriction of productivity on the one hand and foster the susceptibility of processes to error, and on the other hand they promote lack of transparency in value added networks. A further important advantage of RFID in this context is the density of information, e.g. in view of times and places of data input, for this data is normally gathered by reading devices. Thus RFID systems deliver an enormous potential for continual automation of the supply of information in logistics processes.

2.3 RFID technology

Radio Frequency Identification (RFID) is a method of contactless reading and storage of data without visual contact. RFID is the generic term used for the entire technical infrastructure. The data are stored on the RFID chips and read or written using radio waves. In the case of low frequencies, this is done inductively via a near-field region and in the case of higher frequencies, via an electromagnetic far-field region. The distance at which a tag can be read varies between a few centimetres and a maximum of 30 metres (at the current level of development), depending on the design (active/passive), frequency band, transmitting power and environmental conditions. The size of an RFID tag varies depending on the particular application: It is entirely possible to have RFID tags the size of a book (for use in containers), but thanks to today's technology they can also be small enough to be implanted in money bills or sheets of paper (see figure 2). Currently, transponders are used mainly as labels, but they are also used in key chains (immobiliser), glass tubes (animal identification), nails (pallet identification) or chip cards (access control). What distinguishes RFID transponders most clearly is the kind of energy supply they use. Small radio chips without batteries or other sources of energy are known as passive transponders. They receive their energy from base station radio signals through induction. This reduces the cost and weight of such chips, but it also diminishes their range. Passive smart tags can normally be written on only once, supporting read-only access in continuous operation. Passive smart tags are often used for storing unique keys (e.g. a product number) for database entries. On the other hand, active transponders, which have their own power supply, have a much greater range of communication and a greater function range (they are both writable and readable). However, they are also much more expensive and, owing to the battery, they are bulkier and have a shorter service life. Currently, their storage capacity can be as large as 1 MB, depending on the application

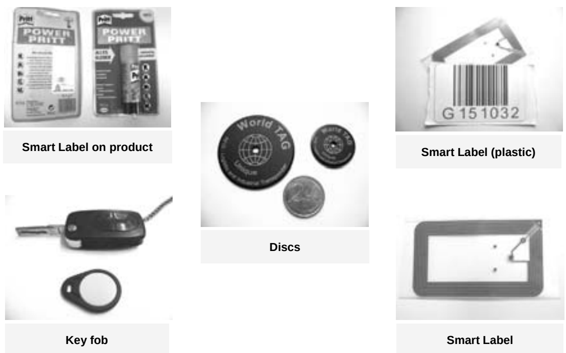

Figure 2: Some examples of transponder applications

Only a very small portion of the vast array of devices and labels are fully compatible. The frequencies and standards used vary nationally and internationally. Problems with the reading rate can crop up in transponders used with products containing a large proportion of water (such as yoghurt, mineral water, etc.) or with products containing metals, such as shopping carts or car parts. Such products can diminish the already weak reflectivity of passive RFID transponders still further. Problems may also occur if the tag is attached directly to a product that has a high density.

2.4 Encryption

For data stored on a transponder to be protected from unauthorised reading, change, deletion or storage, it must be encrypted. Data confidentiality, integrity and authenticity are ensured through encryption. This way the encrypted data cannot be read by an unauthorised person even if he can physically access them.

In the case of symmetrical encryption, one and the same key is used for encoding and for decoding a message. This key has to be exchanged between the communicating parties via a secure channel. The message can then be sent via a non-secure channel. The message's integrity and confidentiality are protected even if it is intercepted.

To avoid problems encountered in symmetrical processes (large number of keys; necessity of exchanging them via a secure channel), asymmetrical encryption techniques – also known as public key techniques – can be used. A pair of keys each consisting of a public and a private key is used with this technique. Public keys are used to avoid security risks when exchanging keys. Each recipient of a message has such a pair of keys. The sender of a message encodes his message with the recipient's public key. In the case shown here, this means that manufacturers of the products mark the information they store with a private key, which only they obtain from a Trust Centre, and the disposal companies decode the information with a public key (also obtained from the Trust Centre). This message can be read only with the recipient's private key, which means that only the authorised recipient is able to decode and read the message (see figure 3).

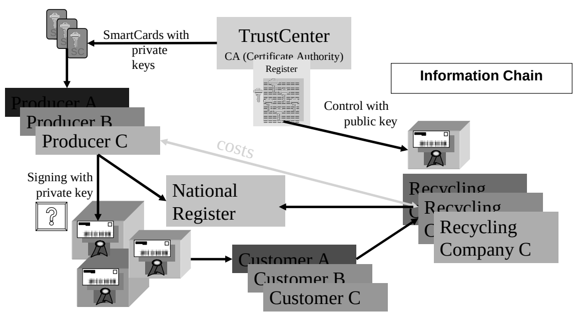

Figure 3: Concept of the project IDENT

2.5 Identification station

Electrical appliances are identified before disposal at the transshipment points at which standard containers with the appliances are emptied. The appliances are grouped at the identification station into recognised and unrecognised appliances. They are passed through an RFID reader gate to read the RFID tags attached to the products. The data acquired in this manner at the station is automatically entered into the web database described above, which the manufacturers and the disposal companies can access. The corresponding manufacturers are automatically billed after the appliance data have been entered to the database (see figure 4).

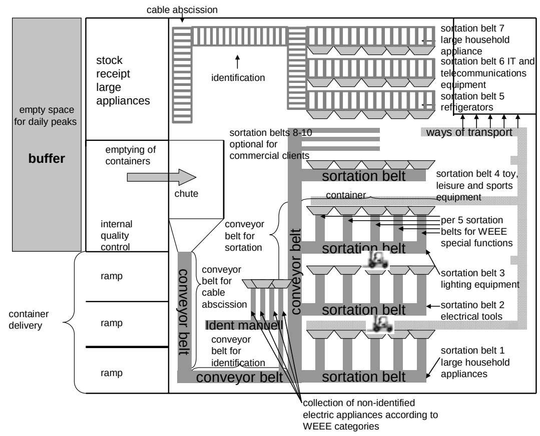

Figure 4: Identification station

The identification process starts with transfilling into a chute. This is the deepest point of the following transportation process. At the identification point RFID-Antennas are like a cube around the conveyer belt. This allows the detection of RFID-Tags in all orientations. In the same process all devices have been weighed. These data are aligned with the web database. A camera takes pictures for documentation (see figure 5).

Appliances without or with damaged RFID-Tags have to be identified separately.

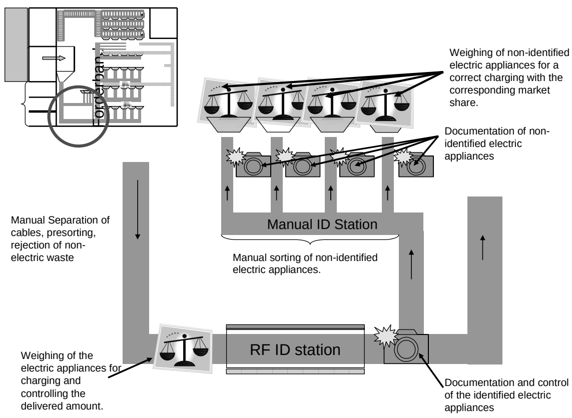

Figure 5: Identification circle

After the identification of electrical appliances the automatical sortation into standard containers follows.

Large household appliances have to be transported on tougher roll conveyors. The process of identification and sortation is analog to the process for small household devices.

2.6 Identification system for non-marked electric appliances

The presented identification and collection system is designed for the future when possibly most electric appliances are marked with RFID technology. For the huge amount of electric appliances a solution to collect it and to fulfil WEEE requirements must be found. One of the most effective and discussed initiatives is the sorting system handled by the ALBA AG in Berlin / Germany. For this system, extensive conceptual considerations and quantitave analyses of the potential of electric appliances in the residual and packaging waste had to be done. As a result the electric appliances are identified by x-ray technology and blown out by air pressure.

3 SUMMARY AND OUTLOOK

Unlike other suggestions, the IDENT transfer project concept for implementing the WEEE Directive envisages implementation of the measures required by the guideline without putting manufacturers of ecologically sound and durable products at a disadvantage through imprecise attribution of old appliances. Unfair distribution of waste disposal costs is ruled out thanks to unequivocal identification of the appliances, other manufacturers will not be able to dodge costs at their expense. By using the RFID technology it would also be possible to expand services and to supply the customer with better information, and to support him as provided for by the Directive. Repair and maintenance, for instance, could be dramatically simplified and improved using information stored on the tags. By implementing the concept, not only the guideline's requirements would be fulfilled and its underlying idea implemented, but it would also be possible to make improvements in other areas.

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Dynamic Process Planning Control of Hybrid Disassembly Systems

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Abstract
Disassembly plays a key role in a life cycle economy since it enables the recovery of resources [1]. A partly automated disassembly system could adapt to a large variety of products and different degrees of devaluation, however, the deviations between the disassembly plan generated by the planning process and the actual situation of the disassembly system cause difficulties in the workshop execution. Controlling is necessary for regulating daily operations. The objective of Dynamic Process Planning (DPP) is to reflect the availabilities of the disassembly tools in the real disassembly cell and offer alternatives when a device or tool is not available. The DPP procedure will propose alternative disassembly processes and tools supported by a knowledge-based network method and will select the best suitable among them.

Keywords:
Disassembly; Process selection; Process Assessment; Shop floor control

1 INTRODUCTION

A conventional production plan usually lacks information on the actual job shop situation due to the time difference between the generation of the production plan and its execution in the workshop. Responding efficiently to unexpected events that occur in the job shop, e.g. failure of devices and tools is a very complicated task since the execution of the production plan takes place at the lowest level of a production system [3], [4], [2].

In this paper, a system for the automatic verification of disassembly processes will be described. The aforementioned processes are generated by a disassembly process planning system. For processes not available at a given time, alternative processes must be selected. The results of the verification will be used to connect the planning system to the cell control system. This verification module targets products at the end of their life cycle.

It is assumed that all devices and device relevant information are already available. It is also assumed that the system has an input in terms of a disassembly sequence in the form of structured text. Each sequence should contain the following information:

- the components of the disassembly object;
- its disassembly method;
- disassembly devices as well as tools used;
- the work station in the disassembly system.

Output of the system is an updated (verified) disassembly process for the disassembly system including the actual job shop conditions. For this purpose, process availability and technical feasibility will be considered.

At first, availability and technical feasibility will be defined. Then a concept will be proposed for the selection and verification of processes and tools. Finally, the suitability of the proposed system will be validated on an exemplary disassembly process.

2 CHARACTERISTICS OF DISASSEMBLY PROCESSES DYNAMIC PLANNING

2.1 Process Availability

In order to verify a disassembly process plan, an inspection of the available tools and processes has to be performed. Furthermore, the verification of a disassembly process requires the technical suitability of the tools proposed for each disassembly step.

The definition of availability can be found in various sources, e.g. DIN 40041 [5], VDI 4003/4 [6], VDI 4004 [7] or VDI 3423 [8] and can be described as the probability that in a certain time and under given conditions no relevant failure causes non-operability of a unit. Availability therefore, can be interpreted as the percentage of time that the unit is operational. The availability of a technical system is distinguished to:

- theoretical availability;
- technical availability;
- practical availability.

Theoretical availability is determined via simulation of the production system. Several statistical methods can be implemented within the model in order to get a realistic image of the system.

The technical availability of tools within a system can be controlled via intelligent tool control, which is executed either centralised, by a cell Programmable Logic Controller (PLC), or distributed by co-ordination of the handling devices.

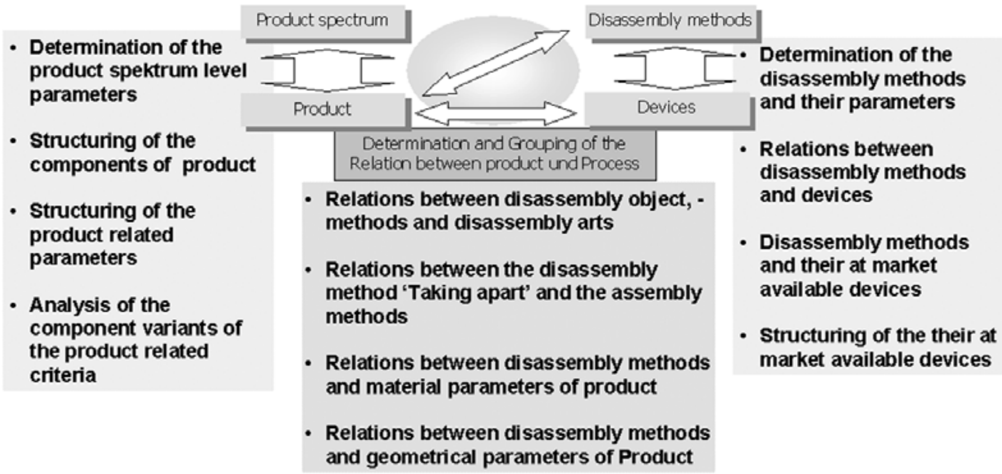


Figure 1: Identifying and structuring product and process related parameters.

In both cases the mechanisms are identical. A tool used by an automated handling device is equipped with an active or passive coding element. In order to define practical availability, all system states have to be evaluated according to usage, idle or service time. This could be managed via a Plant Data Acquisition System. Such a system is based on a real time database. Real time is required to capture all incoming data according to their generation time. Time differences between several time stamps are used to define tool or system availability, reliability or the utilisation ratio.

2.2 Technical Feasibility

Nowadays, process and tool selection for disassembly depends strongly on the experience and even qualitative selection of the process planner rather than rational and systematic planning. For an automated or hybrid disassembly system, the selection of disassembly processes and tools should be quantitative and systematised. The advantages of such a process planning are the following:

- An optimised selection of disassembly processes is possible.
- Under a given framework of process selection a fast adaptation to new unknown products is possible.
- If appropriate processes, devices and tools are not available, alternative processes can be generated by the proposed DPP system.

In this paper, the technical feasibility of a disassembly process is considered as the applicable range of use of a specific process and its required tools. In practice, technical feasibility is limited by product and process related characteristics.

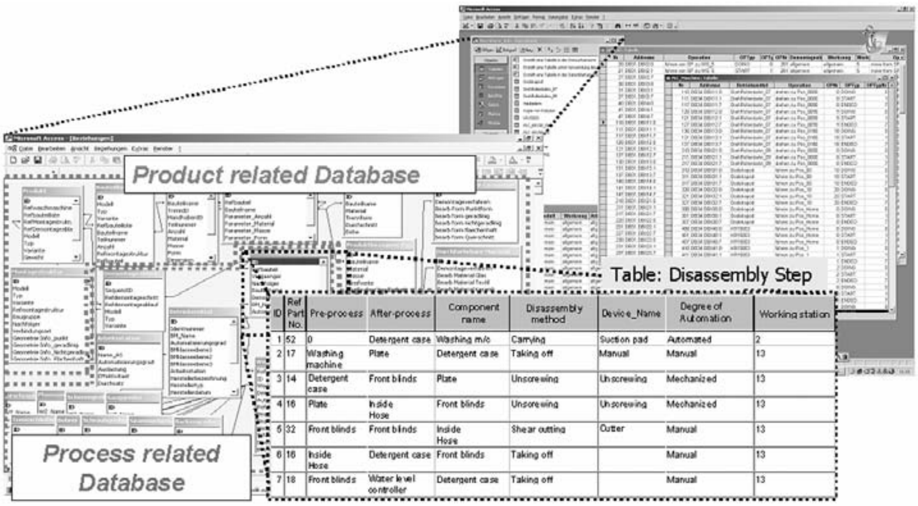
3 PRODUCT AND PROCESS RELATED CHARACTERISTICS

Generally applicable disassembly methods are determined by the characteristics of the disassembly objects. Geometrical, physical and technical characteristics are assessed regarding applicable disassembly methods. For example, a product or component that is assembled with screw joints can be disassembled by unscrewing, drilling, milling, water jet cutting etc. In this way the relation between product-related parameters and disassembly methods is determined.

In addition, disassembly methods and devices are classified and market-available manufacturing equipment compared and sorted. For each assigned disassembly method and device, the degree of automation is determined. For example the disassembly process "shear cutting" can be done manually, mechanised or with automated devices. Figure 1 illustrates product and process related characteristics and their relations as analysed in this work.

Product and process information are realised in a database system. The system consists of a product related and a process related data part. The product related side contains a product identification section, an assembly structure, a component list and a component table as well as tables for product related parameters.

A product can be disassembled in different sequences. Product and process related contents are interlinked. Each disassembly sequence has a relation to the table for the disassembly steps. The disassembly steps table includes the part to be disassembled, the disassembly method and the necessary device/tool as well as the designated work station. The fields that contain the disassembly methods information are linked to the tables that contain information on geometrical and material characteristics involved. The device/tool field refers to the corresponding tool table. Figure 2 illustrates the database structure for products and processes.



ID	Ref Part No.	Pre-process	After-process	Component name	Disassembly method	Device_Name	Degree of Automation	Working station
1	52	0	Detergent case	Washing m/c	Carrying	Suction pad	Automated	2
2	17	Washing machine	Plate	Detergent case	Taking off	Manual	Manual	13
3	14	Detergent case	Front blinds	Plate	Unscrewing	Unscrewing	Mechanized	13
4	16	Plate	Inside Hose	Front blinds	Unscrewing	Unscrewing	Mechanized	13
5	32	Front blinds	Front blinds	Inside Hose	Shear cutting	Cutter	Manual	13
6	16	Inside Hose	Detergent case	Front blinds	Taking off		Manual	13
7	18	Front blinds	Water level controller	Detergent case	Taking off		Manual	13

Figure 2: The products and processes database structure

4 DEVELOPMENT

4.1 Concept

In this chapter, a methodology for the generation and selection of alternative disassembly methods and devices will be discussed. If a disassembly process or tool that is addressed in the disassembly plan is not available at the shop floor, alternative available processes must be suggested.

Figure 3 describes a systematic concept for a dynamic process planning within a hybrid disassembly system that is based on the generation and selection of alternative disassembly processes. As a result, an updated process plan can be generated. Information on the components of the disassembly object, disassembly method, devices as well as work stations of the disassembly system, is the input of the DPP system.

Components to be disassembled are linked to appropriate disassembly processes including tools and their parameters that are found in the product and process database. Once the data base is available, the availability tests are executed. If the disassembly tool for a disassembly step is available, the disassembly proceeds as originally planned, if not, a dynamic process planning takes place. The result is an alternative disassembly step including a technological suitable and available disassembly process and its related utilities.

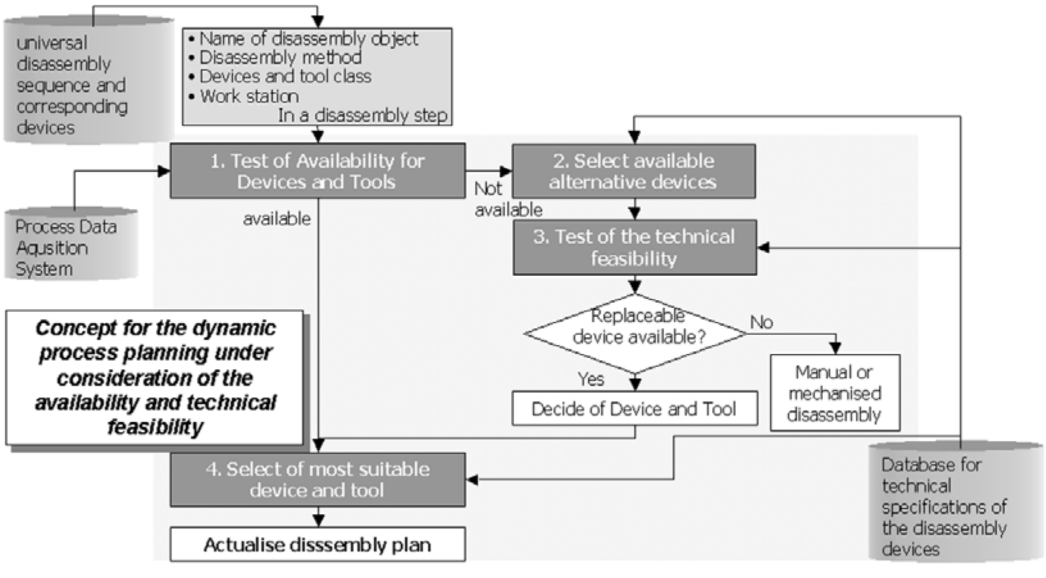


Figure 3: A Dynamic Process Planning Procedure for hybrid disassembly systems.

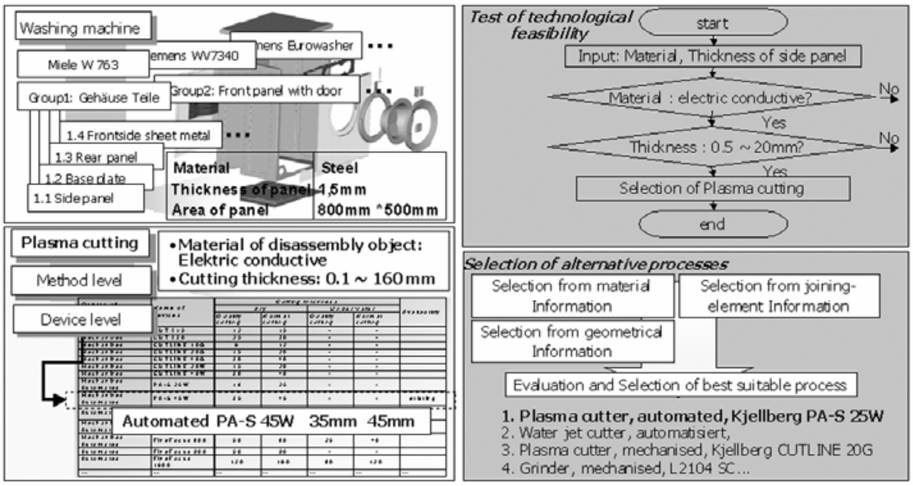


Figure 4: Determining the availability of a process.

4.2 Disassembly devices availability test

Figure 4 presents an availability assessment algorithm. After identifying the disassembly device, its presence in the disassembly system is checked. Then the device is examined by the cell controller regarding its operability. If the device is in operation status at the given time, the work station that contains it is verified.

The next step involves examining whether the device is occupied by other disassembly processes. As soon as all four steps are successfully executed, the availability of the device is determined. For a device that is not available, a dynamic planning procedure will take place.

4.3 Generation of alternative disassembly processes

Dynamic process planning considering technical feasibility consists of several sub-procedures. Initially, product and process related parameters must be assigned, and then all possible alternative disassembly processes are generated by an algorithm. The alternative processes are tested in terms of technical feasibility and finally the most suitable disassembly process is selected. A detailed description of the whole procedure follows.

For the generation of alternative disassembly processes, the product and process related characteristics and their relations as described in chapter 3.1 are used. Our concept provides two options for the generation of alternative processes. One sub-procedure generates alternatives with regard to the relation between the material and geometrical characteristics of the disassembly object and the disassembly process. The other sub-procedure is used for generating alternatives according to information on the joining elements, which are associated with the disassembly process. The set of alternative processes available at the end consists of processes generated by both sub-procedures. Figure 5 describes the generation process.

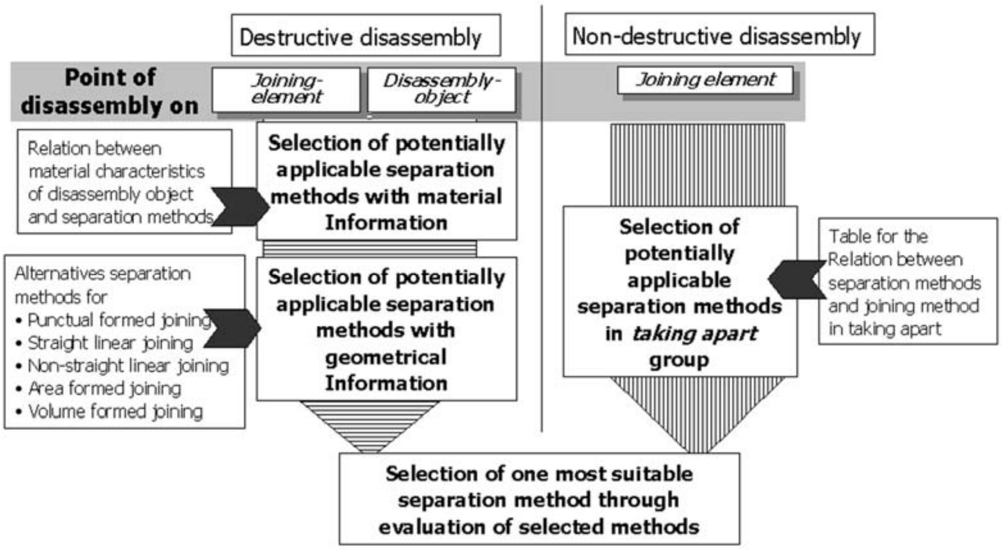


Figure 5: Procedure for the generation of alternative processes.

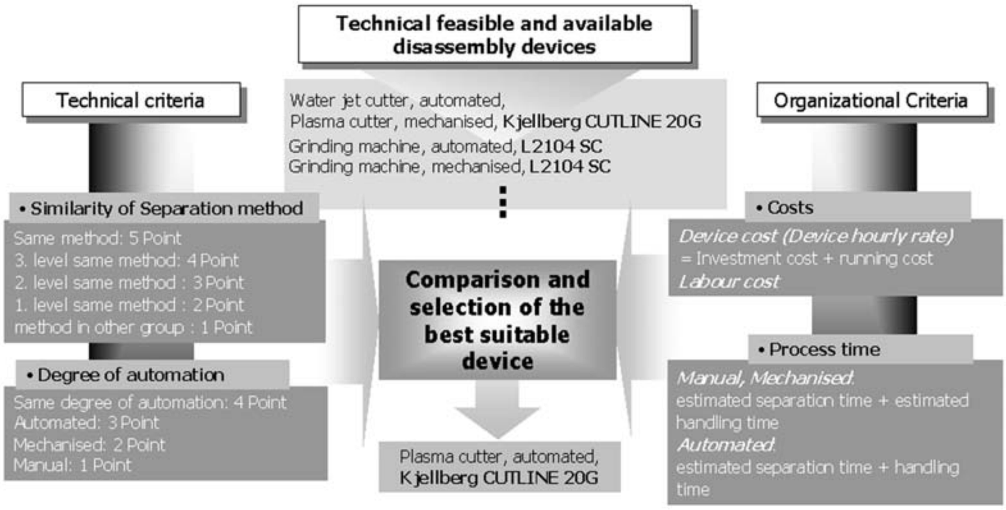


Figure 6: Assessment for the selection of the best-suitable alternative process.

4.4 Assessment for the determination of a best suitable process

The procedure described in chapter 4.3 generates several technically feasible processes. Up to this stage, no device is determined and no priorities are specified regarding which process and device are the optimal ones for the given disassembly step. In this chapter the issue of determining priorities is presented.

An originally planned disassembly step has a fundamental connection with its forerunning and succeeding disassembly steps. For this reason, the original process to be substituted is a very important source of information for the determination of the best suitable disassembly process among the alternatives generated.

In specific, disassembly methods and devices, which are similar to the initially planned process regarding their geometrical and material characteristics, are assigned a high priority. Figure 6 illustrates an assessment procedure for the determination of the best alternative disassembly process.

5 IMPLEMENTATION

Following from the results of sections 3 and 4, a software system has been implemented. The system consists of a database system and the dynamic process generation system.

In the database system, attributes, for example name of disassembly object and name of separation processes, can be selected and the appropriate parameters will be used for the assessment of the technical feasibility. Consider the side panel of a washing machine that has to be disassembled by a plasma cutter. As a first step, disassembly object related parameters, i.e. material, thickness and surface properties of the panel are entered in the database followed by process-related parameters. Process-related parameters are divided into two levels; the disassembly method level and the device level. In this example, parameters of the disassembly method level are the machinable material and shape. Parameters for the device level are the machinable thickness and width. These parameters are read from the data base and used for determining technical feasibility.

In the dynamic process generation system, an alternative separating process should be determined for the disassembly of the washing machines side panel. Parameters for the component to be disassembled and a disassembly process (separation process) are called from the product and process database. Product related parameters for the side panel are:

- material: steel;
- thickness of the panel: 1.5mm;
- dimension: 90mmx60mm;
- bending of the panel surface.

Process related parameters of the process plasma cutting are for example, machinable material, thickness of the panel, cutting speed, distance of the beam, angle of the beam flow and so on. After these conditions are identified, an appropriate separation process will be selected out of the database.

The concept of searching for alternative processes consists of two parts. One part involves the generation of alternative processes based on material and geometrical information on the disassembly object and the used joining element, while the other part generates alternative processes on the basis of the joining method used in the disassembly object.

The ‘Selection module from material information’ examines the relation between material characteristics of the disassembly object and the disassembly process, and the ‘Selection module from geometrical information’ examines the relations between geometrical characteristics and disassembly processes. Alternative processes are provided by both selection modules.

In the ‘selection module from joining-element’, alternative disassembly methods can be provided by examining the relation between separation processes and joining processes. In the given example an automated plasma cutter, a grinder and a water jet cutter were found in the database.

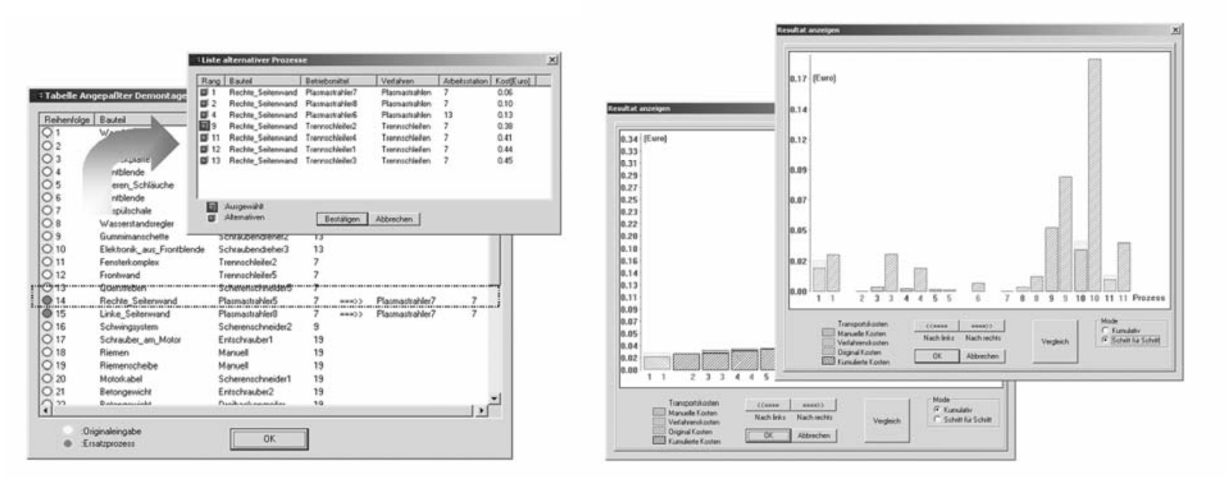


Figure 7: Availability test, generation of alternative processes and derivation of the best suitable.

Finally the evaluation of the alternatives takes place. The evaluation module considers not only technical but also organisational factors since estimated process time and investment and management costs play a key role in the economical evaluation.

All technically suitable processes are compared with the originally planned process and evaluated; the best matching process will be selected. For the above example, a Plasma cutter, automated, PA-S 25W has been selected. In Figure 7, the DPP results, as presented within the software's interface, are pictured.

6 SUMMARY

A disassembly process plan has sometimes large differences compared to the actual shop floor situation. The reason for this is that the disassembly plan is generated in advance, a few hours or even several days before its execution. In this paper, a dynamic process planning system was introduced in order to fit a disassembly process plan to the actual condition of a disassembly system.

The system receives availability information for requested devices and tools. If a device or tool is not available, the system generates available alternatives by a database supported procedure and selects the best suitable among them. Future work steps include the development of an interface module to connect this system with a disassembly cell control system and in addition the integration of the dynamic process planning system into a disassembly planning and control system.

7 ACKNOWLEDGEMENTS

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Development of an automatic cleaning process for toner cartridges

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Abstract
The remanufacturing process at the toner remanufacturing company Scandi-Toner is mostly based on manual work. The work environment is irritating and tiresome for employees due to high noise levels and amount of toner powder in the air. Therefore, Scandi-Toner decided to develop an automated cleaning process concept. The result of this research project was a concept based on different modules that together make it possible to isolate toner powder and absorb disturbing sounds. A high degree of flexibility was achieved by using transport tracks and palettes. The developed final concept is adaptable for future production flow with increased processing capability.

Keywords:
Remanufacturing; automation; work environment; cleaning; toner cartridge

1 INTRODUCTION

Remanufacturing is a concept increasing in importance in today's manufacturing industries. It concerns the treatment of worn-out products which are taken back in order to extend their value on the market. Most experiences of the remanufacturing are related to the automotive industry. However, the concept of remanufacturing has spread during the latest decades to other sectors, such as those dealing with electrical apparatus, toner cartridges, household appliances, machinery, cellular phones etc.

The remanufacturing of toner cartridges is a quite large business area. Printer manufacturing companies are often earning more money on their cartridge sales than the sales of the printers. Toner cartridges continuously need to be refilled with new toner as they are used in printers and copy machines. Therefore, there is a good opportunity for remanufacturing companies to use a trade-in system to provide customers printers with refilled toner cartridges. Users of toner cartridges are dispersed throughout a large area of the world, within which many independent remanufacturers operate. This creates problems for the original equipment manufacturers (OEMs) as they lose market shares to these independent remanufacturers. Furthermore, with several toner cartridge suppliers on the market, the level of competition is raised, while at the same time less profit per sold cartridge is gained. This competition can be seen as positive for the users, since they can obtain cheaper cartridges meeting their requirements [1].

Remanufacturing of toner cartridges is performed by OEMs or independent remanufacturers, the cleaning process is dirty due to the toner powder left over in the retrieved "empty" cartridges. The design of toner cartridges has been studied earlier by for example, Williams and Shu [2] University of Toronto. Furthermore, one must also remember that the essential goal in remanufacturing is part reuse. If a part cannot be reused as is or after refurbishment, the ease of cleaning or reassembly will not be a factor [3].

This paper concerns the Swedish toner cartridge remanufacturing company Scandi-Toner AB. The remanufacturing process at the company is mostly based on manual work. Since the work environment is irritating and tiresome for employees due to high noise levels and amount of toner powder in the air this research project was launched. Scandi-Toner started to collaborate with Linköping University in order to develop a concept for automation of the cleaning process.

1.1 Aim

The aim of this paper is to describe the conceptual development of an automated cleaning process for remanufacturing of toner cartridges. Questions about the potential environmental effect will be discussed. The aim is fulfilled by answering the following questions:

- What are the benefits by automated remanufacturing?
- What is important to know before the start of the concept development?
- How is the environment affected by the changes?

1.2 Methodology

To be able to answer the above stated questions in this paper, the important issues of remanufacturing were investigated and explored. Empirical data was gathered through practical work in a remanufacturing production factory. Interviews with operators, production managers and directors where also conducted to get more practical and theoretical knowledge about remanufacturing at Scandi-Toner AB. In order to be able to draw more general conclusions, data was also collected from previous research. This include, for example, research conducted at several remanufacturing companies in Canada, Japan and Sweden [4].

The product development was performed based on methods written by Ullman [5]. The method divides product development in to seven phases. These phases are: *understand the problem, customer requirements, design specifications, concept generation, concept development, prototype* and *recommendations.* The development of a new automated process was focused on ***understanding the problem, customer requirements, concept generation*** and ***concept development***. The goal was to present a concept that was possible to install into the present production line and flexible for future changes of the production.

2 AUTOMATION FOR REMANUFACTURING OF TONER CARTRIDGES

A new automated cleaning process is crucial to be used for a long time for the company. This research needs to find a solution that is adjustable according to the present and future needs. It is an important task for this research to give the cleaning process flexibility.

2.1 Problem understanding and specifications

This section will briefly describe the development process of the automated cleaning process. Firstly, efforts were used to **understand the problem**. This was conducted by gaining empirical knowledge by practical work in the production line. The practical work allowed seeing things from the operator's point of view. The empirical data was also served as knowledge base for the rest of the product development. Another good part is that you collect more than knowledge about the production, namely trust from the personnel. Without the trust you will be working with people that are more conservative and less interested in changes. The contact with the personnel is hence valuable for this research.

Remanufacturing of toner cartridges is both dirty and noisy. This affect a lot of the operators work. Often, loud noise has its source in the disassembly and cleaning of the toner cartridges. The noise is mostly generated by ventilation and compressed air flows that are needed to clean the toner cartridges. The production line is very simple and easy to follow. Scandi-Toners are remanufacturing various types of toner cartridges. This requires a flexibility that makes it possible to change small volumes of cartridges in a short time range.

Toner is very light and attach to most things that it gets in contact with. It is able to get in to the most unreachable areas. This means that the toner powder is very hard to isolate. The operators in the production line are often affected by the toner powder. They are often complaining about irritating throats and eyes. Operators at Scandi-Toner use high compressed air to remove the toner power from the disassembled cartridges. This is something that must be used due to the toner powders high attach ability. The cleaning process is performed with individual aspects of cleanliness. There are no routine for how the operator shall clean the cartridges. It is more an inspection which has its foundation in the operators experience and personal ideals for approval.

The background research showed that the process with the best potential for an automation and need of a change was the cleaning process. The complex construction of the toner cartridges and the difficult disassembly operations were few of the reasons why the disassembly process was neglected. The cleaning process was also the worst regarding the work environment and the need of a change was really large.

Specifications were written down, after the research, together with operators, production managers and the directors. The issue for Scandi-Toner was to find a solution that was easy to implement into the present production. The specified criteria were afterwards completed by requirements of the designer. The three most important criteria for Scandi-Toner were:

- The concept shall be able to implement into present and future production system.
- The concept shall result in effective production and use the resources/personnel in a better way then today.
- The concept shall improve the work environment and reduce the noise and toner existents in the work area.

This paper will not bring up details about the requirements and specification. The most critical criteria will be discussed in discussion and conclusions.

2.2 Concept generation and development

The **concept generation** was mainly conducted through brainstorming. The cleaning process was decomposed into different processes that made it possible to focus on smaller areas to find solutions. The solutions were afterwards combined with other solutions in other areas that together formed different units. The units was evaluated and ranged by in a scoreboard where the highest scoring units were further analyzed.

The selected unit solution was chosen based on the possibility of realization. The final concept was picked based on the experience and knowledge together with consultation with experts. Economic aspects have not been subject for analyses in this project.

The chosen concept was developed and refined. The concept development was more based on detailed CAD-models (Computer Aided Design). By analyzing the models and step by step find the best solution for the concept, made it possible to come to a result where the customer requirements were achieved. If CAD models did not help, prototypes were made. The prototypes showed if the solution was enough or if something needed to be redesigned. This made it possible to forth see interactions between different units. In order to reduce the time schedule, different manufacturers were contacted.

2.3 The final concept

The **developed concept** shall give Scandi-Toner the possibility to evaluate cleaning methods and in the same time find settings for an effective cleaning process.

The concept can be easily disassembled and assembled. This means that the concept high flexibility and moveability. The concept can very easily be modified after new revealed needs. The concept with modules makes it easy to disassemble the cleaner and transport the unit to another location. The different modules are divided into five sections: transportation, fixation, pneumatics, cleaning chamber and ventilation. These different module sections form the foundation for the automated cleaning unit.

The basic idea is that the cleaning process is isolated by an enclosure. The disassembly of toner cartridges is performed near the cleaning unit. The components that are cleaned by the cleaning unit are transported, during the cleaning, to a manufacturing line where the toner cartridges are remanufactured.

By using already existing transportation carriers more advantages will be gained. One advantage is that the system will be more reliable during operation. The carrier is easy to adjust over the whole track, this because of the manufacturers range of supplied components that can be mounted on the track. By this you will have the possibility to achieve a better overall solution. By using already existing carrier component you will be able to save some money instead of using them for develop new solutions.

The cleaning process is based on using palettes. The palettes will work as an interface between the transport carrier and fixation frame. The idea is that the palette is easy to manoeuvre. In normal cases palettes are more sensitive considering tolerances. The development was focusing on finding a solution where the operator easily can mount different toner cartridges without trouble. The final solution was verified through a prototype where interested parties could try to mount different components and mediate their opinion. The intuitive aspects where pointed out by the operators. The basic idea is that the operator does not need to think how to mount the components on the palettes. By this you will achieve a more effective workflow and increase the efficiency in the production. One opinion that was cleared out during the tests was that the weighed had to be decreased. The smallest weight reduction on the palettes affects the operators work environment multiplied.

Test is showing that there is good potential to adjust the cleaning unit for different toner cartridges. First there are two different palettes that render the possibility to clean more then 80% of the total amount of cartridges manufactured by Scandi-Toner. The cleaning process with compressed air is flexible by moving or rotate the nozzles or/and the nozzle bar. The transport carrier can also change pace to achieve a more optimal transportation of the palettes. The compressed air is pointed in an angel towards the cartridge components surfaces. The nozzles will remove more toner from the components when more testing of different settings has been achieved. When the toner is in the air it will be transported to a waste container. The toner can later on be reused for other product that can use toner powder as building material.

The philosophy of the cleaning unit is that all toner cartridges components are cleaned at the same time. This result in a more efficient cleaning process and in the same time more production friendly. The palette is mounted with cartridge components and when the cleaning is done, the components come out from the

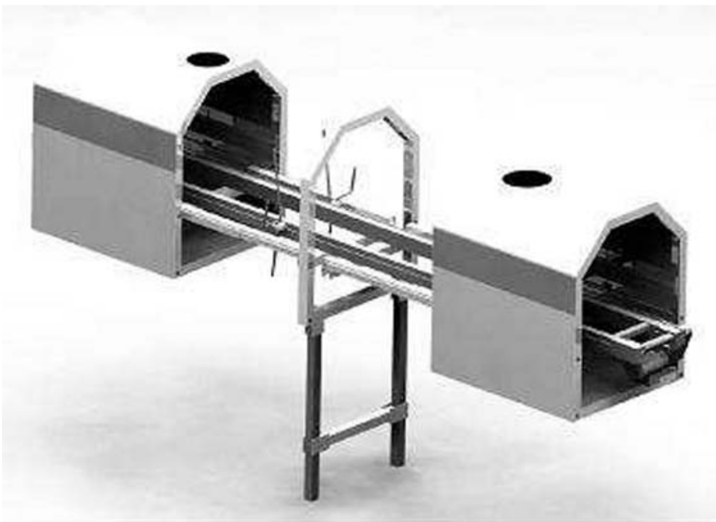


Figure 1. The Developed Concept (final concept)

cleaning unit in one place ready for remanufacturing. This is more of a future idea because Scandi-Toner has to change the remanufacturing process before the automated cleaning unit can be used with its full potential. Combining the cleaning process with the disassembly and remanufacturing processes.

Isolating material as plastics becomes very easily static charged. This results in components that contract toner power, because the power is mostly of plastic material (styrolacrylate). To remove the static charge you can use ionizers. This was also tested but without satisfaction.

The cleaning chamber is constructed so it will achieve noise reduction from the inner wall and toner powder isolation from the outer wall, see Figure 2. The inner wall is made of aluminium with perforated holes. This technique work so sound waives are trapped by the perforated holes in the aluminium walls. High and low sound waves can be trapped depending on the distance between the inner and outer wall. The walls can be replaced if any changes are needed on the chamber. The serviceability is maintained by constructing an opening mechanism that pulls the two different chambers in opposite directions. The opening makes it possible to work inside the cleaning unit without any troubles. On the top of the chamber are the ventilations ducts mounted for an optimal air throughout.

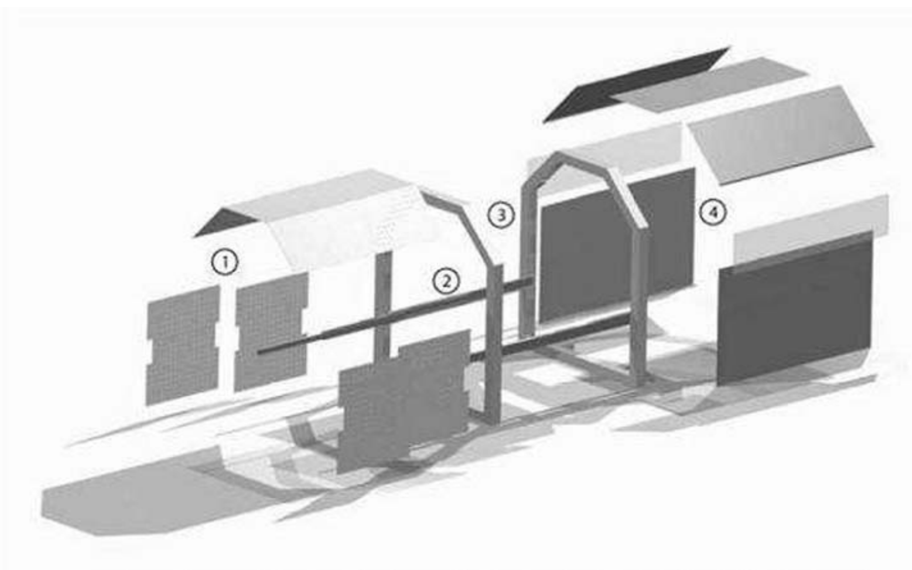
3 DISCUSSIONS

There are today few products on the international market that can be used for automation of a cleaning process of toner cartridges. The thing is that the units often are made for high volumes and when you do not have the right volume in your production you will not achieve anything by investing in such machines. Another issue is that the machines are not flexible enough and there for difficult to implement in a smaller factory. This is the reason why Scandi-Toner need to research the possibility to develop an own automation, flexible to Scandi-Toners needs.

By integrate the transport carrier with the disassembly and the reassembly area you will achieve a unit that does not take much space. The transport carrier has a high flexibility that is needed for possible future changes of the production line or processes. The palettes used for fixation are made in two different models. Possibilities are that the palettes can be modified and there for flexible if new cartridges are processed. The difficulties are that it is impossible to have one palette for all processed cartridges and the second thing is that new cartridges often change from time to time. By implementing a base frame for all cartridges with different modules that can be attached to the base frame, will make it possible to increase the flexibility in the palette system.

At first there will only be one cleaning unit available. If the production should increase one more cleaning unit is possible to install in the factory. The ultimate solution would be to install one cleaning unit for each of the three production lines. By doing this Scandi-Toner will be able to implement all the produced toner cartridges in the automation. One solution is that the unit is installed through a wall. By doing this the unit would act as a floodgate as in the same time it carries the palettes through the cleaning chambers. This would isolate the bad working area of the disassembly process and cleaning process from the manufacturing which needs cleanliness for best result.

Scandi-Toner is today using compressed air for cleaning of cartridge components. Changing the cleaning medium is absurd and therefore not desirable Choosing compressed air as medium is also



1. Sound absorber (inner walls) 2. Telescopic rails 3. Frames 4. Toner isolator (outer walls)

Figure 2. Breakdown of the cleaning unit parts.

more cost effective because the cleaning units can use already existing compressors etc. The static charge is a big issue for the operators. The operators often complain about the shocks that the static charge often leads to. The ionizer solution is a simple and does not demand radical changes. The ionizers can be installed near the nozzle openings and reduce the static charge multiplied.

The time it takes today to change the production from one cartridge to another shall not be exceeded when the cleaning unit is in operation. This is achieved when the disassembly operation is combined with the fixation of the components on the palettes. The operators were advised to verify if the operations where possible to combine and the result where that the combination of disassembling and fixation was achievable.

Scandi-Toner is an independent remanufacturer without connection to the original equipment manufacturer (OEM). The OEMs are trying to put as many obstacles for the independent remanufacturers as possible since they are competing on the same market.

This is a big problem for the independent remanufacturers when they are trying to make their remanufacturing process more efficient and flexible. Hence, the OEMs are designing their cartridges in such a manner that makes them harder to remanufacture (Sundin, 2004). This is particularly shown in the use of fixation methods such as ultrasound welding and design geometries that make it nearly impossible to perform remanufacturing without using any destruction.

A big problem when developing the pallets for this concept was that there were no measurements or similar information available.

4 CONCLUSIONS

This project was focusing on the cleaning process but there are possibilities that automation could be implemented in other operational process. The difficulties are that the disassembly operation and manufacturing operation is very complex at Scandi-Toner. This means that the automation has to be more flexible. Often small screws and clips needs to be mounted and those operations vary a lot between different cartridges.

The final concept that was demonstrated to Scandi-Toner has a potential to give the remanufacturing at Scandi-Toner an improvement they really need. It has the flexibility to be implemented into present and future production solutions. First estimation by the production manager reveals that a prototype development would not be any risk taking for the company. This is due to the design simplicity.

A benefit by automated remanufacturing is that the manufacturer has the possibility to use the resources in a better way. You will also achieve a working environment that is friendlier to the personnel. By using automation you will reach a higher effectiveness in you production. Not only by a higher pace but also because of resources can be transferred to other production stages that is more complex and time consuming.

Product development for a remanufacturing process is not different from other more regular manufacturing processes. You need to have a full support by the directors, managers and personnel. If they don't believe that you can make a difference you will not get enough information to fulfil you goals. You need also to correspond with personnel, directors and managers to succeed in you development stages.

The working environmental effect by automated remanufacturing is for Scandi-Toner enormous. By reducing the loudness and the toner powder in the working areas. Scandi-Toner will be able gain more confidence from the personnel. This will also affects the work ethic in the personnel.

5 ACKNOWLEDGEMENTS

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Study on Disassembling Approaches of Electronic Components Mounted on PCBs

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Abstract

With the rapid development of modern industry, more and more electronic and electric products containing Printed Circuit Boards (PCBs) are produced, consumed, and discarded in our daily life. The disassembling and reuse of electronic components mounted on these discarded PCBs are meaningful to reuse the valuable electronic components, reduce the pollution to the environment, reuse the bare PCBs, and retrieve the materials of PCBs. Four evaluation principles of disassembling methods, components reutilization rate, reliability and uniformity, thermal energy consumption and environmental impact, are analyzed. Based on the analysis of the existing disassembling approach, a new method is presented, which adopts a kind of special liquor, methylphenyl silicone oil, as the medium to transmit heat to the PCBs. The ultrasonic is used in the liquor to accelerate the melting and dropping of soldering tin through ultrasonic vibrations. An experimental framework has been established. The experiment proves that the method has good performances such as high efficiency of energy utilization and high unsoldering proportion.

Keywords:

Disassembling; PCBs; Recycling; Electronic Components

1 INTRODUCTION

With the rapid development of industry, more and more electronic and electric products are produced and consumed in our daily life. Printed Circuit Boards (PCBs), also called printed wiring boards (PWBs), is adopted extensively in household appliances, information products, and almost all other electronic and electric products. As a result of that, many and many PCBs were discarded. According to the China State Bureau of Statistics, there were 15 million discarded household appliances every year, and about 5 million computers and over 10 million mobile phones are out of use ever year only in China. The amount of PCBs needs to be recycled is amazing at present in China [1], and an applicable method is strongly expected by Chinese recycling industry [2].

PCBs consist primarily of three basic components: a non-conducting substrate or laminate, conductive circuits printed on or inside the substrate, and mounted components. PCBs contain not only a significant amount of precious metals (Au, Ag, Pd and Pt) and base metals (Cu, Fe, Ni, and Sn) but also toxic elements such as lead, mercury, antimony, cadmium, chromium, and beryllium. Improper recycling processes of these toxic elements could lead to serious environmental contamination. So the research on disassembling method of electronic components mounted on discarded PCBs has not only economic purpose, but also environmental one. Firstly, reuse the valuable electronic components and soldering tin with economical consideration. Secondly, reduce the pollution to the environment by effective recycling. Thirdly, it is a necessary process before the reuse and recycling of the bare substrate of PCBs.

A lot of institutes and enterprises have paid more attention to the research of quality ensured and simultaneous disassembly. Wa etc. (2005) presents a design on adapting the air heating approach to simultaneous disassembly [3]. More efforts were paid on the component reuse, material recycling, and automated disassembly of PCBs [4-6].

In this paper, the evaluation factors of disassembly method have been analyzed, and we design an effective liquid heating approach based on these factors.

2 DISASSEMBLY METHODS EVALUATION

In addition to identifying and measuring or controlling different variables and methods, it is necessary to develop appropriate metrics in terms of which the effectiveness of disassembly methods can be evaluated. Two issues need to be addressed for this purpose – what should be measured? Further, should the process be evaluated along with the outcome, i.e., the disassembly results?

2.1 Components reutilization rate (CRR)

Quality assurance and evaluation of components is critical for CRR. Unfortunately, it is difficult to evaluate the accurate residual life time of electronic components both technically and economically. Generally speaking, Components Reutilization Rate (CRR) is determined by the reutilization quantity percentage (RQP) and the quality of the components, as shown in formula (1), (2) and (3).

$$\text{RQP} = \frac{m}{M} \quad (1)$$

$$\text{CRR} = \frac{\sum_{i=1}^{m} \lambda_i}{M} = \sum_{i=1}^{m} \frac{\lambda_i}{M} \quad (2)$$

$$\text{CRR} = \frac{\sum_{i=1}^{m} (\text{RQP} \times \lambda_i)}{m} \quad (3)$$

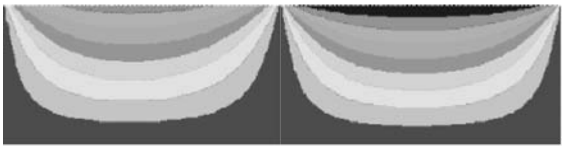
M is the total components quantity, and m is the quantity of the components to be reutilized. λ_i is the quality coefficient of component i decided by the components inspection and evaluation process.

2.2 Reliability and Uniformity

There are mainly five types of join devices used on PCBs: socket pedestal device (SPD), through-hole device (THD), surface mounted device (SMD), screw joint device (SJD), and rivet joint device (RJD). Applicable disassembly methods should break these kinds of connections through nondestructive approaches first. Heating approaches, hot air, hot liquid, infrared ray, and heating pan etc., are widely adopted to unsolder the connection. In the unsoldering processes, the most important thing is to realize the uniform environmental temperature for the disassembly process. That is called reliability and uniformity here.

Given homogeneous environment, airy or liquid or else, it can reduce the damage of the components pins caused by the different stress distortion due to different temperature. Figure 1 presents the temperature distribution in hot liquid and hot air environment at the steady status. At the same time, the uniform temperatures ambient shorten the heating time span. Those are crucial for the quality of the components.

Simultaneous disassembly, characterized by two key operations: heating and separation, is expected to cut down on cost and time consumption. The melting point of the solder, which connects a PCB's substrate and its components, is about 185℃ with neglectable fluctuation between different componen-ts. So the Uniformity can ensure the simultaneous disassembly.



(a) (b)

Figure 1: Temperature distribution in liquid and air

2.3 Thermal energy consumption (TEC)

Thermal energy is consumed in the unsoldering process to heat the temperature higher than the melting point of solder. At present, the most common soldering tin used in electronics industry is the 63Sn/37Pb (contains 63% Sn and 37%Pb, the wastage of this kind of soldering tin was 45 thousand tons in 2004).

The factors that influence the thermal energy consumption efficiency mainly include: time from thermal unsteady status to steady status that is decided by the medium coefficient of heat transmission, and equipment performance of heat preservation etc. The heat transmission coefficient of liquid is about 0.09-0.6 w/mk, and for the air is about 0.006-0.4 w/mk. Usually the gaseous heat transmission coefficient is about 1/10 of the liquid.

Considering steady status, the thermal energy consumption in unsoldering process can be expressed as equation (4).

$$E_T = M_{PCB} \times \lambda_{PCB} \times (T_m - T_i) + M_S \times \lambda_S \times (T_m - T_i) + E_W \qquad (4)$$

Where E_T is the total consumed thermal energy; M_{PCB} is the mass of the PCB and M_S is of the solder; λ_{PCB} is the specific heat of PCB and λ_S is of the solder; T_m is the temperature of solder's melting point and T_i is the initial temperature of PCB; E_W is the wasted energy.

And Generally Speaking, the higher the heat transmission performance of the heating medium, the better is thermal energy consumption efficiency of the unsoldering process.

2.4 Environmental impact (EI)

In PCBs disassembly process, the harmful material producing and emitting have the main impact on environment. Heating in air is difficult to control the temperature accurately and will cause the material of PCBs to burning or oxygenation. The burning in air at the temperature of 300℃ - 500℃ can produce polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-p-furans due to the existence of brominated flame retardant, which can cause cancer, aberrance, mutation and endanger human health. In order to reduce the environmental impact of the disassembly process, the temperature of unsoldering will be controlled, and avoid the harmful material produces and emits to the environment [7].

3 LIQUID HEATING DISASSEMBLY APPROACH

Based on the above 4 evaluation principles, generally, the liquor has much more excellent characters such as high boiling point, low volatility and benign environmental performance. We design a high temperature liquid heating disassembly approach. A special liquid, methylphenyl silicone oil, is used as the heating medium. Good disassembly results are obtained from the experiment, and it indicates that the liquid heating disassembly approach has many advantages.

3.1 Liquid characters

The heating liquid needs many special characters. Firstly, its boiling point must high than the melting point of the solder tin. Normally its boiling point must high than 250℃, and it must have outstanding oxidation resistance ability and thermostability at high temperature. Secondly, it must be innoxious and non-poisonous to the environment and the human beings. Thirdly, it must have well chemical inertia and no reaction with the material in the PCBs. In the experiment, we choose the methylphenyl silicone oil and polydimethylsiloxane with thermo-oxidetive stability additives, as the heating medium. From the experiment, we know the oil is practicable for the heating liquid under the top temperature of 250℃ and the top heating time span of 6 hours.

3.2 Experiment equipment framework

Figure 2 is the structure schematic diagram of the experiment facility. The PCB is clamped by a resizable clamp and heating in the liquid. The PCB immerges into the liquid horizontally with the components mounted surface upwards. The liquid surface is just higher than the components pins. In the position in figure 2, the PCB is heated in the liquid. The vertical mechanical vibration is added on the clamp by a dynamoelectric vibrator. And at the same time, the ultrasonic wave added into the heating liquid by the ultrasonic vibrators on the bottom of the vessel.

3.3 Effect of the vibrators

There are two kinds of vibrations added to the PCB in the disassembly process. One is the mechanical vibration that is produced by the dynamoelectric vibrator. The mechanical vibration is added on the clamp vertically in the heating process, it can help the soldering tin separate from the PCB through the hole and drop into the heating liquid. The soldering tin can be gathered from the liquid with high purity after the heating process. And also the mechanical vibration is added to the separation position. The components mounted on the board drop onto the griddle. Because of the liquid heating effect, the components simultaneous disassembly efficiency is very high.

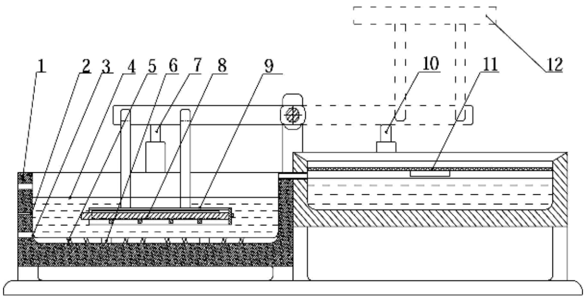


Figure 2: Structure schematic diagram of the experiment facility

1.insulator 2.temperature sensor 3.liquid exit 4.heating liquid 5.electrothermal wheel 6.ultrasonic motor 7.dynamoelectric vibrator 8.PWB 9.clamp 10.dynamoelectric vibrator 11.griddle 12.the separation position disjoining the boards and the components

The ultrasonic wave is also added into the liquid in the unsoldering process. Two ultrasonic motors are installed on the bottom of the vessel. The experimental ultrasonic wave is added to make the soldering tin into the liquid in melting state through the effect of the cavitation and agitation of ultrasonic wave.

The application of ultrasonic wave in the unsoldering process can enhance the soldering separation efficiency, shorten the unsoldering time and simplify the disassembly process.

In the experiment liquid, the sound intensity *I* equals to $0.33W/cm^2$, the sound speed *c* equals to 1468m/s, the liquid density ρ equals to $965kg/m^3$, so the acoustic pressure caused by the ultrasonic wave in the liquid can be calculated by the following equation (5).

$$P_A = (2\rho cI)^{1/2} \tag{5}$$

The calculated result equals to 92Kpa. If the frequency of the ultrasonic wave equals to 40KHz. Then it means that the every particle in the liquid is impacted by the ultrasonic wave 40 thousands times per second. The maximum vibration speed, the maximum vibration displacement and the maximum vibration acceleration of the particle can be calculated by equations (6, 7, and 8).

$$V_0 = \frac{P_A}{\rho c} \tag{6}$$

$$X_0 = \frac{V_0}{2\pi f} \tag{7}$$

$$a = 2\pi f V_0 \tag{8}$$

The acceleration is about 1630 times of the acceleration of gravity through the calculation.

3.4 Experimental design and data analysis

We design the experiment layout by orthogonal experiment design method. Two factors with three levels including a series of temperature (200, 210 and 220°C), a series of different unsoldering time span (40s, 60s and 80s) are chosen to assay the optimal unsoldering result. The design layout and results of the orthogonal experiment are shown in table 1. And the intuitionistic analysis of the orthogonal experiment is shown in table 2. The variance analysis of the orthogonal experiment is shown in table 3. It is indicated in the table 2, that the higher the temperature and the longer heating time is, the better unsoldering result will be.

And the heating time span is the more important effect factor as the table 3 shows. For the experiment results, the optimal parameters are the temperature of 200℃ and heating time of 60 seconds.

The disassembly result of the liquid heating process is shown in the figure 3. And we also disassemble a same kind of component through the hot air heating approach shown in figure 3. The unsoldering result of liquid heating approach is with better quality than the result of the air heating approach because the uniform temperature of the disassembly circumstance.

	Experiment Factors		Results
	Temperature (℃)	Time (s)	Unsoldering effect(%)
1	200	40	0.10
2	200	60	0.30
3	200	80	0.90
4	210	40	0.15
5	210	60	0.80
6	210	80	0.95
7	220	40	0.70
8	220	60	0.95
9	220	80	0.98

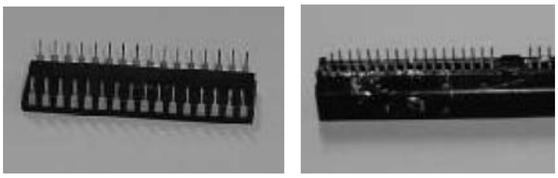
Table 1: Design layout and results of the orthogonal experiment

	Experiment Factors		Results
	Temperature (℃)	Time(s)	Unsoldering effect(%)
1	200	40	0.10
2	200	60	0.30
3	200	80	0.90
4	210	40	0.15
5	210	60	0.80
6	210	80	0.95
7	220	40	0.70
8	220	60	0.95
9	220	80	0.98
Mean1	0.433	0.317	
Mean 2	0.633	0.683	
Mean 3	0.877	0.943	
Range	0.444	0.626	

Table 2: Intuitionistic analysis of the orthogonal experiment

	Sum of squares	Degrees of freedom	F value	critical value of F
Temperature	0.296	2	0.664	6.940
Time	0.595	2	1.336	6.940
error	0.89	4		

Table 3: Variance analysis of the orthogonal experiment



(a) (b)

Figure 3: Results of liquid heating approach VS. air heating approach

4 SUMMARY

The liquid heating disassembly approach has many advantages in the following aspects:

- Higher simultaneous disassembly efficiency: the liquid heating can unsolder the whole PCB at a shorter time due to the higher heat transmission coefficient.
- Higher recycle quality: Both the components and the solder can be recovered in higher quality. Hence, the recycle value will be increased.
- Better environmentally impact: Due to the absence of the harmful material such as: polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-p-furans etc. produces and emits to the circumstance, the recycling process will be environmentally friendly.
- High thermal energy consumption efficiency: Compared with the air heating approach, the liquid heating approach consumes less energy, and will save limited resources.

The liquid characters and the process variables need more study for industrial application in the future.

5 ACKNOWLEDGMENTS

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Product Disassembly Model Based on hierarchy network graph

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Abstract
Disassembly is the precondition of recycling products. And product disassembly model is the basis for product disassembly analysis. A product disassembly model named hierarchy network graph model is introduced. To describe the relation between parts, the model adopts network graph model, in which the nodes describe the parts information and the edges describe the constraints information between parts. To describe the product assembly hierarchy relation, the model adopts the hierarchy model. At the same time, the dynamic transfer mechanism is adopted to satisfy the different disassembly goals.

Keywords:
Recycling, Disassembly, Hierarchy network graph, modelling

1 INTRODUCTION

With the quick development of the society and science & technology, environment protection is increasingly concerned. The excess consumption of resources, severe environment pollution and the increasingly saturated disposal ability of the garbage make the voice requiring the manufacturers to take back and dispose their products higher and higher. Many countries make related laws and legislations to constrain the actions of the manufacturers, such as the take-back law in Europe and the "Home Appliance Recycling Act" in Japan. [1,2]

How to improve the recyclability of their products and how to effectively recycle their products have aroused the attention of the manufacturers, and become one of the research focuses of modern manufacturing technologies. The recyclability of products is decided by the disassembly of products and the complexity of the process of materials recycle, especially disassembly of products. There are more and more researches on design for disassembly (DFD) and disassembly process planning technology(DPPT), and some disassembly models, such as And/OR graph model and Petri nets model, have been put forward. These researches on this field mostly adopt the tree type model structure, with the nodes representing parts, with the depth of the tree representing the assembly hierarchy and with the edges representing the required assembly information. For real products, the complicated assembly relations make it hard to use the model to represent the product. [3~6] So, the most models simplify the structure of the product according to the requirement of certain analysis to reduce the amount of required information. On the other hand, how to realize the integration between models and CAD platform always is a difficult problem. This paper introduces a new disassembly model named hierarchy network graph model trying to resolve this problem.

2 INFORMATION REQUIREMENT OF THE MODEL

The disassembly model should include all required information for the disassembly analysis of the product. There are two ways to get the information: getting from the 3DM model of the product directly and getting by the Human-Computer Interface. The information in the model includes:

(1) Design information, the design attributes defined by the designer according to the design requirement. This includes the design life, material type, dimension, weight and so on. The information decides the engineering performance and the physics and chemistry of the parts. Certainly, the information about the recycling modes of the product or parts is included.

(2) Structure information, the information from the assembly model of the product. This includes the assembly hierarchy, the assembly constraints between parts, the type of fastener and so on. The information is the basis for the plan of disassembly sequence.

(3) Basic information of parts. This includes the type, shape, weight, position and material of the part. The information influences the disassembly plan

.

3 STRUCTURE OF THE MODEL

3.1 Basic concept of network graph

Generally, the graph *G* is comprised of two sets, *V* and *E*, which can be expressed as:

$$G = (V, E) \tag{1}$$

In which: *V* is a non-empty set of nodes;

E is a set of edges;

If every edge in *G* has direction, *G* is named as digraph. And if every edge in *G* has no direction, *G* is named as undirected graph.

The undirected graph $G = (V, E)$ can be used to describe the relations among parts of a product. The node set $V = \{v_1, v_2, \cdots, v_n\}$ expresses the parts and n is the number of parts. The edge set $E = \{e_1, e_2, \cdots, e_m\}$ expresses the assembly relation between the parts. If there are assembly relations between v_i and v_j ($i \neq j$), $(v_i, v_j) \in E$, otherwise $(v_i, v_j) \notin E$.

3.2 Definition of hierarchy network graph(HNG)

To establish a common model, we put forward a hierarchy network graph disassembly model based on the past models. The hierarchy network graph is a finite set of one or more nodes. It only has one node named as root node and the other nodes can be divided into $m(m \geq 0)$ finite sets, and the every set is a network graph too named as child graph. In the hierarchy network graph, if there is affiliation between two nodes, the affiliated node is named as child node; another node is named as the parent node of the child node.

Because of the hierarchy structure of the products, it is hard to express the product structure with a network graph with single hierarchy. But the hierarchy network graph has the ability of express hierarchy relations; it can be used to express the assembly relations of products. [7]

In the hierarchy network graph disassembly model, tree model is adopted to represent the assembly hierarchy of the product; and the network graph is adopted to represent the assembly relations between parts.

An example is showed in figure 1. The basic constituents of the hierarchy network graph are part node objects and relation edge objects. The information about structure, material, disassembly, usage and repair is into the nodes, and the information about constraints relation and disassembly is encapsulated into the edges. The hierarchy network graph has parent graph and child graph. The parent graph' subassembly nodes are related to their part node objects by the edges between hierarchies, and then the hierarchy structure of the product is described.

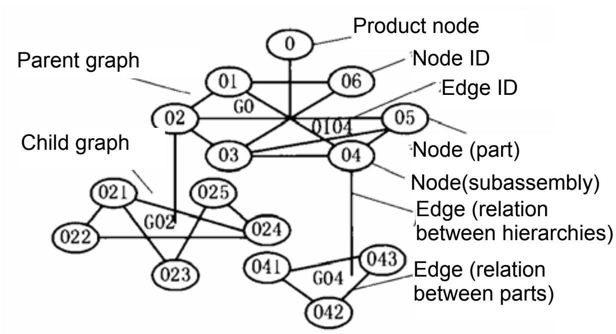

Figure 1 Example of hierarchy network graph

Based on the expression (1) and figure 1, the hierarchy network graph disassembly model can be expressed as:

$$HNG_k{}^P = < V_k, E_k > \tag{2}$$

In the expression,

p : The pointer of parent node;

k : The hierarchy ID;

V_k : Node object (assembly or part) set;

E_k : Edge object (the assembly relationship or hierarchical structure between assemblies or parts) set.

3.3 Establishment of hierarchy network graph

According to the thought of hierarchy-net-graph, the data structure of the model can be defined as:

```
//Definition of node object
class NodeBaseInfo     //basic information of node
{
    char    componentName[MAX_FSPEC_SIZE]; //name
    tag_t   componentID;                   // ID
    int     componentType;                 //type
    GraphInfo *parentGraphInfo; //parent graph
    GraphInfo *graphInfo;       //child graph
   …
//disassembly information
class NodeDisassemblyInfo
{
    logical mated;
    int     assemblyType;       //assembly type
    int     tool;               //disassembly tool
    Double cost, time;
   …
};
//node information
class NodeInfo
{
    NodeBaseInfo              baseInfo;
    NodeDisassemblyInfo disassemblyInfo;
   …
    };
    //Definition of edge object
    class EdgeBaseInfo     //basic information of edge object
    {
            NodeInfo  *node1st;   //first node
            NodeInfo  *node2nd;   //second node
           …
    };
    //disassembly information
    class EdgeDisassemblyInfo
    {
          int ifHaveEdge;
          int  numConstraints; //number of the constraints
          UF_ASSEM_constraint_t
          constraints[];//constraint set
         …
};
//edge information
class EdgeInfo
{
          EdgeBaseInfo               baseInfo;
          EdgeDisassemblyInfo disassemblyInfo;
         …
};
```

```
//definition of the network graph object
// the network graph object information
class GraphInfo
{
        int          graphId;  // ID
        NodeInfo *parentNodeInfo;  //parent node
        NodeInfo  *nodes;    //all nodes
        EdgeInfo  *edges;    //all edges
        …
};
```

In the definition, ① the network graph is undirected graph and is defined with adjacency matrix. The constituent of the matrix is the node objects (Graph. nodes) and the value of the matrix is edge objects (Graph. edges). If the value of Graph.edges. ifHaveEdge is 1, there are assembly relations between the two nodes. If the value of Graph.edges. ifHaveEdge is 0, there are no assembly relations between the two nodes. ② The doubly linked list structure is adopted to describe the hierarchy relations. The pointer of GraphInfo.parentNodeInfo in the network graph object points to the nodes having this graph, and the pointer of NodeInfo. NodeBaseInfo. graphInfo in the node object points to the child graph belonging to the node object. If the node is a part, the pointer of NodeInfo. NodeBaseInfo. graphInfo is NULL,otherwise it points to the address of the child graph.

The model can be established with the information got from three-dimensional CAD platforms by API. The information that can not get from three-dimensional CAD platforms and is necessary for the analysis is input to the model by the Human-Computer Interface. This has been realized by the software we developed.

4 DYNAMIC TRANSFER MECHANISM

As we known, the product disassembly sequence planning is changed with the disassembly goals. So the disassembly model structure should change with the disassembly goals. Mainly, the hierarchy structure and constraint relations are changed which the disassembly analysis should involve. Some dynamic transfer mechanisms are given to satisfy the different disassembly goals.

There are mainly three situations to change the model structure: the subassembly which contains the disassembly goal part becomes the new disassembly goal, and the part which belongs to the disassembly goal subassembly becomes the new disassembly goal, and the disassembly goal changes in the same network graph. The model transfer mainly aims at the former two situations.

Mechanism 1: In $HNG_k{}^P = < V_k, E_k >$, if $v_{ki} \in V_k$ is disassembly goal, and when the parent node p becomes the new disassembly goal, then the pointer of $HNG_k{}^P$. NodeInfo.NodeBaseInfo.graphInfo becomes NULL.

Mechanism 2: if the node p is disassembly goal and it belongs to the kth hierarchy network graph. When its parts v_i becomes the new disassembly goal, then a new network graph $HNG_{k+1}{}^P = < V_{k+1}, E_{k+1} >$ is established with the information from three-dimensional CAD platforms. And the pointer of p . NodeInfo.NodeBaseInfo.graphInfo points to the child graph $HNG_{k+1}{}^P$ and $v_i \in V_{k+1}$

5 DISASSEMBLY SEQUENCE PLANNING BASED ON HNG

The theory related to cognitive map is considered to resolve the generation of disassembly sequences based on HNG.

To extend the cognitive map to show the quantitive relationship among concepts. the fuzzy measure was introduced into cognitive map, and the model of fuzzy cognitive map (FCM) was proposed [8]. It extended the simple relationship to the fuzzy relationship [-1, 1], so it can carry much more information.

In order to clearly express the all relationship among the HNG and simplify the computational process of reasoning, the hierarchical fuzzy cognitive map (HFCM) is proposed[9]. The mathematical mode of hierarchical fuzzy cognitive map is represented as follows:

$$V_{C_{mj}}(t+1) = f\Big(\sum_{k=1}^{s} \sum_{\substack{i=1 \\ ki \neq mj \\ i \in R}}^{n_k} V_{C_{ki}}(t) P(W_{kimj}(t) \mid V_{C_{k1}}(t), V_{C_{k2}}(t), \cdots, V_{C_{ki}}(t), \cdots, V_{C_{kn_k}}(t)) + \gamma V_{C_{mj}}(t)\Big)$$

Where C_{ki}, C_{mj} are the concept node, and can be the thing, aim, feeling and trend.

$V_{C_{ki}}(t)$ and $V_{C_{mj}}(t)$ are value of concept node at the time of t, these express the status of the constraints.

S is the number of hierarchy.

n_k is the number of nodes in the hierarchy of k.

R is casual relationship set related to c_{mj} .

γ is effective factor from obvious status to next status.

$W_{kimj}(t)$ is the intensity of casual relationship from c_{mj} to c_{ki} . If two parts c_{ki} and c_{mj} have mating relationships, and the disassembly of c_{ki} is useful to c_{mj} according to the type and themating number of parts , then $W_{kimj} = 1$. if in othercondition, $W_{kimj} = 0$.

f is threshold function of node. It can be the two-value function, probability function, ors-type function, etc. In the process of disassembly, part has the disassembled or undisassembled status, so the status value of part is 0 or 1 accordingly.

$m \in \{1, 2, .3. \cdots, s\}$

$i \neq j$

The key of the method of HFCM is making full use of assembly information and the features of different type of part. Usually, in the process of assembly for each subassembly, a benchmark part is determined first, so it's disassembled finally in the process of disassembly in this subassembly. Because fasteners, such as bolt, nut, have special feature, and the disassembly sequence of fastener is the first in the parts that have mate relationship with fastener. So when the model of HFCM is establishing, the fasteners without interference are not concluded in the beginning. After disassembly sequences of one hierarchy have been computed, then the fasteners in this hierarchy are added accordingly.

The computation of disassembly sequences for one hierarchy can be as following:

$$\overrightarrow{V_k(t+1)} = \overrightarrow{V_k(t)} M_k(t)$$

$$\overrightarrow{V_k(t+1)} = (V_{k1}(t+1), V_{k2}(t+1), \cdots, V_{kj}(t+1), \cdots, V_{kn_k}(t+1))$$

$$V_{kj}(t+1) = f(\sum_{\substack{i=1 \\ i \neq j \\ i \in R}}^{n_k} V_{ki}(t) P(W_{kij}(t) \mid V_{k1}(t), V_{k2}(t), \cdots, V_{ki}(t), \cdots, V_{kn_k}$$

$M_k(t)$ is the matrix composed of value of W_{kimj} at the time of t.

All parts have not disassembled in the beginning, so the original status of the first hierarchy is $\overrightarrow{V_k(.)} = (V_{k1}(0), V_{k2}(0), \cdots, V_{kj}(0), \cdots, V_{kn_k}(0)) = (1,1,...,1)$

According to the above equation, the disassembly sequence of one hierarchy can be got, and so the whole disassembly sequences are gained.

6 EXAMPLE

In current products in the society, home appliances take a large proportion and are representative, so a kind of air-conditioners is taken as an example. Based on the, three-dimension modelling of the air conditioner (figure2) and the software development, the hierarchical network graph of the air conditioner (figure3) can established automatically.

Figure 2Three-Dimension Model of the air conditioner

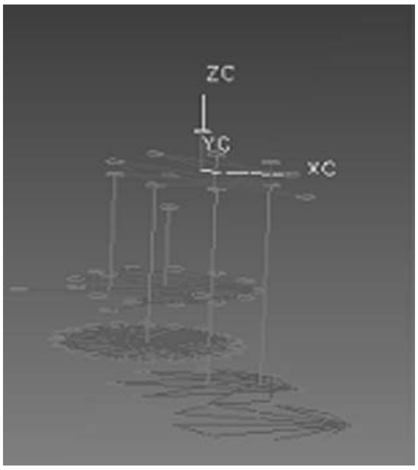

Figure 3 Hierarchical Network Graph of the air conditioner

From the hierarchical network graph of the air conditioner, we can know about the assembly relations and hierarchy structure clearly. Especially, with the help of the software, we can know about the information about the nodes and edges easily.

According to the transfer mechanisms, the model can be transferred with the disassembly goal, and it can be showed directly by the developed software

7 SUMMARY

Based on the existing and our research, this paper introduces a new disassembly model named hierarchy network graph model. This model not only gives a good foundation for the disassembly analysis, but also gives great support for Design for Disassembly (DFD) and product recycling analysis.

1) The model gets information from three-Dimension CAD directly. This is a progress for the integration between the disassembly analysis and CAD and reduces the large amount information input for disassembly analysis.
2) The information obtaining mode makes it possible to design interactively aimed at disassemblyablity.
3) Because the model saves the disassembly process information, it is easily to assess the product disassemblyability based on the model.
4) The model has the parts information (materials, weight, and so on) and the disassembly information which are necessary for the product recycling analysis including the recycling process planning and the recyclability assessment.
5) The HFCM method based on the model can revolve the problem of the product disassembly sequence planning.

8 ACKNOWLEDGMENTS

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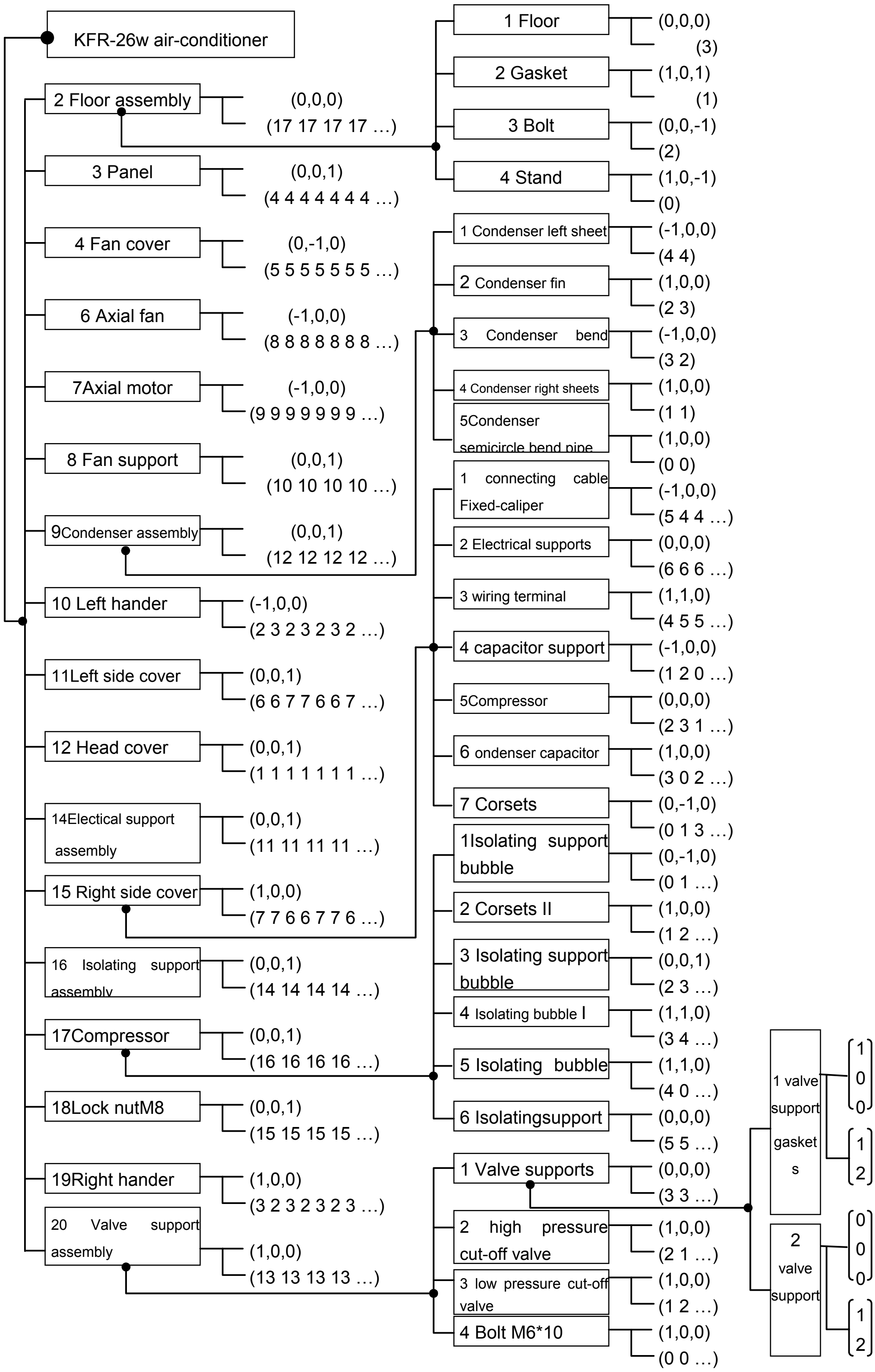

Figure.4 the disassembly sequence of air-conditioner

Ecoselection of Materials and Process for Medium Voltage Products

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Abstract

This article addresses the ecodesign of medium voltage electrical switchgear. These products are electrical units possessing particular specificities, associated with the conditions of use. They operate at elevated voltage and current, and are guaranteed for a minimum service life of twenty years. This demands a very high level of quality and implies the use of specific materials and manufacturing processes. This requirement makes it difficult to predict the end-of-life management. It is therefore important to examine the various alternatives for incorporating ecodesign in these units. This entails the assessment of the environment of existing products and the study of the design procedure employed. The approach described here is valid for other products in different sectors. It is based on the simplification of life cycle assessments to focus only on the most important life cycle phases and environmental indicators which offer a wider margin for improvement. For the case of medium voltage switchgear, stress is placed on the manufacturing and end-of-life phases.

Keywords
Ecodesign, Life Cycle Assessment, Medium Voltage, Electric and Electronic Equipments, Protection

1 INTRODUCTION

Electrical equipment represents a major world focus, given the current energy challenges. Furthermore, the establishment of European directives associated with waste management and the restriction of the use of certain hazardous substances in electrical and electronic equipment (WEEE) [1] and (RoHS) [2] have sparked international consideration of ecodesign of these products. A directive associated with the ecodesign of energy consuming products is also in the course of validation (2005/32/EC). Medium voltage switchgear is not subject to these directives, but many companies like AREVA TD/DRC[1] have adopted these regulations. Various research projects have investigated the ecodesign of low voltage electrical equipment, but no known study includes medium voltage products. The article discusses medium voltage units, their environmental impacts, and the approach pursued to develop an ecodesign methodology that is appropriate, simplified and consolidated at the environmental level.

2 MEDIUM VOLTAGE SWITCHGEAR

These units are used in power supply networks. They operate at voltage levels from 6 to 52kV. They play a very important role in the protection and operation of the electricity grid. These units are classed according to their functions: circuit-breaker, switch, disconnect, transformer, etc.

They are designed for a maintenance free service life longer than 20 years. Due to these technical requirements, medium voltage equipment displays different design features from low voltage units.

They employ specific materials such as:

- technical ceramics for vacuum interrupters, bushings and surge arresters
- thermosetting resins of the epoxy, BMC or SMC type for insulating parts (poles, supports, correcting rods)
- sulphur hexafluoride gas (SF6) for dielectric insulation
- dielectric insulating oil
- certain grades of thermosetting, thermoplastic resins or elastomers.

They use specific overmoulding techniques and combinations of materials:

- Overmoulding of thermosetting, thermoplastic resin or elastomer on metal conductors or on ceramic.
- Brazing of ceramic on metal.

They need very powerful mechanical controls demanding a specific assembly mode.

3 ENVIRONMENTAL ASSESSMENTS OF MEDIUM VOLTAGE PRODUCTS

The environmental assessment of these units is based on a "Life Cycle Assessment" (LCA) approach. LCA is generally acknowledged as the method for evaluating the environmental impacts associated with a product or a service [3]. The aim is to determine the environmental impacts of these products and to identify ways for improvement.

Precise environmental data are lacking for a good number of specific methods for manufacturing medium voltage switchgear. The environmental assessment takes into account of this lack of information. Energy equivalents are estimated from data compiled on production sites or technical literature on manufacturing machines.

Like most electrical products, the power consumption during the operation phase generates a significant environmental impact. However, it is technically very difficult to reduce this consumption due to the high voltage and current and long lifetime. The manufacturing phase also sometimes has a more important impact than the operating phase. The distribution phase generates much less pollution [4]. The end-of-life phase is not modelled because environmental data are lacking. Only power consumption associated with grinding and crushing is known. It is nonetheless fair to consider the end-of-life phase as a second manufacturing phase with various steps of recovery, sorting, recycling, incineration and waste production. These methods consume energy and can produce toxic emissions in water, air and the soil.

Electric power consumption due to a Joule losses, during the operating phase is very low (<10Wh), so that the margin for improvement remains limited. However, work is constantly being done to find solutions to reduce power consumption. Hence it appears that the manufacturing and end-of-life phases offer a wider margin for environmental improvement. In fact, these two phases are intimately linked with the choice of the product architecture and materials.

4 ECODESIGN METHODOLOGY

The ecodesign methodology proposed is based on the consideration of the life cycle phases displaying the maximum of environmental importance, and in the present case, these are the manufacturing and end-of-life phases. It is then important to identify the most relevant environmental impacts during these phases. This is based on a multicriteria approach: the legislation in force, the environmental strategy of the producer, and the synthesis of the results of environmental assessments.

4.1 Legislation in force

Apart from the WEEE and RoHS directives associated with electrical products, many regulatory texts have been enacted concerning industrial wastes, toxic emissions and greenhouse gases. Moreover, the REACH directive “Registration, Evaluation and Authorisation of Chemicals” [5] is currently being extended, and this could lead to restrictions on the use of certain chemicals. Work on ecodesign serves to reduce pollution at the source and promotes compliance with these regulations.

4.2 Environmental assessments

Environmental assessments on existing products serve to identify the negative environmental impacts and to trace back the sources of these impacts. They also help to make an overall review and compare the environmental quality of all the products. Companies can use these data to organize their ecodesign approach.

4.3 Company strategy

Since it is highly difficult to improve the environmental quality of a product at all levels, it is indispensable to set precise objectives for the design office and to incorporate them in the product specification [6]. These objectives may evolve over time and can also be programmed over the medium and long term. For example, stress can initially be placed on eliminating hazardous substances, and then on recyclability in a second phase. There is no standard approach, each company has to select an environmental strategy according to several criteria associated with the nature of its activity, the resources it has, and the demand of its clients. This strategy is based on clearly identified and generally quantified objectives. Employee protection often appears in the frontline of environmental policies.

4.4 Study: AREVA TD/DRC

The following study is based on the case of AREVA TD/DRC specialized in the design and manufacture of medium and high voltage switchgear. Three medium voltage units of various categories were analyzed: a catenary switch insulated with SF6 gas, a circuit-breaker with mixed solid-air insulation, and a surge arrester (figure1).

The single-phase catenary switch for outdoor use is mounted on a post, fully protected. The components are assembled in a casing filled with SF6, completely sealed, without static or dynamic seal, and guaranteeing perfect tightness. It is mainly designed for load operations and cutoffs for medium voltage catenary rail networks. Its service life is estimated at 30 years.

The circuit-breaker with mixed solid/air insulation is protected by a rigid epoxy resin casing. It is mainly designed for voltage operations and cutoffs. Its service life is estimated 30 years.

The surge arrester is a device for protecting AC electrical networks against surge voltages to guarantee service quality. The surge arrester examined is a surge arrester containing varistances based on zinc oxide.

The table 1 shows our proposal for an environmental strategy with regard to the regulations and the results of environmental analysis:

The implementation of this strategy in the company requires the development of an ecodesign aid tool. This tool must be integrated in the design process used by the design office and associated with existing design aid tools.

5 ECOSELECTION OF MATERIALS AND MANUFACTURING PROCESSES

As stated above, the tool developed is based on aid in the selection of materials and manufacturing processes during the manufacturing and end-of-life phases. The goal is to combine economic and technical criteria, already in place, with environmental criteria. The task is to assess the environmental quality of the various design possibilities of a given product according to environmental indicators in line with the company’s ecodesign strategy.

5.1 Step 1: compilation of databases

A number of environmental databases are available today on materials. However, there is a considerable lack of information about manufacturing processes. It is in fact difficult to generalize the impacts of a manufacturing process because of the dependence on several parameters, including: the type of equipment used, quantity manufactured, the energy used, etc. This approach proposes to construct an environmental database adapted to medium voltage products. It would contain calculated or measured data on the production sites of these products and at the main suppliers. The aim is to have the most accurate possible data and to target the specific processes such as process for manufacturing vacuum interrupters and surge arresters. It is also planned to compile data on the environmental impacts of operations performed during the end-of-life management phase: grinding, recycling, incineration. Some data are already available, while others can temporarily be estimated or measured. Other data, such as air emissions during grinding operations, are being investigated by the French National Institute for Research and Safety (INRS).

Apart from purely environment data, these bases will contain technical and economic data to help the designer in selecting these materials. For example: control of the manufacturing process or availability of the material worldwide, cost of the process and material, difficulties associated with the product selected, as well as new technologies for replacing the process or the material [7].

Another database concerning methods for assembling materials and subassemblies gives the degree of freedom connected with each mode. This will serve to determine the potential disassembly modes and the degree of difficulty involved.

5.2 Step 2: Choice of Environmental Indicators

The environmental indicators must meet the environmental requirements of the company and help assess the environmental impact of its products [8]. The suggested indicators are comprehensible to the designers. The concerns are the energy consumption, consumption of material resources, greenhouse effect, toxicity, recyclability, disassembly : Table 4.

The aim is to see how these indicators evolve over time according to requirements and feedback. The toxicity, assembly and disassembly indicators can be translated into quantitative indicators. For example, the toxicity of a product can be translated into mg Pb equivalent, and disassembly can be transferred into time (min).

5.3 Step 3: Weighting of Environmental Indicators

It is often difficult to work on all the pollution sources of a product. To do this, it is indispensable to weight the environmental impacts and even to set a weight on the various parameters to be considered: economics, technique, environment, social [9]. The weighting of the environmental indicators is based on the company’s strategy. This strategy may evolve according to regulatory, economic and societal constraints, as well as developments in technological knowhow [10]. It is also possible to program an upgradeable weighting of these indicators. Our proposal for weighting is as Table 2. This weighting serves to class the indicators by order of priority and to compare the environmental quality of two or more products.

5.4 Step 4: Product Information

The design office must fill in a database concerning each option proposed: materials used, corresponding processes, material connecting method for a given subassembly, type of assembly between different subassemblies (table 3). These data must be standardised in order to compare different options and different products. It is also possible to recover these data directly from the design software used, which will accelerate the process.

5.5 Step 5: Assessment of Environmental Impacts

Once the data are compiled, the product data serve to assess the environmental impacts. In fact, the calculation criteria must be applied to the databases of the processes, materials and assembly modes, to define these impacts. The following criteria are applied: Table 4.

5.6 Step 6: Comparison of the Environmental Quality of the Products

It must be observed that the main objective of this approach is to support the designer's choice during design and more especially during the detailed designed phase. This implies establishing rules for comparing the environmental quality of the different design options [12]. These rules are based partly on the weighting of the indicators and on technical, economic and regulatory criteria already mentioned. Conventionally, the design options are compared against option number 1: Table 5. The total impact the design option is calculated using the following equation:

$$\textbf{Impact option}_i = \sum \textbf{poids absolute weight of indicator}_i \textbf{ x relative weight of indicator}_i$$

The relative weight of the indicator serves to identify the differences between the indicators:

- Relative weight of indicators (E, W, GW, T) : table 6

Ind_i/ Ind1st =	1 to 3	3 to 5	5 to 10	10 to 20	>20
Relative weight of indicator i	1 + r x 0.05 with r = 1 if Ind_i/Ind1st ∈]1, 1.1[r = 2 if Ind_i/Ind1st ∈ [1.1, 1.2[…	1 + r x 0.025 with r = 1 if Ind_i/Ind1st ∈ [3, 3.1[r = 2 if Ind_i/Ind1st ∈ [3.1, 3.2[…	1 + r x 0.01 with r = 1 is Ind_i/Ind1st ∈ [3, 3.1[r = 2 is Ind_i/Ind1st ∈ [3.1, 3.2[…	1 + r x 0.005 with r = 1 is Ind_i/Ind1st ∈ [5, 5.1[r = 2 is Ind_i/Ind1st ∈ [3.1, 3.2[…	3.5

*Ind1st is indicator i which has rank 1

Table 6: Calculation of Relative Weights of Indicators E, W, GW and T

- Relative weight of material resources indicator (M) : table 8

Relative weight of the indicator Mi = 1+ r x 0.01

Ind_i/ Ind1st =	1 to 10	10 to 100	100 to 1000	1000 to 10000	…
Relative weight of indicator i	1.01 + r x 0.01 with r = 1 if Ind_i/Ind1st ∈]1, 2[r = 2 if Ind_i/Ind1st ∈ [2, 3[…	1.1 + r x 0.01 with r = 1 if Ind_i/Ind1st ∈ [10, 20[r = 2 if Ind_i/Ind1st ∈ [20, 30[…	1.2 + r x 0.01 with r = 1 if Ind_i/Ind1st ∈ [100, 200[r = 2 if Ind_i/Ind1st ∈ [200, 300[…	1.3 + r x 0.01 with r = 1 if Ind_i/Ind1st ∈ [E3, 2E3[r = 2 if Ind_i/Ind1st ∈ [2E3, 3E3[…	

Table 7: Calculation of Relative Weight of Indicator M

- Relative weight of assembly and disassembly indicators

Ai and Di = Easy → 1 ; Medium → 1.5 ; Difficult → 2

*If the assembly/disassembly time is known, the weights can be allocated as for the other indicators.

5.7 Step 7: Ecodesign Report

As with any information design, ecodesign information needs to be presented in a style that is appropriate for the user. One of the biggest problems with existing ecodesign tools was the way in which the information was being presented. As such, evidence shows that designers do not react well to manuals and often 'file' them, rather than use them. Instead designers are motivated by visual communication and like information to be presented with maximum use of graphics and minimal text. Industrial designers also need ecodesign information presented in a language that they understand. The findings from the pilot study showed that many designers favoured a nontechnical approach [13]. To take these requirements into consideration, the ecodesign report contains two aspects: A numerical aspect and a textual aspect.

The numerical aspect contains the following information (table 8):

Data	Option i
Material balance	
Energy balance	
Water consumption	
Value of toxic emissions	
Value of greenhouse gas emissions	
Recyclability rate	
Incineration rate	
Heating value	
Landfilling rate	
Assembly	
Disassembly	
Cost	

Table8: Numerical Results of Environmental Assessment

The numerical report may be partial or complete depending on the information available. It is also possible to add curves and graphs to facilitate access to the information.

The textual report comprises the following information [14]:

- Conformity to the legislation → a warning message may appear in the case of nonconformity or existence of an item liable to be prohibited
- Potential solution to substituting a material or a manufacturing process
- Data on the control of manufacturing processes
- Data on materials availability
- Ecodesign recommendations
- Links with other data sources

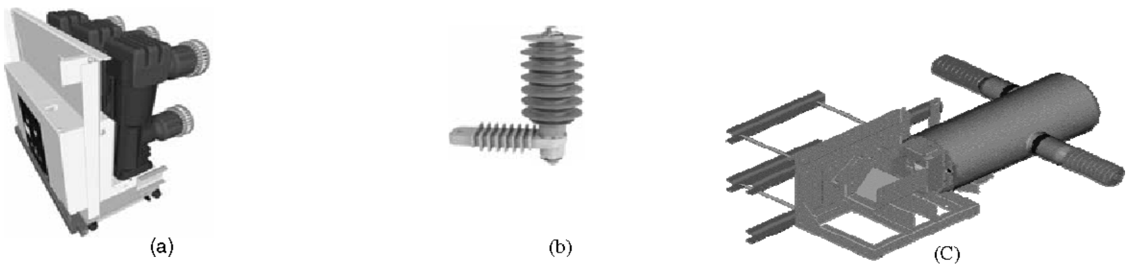


Figure 1: (a) Mixed insulation circuit-breaker (b) Medium voltage surge arrester (c) Catenary switch

Legislation	Environmental Assessments	Company Strategy proposal	
		Actions	**Priorities**
WEEE	Recyclability limited by the use of thermosetting resins, ceramics and SF6 gas.	Improve the recyclability with a recycle target of 95% of total weight.	Medium term: achieve 85% recyclability.
			Long term: achieve 95% recyclability.
		Facilitate dismantling.	Short term
	Toxic wastes due to lack of treatment and recycle systems.	Eliminate hazardous substances contained in these products.	Find appropriate recycling systems.
RoHS	Use of hexavalent chromium.	Eliminate the hazardous substances contained in these products.	Immediate priority.
	Use of lead in electronic circuit boards.		Medium term
	Use of trichloethylene for cleaning.		Immediate priority.
Kyoto	SF6 greenhouse gas emissions.	Reduce SF6 leakage.	Immediate priority.
		Seek substitute for gas, liquid, solid or mixed solutions.	Medium term
	Electricity consumption for manufacturing and end-of-life management.		Medium term
REACH	Use of substances liable to be recognized as hazardous.	Seek substitutes for hazardous substances.	Medium to Long term
Environmental regulations	Toxic emissions in manufacturing phase.	Eliminate the toxic substances.	Short term
None	Consumption of water resources.	Reduce water consumption.	Medium term
	Presence of massive parts with sometimes incompatible materials.	Reduce the consumption of natural resources.	Short term
	Use of materials and processes emitting greenhouse gases.	Reduce greenhouse gas emissions.	Short term

Table 1: Proposal for an environmental strategy for medium voltage application

Indicator	Air + water toxicity	Greenhouse effect	Material resources	Power consumption	Water consumption	Disassembly
Order of priority	1	2	2	3	3	4
Absolute weight	5	3	3	2	2	1

Table 2: Weighting of Environmental Indicators

	Materials/ Processes	Connecting Modes	Assembly Modes
Subassembly 11			
Subassembly 12			
Subassembly 1n			

Table 3: Input Data for Environmental Assessment of the Product

Indicator	Calculation Criteria	Units
Power consumption	Power consumed for manufacture **+** by grinding, recycling **+/-** energy dissipated or recovered by incineration	MJ
Water consumption	Water consumed by manufacture **+** consumed by recycling	dm3
Material resources	$\sum$ availability factor **x** **(**Material availability factor$_i$ used for manufacture **+** manufacturing waste **-** % of recyclability x materials used by manufacture**)**	Kg

Global Warming	Air emissions of greenhouse gases from materials extraction and processing operations **+** grinding recycling (CO2, CFC, SF6)	g CO2 equivalent
Air + water toxicity	Materials **+** additives **+** substances used during manufacture The degree of toxicity is set according to the classification of the waste (Directive 91/689/CEE) and according to REACH • Items prohibited by WEEE regulation are considered as priority hence with high toxicity (Pb, Cd, CrVI, Hg, PBDE, PBB, trichloroethylene) → high toxicity • Items which may be prohibited in the short or medium term are considered as high → medium toxicity	Inert / low / Medium / high
Disassembly [11]	Degree of ease of disassembly → • Difficult disassembly: welding, bonding, overmoulding, brazing, gearing • Medium disassembly: clipping, stamping • Easy disassembly: positioning, screwing, riveting	Easy / medium / Difficult

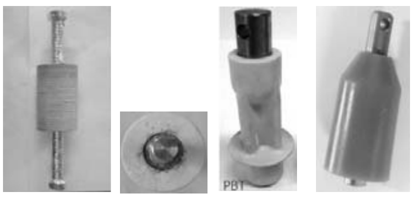
Table 4: Criteria for Calculating Environmental Indicators

Indicator	**Design Option 1**	**Design Option 2**	**Design Option 3**	**Rules**	**Classification by order of merit**		
					Opt 1	***Opt 2***	***Opt 3***
Power consumption	E1	E2	E3	class E1, E2 and E3	Rank	Rank	Rank
Water Consumption	W1	W2	W3	class W1, W2 and W3	Rank	Rank	Rank
Material resources	M1	M2	M3	class M1, M2 and M3	Rank	Rank	Rank
Global Warming	GW1	GW1	GW2	class GW1, GW2 and GW3	Rank	Rank	Rank
Air + water toxicity	T1	T2	T3	Compare the concentrations of hazardous substances → $T = \sum_i \frac{\text{Quantity of toxic substance}_i}{\text{Toxicity limit}_i}$	Rank	Rank	Rank
Disassembly	D1	D2	D3	Class the disassembly models according to the degree of ease	Rank	Rank	Rank

Table 5: Rules for Comparing Environmental Indicators

6 EXAMPLE OF APPLICATION

This tool was calibrated on a dielectric insulating tie rod used in medium voltage. This part isolates dielectrically two subassemblies and ensures their contact. It comprises two metal inserts overmoulded with the insulating material. A technical analysis was conducted to check the technical feasibility of the product [15]. This study gave rise to several design options. The insulating substance of the tie rod can be manufactured in thermosetting resin, thermoplastic resin, wood or ceramic (figure 2). The inserts can be made from either brass or steel.



(a) (b) (c) (d)

Figure 2: (a) Woden tie rod (b) Ceramic tie rod (c) Thermoplastic tie rod (d) Epoxy tie rod.

Since it is possible to use the two types of inserts with the five materials grades for the tie rod body, the environmental assessment can be made in two steps:

- Comparison of the environmental grade of the inserts
- Comparison of the environmental grade of the tie rod bodies

In a first step, the both brass and steel inserts are compared. It is then possible to associate the inserts selected with the different tie rod bodies. However, a combination between inserts and tie rod bodies can be evaluated directly. It turns out that the steel inserts are less polluting than the brass inserts. This makes it possible to go on to the assembly step of inserts + tie rod body.

Textual report:

The design option of "ceramic tie rod + steel inserts" is the most ecological.

<u>Precautions</u>:

1. The product "ceramic tie rod + steel inserts" has a low recyclability rate.
2. The "galvanizing + chromating CrVI" treatment contains CrVI. CrVI is prohibited by the European directive RoHS.
3. The "epoxy" material uses a toxic anhydride hardener.

<u>Ways of improvement</u>:

1. Use the "galvanizing + CrIII passivation" treatment to replace "galvanizing + chromating" treatment.

Graphical report:

The figure 3 resumes the environmental indicators calculation and comparison for the different design options :

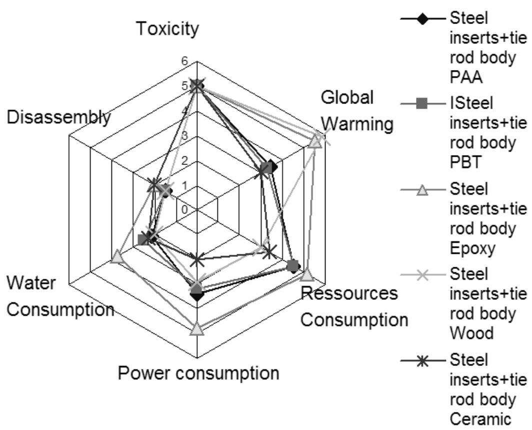


Figure 3: Environmental assessment of design options of the insulating tie rod

Numerical report:
The calculation of environmental indicators of the different design option allows to affect a single score for each one and to classify them as seen in table 6.

Indicator	Steel inserts + Ceramic tie rod body	Steel inserts + PAA tie rod body	Steel inserts + PBT tie rod body	Steel inserts + Wood tie rod body	Steel inserts + Epoxy tie rod body
TOTAL	18.69	20.01	20.03	20.25	26.18
Classification	**1st**	**2nd**	**3rd**	**4th**	**5th**

Table 5: Calculation of Environmental Score of design options of the insulating tie rod

7 CONCLUSIONS

The approach described is not yet completely finalized. The values used are taken from existing databases which have not been updated. It therefore remains to implement and update these databases and to calibrate the associated tool. This tool can then be integrated in the existing design process.

The tool can be divided into two parts: a designer part in which access is limited to the results of the indicators and the textual report, and an expert part in which all the data are accessible and in which the calculation parameters and input data can be changed.

The limits of this tool are linked in particular to the availability and quality of the environmental data and the calculation methods. In fact, uncertainties on the data are not taken into consideration, and this could yield completely different results in certain cases. It is therefore planned to examine this problem in order to integrate it in the calculation method. Thus the calculation methods can be limited in the case of values that are too close or too distant, and also in the case of too many options. In this case, it is preferable to compare a maximum of five options. The weightings used are taken from calculations and mathematical approximations which result from two existing methodologies at AREVA TD. This approach has the advantage of offering designers the results of an environmental analysis which can help them in these design decisions. These results are simple and accessible to the users who are not specialized in ecodesign. Besides, the precautions draw the user's attention to the gaps and risks associated with his product and the ways of improvement help to provide answers to these precautions and to propose other useful data for ecodesign. Thus this tool proposes links with other information sources: internet, intranet, regulatory and standardization intelligence, competitive intelligence, databases, miscellaneous documents, etc. To supplement the ecodesign tool with an economic approach, it is planned to incorporate therein the economic model of EMERY et al [16]. This model integrates the costs of use and recovery at end-of-life.

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Sustainable Design of Geopolymers - Evaluation of Raw Materials by the Integration of Economic and Environmental Aspects in the Early Phases of Material Development

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Abstract
Materials, defined as solids with a function, are basic modules for products in our everyday living and work environment. The development of products facing a complex qualification profile, which includes besides other technical, but also economic and ecological aspects. The two later aspects are not sufficient included in material development, especially from a Life cycle point of view, to provide them for the phase of product development.
In this project, Life Cycle Thinking is integrated in the development phase of materials right from the beginning, in order to identify technical, economic, and ecological benefits and drawbacks of developed geopolymers in comparison to traditional materials (functional unit). In the following contribution, the authors focus on the first of three steps, the evaluation of raw materials, which include the screening, and classification of raw materials.

Keywords:
Systems analyses, material design, Life Cycle Thinking, geopolymers, evaluation of raw materials

1 INTRODUCTION

Materials in this report are considered to be the building blocks for products. In this contribution the authors do not consider simple materials or products (e.g. adobe) but more complex composite materials and products which might be used in building, construction or industrial application. The presented example of material development faces a special situation, as a broad variety of raw materials are available for the manufacturing of geopolymers.

Material development is quite often referred to as ground research, and is conducted by material scientists. The main focus of investigations on material development lies on technical aspects, such as mechanical strength. If and when economic and ecological assessment are carried out in material development, it is performed after technical investigations are finished (TM, Figure 1). Quite often, these assessments are postponed until the subsequent phase of product development (TM-TP, Figure 1), cf. [1] and [2].

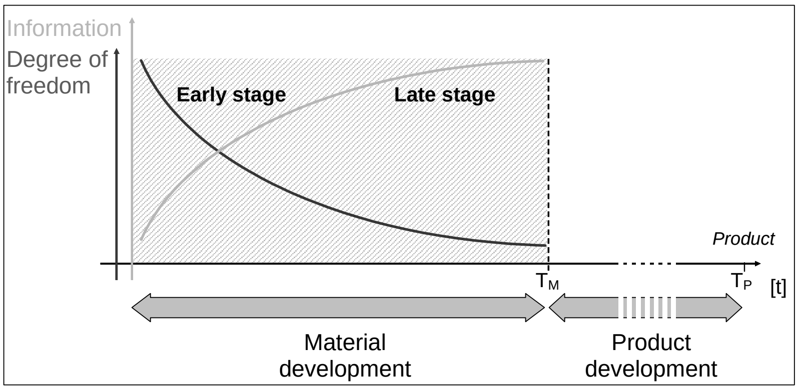

Figure 1: Degree of freedom for modifications of material combinations or the manufacturing process in the phase of material and product development

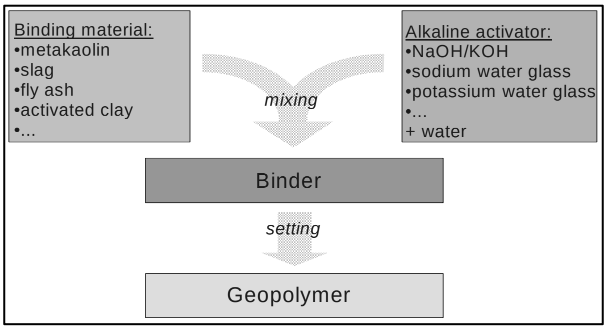

Figure 2: Production of the geopolymer

In contrast the design phase of a product takes into account different aspects for a successful product implementation. Products are developed by product designers together with manufacturing engineers, and the design phase considers technical aspects for a very specific application, (including guidelines, regulations, and standards) but also production costs, emotions, or other specifics of the market. Moreover environmental aspects in a Life cycle have gained their importance in recent years [3]. Environmental aspects may get even more attention in the future, if an environmental product declaration (EPD) becomes obligatory in the European Union [4].

The outcome of discussions with designers, scientists, and practitioners from the industry confirms our perceptions that material and product development are often divided into two separate worlds, which are not sufficiently linked to each other. The introduction of Life Cycle Thinking in material development, with respect to technical, economic, and ecological aspects, brings both worlds (disciplines) closer to each other. This brings also advantages for both material and product development. The main advantage for material development is the opportunity to guide the development of materials in a sustainable direction thanks to the high degree of freedom for changes granted in the early phase (Figure 1).

Due to the provision of technical, economic, and ecological material informations, the early phase of product development has the advantage of a broad information base, (costs, performance, environmental impact) which allows the most promising materials to be selected for a defined goal or application field.

In addition time and working load in the laboratory can be reduced to a minimum. A screening process will give an selection of all sensible materials and then successively filter the less promising materials from the further investigation. Thus, small or medium sized projects are able to consider all sensible raw materials, and not just a specific group of raw materials. The level of screening must be adjusted to the availability of information, the objective, and the time span of the project.

2 BACKGROUND OF GEOPOLYMER

2.1 Geopolymers

Geopolymers consist of a silicate-aluminate solid component (binding material) and an alkaline liquid component (alkaline activator), see Figure 2. After a simple mixing of both components, dissolution takes place, accompanied and followed by a polycondensation . The formed polymeric network of alumosilicates (geopolymer binder) hardens in an amorphous to semi-crystalline structure. Depending on the amount of soluble calcium oxide in the raw materials, mineral phases may also occur that are similar to the hydration products of portland cement (Buchwald et al. 2005a). In this respect, geopolymers represent a link between ordinary Portland Cement (OPC) and sodium silicate binders.

Alkali activated materials (“geopolymers”) have been investigated for more than 30 years. Despite these long-lasting and continuous investigations, geopolymers have not yet to be widely applied. In fact, a wide range of possible applications are described in literature, but only a few niche applications can be found on the market.

This is surprising, especially since geopolymers (in comparison to cement-based composite materials or ceramics) are reported to have many advantages:

- Resistance against acids
- Temperature resistance
- High strength
- High durability
- Cold setting
- Quick setting
- Stable bonding of heavy metals and harmful substances
- Simple manufacturing technique

The favorable technical properties are proved by numerous investigations, cf. [5]. But they depend on the curing time and temperature and very strongly on the mixture composition of the chosen solid and liquid components.

Ecological and economic features of geopolymers have hardly been investigated so far. But it can be assumed that they depend very strongly on the mixture composition, too. So far, metakaolin has been applied mainly as a solid component to produce high-performance geopolymers. However, thermally activated kaolin (metakaolin) is a relatively expensive raw material. Consequently, the application fields are restricted due to the costs. In addition, due to the high energy demand metakaolin possess a relatively high environmental impact.

In contrast to this, relatively cheap industrial by-products or residues, such as blast furnace slag, fly ashes or sewage sludge ashes, can also be used as environmental advantageous solid components. These kind of solids, however, may be associated with some drawbacks regarding the technical performance, e.g. retarded setting or low mechanical strength.

The awareness of these conflicts of objectives represent a important background for the presented approach.

3 SCRENING OF RAW MATERIALS

3.1 Goal of the screening step

The goal of the screening step is the selection of the most promising raw materials for a specific field of application under the consideration of technical, economic and ecological aspects.

3.2 Considered raw materials and samples preparation

More than 58 raw materials has been collected and tested in this 1st step.

The materials can be assigned to the following six groups:

Ceramic waste materials

- tiles
- sanitary porcelain
- kiln lining material

Ashes

- hard coal ash
- soft coal ash
- sewage sludge ash

Slags

- blast furnace slag
- steel slag
- copper slag
- municipal waste slag

Others

- broken down masonry
- brick scrap
- glass industry waste

Clays

- kaolinitic clays
- ilitic clay
- dolomitic clay

Volcanic deposits

- trass
- tuff
- basalt

Coarse raw materials, like slag, were milled smaller than 125 µm. For the comparability of laboratory results, all raw materials are activated by one standard alkaline activator (with 8 molar NaOH solution). The amount of solution has been levelled on identical paste workability. All samples were cured for one day at 40°C inside the moulds, and afterwards until strength testing without drying, at room temperature about 90% relative humidity (over water in closed boxes). Further Information to the measurement technique of the geopolymer properties are published in [5].

3.3 Considered indicators

In order to get a meaningful screening the right indicators were chosen for the later evaluation of the materials by intense discussion within the interdisciplinary working group. The technical parameters were selected depending on the needs of the application; ecological and economical parameters were selected based on life cycle thinking. The following indicators were chosen for the three objective fields:

Technique

mechanical strength (including reactivity, quantitative)

resistance against acids (qualitative)

temperature resistance (quantitative)

setting time (quantitative)

workability (qualitative)

Economy

raw material costs (quantitative)

costs of the thermal activation of raw materials (qualitative)

costs of grinding raw materials (qualitative)

follow-up costs caused by slow setting (qualitative)

follow-up costs caused by high water sorption (qualitative)

Ecology/Health

availability/consumption of mineral resources (quantitative)

consumption of energy resources (qualitative)

toxic load (qualitative)

health and safety at the workplace (qualitative)

3.4 Selection of raw materials by the help of Multi Criteria Decision Analyses

The evaluation and selection of materials under the consideration of different objectives is difficult. The decision making process for the selection of the best candidates reach high complexity, if the number of alternatives are high and the number of objectives is higher than 1. In the presented geopolymers project both is true. The number of considered raw materials are high (58 different raw materials) and 14 indicators for three different objectives (economic, ecological and technical objectives, c.f. Chapter 3.3) are considered. The methods of Multi Criteria Decision Analyses (MCDA) are potentially helpful to support decision-making in complex decision situations [6]. Besides compensatory methods [7], also a non-compensatory method called “dominance concept” has been applied to identify the most promising candidates for a specific application fields.

The economic and ecological investigations together with the laboratory results, are stored in a data-base. The different

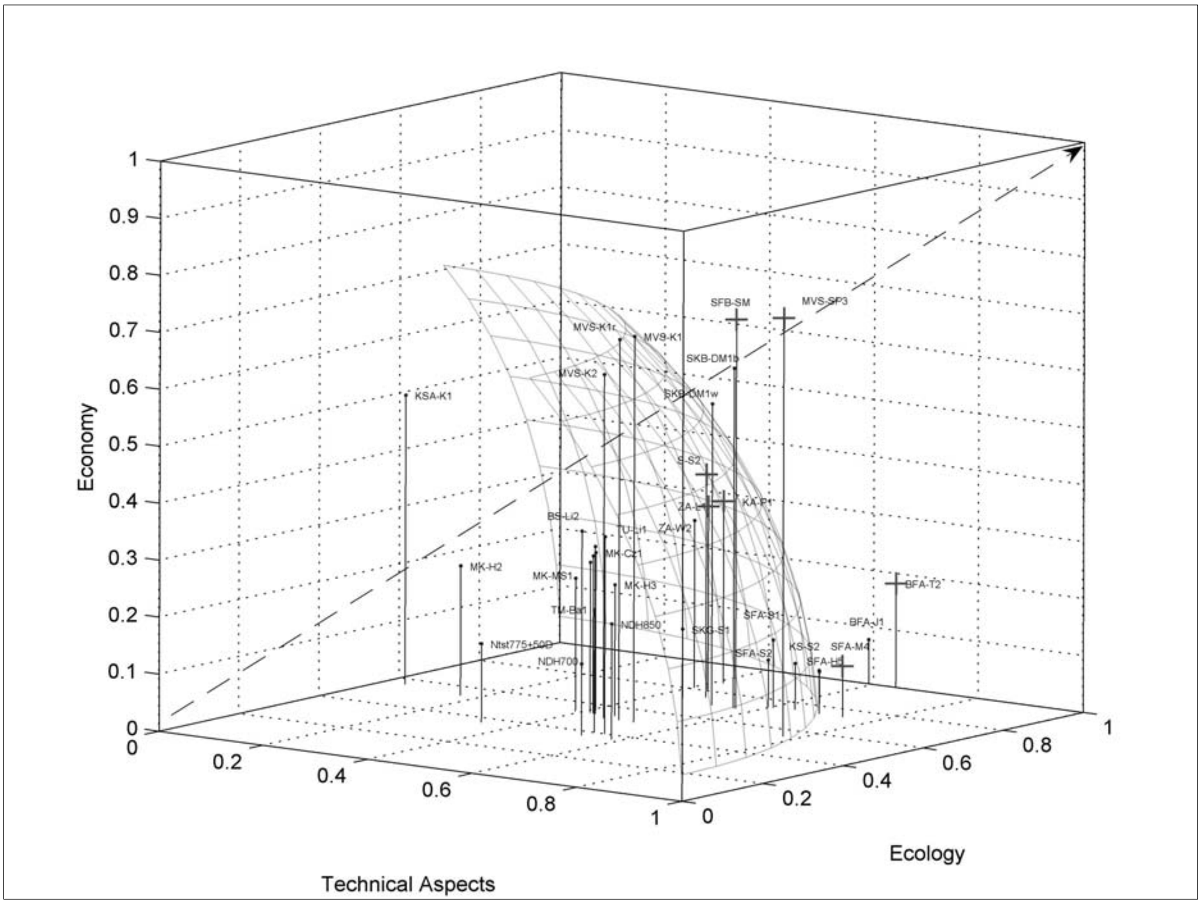

Figure 3: Identification of promising candidates. Crosses refer to pareto optimum, called dominant altenatives, nappe refers to pareto front. (Figure created with MATLAB)

quantitative and qualitative indicator values are comparable and countable, as they are normalized to values between 0 and 1. Values close to 0 are less favourable, values close to 1 are highly favourable. For each indicator, a proper scale of transformation has to be determined, cf. [8].

4 RESULTS

In Figure 3 the results of the non-compensatory method are shown for one selected application field. The alternatives (raw materials) in the diagram, which are far away from the origin, represent better solutions (high values), the alternatives close to the origin are suboptimal. The pareto optimums (which is not dominate by the other alternatives) are highlighted as crosses (Figure 3). Pareto optimums are the materials SP3, M4, SM, T2, P1, L1, S2. In the case of the non-compensatory method the solution space is afflicted with two problems:

- A pareto optimum does not necessarily represent a promising raw material. For instance, one alternative from a ecological perspective is the best solution (highest value on the ecology axis), but from a technical and economic perspective it is quite bad (low values). The ecological advantages cannot compensate, in this case, for the technical and economic disadvantages. To overcome this problem in general, each objective minimum requirements has to be defined to shorten the solution space.
- Alternatives, which are close to pareto optimum, represent interesting and valuable candidates. In addition, every indicator value is more or less tainted with uncertainties. To identify all valuable candidates, also under the consideration of the uncertainties, a 3-D nappe (“pareto front”) is used to separate the promising from the less promising alternatives. The materials on or above the nappe represents the valuable alternatives (cf. Figure 3).

After the described procedure the promising candidates can be determined. The result are compared with the results of the compensatory method [5]. Hence, after an expert discussion, the most promising raw material are selected for the design phase of geopolymer mixtures for specific application fields in the ongoing project.

5 CONCLUSION

The sustainable development of materials with enhanced properties, but also with economic and ecologic advantages, is one of the challenges of modern materials science. In practice, economic and ecological aspects are rarely considered, probably due to the lack of information available in the early phase of material development. Based on the example of the development of geopolymers, the authors presented a methodological approach to integrating technical, economic, and ecological aspects in the early stages of material development. This approach is subdivided into three single steps.

It is started from a broad variety of raw materials, which will be reduced step by step to a few promising material combinations for specific applications.

This course of action is supported by the use of systems analysis tools. Besides LCA, LCC and MFA especially Multi-criteria Decision Analyses tools play a prominent role.

Acknowledgements

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Conductive Adhesives vs. Solder Paste: A Comparative Life Cycle Based Screening

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Abstract

Electrically conductive adhesives (ECA) could soon constitute a realistic alternative to solders. The present research compares 10Sn90Pb solder paste in Japan to an epoxy based and isotropical ECA containing pure silver. The findings are that the silver containing adhesive likely is environmentally more advantageous than 10Sn90Pb. Environmental trade-offs exist especially between the ecotoxicity of Sn1090Pb and the resource consumption of silver-epoxy ECA. Palladium is significant platings included. Overall, the next steps would be to use improved global LCI metal production models and also to compare the life cycle cost to the social cost.

Keywords:

Electrically Conductive Adhesive; Solder Paste; Life-Cycle Assessment

1 INTRODUCTION

The competition in the global microelectronic industry is strong and demands on new materials are gradually advancing. Japan, a nation in the technological forefront, realises this as well as the need for ecologically sustainable system solutions, especially in an age of fears of climatic disorder. The interconnection materials, which can be regarded as an important “electronic component”, are no exception and the manufacturers choose between Pb-free solders and polymer based electrically conductive adhesives (ECA). ECAs consist of a polymeric binder matrix and metal fillers. Further the ECAs are commonly divided into anisotropically, isotropically and non conductive adhesives. Li et al. suggest that ECAs generally are more environmentally friendly than solders as both Pb and flux cleaning are eliminated as well as fewer overall processing steps are required. [1]. Moreover, lower curing temperatures are thought to offer reduced energy use. Nevertheless, ECAs are no drop-in replacements for conventional solders due to different material properties and reliability issues such as low conductivity, unstable contact resistance, low joint strength, and silver migration. Furthermore different surface plating metals are used to protect the pads of the printed wiring boards and the component leadframes. Several authors have attempted environmental consequence analysis of the global shift to Pb-free solders, whereas less transparent research has been published about the environmental properties of ECAs. Moreover, a Danish life cycle assessment (LCA) could not establish whether the adhesive technology was better or worse than the soldering technology, as it was judged the data available on material consumption and discharges throughout the life cycle were too uncertain. [2]. Andrae et al. performed an attributional LCA screening from a Japanese perspective, based entirely on literature data and the LIME (Life cycle Impact assessment method based on Endpoint modeling) for impact assessment comparing a silver based ECA to a Pb based solder paste showing a clear advantage for the ECA. [3]. Nevertheless, the objective of the present study is to improve the understanding of the most important environmental loadings and effects associated with one isotropically conductive adhesive (ICA), silver-epoxy ICA, and one solder paste, 10Sn90Pb. Compared to a literature [3], the present model is updated with primary data from manufacturers as well as a new literature sources and end-of-life scenario. The environmental impacts of including surface metal plating for printed wiring board pads and leadframe terminals will also be explored. Japan has ratified the Kyoto protocol and Japan will likely follow in the footsteps of the other nations and join a market for trading of CO_2 emission rights. Globally a price range of 3-74 US Dollar per ton with an average permit price of 27 USD/ton is mentioned, and it is assumed Japan will have a similar cost expressed in Yen (3,270 Yen) and that greenhouse gases will cost according to their global warming potential during 100 years. [4]. Here this cost is called PGWP. Moreover Harada et al. recently developed the Total Material Requirement (TMR) method which expresses the amount of hidden material flows by extraction of lithospheric and ecospheric resources. [5]. Comparing silver-epoxy ICAs to 10Sn90Pb solder paste the hypotheses for the present research are that 1) silver-epoxy ICAs have a lower LIME based environmental impact score, 2) silver-epoxy ICA has a lower PGWP, and 3) silver-epoxy ICA has a higher TMR. The problems addressed in order to falsify the hypotheses are: What are the comparative LIME, TMR, and PGWP scores for an LCA comparison between silver-epoxy ICA and Sn10Pb90 solder paste? What are the contributions of surface pad and terminal platings?

2 SCOPE OF THE PRESENT STUDY

2.1 Outline

The work flow in the present study followed the usual steps in LCA practice. Table 1 provides a summary of the analysed materials.

Material type	Area/ one Printed Wiring Board Pad, 1.0E-2 cm^2 **Plating material**	Area/one terminal, 8.6E-3 cm^2 **Plating material**
10Sn90Pb	Tin, 8.0E-4	Tin, 8.0E-4
Silver-epoxy ICA	Gold, 3.0E-7 Palladium, 2.0E-6 Nickel, 5.0E-5	Gold, 3.0E-7 Palladium, 2.0E-6 Nickel, 5.0E-5

Table 1 Summary of the evaluated materials. Values represent thicknesses in cm of surface plating materials.

For the gold/nickel/palladium and tin platings the layer thickness values were given by manufacturers. The value for palladium thickness is 100 times lower than used by Andrae. [3].

2.2 System boundary and inventory analysis

The present study has attempted to include the entire life-cycle for the adhesive and solder paste, meaning most processes from metal mining to final waste treatment of which most are supposed to take place in Japan. More details of the outline of the project are described by Andrae et al. [3] whereas the present paper provides the latest results of the research project.

2.3 Assumptions

The functional unit chosen in this study is the volume interconnection material needed to mount two microcircuits of type Quad Flad Pack-200 onto one test Printed Wiring Board. The density is higher for 10SnPb90, about 5.3 g/cm^3 compared to about 4.5 for silver-epoxy ICA. Literature figures assuming that the adhesives use less material per joint, 0.08 mg compared to 0.5 mg for solders, were used to calculate the volume per functional unit, 0.0377 cm^3 (0.2 g) for 10Sn90Pb and 0.0071 cm^3 (0.032 g) for silver-epoxy ICA. The present silver-epoxy ICA generally consists of 80 mass% silver flakes, 12 mass% epoxy glue and the remaining mass of speciality chemicals. The flux constituent was assumed to be 10 mass% for the 10SnPb90 solder paste. For solder paste manufacturing and surface plating of tin, 5 mass% material losses, which were not recycled, was used for metals tin and lead. However, for adhesive manufacturing and surface plating of Au/Pd/Ni 99 mass% of the losses for silver, gold, palladium, and nickel were recycled but only 50% mass% were discounted for the present life cycle, i.e. the so called 50/50 allocation method was used. [6]. This method is suitable when the studied material is recyclable and is used in more than one product. All main metal production processes, except silver and gold, from cradle to gate were modeled using data for primary metal production from the Swiss based Ecoinvent, currently one of the leading life cycle inventory databases in the world. Chemicals used in different unit processes were also modeled using data from the Ecoinvent. For inorganic and organic chemicals for which no life cycle inventory data were available, a hybrid-LCA method was applied using an input-output table which approximates the magnitude of aerial emissions of CO_2, SO_2, CO, NO_x, Pb, Particulates, CH_4, N_2O, and soft chlorofluorocarbons and finding approximate prices on the World Wide Web. [7]. Data for Japanese average electricity production from cradle-to-gate was used in all operations assumed to take place in Japan. The used mix emitted 116 g CO_2-equivalents/MJ electricity from cradle-to-gate for IPCC GWP 100, i.e. the global warming potential for 100 years.

Production of solder paste was based on 63Sn37Pb figures for electricity, fuel oil, and natural gas consumption. For the adhesive the electricity consumption was based on manufacturer's data. For those processes not using silver, 10 mass% manufacturing material losses which were not recycled were used for alloy, powder and flakes, processes as well as for screen printing. 99 mass% of the silver losses were assumed to be recovered and the 50/50 allocation method was applied. The electricity consumptions of the reflow soldering process and the reflow curing process were modelled according to Equations 1-3:

$$n = \frac{(100 - t)}{100} \times \frac{y}{x} \tag{1}$$

$$E = \frac{U \times S}{n \times 10^6} \tag{2}$$

$$M = \frac{E}{I_m} \tag{3}$$

Equation 1 gives n which is the number of boards (real number inserted in Equation 2) in the oven at the same time, t is required free space in reflow oven in % of the belt area, x is test board area (m^2), y is reflow oven belt area (m^2), E is electricity consumption in MJ per Printed Board Assembly (PBA), U is power consumption during Reflow (W), and S is process time (s) per board. The reflow curing time of the present ICA was assumed identical to the reflow soldering time, however the curing consumes about half the electrical energy as the peak processing temperature 160 °C is considerably lower for ICA than Pb/Sn based solders pastes, 325 °C. Equation 3 describes the energy per amount solder/adhesive, M, and is dependent on the type of PBA produced. The present test PBA used a proportionally small mass of material, I_m, as only two circuits were mounted. After the use phase the solders or adhesives, following the route of electronic devices, were set for one of the following five main scenarios; entered controlled landfills, incinerated together with municipal solid waste, exported from Japan to foreign nations, recycled to extract the metals, or otherwise illegally disposed of. According to literature a possible distribution could be 0.1 (1) mass% put to landfill, 1% incineration, 22.6 (23) % export to Guiyu in China (some material recovery), 48% recycling at recycling facilities (some material recovery), 27 (26) % recycling at disposal facilities (no material recovery), and 1% illegal dumping. [8]. Here the parenthesized figures above were employed. In total, 0.18 g 10Sn90Pb, 0.032 g silver-epoxy ICA, 0.04 g Sn plating, and 0.0035 g Au/Pd/Ni plating entered the waste management phase. Landfill, 135 mg/kg 10Sn90Pb, and illegal dumping, 23 g/kg 10Sn90Pb Pb emissions, assumed to be taking place during about 100 years, to water/soil were estimated by literature. [9], [10]. For gold, nickel, and palladium an emission factor for silver was used. [11]. As no literature values could be found distinguishing between landfills and illegal dumping emissions for other metals than Pb, identical landfill and illegal dumping values were used for these metals. For incineration all metals were modelled to behave as arsenic inside a mobile phone. [12]. Per metal 0.2 mass% air emissions, 20 mass% leachate (emission to water according to landfill assumption) and the remaining insoluble residue. For material recovery in recycling and export scenarios 99 mass% of the metal could be recovered and the 50/50 allocation method was used. For example 25 g palladium, 6 g gold, and 468 g nickel production was avoided per kg recycled/exported Au/Pd/Ni plating, and 400 g silver per kg silver-epoxy ICA.

2.4 Impact assessment method

LIME (Life cycle Impact assessment Method based on Endpoint modeling) complemented by TMR and PGWP were used to interpret the inventory results. A price of 3,189 Yen (20 euro) per ton CO_2 was used for PGWP calculations. LIME is a method adjusted for Japan aiming to evaluate the threats to its four safeguard objects (damage categories) Human Health, Bio-diversity, Social Assets, and Primary Productivity. Different environmental loadings in one way or the other affect these safeguard objects by contributing to impact categories which in turn are correlated to damage categories. The LIME model is based on connections between e.g. emissions and their endpoints, and by weighting impact categories or damage categories the overall single index can be expressed in Yen. One example is the emissions of NO_x which lead to acidification of freshwater systems, eutrophication of aquatic ecosystems, and which can also reach dangerously toxic levels for aquatic animals. The connection between NO_x emissions and adverse effects on human health and economy has been identified by research by which the LIME method is constantly updated. [13]. LIME is based on a so-called contingent valuation approach which leads to the Japanese society's 'willingness to pay' for the reduction of pollution. It can thus be regarded as a kind of social cost. Other models try to estimate, i) the decrease in market value of the resource impacted by pollution, i.e. market valuation, ii) the cost of pollution prevention or pollution remediation, i.e. maintenance cost, or finally iii) the cost of the impact of pollution on ecosystems and human health, i.e. dose-response. [14].

3 ASSESSMENT RESULTS

3.1 Inventory analysis

In the life cycle inventory analysis the energy and raw material requirements, air emissions, waterborne effluents, and solid wastes are quantified per functional unit. In Table 2 the selected inventory results are shown for both interconnection materials with and without surface plating. The metal resource consumptions are roughly indicated by the respective material composition. Independently of plating inclusion, CO_2 emissions to air mainly occur in electricity production, Pb emissions to air and to water are dominantly occurring in Pb production processes.

Subst.	SP	SPP	AE	AEP
Input (res.)				
Coal	5.0E+00	1.2E+01	4.0E+00	1.1E+01
Oil	1.2E+00	2.7E+00	1.1E+00	2.5E+00
Gas	4.0E+01	6.2E+01	7.0E+00	1.5E+01
Au (r)	0.0E+00	0.0E+00	0.0E+00	2.9E-05
Ag (r)	1.4E-08	1.8E-08	1.9E-02	2.0E-02
Pd (r)	2.8E-10	4.9E-10	6.8E-12	1.2E-04
Sn (r)	1.8E-02	4.5E-02	1.0E-09	2.8E-08
Pb (r)	1.6E-01	1.6E-01	1.8E-06	5.6E-06
Ni (r)	6.6E-7	8.1E-07	1.1E-7	2.3E-03
Output (emi.)				
CO_2	2.6E+01	6.0E+01	2.2E+01	5.6E+01
Pb (a)	9.9E-05	1.0E-04	2.0E-06	4.9E-06
Pb (w)	2.9E-03	2.9E-03	6.0E-07	2.1E-06
Pb (s)	2.5E-07	2.5E-07	6.7E-10	1.4E-09
NO_x	1.7E-02	3.4E-02	1.4E-02	2.9E-02
SO_x	3.6E-03	8.5E-03	9.7E-03	3.3E-01
SO_2	1.7E-02	2.7E-02	3.0E-03	5.1E-03

Table 2: Selected inventory results given in gram per functional unit. Air (a), water (w), soil (s), and resource (r). SP = 10Sn90Pb, SPP = 10SnPb90 + Sn, AE = Silver-epoxy ICA, AEP = Silver-epoxy ICA + Au/Pd/Ni. Total 883 substances.

3.2 Impact assessment results

Below in Figures 1 and 2 are shown the LIME single scores as a result of weighting the safeguard objects against each other. Figure 1 shows the results excluding plating and Figure 2 including.

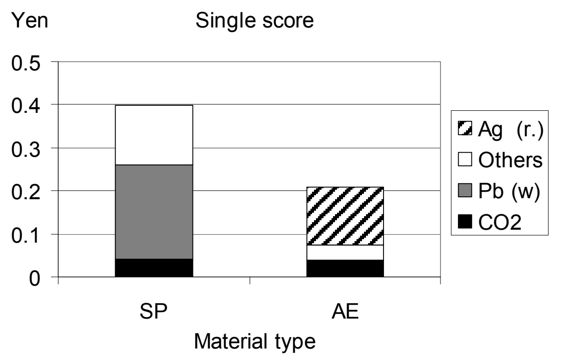

Figure 1: Overall LIME score for materials excluding platings.

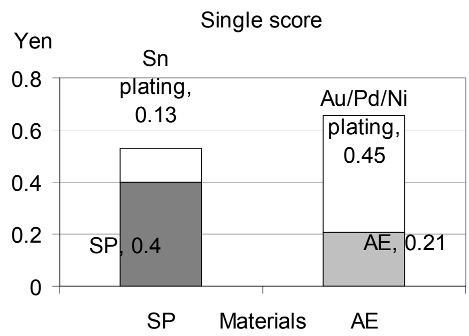

Figure 2: Overall LIME score for materials including platings.

It means that the application of about 0.22 g of 10Sn90Pb could lead to a social cost of around 0.4 Yen, and that the 0.00355 g Au/Pd/Ni plating raises the cost for Silver-epoxy ICA from near 0.2 to 0.65 Yen mainly due to Sulfur oxide emissions from palladium production.

3.3 Interpretation and Verification

The permit price for avoiding global warming was compared to the single 'willingness to pay' score for the weighted impact categories of Global Warming in LIME. The share of GWP costs of the total LIME score were about 47 mYen for 10Sn90Pb and about 44 mYen for silver-epoxy ICA, which are lower than the permit prices shown in Figure 3.

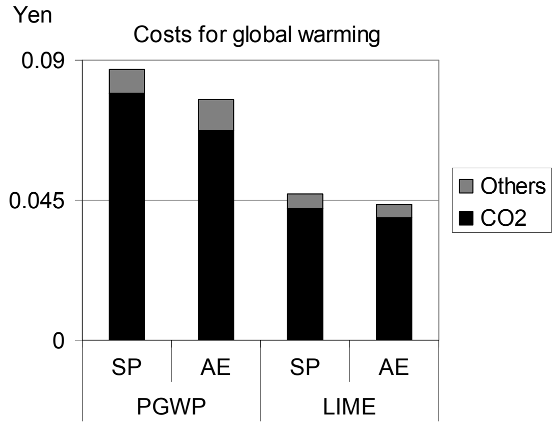

Figure 3: Permit price and 'willingness to pay' costs for global warming for materials excluding platings.

4 DISCUSSION

It is necessary to put the present research into a global perspective as part of the life-cycle is outside Japan. In 2004 the global consumption of primary and secondary tin was some 296,000 tonnes of which about 46% was used for all kinds of solders and 40% of those were used to manufacture electronic bar solders. [15]. Assuming an 88% share for 63Sn37Pb, 10% for 10Sn90Pb, and 2% Pb-free, about 93,000 tonnes of electronic bar solders were produced globally in 2004. In 2004 the economic value of the globally produced electronics was about $1.2*10^{12}$ U.S. dollars. Japan's share was around 16% and the nation is assumed to use the same relative share of the mass of global electronic bar solder, i.e. 14,880 tonnes and the global share for 10Sn90Pb is assumed to reflect Japanese conditions. [16]. These 1,488 tonnes of 10Sn90Pb solder (1,653 ton 10Sn90Pb solder paste) would according to the present LCA emit [26 g per 0.22 g = 118 kg/kg] $1.95*10^5$ tonnes CO_2. Moreover, for the year 2004 the Intergovernmental Panel on Climate Change estimated that the total global anthropogenically induced CO_2 emissions were near $2.64*10^{10}$ tonnes. [17]. This would mean that around 0.0007% of the global CO_2 emissions are emitted from the 'Japanese' 10Sn90Pb solder paste life-cycle. This might be an overestimation as the present test board is not representative of a typical printed board assembly, therefore overestimating the CO_2 intensive electricity consumption per mass applied solder. For the Silver-epoxy ICA on the other hand the CO_2 emissions might be underestimated. The second doubt is the small global share of reflow solder paste compared to wave solder which has a lower environmental load than the former. It is not apparent how the price for being allowed to emit CO_2 will be set. Anyway the 3,189 Yen permit price gives a score for PGWP near the GWP share of the total LIME score, indicating that the willingness of the Japanese people to pay for reducing greenhouse gas pollution is in the same range as a probable permit price. Regarding the overall single LIME score for the silver ICA, the reflow electricity consumption is responsible for 21% platings excluded and 2% platings included and for 10Sn90Pb 14% and 5% respectively. Electricity is usually an important flow in LCA and the present study is no exception. Regarding transports due to lack of reliable information, flight transportation of metals to Japan were excluded. A proxy of 300 km lorry transport, which overall were shown to be negligible, was used between activities in Japan. Nor ship transports when exporting e-waste presently were noticeable. However, packaging ancillaries and possible aircraft transports were not possible to include at this stage of the LCA project.

Silver-epoxy ICA is more resource demanding than 10Sn90Pb, however, according to LIME methodology this seems to be less important than the toxicity impacts of the 10SnPb90. Silver is likely the metal embodying the highest overall environmental load compared to other materials which also have been suggested as filler (e.g. silicones, metal coated polymers and nickel) for ECAs.

Nevertheless, the LIME evaluation does not focus on material requirement as much as human health costs and precious metal cost. As shown in Figure 4, the TMR for 10Sn90Pb is lower than Silver-epoxy ICA also assumed in the introduction. Coal has a TMR value of 12 kg/kg, silver 4,800 and palladium 813,000 kg/kg.

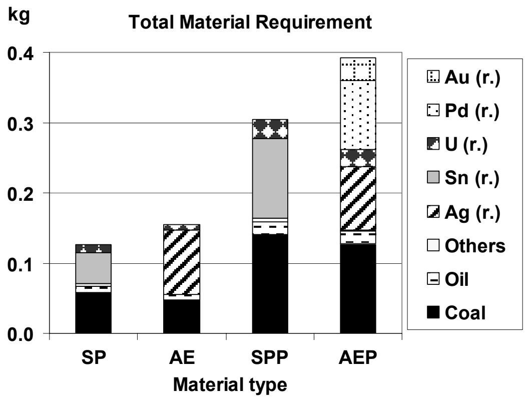

Figure 4: Total Material Requirement for materials excluding and including platings.

According to the assumptions made regarding Pb leaching in landfills, they have a smaller significance than Pb emissions from illegal dumping of 10Sn90Pb. Regarding “recycling” in China, with a high likelihood significant Pb emissions per functional unit are released to water and soil which would strongly have emphasised the disposal problems with the 10Sn90Pb. The actual amounts emitted and to which compartments are dependent on the distribution of recycling procedures and which measures are taken to prevent emissions.

The results of a preliminary uncertainty analysis (SimaPro7 and Monte Carlo simulation was used) are shown in Figure 5 for total LIME score. The possible values of Pb emissions to soil and water were many and those are the main reasons for the high uncertainty of the Sn10Pb90 score. Figure 5 exclusively illustrates input uncertainty for most inventory flows. A proper sensitivity analysis and inclusion of impact assessment uncertainty is out of scope of this study.

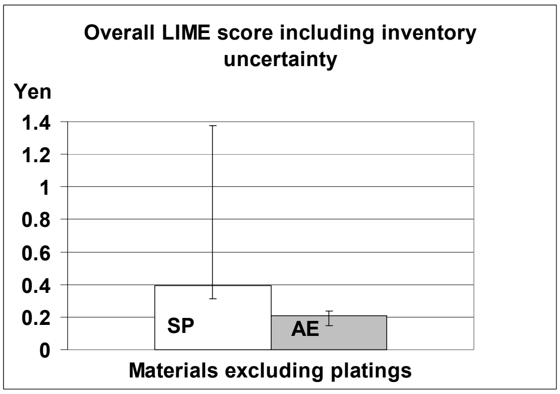

Figure 5: Uncertainty analysis results for LIME score excluding platings.

5 CONCLUSIONS

A screening life-cycle assessment has been performed comparing two different interconnection materials including two different plating materials of printed wiring board pads and component leadframes. Platings excluded, Silver-epoxy ICA shows signs of environmental soundness compared to 10Sn90Pb especially in potential toxicity. Concerning the total material requirements and global warming costs it is more doubtful. There is a trade-off between the human and ecotoxicity of Pb emissions connected to 10Sn90Pb on one side, and the resource consumption of silver connected to silver-epoxy ICA on the other. The plating materials are dominated by sulphur oxide emissions from palladium production.

6 OUTLOOK

An LCA result can be validated by applying more primary data and new modelling methods, especially uncertainty analysis and dynamic modelling. For certain systems, consequential life cycle thinking to study market shifts could be worthwhile. Parts of the present study is based on various data from literature sources which might deviate from primary data. More accurate data describing curing time and reflow time and the related power consumption, as well as alternate models describing global metal production (especially silver) for Japanese conditions as well as various end-of-life emissions, are the most important issues to improve the inventory analysis of the present materials. Furthermore for environmental impact analysis, tin and silver emissions to water, air and soil have no LIME quantification yet. The life cycle economic cost of the present materials, and of other conductive adhesives based on less burdensome materials than silver, would be worthwhile to compare to their social cost. Future LCA studies should focus on materials replacing silver–based solders and adhesives.

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Framework Research on the Greenness Evaluation of Polymer Materials

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Abstract
With the increasing usage of polymer in modern products, polymer waste has become an important source of the waste stream with huge environmental impact (EI). Many countries have launched laws that mandate producers to be responsible for 3R (reuse, recycle and reduce) of End-of-Life (E-O-F) products, in which polymers account for a large proportion. This situation requires that not only performance and cost, but also environmental impact must be taken into consideration when evaluate polymer materials. This research manages to build up a framework to evaluate the Greenness of polymers at manufacture, usage, 3R and disposal stages.

Keywords:
LCA; Neural Network; Polymer Material

1 INTRODUCTION

With the increasing usage of polymer products, polymer waste has become an important source of the waste stream and causes huge EI during the process of taken-back and disposal. Many countries launched laws or regulations that mandate producers to be responsible for 3R (reuse, recycle and reduce) of the E-O-F products, in which polymers account for a large proportion. For example, HARL was enforced in April 2001 in Japan; WEEE and RoHS directives were published in 2003 in EU.All those laws require minimum reuse, recycle and recovery ratio (weight ratio) of E-O-F products. Figure 1 shows the current situation of the recycle of different materials. It indicates that polymer material is the bottle-neck of all product recycling and requires researchers who work on material design and polymer processing technology to take into consideration not only the performance and cost, but also the greenness of new polymers. Then an approach is needed here to evaluate the Greenness of polymers that can reflect the whole life cycle of polymer. However, the life cycle of polymer material is a complex process. In this regard, a systematic and integral framework and evaluation approach needs be established to analyze the greenness of polymers.

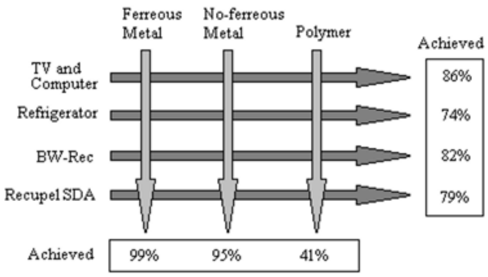


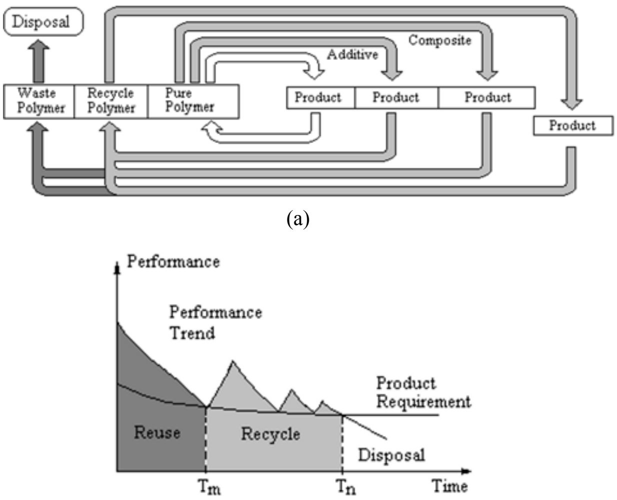
Figure 1 Situation for Recycle of Different Materials

Due to the importance of polymer materials, many researches were carried out in recent years. K.G. Snowdon denoted a life cycle assessment for product flow of Polycarbonate plastic and made comparison for faceplates product of Polycarbonate/ABS and Aluminum [1]. H. Terho made LCA (Life Cycle Assessment) research for Nokia cables made of PBT and LDPE, and compared the selection scenarios for LDPE, LLDPE and HDPE to evaluate the EI of different polymer selection [2]. G. Lewis, etc made analysis and life cycle simulation of photovoltaic module design for UPM-880 of United Solar Systems Corporation in which the main material is Tefzel (a Teflon based polymer) and EVA [3]. D. Pollock etc denoted a LCA for Inkjet Print Cartridge. Although it mainly focuses on the life cycle of Cartridge product itself, polymer contributes a lot to the total EI since the main materials of Cartridge are PE, PP and Polyester [4]. H. Tomita, etc presented a LCA research for Audio Compact Cassette Tapes and Mini Disk, which mainly consist of PS, Polycarbonate and PC. Recycling of polymer is the key point [5]. J. A. Stuart summarized material selection methods for life cycle design of product [6]. R. Kulkarni developed an evaluation framework for EI of electronic product based on the existing Environmental Assessment (EIA) software system [7]. E. Masanet made research on assessment and prioritization method of "design for recycling" for plastic components [8]. S. Moriya Make reseach on recycling method for manufacture of recycled fuel oil from waste plastics disposals[9]. All these researches took polymer materials as an important part of LCA. However, most of the evaluation methods focused on the life cycle process of products, not polymer materials. Different from other materials, new polymers are developed very quickly with the development of new additives and composites. Meanwhile, new processing and molding technologies are also developed rapidly. All these make it necessary to take polymers as the research target to help designers of material and processing to evaluate and forecast the 3R and greenness of polymer.

2 LIFE CYCLE AND 3R FOR POLYMER

3R represents Reuse, Recycle and Reduce. In normal life cycle of product, Reuse means the refurbishing dismantled old components directly into original use. Recycle means taking-back and recycle of materials. Reduce means decreasing the amount for final disposal. However, the life cycle process of polymer is not a simple single cycle, the 3R concept for polymer must be extended to its whole life cycle process. As shown in Figure 2, the whole life cycle process of polymer can be divided into three different stages.

1) Reuse Process is defined that purified polymer material from E-O-F products can be taken back and reused to manufacture new products without new adding of additives and composites. However, reuse process cannot be repeated endlessly. Each cycle of reuse will change the performance. So if the performance of reused polymer failed to fulfill requirements of product, reuse will end.



(b)

Figure 2 Life Cycle Process of Polymer

2) Recycle of polymer is defined as that additives, fibers or other polymer materials have to be added to improve the performances of the taken-back polymer if it can't fulfill the requirements of remanufacturing. Recycling operation will change the polymer forever since the additives or other materials are inseparable.

3) Disposal Process means final disposal when polymer cannot be reused or recycled. There are many possible disposal approaches, such as decompose, energy recovery, filling and landfill, of which landfill is the worst choice.

Normally, based on ASTM (American Society for Testing Material) D0883-92, polymers are classified into 5 types, that is, degradable, biodegradable, hydrolytically, oxidative degradable, photodegradable and combustion. These kinds of ASTM standards can be used as the judging rules to select the final disposal methods for polymers.

Those three stages are illustrated in Figure 2 (b). In Figure 2 (b), the curve indicates performance of polymer material. Performance decreases with time. When it falls short of product requirement (Time T_m), recycle operation will be used to prolong the lifetime of polymer. When the performance of recycled polymer falls short of product requirement (Time T_n), polymer comes into the disposal process. Here, T_m means the end time of reuse process; T_n means the end time of recycle process. It is obvious that if polymer cannot be recycled, it will proceed into the disposal process after T_m directly. Under this condition, $T_n=T_m$.

Polymer design and selection of proper processing method can influence the life cycle of polymer. Normally, the following methods can be used to comply with 3R design:

1) Increase the performance of original polymer; 2) Prolong T_m; 3) Prolong T_n; 4) Decrease the final landfill.

Based on above analysis, it is important to design proper ratios of polymers for reuse, recycle and landfill, and to get the lowest EI per unit time in its whole life cycle.

3 KEY POINTS OF ASSESSMENT FOR POLYMER

To improve the 3R design of polymer and processing methods, the following key points are selected to establish the evaluation framework.

3.1 Additives (incl. Hazardous Substances) and residues

Polymer used in real manufacture is a multi-component admixture. Normally, additives and residues in taken-back polymer materials can be divided into three types. The first type is additive that used to improve the performance of the original polymer. The second type is residue of pollutions during manufacture, usage and take-back process. The third type is low molecular polymer produced by degradation of original material. Table 1 gives some example of different type of additives and residues.

TABLE 1 different type of additives and residues

Poly.	Additives for improving the Performance	Residues of Pollution	Degradation of Polymer
SBR	Argil, ZnO, $BaSO_2$, TBBS, Stearic Acid, Sulfur, Fiber, Metal Bar, Charcoal Black, Olefin, PPD, TMQ,...	Dust, Axunge, Metal Fragment, Other Polymer, ...	Degradation Rubber, …
PET	Sb, Co, Mn, Fe, Ti,Chloroform, Toluene, Stearic Acid, CH_3CCL_3, Benzophenone, Hexachlorobenzene, …	Dust, Axunge, Dye, Printing Ink, PVC, PE, EVA, ...	Acetaldehyde, …
PE		PP, PET, Metal Fragment, Dust, Paper Fiber, Dye, …	Acetaldehyde, Ketone, …
PVC	Plasticizer, Heat Stabilizer,	PE, PETG, BP, …	HCl, …

After E-O-F, all these additives, pollution residues and degradation polymers become elements that will affect the recycle and reuse.

Since the use of Hazardous Substances (HS) are now banned or restricted by regulations such as RoHS in some countries and those innocuous additives can influence the performance of recycled materials, the amount and EI of substances must be regarded as a key point for the LCA of polymer.

Here, restriction of Hazardous Substances (HS) is the baseline that must be complied. In this regard, some researches have been done. Raymond B. etc addressed issues related to the benefits, risk in use, and E-O-F options for plastics containing brominated flame-retardants in order to determine the recyclability of this kind of plastics under a variety of conditions [10]. Those kinds of methods can be used to prolong the life cycle of recycled material that complies with the HS's restriction. Here, use parameter union {H} to denote the amounts of HSs and {R} to denote the amounts of other additives or composites.

3.2 Performance

Performances of the recycled material are normally different from the original one. This condition will increase the difficulty of material reuse and recycle. In this case, how to reduce the performance change shall be taken into account to prolong the lifetime of materials. During evaluation, materials with less performance change shall be regarded as having better recycleability then those with larger performance change.

Performances of some materials are shown in Table 2.

For rubbers, adding recycled rubber in new rubber will increase Viscosity and decrease Tensile Strength, Resiliency and Degree of Resistance to Fatigue. It is why recycled rubbers are usually used in unimportant products. Although recycled rubbers are introduced in tyres with the development of recycling technology, they are only used as tread rubbers and sidewall rubbers. And the amount of recycled rubber must be restricted strictly.

Here, select Viscosity, Tensile Modulus, Elongation of Break, Torsion Modulus, Heat Shrinkability (plastic), Impact Strength (plastic), Hardness (rubber) and Avulsion Strength (rubber) as performance parameters in the evaluation framework. And use parameter union {P} to denote values of those performance parameters.

TABLE 2 PERFORMANCE OF RECYCLED AND ORIGINAL POLYMER

	PET	Re. PET	PVC	Re. PVC	HCM	Re. HCM
Young's Modulus /Mpa	1850	1620				
Tensile Modulus /Mpa					500	700
Tensile Stress /%	48	23			26	26
Break Elongation /%	3.5	100	140	115	250	185
Impact Stress / (J/m)	14	19	62	61		
Heat Shrinkability /%			1.6	1.4		
Strength of Fusible /N			8200	7500		
Torsion Modulus /MPa					600	800

3.3 Compatibility

The compatibility of polymers is not only relevant to the manufacturing process of product, but also to the recycling process. It is common that different polymers from different products come into the same recycle process at the same time. At this stage, compatibility is an important factor for the recycling method selecting. Compatibilities of main polymer are shown as Figure 3.

Compatibility of polymers can't be regarded as indicator of material greenness in the evaluation framework. However, compatibility can influence the choice of the recycling method, then will impact on the material life cycle process, and hence impact on the greenness of the material.

3.4 LCA Analysis

To analyze the EI of polymers, LCA shall be used as a basic method that not only applies to the material itself, but also to the product manufacturing and recycling process. Of course, this will make the LCA analysis more complex. For example, the design of die and mold and selection of one-step or two-steps manufacturing processing can all influence the evaluation results.

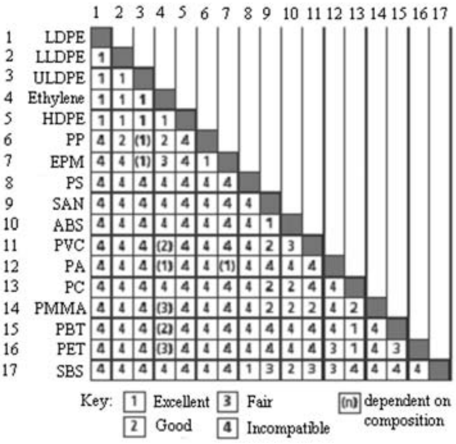


Figure 3 Compatibility of Plastic Material

To make all-around evaluation of polymer material, some models will be built to denote the greenness of the manufacturing and recycling process. In manufacturing process, different selections of manufacturing method such as extruding and injecting will cause different energy consumption. Recycling process is more complex. Mechanical recycling such as the usage of disintegrator and crusher can impact on the energy consumption, however, the major EI are solid waste, atmosphere emission and wastewater produced by chemical recycling methods such as normal reclaimed method for rubber desulfuration and energy recovery by polymer combustion.

Here, the following parameters will used to evaluate the polymer material:

E_C: Energy Consumption (KWh); W_W: Wastewater (Kg);

A_E: Atmosphere Emission (m^3); S_D: Solid Disposal (Kg).

3.5 Lifetime of the Whole Life Cycle

Different applications of certain material will lead to different LCA results and different lifetime. Here use parameter union {G_D} to denote the greenness of polymers. And set:

$$\{G_D\}=\{E_C/T_n, W_W/T_n, A_E/T_n, S_D/T_n\}$$

3.6 Cost

The Cost of material and processing is another key point that must be taken into account. However, 'Greenness' and cost are two counteractive factors. In this research, cost is not the major research point.

4 EVALUATION FRAMEWORK

All parameters of evaluation framework defined above can be divided into three types. The first type acts as the judging point that decides whether life cycle process of polymer can continue. It includes {H} (amount of HS) and {P} (material performances). The second type is the judging point that decides which recycling and reuse method can be selected for E-O-F polymers. It includes {R} (amount of innocuous additives) and compatibility of polymer. The third type is the normal analysis results that denote the evaluation results of polymer. It includes $\{G_D\}$ (greenness results) and cost.

The evaluation framework for polymer material can be illustrated in Figure 4.

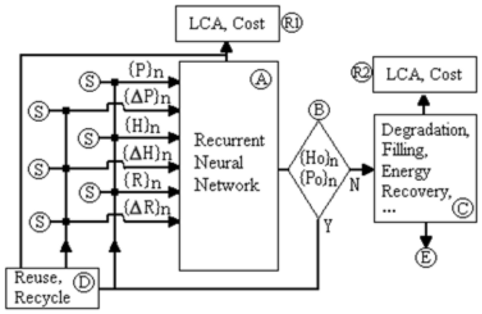


Figure 4 Evaluation Framework for Polymer Material

In Figure.4, 'S' means the starting points and 'E' means the terminal of the material life cycle. Input parameter union means the conditions of polymer that will be put into manufacturing process, in which $\{P\}_n$ means performance of polymer, $\{\Delta P\}_n$ means changes of the performance, $\{H\}_n$ means the amount of HSs, $\{\Delta H\}_n$ means change of HS amounts, $\{R\}_n$ means amount of innocuous residues in material, and $\{\Delta R\}_n$ means amount change of innocuous residues. Here subscript n means that all those parameters are for stage n of model's recycling. 'A' is a model of recurrent neural network that denotes manufacture and usage process of material. Output parameter union of 'A' means the conditions of polymer separated from the taken-back products, in which $\{Ho\}_n$ means the amount of HSs remained in the polymer taken-back at stage n, $\{Po\}_n$ denotes performance of material taken-back at stage n. 'B' denotes a decision-making procedure to identify which reuse/recycle or final disposal method shall be selected for the taken-back material. If the $\{Ho\}_n$ and $\{Po\}_n$ of the taken-back material can fulfill with the requirements for new product's manufacture, then the taken-back material will go to Reuse and Recycling process (Model 'D') directly. And then the output parameter union $\{Ro\}_n$, $\{Ho\}_n$ and $\{Po\}_n$ become the input parameter union of model 'D'. The Output parameter union of model 'D' will become the input parameter union of model 'A' for the new manufacturing process (stage n+1) defined as $\{R\}_{n+1}$, $\{H\}_{n+1}$ and $\{P\}_{n+1}$. Different remanufacture method selection in 'D' will lead to different input values of $\{\Delta R\}_{n+1}$, $\{\Delta H\}_{n+1}$ and $\{\Delta P\}_{n+1}$. If $\{Ho\}_n$ and $\{Po\}_n$ of the taken-back material cannot fulfill the requirements for reuse and recycling, it shall be taken to the final disposal process and select a suitable method from model 'C'. 'R1' and 'R2' denote, respective, LCA results and cost calculation for process in model 'A', 'D' and 'C'.

Detail descriptions of model 'A', 'D' and 'C' are presented as follows:

4.1 Reuse and Recycle Model (Model 'D')

Each process technology of polymer reusing and recyling has different requirements for taken back polymer material, and need new addtives or materials to apply remanufacture process. Based on existing process technologies of polymer resuing and recycling, a support database can be made as support environment for model 'D' to simulate reuse and recycling process that selected from this database.

The reuse and recycling process is a two-step process as shown in Figure 5. The first step is Pre-recycling process including material separation, crashing and purifying from taken-back polymer. Based on $\{Po\}_n$, $\{Ro\}_n$ and $\{Ho\}_n$ of the taken-back polymer, suitable pre-recycle methods can be selected which can lead to different LCA and Cost results. The second step is the polymer remanufacturing process to refine and improve the performance of the polymers by additives. Based on $\{Po\}_n$ and $\{Ro\}_n$ of polymers pre-recycled, choose suitable remanufacturing method. Different method can create different polymers with different preparations and will lead to different input values of $\{\Delta R\}_{n+1}$, $\{\Delta H\}_{n+1}$ and $\{\Delta P\}_{n+1}$. The reuse process is a one-step process that is the pre-recycling process as defined above.

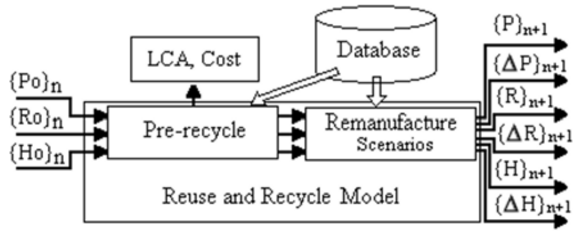


Figure 5 Reuse and Recycle Model

4.2 Final Disposal Model(Model 'C')

Based on research and analysis for existing final disposal process for taken-back polymers, a database can be made to support model 'C' to simulate final disposal process. The final disposal can also be divided into two steps as shown in Figure 6. The first step is the preparation process that makes it ready for final disposal including Material Separation, Cleaning and crashing, etc. The second step is the final disposal including Combustion, Energy Recovery, Vaporization, Degradation, and Landfill, etc. Different preparation and final disposal will lead to different LCA and cost results.

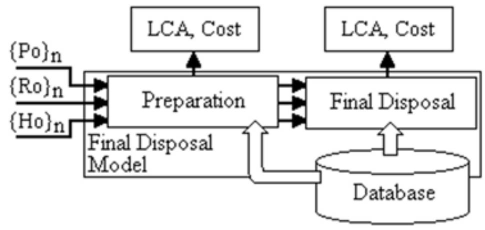


Figure 6 Final Disposal Model

4.3 Recurrent Neural Network Model (Model 'A')

Recurrent Neural network model is used to denote the manufacturing and usage process of polymer products as shown in Figure 7. A three-layers neural network with one hidden layer is used to simulate this process. If one-step method is selected, input and output of the recurrent neural network can denote the conditions of polymer before and after the manufacturing process, respectively. If two-steps method is selected, recurrent neural network will execute twice to simulate whole manufacturing process. After manufacture, recurrent neural network will execute to simulate the usage process. Output parameters of this cycle denote the conditions of E-O-F polymers.

This neural network model has two functions. One is to forecast the LCA & cost results for manufacturing and usage process. During the manufacturing and usage process, most LCA and cost come from energy consumption. In the manufacturing process, energy consumption can be calculated simply by the power and output of the machine. In the usage process, the EI from the polymers can be neglected. Another is to forecast the performance changes, the amount of HSs and residues. Trained with the real manufacture and usage data of certain material, neural network model can simulate performance changes, HSs and residues amount for same material during the manufacture and usage process.

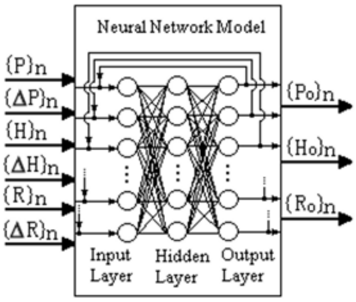


Figure 7 Neural Network Model

Based on this evaluation framework, a simulation can be made for a certain polymer material to forecast its treatment methods after E-O-F, that is, reuse, recycle and final disposal. And different treatment will lead to different LCA results that can be interpreted as the greenness of this polymer.

5 CASE STUDY

Here, four different PVC profile products are selected as case studies. Table 3 shows the material scenarios of the four PVC profile. Here set PVC-S (PVC series) to represent the four PVCs. The scenario of any PVC-S can be regarded as input parameters union $\{R(j)\}_1$ in the evaluation framework. Here parameter j means component j in PVC-S. Some PVC-Ss have Pb or other HSs, and set amount of those HSs as parameters union $\{H\}_1$.

TABLE 3 MATERIAL SCENARIOS OF PVC PROFILE PRODUCT

Material	$\{R\}_1$ and $\{H\}_1$	S1# Unit	S2# Unit	S3# Unit	S4# Unit	Cost USD/ton
PVC	$R(1)_1$	100	100	100	100	1000
CPE	$R(2)_1$	8	8	10	--	1650
3ST	$R(3)_1$	--	3	--	3	1050
2ST	$R(4)_1$	--	1.5	--	1.5	1170
PbST	$R(5)_1$, $H(1)_1$	--	0.6	--	0.6	1510
CaST	$R(6)_1$	1.5	0.5	--	0.5	1350
HST	$R(7)_1$	0.25	0.2	--	0.2	1070
T-137	$R(8)_1$	1.5	--	--	--	5880
ACR201	$R(9)_1$	2	2	1.5	2	2350
ACR-AL	$R(10)_1$	--	--	--	7	2430
WaX	$R(11)_1$	1	0.2	0.2	0.1	520
OPE-1	$R(12)_1$, $H(2)_1$	--	--	--	0.2	2030
TiO_2	$R(13)_1$	5	4	5	5	2040
$CaCO_3$	$R(14)_1$	6	5	10	5	14
UV-531	$R(15)_1$	--	0.25	--	--	20000
SR1+2	$R(16)_1$	--	--	8	--	900
TPP	$R(17)_1$	--	--	0.4	--	1500

To simplify the evaluation process, set conditions for the framework as follows:

5.1 Manufacturing and Usage Process

Set the manufacturing method of the PVC profiles as a one-step extruding process using the same twin-screw extruder. Set parameter $P(1)_n$ and $Po(1)_n$ to denote 'Break Elongation /%', set $P(2)_n$ and $Po(2)_n$ to denote 'Yielding Stress /MPa'. Here $P(1)_n$ and $P(2)_n$ are elements of union $\{P\}_n$; $Po(1)_n$ and $Po(2)_n$ are elements of union $\{Po\}_n$. Trained with the experiment results, the framework can simulate the relationship between performances and manufacture condition as in Figure 8. Output parameters $\{Po\}_1$ of the PVC-S have direct relationships with the rotate speed of screws, and different screw speed will lead to different output and energy consumption.

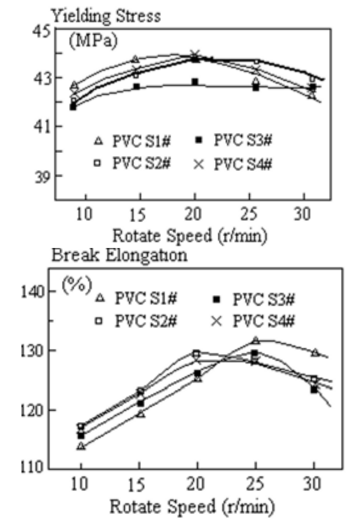


Figure 8 Relationship between Performances and Screw Rotate Speed

To get the best performance, suppose the manufacturing speed of PVC-S1# and PVC-S3# is 25r/min, the speed of PVC-S2# and PVC-S4# is 20r/min. Then the value of $Po(1)_1$ for PVC-S1# to S4# are 43MPa, 44MPa, 42MPa and 44MPa respectively; and the value of $Po(2)_1$ are 132%, 130%, 128% and 128%, respectively. In real situation, performances usually change within certain scope. In this paper, use average value to simplify the calculation.

Performance of the waste PVC-S polymers can be gotten from polymer handbook. With training the neural network with these data, tendency of performance change of the four PVC-Ss during usage process can be simulated. Then values of $\{Po\}_2$ (performances of taken-back PVC profiles) can be calculated. The change process for values of $Po(1)_2$ and $Po(2)_2$ are shown in Fig.9. Normally, usage life time of taken-back PVC profiles are 6 to 20 years. Taken-back materials with different usage life time have different performances and will cause different selection of reusing and recycling process.

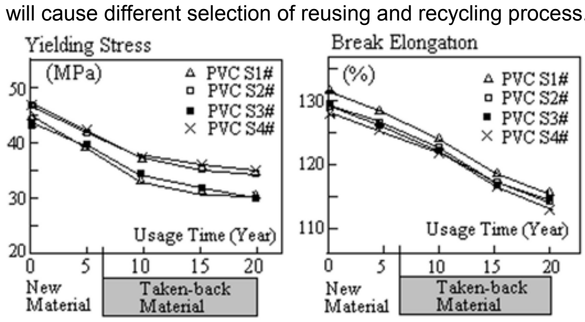


Figure 9 Performance Changes between New and Taken-back PVCs

Because there is no chemical reaction during the PVC manufacture and usage process, set:
$\{Ro\}_2=\{R\}_1$, $\{Ho\}_2=\{H\}_1$.

5.2 Pre-recycle and Preparation Process

The normal pre-recycling and preparation process of PVC profiles is shown in Figure 10, which can purify the PVC-S from the PVC profiles taken-back.

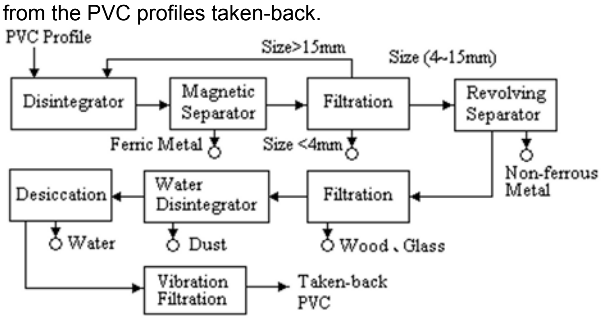


Figure 10 Pre-recycle Process of Taken-back PVC Profile

5.3 Final Disposal Process

Suppose all PVC-Ss that cannot be recycled can be used for energy recovery. Here use PVC component of PVC-Ss to produce muriatic acid (HCl) as shown in Figure 11 to achieve the energy recovery.

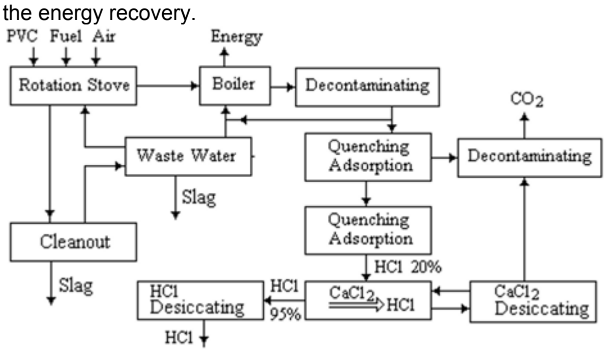


Figure 11 Final Disposal Process for Taken-back PVC

In this process, Slag (Solid Waste), Waste Water and CO_2 emission are key indicators for LCA analysis.

5.4 Remanufacture Scenarios

Commonly used remanufacture methods for taken-back PVC profiles are shown in Table 4.

TABLE 4 REMANUFACTURE SCENARIOS FOR TAKEN-BACK PVC

Product	Machine	Requirements
Multi-layers PVC Pipe	Extruder	New PVC>80% (Wt%), Heat Stabilizer Supplement
Architecture Material	Extruder	New PVC>60% (Wt%), Heat Stabilizer Supplement
Floor Cushion	Imprinter	New PVC>30% (Wt%)
EEE Product	Injector	Requirements of RoHS

Requirements for each remanufacturing method can be summarized as follows:

1) Multi-layers PVC Pipe: Each unit of taken-back PVC-S requires 4 units new PVC-S. Because the multi-layers extruding process will lower the extruding speed, 0.6 units PbST or 1.5 unit CaST will be added to keep the heat stabilization of the PVC component.

2) Architecture Material: Each unit of taken-back PVC-S requires 1.5 units new PVC-S. For the same reason as above, 0.6 units PbST or 1.5 units CaST will be added to keep the heat stabilization of PVC component.

3) Floor Cushion: Each unit of taken-back PVC-S requires about 0.45 units new PVC-S.

4) EEE Product: If the recycled PVC-S is used for this purpose, it will have strict requirements for HS. Because PbST additive is used in PVC-S2# and S4# as heat stabilizer, these two PVC-Ss will have lower possibility to be reused in EEE product.

Normally, the average lifetime of PVC profile and EEE product are 15 years, that of PVC pipe and architecture material are 10 years, and that of Floor Cushion is 7 years.

6 CALCULATION

The analysis process for the four PVC-Ss can be described as follows:

6.1 LCA for the Four PVC-S and the manufacture process

LCA results for the four PVC-Ss are shown in Table 5.

TABLE 5 LCA FOR FOUR DIFFERENT PVC MATERIALS

1Kg	Wastewater (Kg)	Energy (KWh)	Solid Waste (Kg)	Gas Emission (m^3)
S1#	413	1.3	0.2	2.45
S2#	424	1.9	0.4	2.78
S3#	435	1.6	0.5	2.61
S4#	426	1.8	0.4	2.69

When the rotate speed of the screw is 20r/min, energy consumption is 1.2KWh per 1kg PVC-S. When the speed is 25r/min, energy consumption is 1.5KWh per 1kg PVC-S.

6.2 LCA for Final Disposal Process

In the final disposal process shown in Figure 11, every 1Kg PVC will produce 0.36Kg HCl and consume 0.4KWh energy. At the same time, it will produce 0.22Kg slag, 1.4m^3 CO_2 and 0.10Kg other solid waste. The other components of the PVC-S will produce additional LCA results mainly solid waste. And for S2# and S4#, Pb is the major HS.

6.3 LCA for Recycle and Remanufacture

The pre-recycling and preparation process only involves physical method, so LCA only analyzes energy and water consumption. Generally speaking, every 1kg PVC-S, will consume 3.2KWh electricity and 10kg water.

In remanufacturing process, because of the existence of Pb, S2# and S4# can't be reused in EEE product.

6.4 Life Cycle of PVC-S Materials

Based on the above analysis, the life cycle of the four PVC-S shown in Table 3 can be simulated. This research compares the LCA results of two different situations.

The first is that polymers will come into final disposal process directly after one-cycle of usage. (ST1)

The second is that the polymers will be recycled once before final disposal. (ST2)

For ST1, calculation results in section 6.1 can be regarded as LCA results of PVC-Ss. But for ST2, calculation process can be described as Fig. 12. For each kinds of taken back PVC-S, different selection of recycling scenarios will cause different LCA results. Take all possibilities of recycling into consideration, the largest and the lowest LCA results can be calculated.

With LCA results, EI and usage efficiency of scenarios ST1 can be evaluated. And ST2, EI and usage efficiency of each kind of PVC-S can also be analyzed.

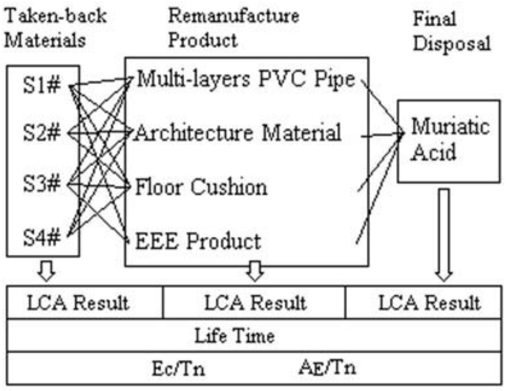


Figure 12 Calculation Process for PVC-Ss

For this case study, calculation results are shown in Fig.13. It can be found that recycle of PVC-S can decrease gas emissions distinctly, but have less effect on energy consumption. And for material itself, EI and usage efficiency of PVC-S1# obviously better than other PVC-S materials.

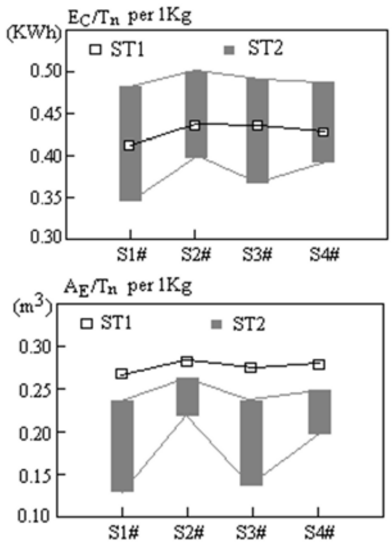


Figure 13 Greenness Evaluation of PVC-Ss

7 CONCLUSION

The life cycle of polymer is a very complex process. It is difficult to use normal method to evaluate whether a polymer is “green” or not. This paper manages to present a framework model to simulate polymer life cycle and analyze the greenness of polymer.

Based on this framework, four different PVC profile materials are selected as case study. Energy consumption and gas emission are used as indicators in the framework to analyze the greenness of PVC-S in its life cycle.

With the evaluation results, this model is proved to be a feasible tool to analyze the EI of polymers giving the complex life-cycle process. It also avails of the possibilities for further optimization of polymers.

8 ACKNOWLEDGMENTS

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Coolants made of native ester – technical, ecological and cost assessment from a life cycle perspective

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Abstract

The use of conventional coolants at the machining of metals causes different environmental problems. Besides plant seed oil, animal fat and used cooking oil proved to be other possible raw material sources for alternative ester based coolants. In this paper their properties are compared with those of mineral oil and plant seed oil ester products regarding technical, economical and ecological aspects from a life cycle perspective. In this context grinding tests, Life Cycle Assessment and Life Cycle Costing were performed. The three disciplines are brought together in a material flow model and therefore results are well harmonized.

Keywords:

Coolant, Animal Fat, Used Cooking Oil, Life Cycle Assessment, Life Cycle Costing, Grinding

1 INTRODUCTION

Sufficiency, efficiency and substitution belong to the strategies of sustainable manufacturing [1]. For the machining of metals coolants − water miscible or non water miscible − are required. They are responsible for cooling and lubricating the contact zone between workpiece and tool and also for rinsing the resulting chips away. In general, conventional petrochemical products are used which lead to health risks for the people working with them as well as to environmental and disposal problems. One ecological disadvantage is the limited resource of mineral oil. In addition, used coolants and oily swarf (e.g. oily grinding chips) need special and expensive waste treatment. Dry machining (sufficiency) and minimal-quantity-lubrication (efficiency) are possible solutions to these problems but are often not applicable in practice. Therefore, it is of great interest to replace conventional coolants with alternative products based on renewable materials that are less toxic and produce less oily swarf [2].

2 ESTER COOLANTS

2.1 Alternatives

A substitution alternative has been found in products based on plant seed oil esters. Plant seed oil esters fulfil all technical demands. But in contrast to petrochemical products, it is not necessary to add critical additives to reach this goal. At the same time, the amount of coolant that adheres on the chips is comparatively small when using plant seed oil esters. Therefore, e.g. a given grinding process produces a reduced quantity of oily swarf. Additional advantages of the plant seed oil esters are their renewable source, their biological degradability, the lack of aromatic hydrocarbons and that they are not water-endangering. Despite these qualities, plant seed esters are still used in industry quite seldom due to their comparatively higher price. Because of their similar chemical structure animal fat and used cooking oil may be suitable coolant base stocks, too (Figure 1). Until recently, these cheap secondary raw materials have been in wide use as nutritional additive for cattle and other animals but now they have been banned because of their assumed role in the transmission of BSE (bovine spongiform encephalopathy). Therefore, they should be excluded from the food chain. Considering their high calorific value (e.g. 36,000 kJ/kg for animal fat), most of the so far proposed alternatives focus on an energetic use. But thinking in cascades, they should first be regarded as valuable raw material for technical products (e.g. for ester based coolants) and just subsequently as derived fuel.

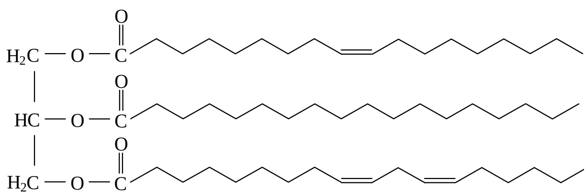


Figure 1: Common chemical structure of native fats and oils.

2.2 Animal Fat

Together with meat and bone meal, animal fat is a waste product of rendering. In Germany, 2.5 million tons of slaughtering offal and animal corpses have to be treated in rendering plants every year. As a result, Germany has an annual production of around 400,000 tonnes of meat and bone meal and additional 200,000 tonnes of animal fat [3]. After BSE crisis, rendering by-products are mostly used as derived fuels. Among different possibilities for animal fat, combustion directly at the rendering plant is getting more and more popular in Germany. For a use as lubricant base oil the fatty acid profile is of big interest. Approximately 45 % of animal fat's fatty acid compounds are saturated. Tribological tests showed that esters of these saturated fatty acids provide better technical skills than unsaturated ones [4]. In rapeseed oil (canola oil), for comparison, the suitable fatty acids make up only about 10 % whilst palm oil consists of 55% saturated esters [5].

2.3 Used Cooking Oil

In Germany ca. 120,000 tons of used cooking oil are collected every year, mainly from gastronomy and food industry. More than 90 % of this amount is exported to the Benelux countries (Belgium, The Netherlands, Luxembourg) and there used as derived fuel [6]. But 20 to 40 % of the fatty acid components are of the suitable kind (saturated). Hence, used cooking oil also has the potential to be a lubricant raw material.

3 METHOD

Within the framework of two research projects coolants based on animal fat and used coking oil esters were developed in co-operation with the Chair for Energy and Environmental Technologies of the Food Industries, TU Munich, the Federal Institute for Materials Research and Testing, Berlin, the Institute of Ecological Chemistry and Waste Analysis, TU Braunschweig, and several industry partners including Volkswagen AG and Castrol Industrie GmbH. To investigate whether these ester coolants are really interesting alternatives for the user, technical aspects as well as cost aspects have to be considered. In addition, a life cycle spanning observation of their environmental impact is necessary to justify their marketing as eco-products. Hence, this paper does not only focus on the technical performance of the observed coolants but also includes economical and ecological criteria. As a reference, a conventional petro-chemical product and a plant seed oil ester product have been chosen. The technical tests of different coolants include screening of relevant physical properties and grinding tests on pilot station and on industry scale. To assess the potential environmental impact of the coolants throughout their life cycle, LCA methodology (life cycle assessment) is applied. In addition, a material flow oriented cost assessment is performed as one variant of LCC (life cycle costing). Technical, environmental and economical evaluation aspects are brought together in a material flow model and therefore are well harmonized allowing further interpretation of results.

4 TECHNICAL ASSESSMENT

4.1 Physical parameters

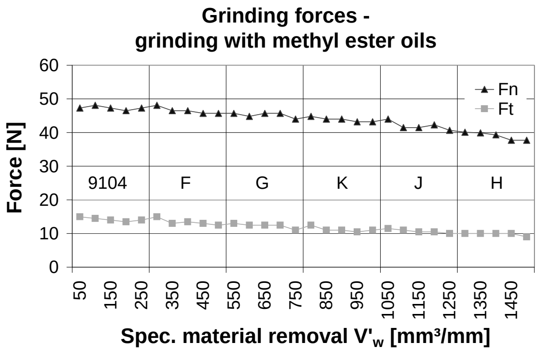
In a first step, the relevant physical parameters of more than 40 developed ester oils were observed. They all met the general requirements regarding flash point and viscosity. The only excluding criterion was the high pourpoint of the methyl, butyl and propyl esters of the stearic fraction. Finally, the methyl ester group and the 2-ethylhexyl ester group were chosen for further investigation because of their very good results and their probably lowest costs of production.

4.2 Grinding test

With these ester oils two different kinds of grinding tests were performed. On the one hand, they were directly compared to each other in uninterrupted tests for both groups (ca. 5 minutes delay between fluid changes). On the other hand, their influence on the tool wear was observed in separate long-time tests for every single ester. During these tests grinding forces, grinding force ratio and workpiece roughness were inspected. In addition, the wheel wear was monitored during the long-time tests. Grinding process parameters are summarized in Table 1. As a reference, a plant seed ester based product (9104) and a mineral oil based product (G500) from Castrol were used. A stable grinding process was possible with all tested ester oils. Figure 2 shows this in order of application for five methyl esters on behalf of grinding forces. The tendency to lower forces the longer the test lasts is caused by sharpening grinding wheel topography but not by the change from one ester oil to another. The grinding force ratios stay on the same level.

grinding process specification	
Grinding process	internal grinding
Grinding wheel specification	CBN, vitrified bonded, B126 M8 VD49
Wheel diameter	ds = 40 mm
Cutting speed	vc = 60 m/s
Workpiece material	100 Cr6, 62 HRC
Workpiece diameter	dw = 110 mm
Width of cut	ap = 10 mm
Spec. material removal rate	Q'w = 2 mm³/(mm*s)

Table 1: Grinding process parameters.



9104 reference product (veg.)	F animal fat methyl ester
G used cooking oil methyl ester	K suet methyl ester
J lard methyl ester	H oleic fraction methyl ester

Figure 2: Grinding forces using methyl esters as coolant [2].

The quality of workpiece surface was not influenced negatively by the developed native coolants. The measured values fluctuated in a normal range for a grinding process under the chosen conditions. Due to high grinding wheel prices and to the time effort necessary to change a grinding wheel, the influence on wheel wear is an important economic aspect when assessing a coolant. Probably caused by their relatively low viscosity the methyl esters seemed to forward wheel wear whereas the ethylhexyl ester oils based on used cooking oil showed an even higher performance than the reference products. An interesting question was if changing raw materials in the rendering plant (e.g. more pig cadavers have to be treated than normal due to an epidemic) will influence the animal fat's suitability for coolant production. But as the results achieved by lard and suet methyl ester were nearly equal regardless of their differing fatty acid spectra, no adverse effects have to be feared.

4.3 Praxis application

As a result of the grinding tests and practical aspects, 2-ethylhexyl esters of the animal fat stearic fraction and of used cooking oil were chosen for a praxis test at Volkswagen plant Salzgitter. They were produced in a quantity of 3 tons each and applied at the machining of crank shafts. Regarding their tribological performance, the praxis test confirmed the perfect performance of ester oils. But a high amount of free fatty acids in the test samples lead to problems with the filter system's auxiliary material. Therefore, low fatty acid content is a condition for market maturity.

5 LIFE CYCLE ASSESSMENT

Even though the usage of renewable sources is one of the main principles of sustainability, products based on renewable materials can also have adverse effects on the environment. To assess these effects, the entire life cycle of the product has to be considered and observed. As for this purpose, the mass and energy fluxes throughout the life cycles of five coolants are compared using the LCA (life cycle assessment) methodology according ISO 14040 family [7]. For the establishment of Cumulated Energy Demand (CED), procedure is based on VDI guidelines [8]. Among the five products one is based on mineral oil, others on rape seed oil ester, palm oil ester, animal fat ester and used cooking oil ester. System boundaries include life cycle phases from crude oil extraction, plant cultivation, slaughtering offal collection and used cooking oil collection respectively till coolant disposal. Environmental burdens are compared regarding a system output of 1,000 workpieces processed with the respective lubricant.

Figure 3 shows the results for global warming potential (GWP). Regarding this impact category, the application of used cooking oil and animal fat lubricants before plant seed oil esters and at last mineral oil based lubricants should be preferred. For all coolant types carbon dioxide has the lion's share on the GWP. In the case of rape seed oil ester, agricultural processes contribute with significant amounts of N_2O from fertiliser production to the GWP.

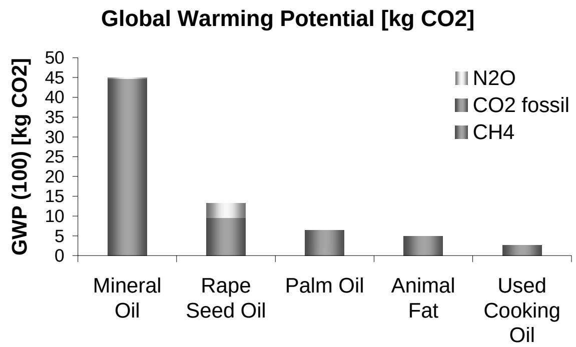


Figure 3: Global warming potential [2].

Altogether, eight impact categories were observed. In Figure 4 results are normalised to category high scores as reference. The indicators show that the used cooking oil product and consecutively the animal fat product cause the lowest potential impact on the environment whereas results for plant seed ester oils and conventional coolants are ambiguous. Advantage of native ester products is very clear in energy balance (CED) and abiotic resource depletion (RD) but in some impact categories scores of plant seed esters clearly exceed those of mineral oil. From the eight assessed categories the mineral oil based system scores the highest values in five categories (abiotic resource depletion RD, cumulated energy demand CED, global warming potential GWP, cancer risk potential CRP, photochemical ozone creation potential POCP) followed by the rape seed oil ester system (acidification potential AP, nutrification potential NP). The palm oil ester system is the reference for particulate matter with a diameter less than 10 µm (PM10). The used cooking oil based variant always has the lowest contributions.

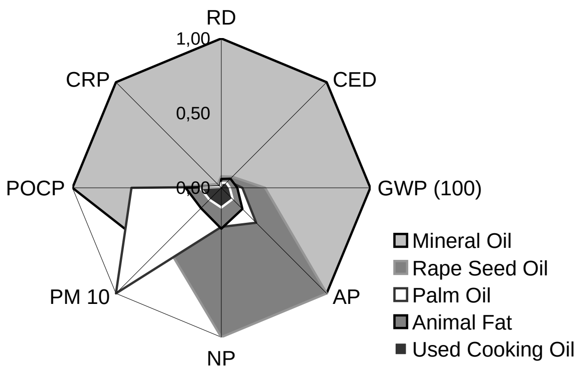


Figure 4: Results for chosen impact categories [2].

Additional scenarios made clear that the positive effect for the environment is several times higher when using animal fat as coolant base stock compared to the actually favoured combustion at rendering plants. A cascadic use of animal fat and used cooking oil – which means the combination of technical use (coolant) and energetic use (fuel) – would be most preferable (Figure 5).

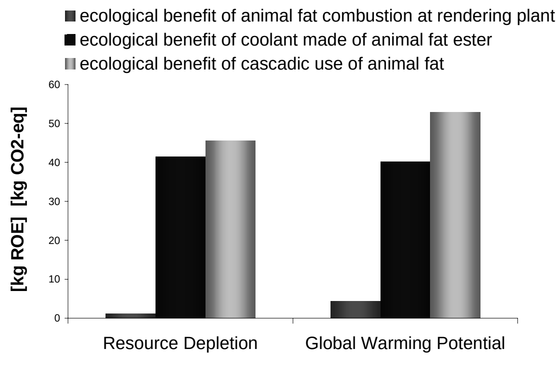


Figure 5: Ecological benefit of animal fat use [2]

6 LIFE CYCLE COSTING

The main disadvantage of native products based on plant seed oil is their relatively high market price. These higher prices cause extra costs for a new filling of a filter unit in case of ester application but they can be compensated by savings due to extended tool life and reduced coolant loss. To achieve transparency in this context, a material flow oriented cost assessment was performed as one variant of LCC (life cycle costing). Therefore, the existing material flow model from LCA procedure was used to assess market prices for used cooking oil and animal fat esters on the one hand and the overall coolant costs for the user on the other hand.

6.1 Market prices

As a conventional mineral oil based coolant costs around 1.35 € per kg, a plant ester product has got a market price of approximately 3.30 € per kg. The examination of cost flows resulted in a production price of 0.93 € per kg for the used cooking oil ester and of 1.01 € per kg for animal fat ester because of significantly lower raw material costs. Including 1.25 € per kg for filling, packaging, sales and profit, market prices of 2.18 € per kg and 2.26 € per kg are achieved (Table 2). So, the developed ester coolants take a mid-position between mineral oil product and plant seed oil ester.

nwmb coolant based on	market price [€/kg]
mineral oil	1,35
plant seed ester	3,30
animal fat ester	2,26
used cooking oil ester	2,18

Table 2: Market prices for different types of coolant [2].

6.2 Life Cycle Costs

Even though users are often attracted by low market prices real costs come clear only when looking at the overall costs of product application. Figure 6 shows life cycle costs for ester oil usage (used cooking oil ester) in comparison to those of mineral oil application from user perspective. Costs for necessary re-filling volumes as well as for disposal and recycling are shown over time. Calculations were made for the modelled contour grinding process. Given a filling volume of 3 tons of coolant per machine tool and a production of 30,000 workpieces per machine tool and week, the extra costs for a new filling (2,500 €) will be compensated by savings due to reduced coolant loss after less than two months.

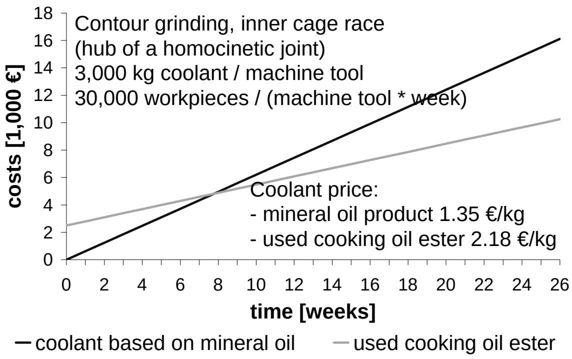


Figure 6: Re-invest of used cooking oil ester coolant

For different machining processes payback periods will vary in dependence of coolant loss rate, workpiece surface and intensity of machine use. Especially in case of ladling workpiece elements re-invest times can sometimes be critical.

7 CONCLUSIONS

Looking at the market prices in relation to the potential environmental impact, it is most striking that the mineral oil product can be offered cheapest while potentially causing biggest harm to the environment (Figure 7). Ongoing rise in crude oil prices will lessen this disproportion. Plant seed ester oils take a mid-position regarding environmental impact, but are most expensive in purchase phase. Animal fat and used coking oil esters show the best ratio − low environmental impact combined with medium market prices. In Figure 7 market prices were chosen instead of life cycle costs because of their still crucial influence on consumers' choice. Size of ellipses stands for technical maturity of the different coolants. While mineral oil and plant seed ester products are fully developed, last steps are necessary for animal fat esters and used cooking oil esters until market maturity (free fatty acid reduction).

The developed esters are less costly alternatives to other environmentally friendly ester products. They stand for a reasonable technical use of high-grade secondary raw materials that should neither be just incinerated without using their technical properties nor re-enter the food chain (Figure 8). Their example is a proof for the high potential of use cascades and should encourage further research.

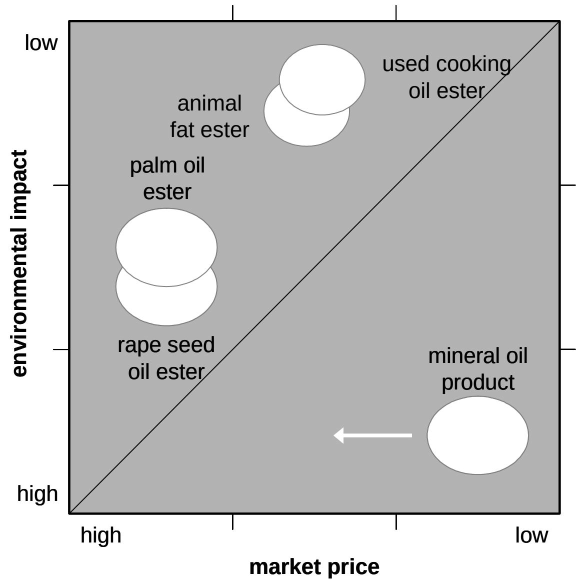


Figure 7: Market price / environmental impact portfolio

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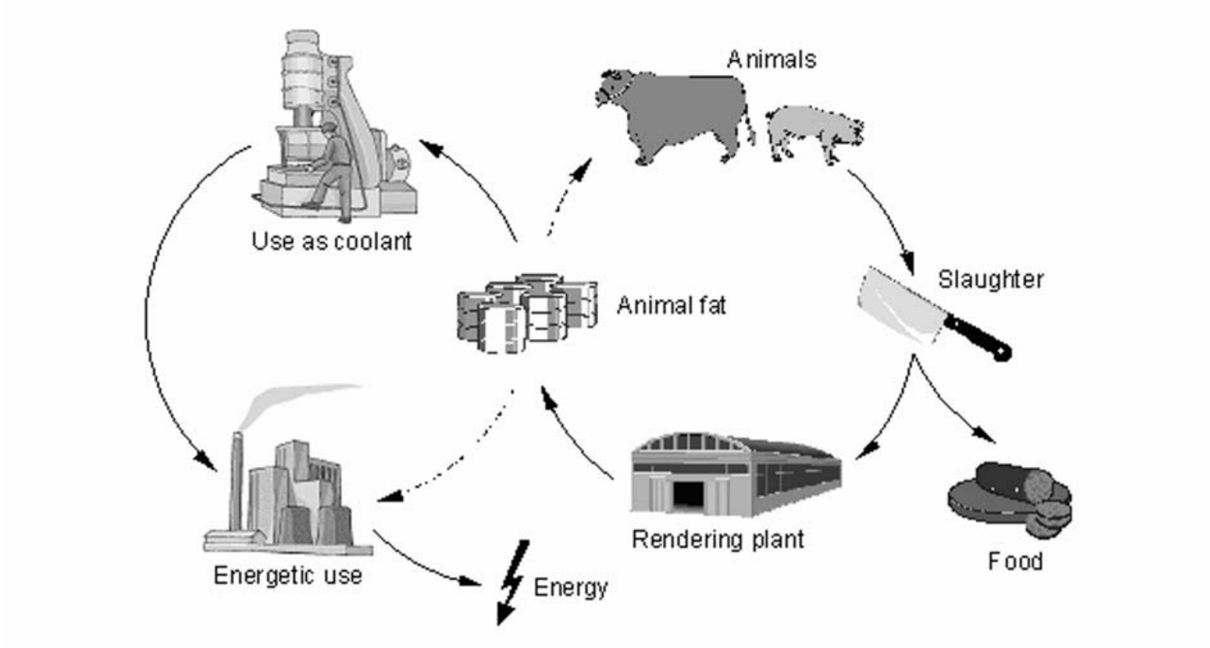

Figure 8: Alternative use of animal fat as coolant instead of re-entry in the food chain or incineration

Investigation of Minimal Quantity Lubrication in Turning of Waspaloy

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Abstract

In order to achieve a more productive and environmentally friendly manufacturing of aerospace propulsion components, minimal quantity lubrication (MQL) can potentially replace the traditionally used flood cooling in different machining operations. These components are manufactured of difficult to machine alloys, which show great hardness even at elevated temperatures. Waspaloy is one of the more demanding super alloys to machine and serve as reference material in this investigation. In this paper, a turning operation is used to investigate the influence of MQL parameters such as oil type together with cutting data on cutting forces and tool wear. As a reference flood and air cooling was used. Two different type of oils were investigated, ester vs. fatty alcohol. The aerosol was directed towards the tool by two different nozzles. Responses that were measured include particle size, aerosol generation capability, cutting forces and tool wear. The experiments were conducted as a D-optimal design of experiments and evaluated by a regression analysis. No evidence of any lubrication effect can be seen. The most plausible explanation of the effects seen is the effects of cooling and heat transfer.

Keywords:

MQL, Waspaloy, Turning, Lubrication, Wear

1 INTRODUCTION

Machining of super alloys is a substantial volume of the manufacturing efforts of aero engine components. Although these alloys have been used for some forty years, many of the manufacturing processes still have quite an improvement potential. The need for process improvements and especially increasing the level of automation is evident in the increasing commercial pressure that is seen in this business. One of the present trends in the metal working industry is to re-evaluate the use of cutting fluids, both from economical and environmental viewpoints. Cutting fluids bring operator health hazards as well as environmental problems in waste disposal, which have resulted in strict regulations for the use and disposal of such fluids. Cutting fluids also represent a substantial proportion of the total production cost. These factors have resulted in a move towards “dry” cutting in the industry. However, dry machining has drawbacks such as increased tool wear and quality limitations. In such cases, MQL (Minimum Quantity Lubrication) provides an alternative to conventional cooling. The technology has the potential to deliver improved machining performance, reduction of overall operational costs, dramatically reduced environmental loads and improved work environment. In preliminary trials on super alloys, MQL-technology has shown promising results in increased robustness of the cutting process.

To fully support a cost-effective industrial implementation of MQL it’s necessary to develop a deeper understanding of the effect of MQL in metal cutting operations. MQL stands for Minimum Quantity Lubrication. One of the central questions in understanding the process is how much of lubrication and how much of a cooling phenomenon that is actually active in the machining process. Is it MQL or MQC (Minimum Quantity Cooling) that is active? Earlier work has not completely clarified this question.

In a paper by Autret et al. [1] the MQL method was investigated on high carbon steel in finish hard turning operation with a CBN tool. Results show that MQL did not affect the cutting force level in any noticeable way. Tool wear was however reduced, indicating other mechanisms than lubrication as active. Their experiments also showed that MQL had no evident effect on surface roughness compare to dry cutting. In another work, Attanasio et al. [2] examined the difference between MQL and dry cutting in turning 100Cr6 steel. The results showed that using MQL on the rake face did not have any obvious wear reduction but that MQL on the flank surface reduces the tool wear and thereby increases the tool life. The conclusion made was that MQL gives some advantages but it still presents some limits. The lubrication effect was however not clarified. Rahman et al. [3] investigated the effect of minimum quantity lubrication on tool wear and surface roughness in turning AISI-4340 steel. They claim reduction of cutting forces as compared to both dry and flood cooling conditions. However, this is shown for short cutting times while at longer times the forces are higher for MQL than for dry and flood cooling. Klocke and Esenblätter [4] reported in a key note paper increased tool service life in general and also in particular for milling in super alloys. The lowering of friction by MQL is claimed, but no evidence by measurements of cutting forces was given.

The aim of the work of which this study forms one part, is to develop a deeper understanding of the MQL machining process and to shed some light on the question of how much of lubrication and how much of a cooling phenomenon that is actually active. In this study the focus is on factors that influence the machining of Waspaloy, a nickel-base, age-hardened super alloy with excellent high-temperature strength and good resistance to oxidation and corrosion. Special emphasis is given to how process parameters are affecting cutting forces and tool wear.

2 EXPERIMENTALS

Experiments described in this paper involve parameter studies, such as oil type, volume flow, cutting velocity and feed rate, measuring how they affect cutting forces and tool wear.

2.1 Experimental setup

Experiments were conducted through a turning operation. Cutting- and feed forces (denominated in figures as Fc and Ff respectively) were continuously measured using a piezoelectric dynamometer. The analysis of these results was performed for two cutting times, three seconds after start (denominated in figures as Fcini and Ffini respectively) of the experiment and a three seconds before the end of the experiment. This was done to avoid impact of tool wear on the results. Tool wear was evaluated at the end of the experiment using optical microscopy. The experiments were executed according to a run order generated by the Design of experiments methodology. As the experimental consists of a qualitative factor with more than two levels the design used was the interaction D-optimal design [5]. Each experiment was conducted with one replicate. The insert material used was carbide and insert type was TCMW 16T308. The carbide insert was uncoated. A tool holder with integrated nozzles for aerosol supply on both the clearance face and rake face simultaneously was used, Figure 1.

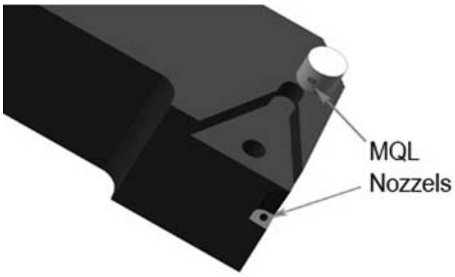

Figure 1: Tool holder with two nozzles for MQL supply

2.2 Cutting conditions

The cutting data was varied in three levels. The levels are shown in Table 1.

	Cutting velocity [m/min]	**Feed rate** [mm/rev]	**Depth of cut** [mm]
Carbide	40, 60, 80	0.05, 0.15	2.5

Table 1: Cutting data range.

The engagement time was converted in to a spiral cutting length of 60 m that was remained constant through all the experiments.

2.3 Cutting fluids

As MQL fluids two types of oils were used, ester and fatty alcohol. The fluids were evaluated for particle size and volume distribution through aerosol spectrometry in order to study its performance to generate aerosol. The settings on the MQL unit were adjusted in order to achieve maximum amount of aerosol and the settings was maintained constant during all experiments. The reference flood coolant was a semi synthetic emulsion (6%).

2.4 Statistical treatment

The total number of experimental runs, 64, were evaluated as follows:

- Evaluations of raw data to assure that no unreasonable values (outliers) exist.
- Regression analysis. The regression model was made according to MLR [5]. The performance of this regression model is shown as a summary plot, Figure 5.
- Interpretation of the model and prediction of values for the different responses. Predictions should here be interpreted as statistical values when repeating the experiments.

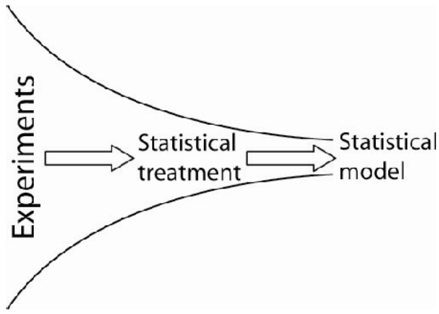

Figure 2: Schematic view of creation of the statistical model.

3 RESULTS

3.1 Aerosol generation

The aerosol spectrometer values show that the different types of oils produce basically the same droplet size, with a mean value approximately 0.45 µm. The main difference is the number of oil particles produced. The fatty alcohol oil is generating more particles than the ester oil, giving a higher volume ratio in the region of 57% more, carried to the cutting tool.

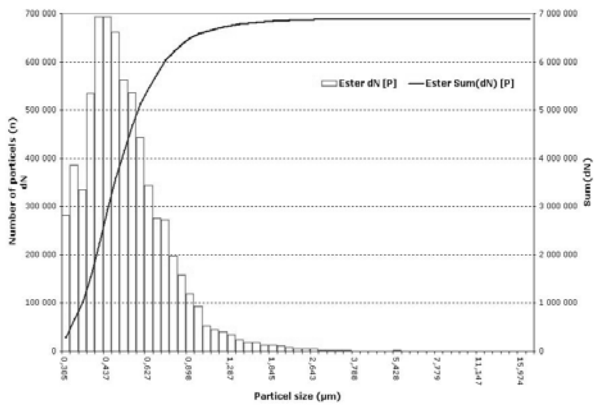

Figure 3: Particle size distribution and number of particles (Sum dN) for Ester.

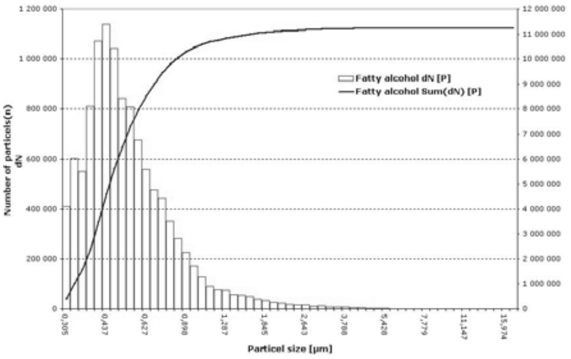

Figure 4. Particle size distribution and number of particles (Sum dN) for Fatty alcohol.

3.2 Cutting forces and Tool wear

Statistical analysis of the experimental results on cutting forces and tool wear shows good model validity, reproducibility and prediction. As shown in Figure 5 the regression model has a high value of significance. As the computed regression models has such a high significance it reasonable to use this model for conclusion and discussions.

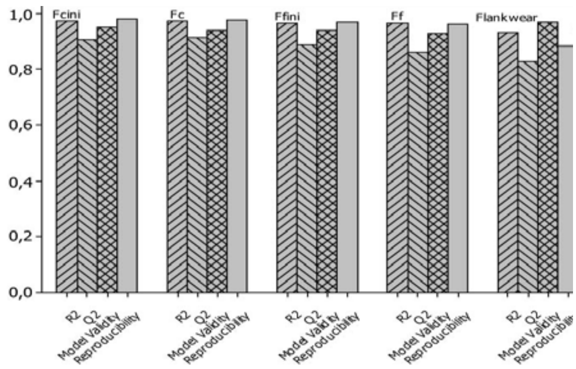

Figure 5. Summary plot of the regression model.

The results for the cutting force and tool wear are given as a mean value with 95 % confidence interval. Results given in the figures below are representative for all the results obtained in this work. The main trends are explained for cutting velocity 40 m/min complemented with the major differences for the results at 80 m/min.

Cutting forces

The main cutting force shows very small discrepancies between the values obtained in the beginning of the experiment and the values obtained just before the end of the experiment, Figures 6 and 7. This is valid for both the actual level of the forces and how the levels are affected by the different cutting conditions. The confidence levels are also similar for the two different cutting times. The robustness of the results on forces is highest (narrow confidence band) for air cooling only and lowest for dry conditions. For all occasions when cutting fluid is used, the main cutting force is increased compared to dry cutting.

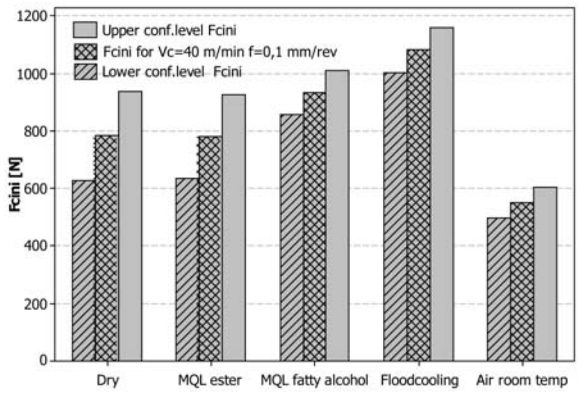

Figure 6: Statistical Cutting force, F_{cini} at v_c 40 m/min, f 0.1 mm/rev

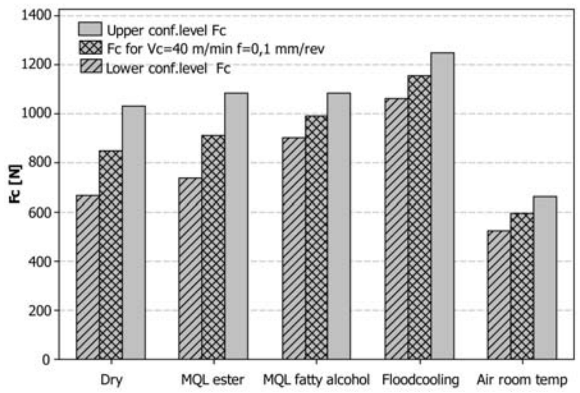

Figure 7: Statistical Cutting force, F_c at v_c 40 m/min, f 0.1 mm/rev

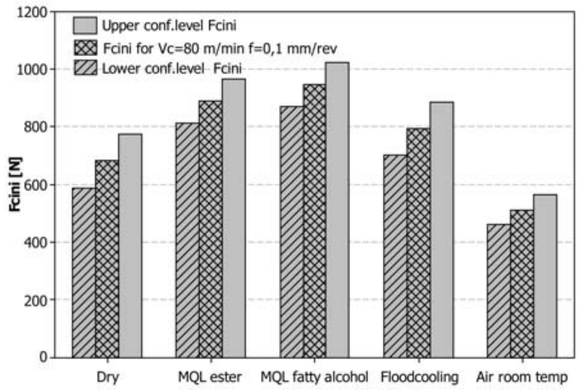

Figure 8: Statistical Cutting force, F_{cini} at v_c 80 m/min, f 0.1 mm/rev

Comparing the results from 80 m/min, Figure 8 (initial values), to the results from 40 m/min, the main difference is that the increase of the main cutting force when using both MQL fluids is higher for higher cutting velocity. The same trend was also seen for the values from the end of the experiment. As for the main cutting force, the feed force also show very little discrepancies between the values from the beginning of the experiment as compared to the end of the experiment, Figures 9 and 10. The main difference is that for the feed force, the level is increasing at longer cutting times when using MQL. The confidence levels show the same trends as for the main cutting force. For one occasion, MQL ester, the feed force shows a tendency to decrease as compared to dry cutting.

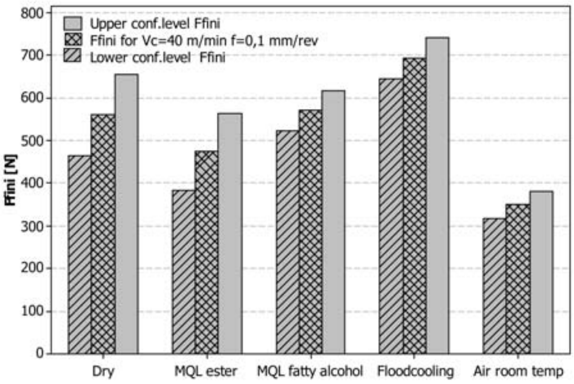

Figure 9: Statistical feed force, F_{fini} at v_c 40 m/min, f 0.1 mm/rev

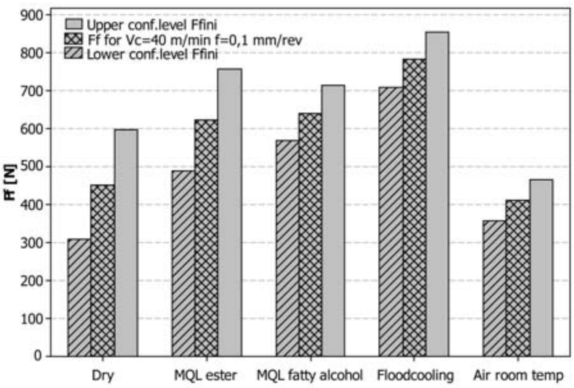

Figure 10: Statistical feed force, F_f at v_c 40 m/min, f 0.1 mm/rev

As for the results of the main cutting force, the feed force show the same difference between the results from 80 m/min, Figure 11, to the results from 40 m/min. The feed forces are higher for higher cutting velocity. This is valid for both types of MQL fluids.

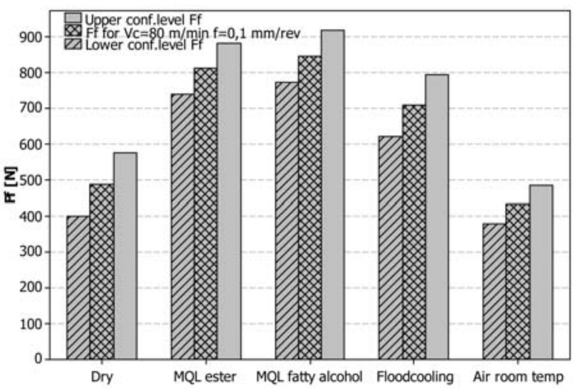

Figure 11: Statistical feed force, F_f at v_c 80 m/min, f 0.1 mm/rev

Tool wear

At a cutting velocity of 40 m/min, the tool wear, Figure 12, is lowered when using cutting fluid (both MQL and flood cooling) or air cooling through the MQL unit as compared to dry conditions. The wear is reduced by approximately 50% when using cooling conditions. There are however very small differences between the results from the different cooling conditions.

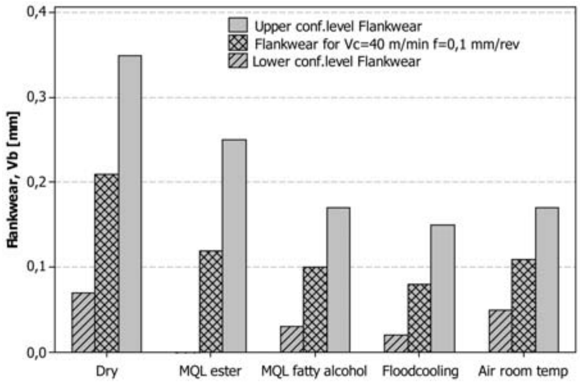

Figure 12: Statistical flank wear, V_B at v_c 40 m/min, f 0.1 mm/rev

For higher cutting velocities, Figure 13, it can be observed that the flank wear is lowered in the range of 25% when using cutting fluids, but up to 50% when using only air as the coolant. The wear reduction is however from a higher wear rate in the v_c 80 m/min- case.

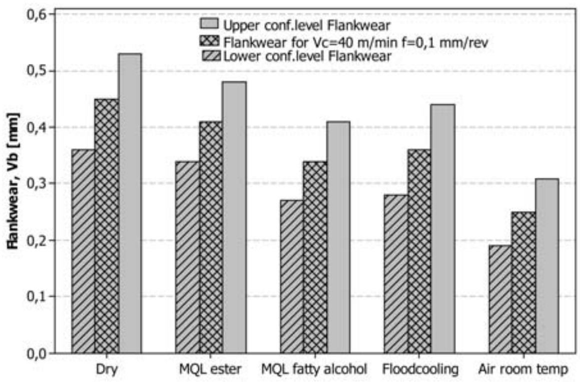

Figure 13: Statistical flank wear, V_B at v_c 80 m/min, f 0.1 mm/rev

4 DISCUSSION

4.1 Cutting forces

In almost all of the cases the cutting forces, both main and feed forces, increase when using cutting fluids. For the only case where a tendency of a lower cutting force is seen, F_f at v_c 40 m/min with MQL ester, this is not a statistically significant difference from dry conditions. If there would be a dominate lubrication phenomenon behind MQL, one would expect the main cutting force to decrease with the use of

MQL oils e.g. aerosol. Thus, no evidence is found in this work for a lubrication effect.

Given the geometrical conditions in turning where the tool is constantly engaged and a new surface is constantly created between the tool and the work piece/chip, it is not likely that the cutting fluid can enter in-between these surfaces. The need for quite a high energy of the cutting fluid to ensure high penetration ("high jet" assisted turning) [6] is also indicating that the lubrication effect is not likely. This is also in agreement from the findings by Autret et al. [1] who found no effect on cutting forces.

The fact that no lubrication effect can be seen in the results of this work but that the cutting forces are rather increasing than decreasing must have other explanations than increased lubrication. The most plausible explanation of the effects seen is the effects of cooling and heat transfer.

Dry machining showed overall low cutting forces, both main and feed, with a tendency towards lower forces when a higher cutting velocity was used. This is not surprising since it is well established that increasing cutting velocities generates higher temperatures in the cutting zone and thereby enhance thermal softening of the work piece material.

For the main cutting force, flood cooling showed the highest values at low cutting velocities. This may be due to the high amount of coolant that is supplied to the cutting zone. This cools down not only the insert but also the work piece. Low temperatures reduce the thermal softening in shear zone and thereby give rise to higher main cutting forces. At high cutting velocity, 80 m/min, a lot more energy is generated in the cutting zone. It's possible that the amount of energy is so large that the flood cooling is not able to provide a sufficient heat transfer from the cutting zone and thereby higher temperatures are present. This may lead to thermal softening of the work piece material in the shear zone. This is also in agreement with the observed increase of main cutting forces for v_c 80 m/min at the end of the experiments.

Flood cooling also exhibit the highest feed forces at low cutting velocity, 40 m/min. However, for the feed forces the values remain approximately the same at higher cutting velocities, e.g. 80 m/min. This is contradictory to the discussion above regarding that the flood cooling is not able to provide a sufficient heat transfer from the cutting zone and thereby higher temperatures are present. This could indicate that there is a redistribution of forces due to changed conditions, e.g. shear angle. Further investigations have to be conducted in order to clarify this.

For MQL fluids, fatty alcohol show higher main cutting forces than ester, this for v_c both 40 and 80 m/min. This may probably depend on the superior capability of generating aerosol, 57 % more particles than ester. In turn this would make it possible to achieve a much more improved heat transfer (higher cooling) as compared to ester.

For the feed forces, MQL oils show lower values than for flood cooling when a cutting velocity of 40 m/min was used. A discrepancy is observed between the feed force measured in the beginning of the experiments and the feed force measured near the end of the experiment for the ester oil. This could be explained by the higher flank wear observed for v_c 40 m/min at the end of the experiment. Fatty alcohol shows in general a higher feed force as compared to ester. However, for a cutting velocity of 80 m/min, a significant increase in feed force for both MQL oils was observed. No explanation could be found for these observations.

The results that air cooling exhibit the lowest both main and feed forces and this at both cutting velocities used in the investigation were unexpected. Especially as the pressure remained the same as in experiments regarding MQL fluids. It is also remarkable to notice the small scatter observed in the results when using air cooling. Since the pressure remained constant, the air velocity should also be unchanged. This implies that the convection heat transfer coefficient would be the same for air streams, both with and without aerosol particles.

However, an air stream with a high share of oil particles will certainly affect the air flow with respect to turbulence etc. No conclusive explanation can be presented to the results obtained in this work. Nevertheless, the results acquired indicates that there is more of a heat transfer process than a lubrication process that govern the low cutting forces observed when using air cooling instead of air plus oil. This is also supporting the theory that if there would be a dominate lubrication phenomenon behind MQL, one would expect the cutting forces to decrease with the use of MQL oils as compared to dry or air flow conditions.

4.2 Tool wear

Regarding tool wear it was shown that dry machining exhibits the largest flank wear and this for both cutting velocities. For cutting velocities of 40 m/min, all coolants, MQL and flood as well as air cooling, the flank wear was approximately in the same range. At the cutting velocity of 80 m/min. the two MQL oil differed somewhat with the fatty alcohol showing lower flank wear.

Since it was found that the fatty alcohol oil could generate a lot more aerosol than the ester oil, this could be the explanation to the lower flank wear that was observed. The lowest flank wear at v_c 80 m/min. was observed for air cooling. It was significantly lower than MQL. One would expect that cutting conditions generating high main cutting forces and thereby generating a lot of heat, softening the carbide and also shows a high feed force, creating high normal forces acting on the flank would show high flank wear. This is not the case in the experiments observed in this work. Instead, air cooling shows both low main cutting forces, low feed force in combination with low flank wear. Further work is needed in order to explain these observations.

5 CONCLUSION

The answer to the question of how much of lubrication and how much of a cooling phenomenon that is actually active in the MQL machining process is that from this work no evidence of any lubrication effect can be seen. The cutting forces are rather increasing than decreasing. This must have other explanations than increased lubrication.

The most plausible explanation of the phenomena is the effects of cooling and heat transfer.

The term MQL is not really accurate but should rather be exchanged to MQC (Minimum Quantity Cooling).

The number of particles generated is the main factor contributing to the positive effect of MQC.

Findings from the experiments reveals that the use of compressed air maybe considered as a low cost and environmentally friendly way of improving machining performance of Waspaloy.

6 ACKNOWLEDGMENTS

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Improvement Potential for Energy Consumption in Discrete Part Production Machines

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Abstract
Industrial production inevitably results in an environmental impact. Energy consumption is responsible for a substantial part of this impact. Currently, machine designers spend little attention to minimising the energy consumption, since their primary focus is on the well-functioning of the machine.
This paper indicates the potential for energy improvement measures. According to Gutowski et al [1], a major part of the total energy consumption of a machine does not depend on the production rate, but is fixed. This paper searches for possible measures to reduce this independent fraction. Another aspect is the importance of the machine occupancy: in a lean manufacturing approach, machines only operate when a product order is released. This implies a constant availability of the machine in a stand-by mode, since high flexibility is required, while the actual processing time may be limited.
This paper audits these energy aspects for two discrete part producing machines types: a press brake and a multi-axis milling machine, and proposes initial design improvements to reduce the overall energy consumption. The possible economical and environmental impact of such energy saving measures from a life cycle perspective is quantified in order to allow cost-benefit analysis.

Keywords:
Energy consumption; discrete part production; machine design

1 INTRODUCTION

Companies investing in new machine tools primarily take functional performance and the initial purchase price into account as selection criteria. Linked to the increasing energy prices, a growing interest in the operational energy consumption can be observed from the end-user side [2,3]. Despite this demand driven interest, no EU initiative is visible today related to regulation of the energy consumption aspects of production machines. With the current European Integrated Pollution Prevention and Control (IPPC) directive (96/61/EC), the focus lies on the so-called 'high energy consuming' industries. In Belgium [4] and the Netherlands [5] the scope of this directive is translated to the level of industrial installations consuming more than 0.5 petaJoule of primary energy per year. Most of these industries are situated in the chemical sector, steel industries and refineries.

The envisaged level in this directive does not apply to common types of machine tools. In this paper this category of investment goods, more specifically, the machine tools used in the metal processing industry, is focused upon. The number of such machine tools installed in the EU is not known. In the US, however, detailed statistics are available as depicted in Figure 1 [6]. From this figure it can be concluded that the metal processing industry (fabricated Metal Products) is responsible for about 5% or 47 billion kWh of the total industrial electricity consumption. Assuming a 3500 kWh [7] yearly electricity consumption per 4-member household, this equals to about 13,5 million households. Assuming a similar situation in Europe indicates the high potential for improvement measures.

In literature, Gutowski et al. [8] already reported detailed measurements on machine level for a number of machine types. They distinguish 8 process categories (machining, grinding, electrical discharge machining, abrasive water jet machining, sand casting, die casting, injection molding, and advanced composites autoclave processing).

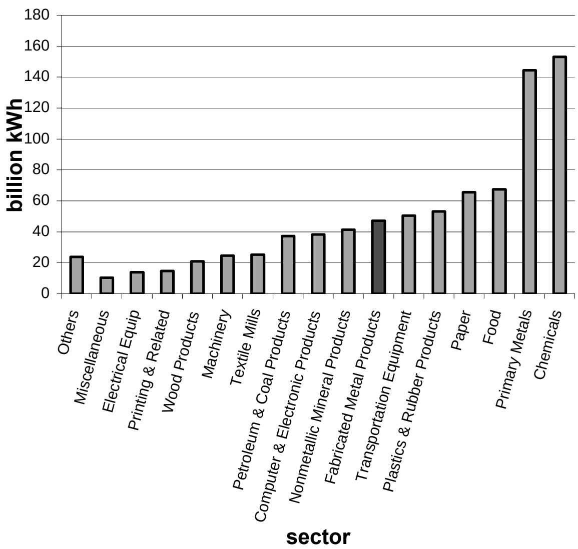

Figure 1: Energy consumption per sector in US [6]

Gutowski et al. indicated that energy requirements depend on the production rate and are consequently not constant as assumed by ecological impact-software packages such as Simapro [9] or Umberto [10]. These software tools assume energy requirements only to be proportional to the physical amount of material processed, thus neglecting the fixed energy consumption due to unloaded motors, coolant pumps controllers and fans, or other peripheral equipment. In the case of an automated 5-axes milling machine this constant energy requirement is, for example, responsible for 40 to 90% of the total energy consumption [11]. Complementary to this source, a similar study was conducted in a European context for a bending and a milling machine, as explained in detail in the following section.

2 APPROACH

This paper discusses the improvement potential for energy consumption of discrete part production machines, emphasising the importance of the non-productive time. In particular, cases are investigated for respectively a press brake (Section 3) and a 5-axis milling machine (Section 4). The general approach, depicted in Figure 2, follows an LCA-like systematic.

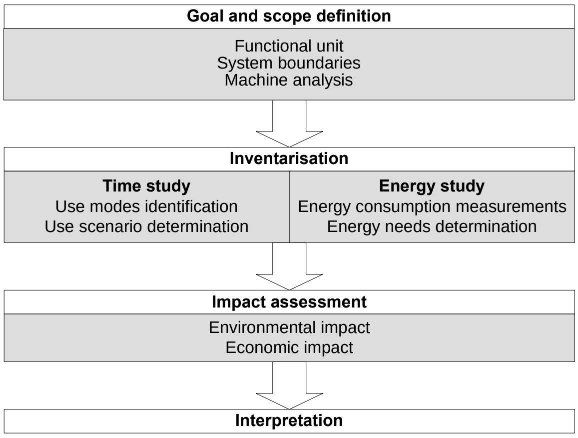

Figure 2 : Research approach

2.1 Goal and scope definition

First, the goal and scope of the study is clarified. The functional unit of the studies is expressed as the availability of a specified manufacturing process functionality for a specified time period. Hence, this functional unit includes both productive and non-productive time.

The system boundaries are set to include only the use phase of the machine, disregarding materials processing, production, maintenance and disposal of the machine. Moreover, the functioning of the manufacturing machines is isolated, disregarding the influence of other elements of the manufacturing system, such as material handling systems, feeding robots, etc. Potentially reduced heating requirements for production halls, due to the availability of waste heat from inefficiently functioning machine components, is also not included. The study moreover focuses on energy consumption; other consumables such as lubricants and coolants are not included. The material being processed is also outside the system boundaries, since these are assumed irrelevant for the goal of the studies. The studies concentrate on Belgian boundary conditions. Finally, the energy consuming units (ECU) of the machine under investigation are identified, together with the functionality of each ECU.

2.2 Inventarisation

Time study

In a second step, time studies are performed in order to identify the different use modes of the machine and their respective share in the covered time span. The identified modes start from the connection of the machine to the electricity grid, over a warm-up run and an operational period, to finally switching off the machine. The operational time can further be subdivided in a number of productive and non-productive modes (idle, tool change,…), each with different energy needs.

The time studies result in an average use scenario for the envisaged machine.

Energy study

All use modes identified in the time study are subsequently scrutinised by measuring the power of the active energy-consuming units (ECU).

2.3 Impact assessment

By combining the results from the time and energy studies, the energy consumption of the investigated machine over the envisaged time span is determined. Both environmental and economic aspects can be investigated.

2.4 Interpretation

The last step covers the interpretation of the results. In particular, the importance of the energy consumption during non-productive time is investigated. This leads to an upper bound for the energy reduction potential of switching off a number of auxiliary systems during stand-by of the machine. Assessing the feasibility of such switch-off actions of course needs further discussion with machine constructors.

3 CASE 1: PRESS BRAKE

In the bending process, a flat sheet metal blank is transformed into a complex 3D structure. A workpiece made of sheet metal, is placed on a die and horizontally positioned against stops. (=backgauge). A bend angle is produced by a punch, forcing the work piece into the die (Figure 3). In this study, air bending, the most common technique [14] in sheet metal bending, is analysed in the further described measurement.

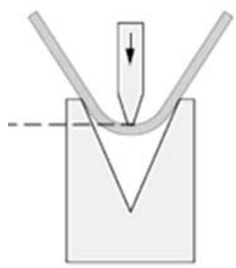

Figure 3: Air bending technique with punch, sheet and die [14]

The next sections apply the methodology described in Section 2 for the case of a press brake with a capacity of 50 tons (Figure 4).

Figure 4: Hydraulic press brake [14]

3.1 Goal and scope definition

The goal of this study is to identify the importance of non-productive time in view of the energy reduction potential of a press brake. The functional unit is defined as the availability and functionality of a 50 ton press brake for bending operations during 1 year. System boundaries are set in accordance to those stipulated in Section 2.1 of the general approach. The studied machine is actuated hydraulically, has a working length of 2,5 meter and has 5 adjustable axes. The data sheet of the machine indicates a maximum capacity of 50 tons (500 kN) and a maximum power consumption of 10.5 kW.

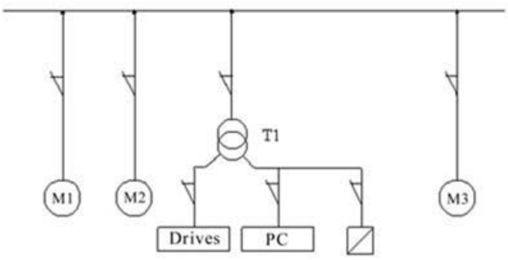

Figure 5: Simplified electric scheme

The press brake consists of two hydraulic systems: a main circuit to actuate the punch and a smaller circuit to clamp the tool set. Four electric systems can be distinguished as depicted in Figure 5.

The main hydraulic system is connected to the electric system by pump M1 and the smaller hydraulic systems by pump M2. The electric system with transformer T1 consists of a subsystem to power the drives, a subsystem with a computer and a last subsystem with a 24V supply. The last electric system consist of motor M3 to compensate the deformation of the punch. The identified machine units are listed in Table 2.

All three motors, M1, M2 and M3, are mounted on top of the machine; hence their generated heat can directly be dissipated to the environment without heating up other machine units. The same situation applies for the five servo motors. The situation is however different for the drives of the servo motors. They are located in a closed housing together with the other electronic devices, including a computer. A ventilator is installed to cool this housing.

3.2 Inventarisation

Time study

In order to identify the use modes of a sheet metal bending press brake, detailed time studies have been performed in three Belgian companies. 12, 8 and 5 hours of bending operation for respectively 15, 7 and 5 distinct orders were filmed and subsequently analysed. A total of 19 different operations could be distinguished, which were subsequently aggregated into 9 use modes, as listed in Table 1. It can be seen that the actual bending operation (5a) is relative short compared to the total production time. Note, however, that this percentage shows a quite large variation if separate orders are evaluated.

n°	*production mode*	*% of total time*
1	*tool setup*: get tool, change and carry away	**4.6**
2	*preparation on pc*: load new order from central server + programming or adapting bending program	**7.2**
3	*supporting task:* move pallets, rearrange sheets, counting, administrative tasks	**16.6**
4	*new sheet:* take a new sheet and position it against backgauge	**13.0**
5a	*punch moving downwards and bending:* actual bending process	**9.4**
5b	*punch moving upwards*	**3.1**
6	*intermediate action:* consult instruction screen and turn the part around between two bends	**14.9**
7	*transport workpiece:* put workpieces away+ rearrange them	**14.0**
8	*measure:* measure the workpiece	**6.8**
9	*human needs and distraction:* being absent, non-productivity: drinking, talking,…	**10.2**

Table 1: production modes and relative time distribution of press brake

Energy study

Since the press brake has a 3-phase power supply, a two-wattmeter method is used for measuring active power, P_{eff} in Equation 1. This method is generally known and can be consulted in [15].

$$P_{eff} = U_{eff} \cdot I_{eff} \cdot \cos \Phi \qquad (1)$$

where P_{eff} , U_{eff}, I_{eff} and Φ represent respectively the effective power (Watt), the effective potential (Volt), the effective current (Ampere) and the phase angle between potential and current (radials).

Overall power requirements

In a first set-up, the overall power requirement of the machine is measured at its main switch. In different use modes, the power requirements are measured and recorded. During start-up, only the computer and some associated devices, such as control panels and instruction screen, are turned on, requiring 260 W (Table 3). Before launching the software program in which the workpieces are designed, the machine should be ‘unlocked’. By doing this, the machine prepares for the production mode, hereby building up pressure in the hydraulic circuits and activating the servo motor. Table 3 refers to this mode as the stand-by mode of the machine and indicates the measured power requirement of 1690 Watt.

	Energy consuming units	function
M1	Hydraulic pump 1 (main pump)	move the two pistons connected to the ram
M2	Hydraulic pump 2 (pump to clamp)	clamp the dies
M3	Small motor	Compensate the deformation of the punch
Drives	servo motor X-direction + drive	move backgauge towards or away from the machine table
	servo motor X * direction + drive	move backgauge towards or away of the table, to support asymmetric parts
	servo motor Z1 direction + drive	move backgauge parallel to the table
	servo motor Z2 direction + drive	move backgauge parallel to the table
	servo motor R direction + drive	move backgauge up and down
PC	PC + control panel 1 (screen, panel with buttons,...) and control panel 2 (pedal with instruments)	programme the machine process and give commands to the machine

Table 2: machine units and its function

The actual bending mode needs multiple recordings since the power requirement in this mode depends on the force to move the punch and bend the sheet. Consequently, the minimum and maximum applicable forces determine the power limits. The maximum applicable force for the studied press brake is 500 kN. Using the methodology described by Aerens et al. [16], one can verify that this limit is reached by bending a 6mm thick and 1000mm wide steel plate (St-37) over an angle of 130° in a 40 mm die. Actual measurement data to perform this bend shows a 10 kW power requirement during downward movement of the punch, including actual bending of the sheet. Returning the punch upwards to its initial position requires 6,3 kW.

Machine mode			M1 k*W*	M2 k*W*	M3 k*W*	pc +…	total *kW*
start-up /shut down			-	-	-	0,26	**0,26**
stand by			1,40	0,03	0	0,26	**1,69**
Production	move down & bend	max	9,50	0,03	0	0,26	**9,79**
		min	2,80	0,03	0	0,26	**3,1**
	move up		6,00	0,03	0	0,26	**6,29**

Table 3: power consumption of the press brake

A lower boundary for the press brake load of ca. 1 ton is sufficient to bend a 1,5mm thick and 170mm wide steel plate (St-37) over an angle of 170° in a 12mm die. Executing this bending operation showed a power requirement of 3,1 kW during downward movement of the punch, including actual bending of the sheet. Returning the punch upwards again required 6,3 kW.

One can conclude that the power demand to move the punch downwards remains equal before and during bending, and lies between 3,1 kW and 10 kW. The total power to move up the punch is independent of the load and equals 6,3 kW.

Finally, the shut-down mode is comparable to the start-up mode.

Power requirements of individual machine units

This section reports on the measurements of the power requirement of individual machine units, starting with the main pump M1. When the machine is in standby mode the pump demands 1,4 kW. It should be noticed that this power consumption is in reality not constant, but decreases due to changing viscosity of the oil. During the measurement campaign, the required power reduced from 1500 watt in the first minutes to 1280 watt after 3 hours. An average of 1.4 kW is used in this paper. When pushing the machine to its maximum by bending the 6 mm sheet, a power demand of 9,5 kW was recorded. Bending the 1,5 mm sheet required 2,6 kW. Moving up the punch demanded 6kW in both cases.

Note that pump M1 runs continuously during all use modes except start-up and shut-down, and represents a considerable share of the required power. The product specifications indicate that it concerns a 'high efficiency' pump [17], though no further data are available to date.

Five servo motors position the backgauge to support the work- piece. Table 4 summarizes the power requirements for each servo motor while moving them separately. The drives move over two meters maximum and this only for a few seconds. For this reason they are not taken into account when calculating the energy requirement for the machine.

servo motor	X	X*	Z1	Z2	R
power (kW)	0,45	0,10	0,10	0,10	0,30

Table 4: power consumption of servo motors

The pump building up the pressure to hold the tools (M2) continuously consumes 30 Watt. When the tools are clamped and unclamped, the pump consumes 700 watt. However, since this process only takes a few seconds, this extra energy consumption is not considered further.

Motor M3 compensates the deformation of the punch. Only during a compensation operation, which takes only a few seconds, the motor consumes electric power, i.e. 500 Watt. Due to the short operation time span, this energy consumption is negligible, and not considered in Table 3.

3.3 Impact assessment and interpretation

The results of the power measurements are combined with the time study and summarized in Figure 6. The total share of non-productive use modes in the overall energy consumption of the press brake proves to be 65% (Figure 7). Assuming that the bending machine operates 2000 hours (8 hours a day, 5 days a week, 50 weeks a year), it consumes a total of 4,5MWh. The energy consumption during non-productive time amounts to 2,9MWh. This corresponds to the energy consumption of 0,8 Belgian households.

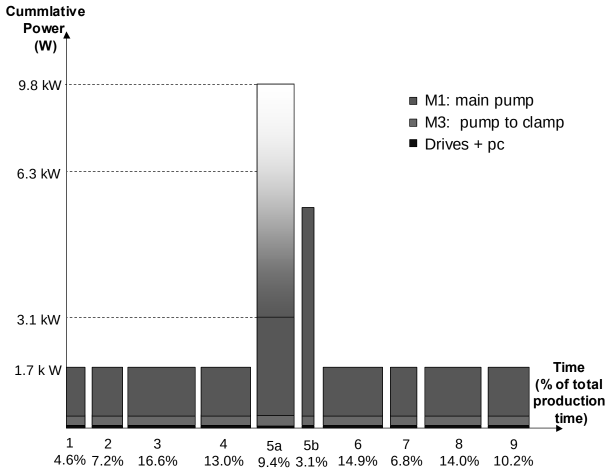

Figure 6:Relative energy consumption per production mode

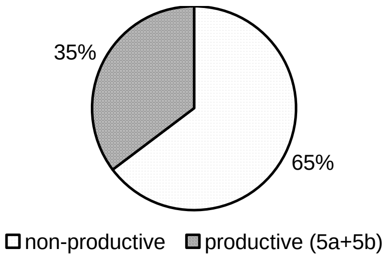

Figure 7: Total energy consumption of the press brake

As indicated higher, the major electric energy consumption is due to the hydraulic pump M1. An electromotor could provide the same functionality, as is being implemented in a newly emerging press brake type [18]. In addition to the energy savings, an electromotor also requires less maintenance, which results in lower operational costs. The responsible machine constructor applies an electromotor system for press brake capacities up to 200 ton. The higher the maximum load of the machine, the higher the potential energy savings by implementing such alternative drive system.

4 CASE 2: MILLING MACHINE

In a second case study, the approach outlined in Section 2 is applied to a 5-axes milling machine.

4.1 Goal and scope definition

The functional unit is defined as the availability and functionality of a 5-axes milling machine for milling operations during one year (2000 hours). The studied machine disposes of a main motor activating the spindle and five servo motors for positioning and orienting workpiece and spindle along the 5-axes. Energy consuming peripheral equipment includes a hydraulic pump, a lubrication pump, 3 ventilators and some electronic equipment.

4.2 Inventarisation

Time study

In a previous study, Dahmus and Gutowski [11] identified three use modes: the idle-mode; when the machine is ready for production, the run-time mode; when the machine positions and loads the tools, and the production mode; the actual milling operation. The relative amount of time spent in each production mode is listed in Table 5.

n°	***production mode***	***% of total time***
1	*Idle:* ready for production	**26**
2	*Run-time:* positioning and loading	**39**
3	*Milling:* material removal operation	**35**

Table 5: production modes and relative time distribution of milling machine [11]

Energy study

Energy measurements on a five-axis milling machine show that, in idle or stand-by mode, the machine consumes ca. 1.7kW (Figure 8). The largest consumer is the hydraulic pump, responsible for nearly 0.9kW.

In run-time mode, additional power consumption is caused by e.g. tool changes or workpiece and spindle positioning. The power requirements of the servo motors depend on speed and vary between 0,4 and 0,5 kW for horizontally moving servo motors and between 0,5 and 0,9 kW for vertically moving servo motors (Table 6).

During actual milling operations, the power consumption increases to ca. 4.5kW at 40% load, which corresponds to the maximum capacity of the test set-up. Evidently, the visible trend continues beyond the test limit.

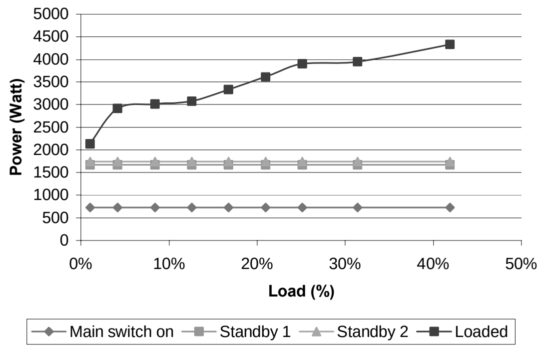

Figure 8: Power consumption as a function of machining load for the 5-axis milling machine

Power	servo motor X	Servo motor Y	Servo motor Z	Tool change
min (kW)	0,4	0,5	0,4	1,5
max (kW)	0,5	0,9	0,5	2,1

Table 6: power consumption of servo motors and tool change

Two comparable automated milling machines described in [11] indicate a power consumption of 1,2 kW and 3,4 kW during idle mode; increased by 1,8 kW and 3,1 kW during run-time mode and by another 5,8 kW and 6,0 kW during the actual milling mode for each machine respectively.

4.3 Impact assessment and interpretation

The results of the time study and the power requirements are summarized in Figure 9. The total share in energy consumption of the non-productive modes is in this case the sum of the energy consumption during the idle and the run-time mode and is as high as 47% (Figure 10).

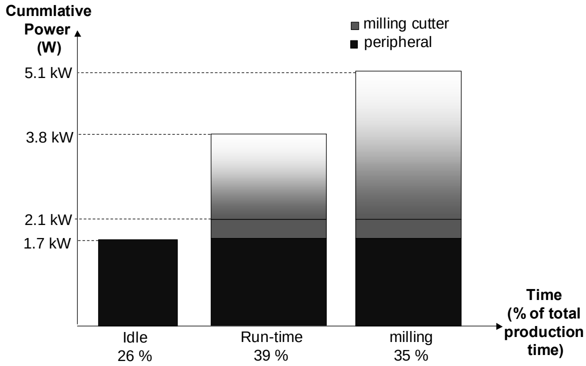

Figure 9: relative energy consumption per production mode

Assuming a year with 2000 operating hours, the milling machine consumes a total of 6,7 MWh. The non-productive modes are responsible for 3,2 MWh. This equals the total electricity consumption of 0,9 Belgian households. As indicated earlier, the peripheral equipment demands a constant amount of 1,7 kW during all production modes adding up to a total of 3,4 MWh per year.

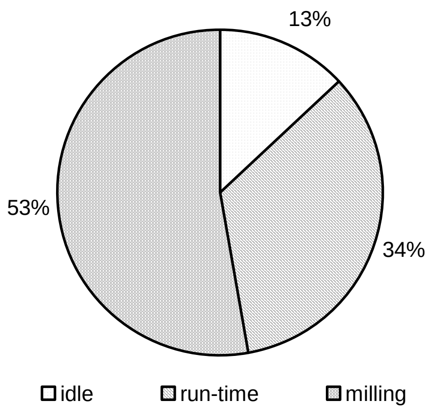

Figure 10: Total energy use of the milling cutter

5 CONCLUSIONS

This paper points out that the energy consumption during non production modes is substantial and hence has a large potential for reduction. In the case of the 50-ton press, it is shown that this mode is responsible for 2,9 kWh per year, or 65% of the yearly total energy consumption. In the case of the milling machine 3,2 kWh or 47% of the total yearly energy consumption could be allocated to this mode.

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A Variational Approach to Inspection Programs of Equipment Subject to Random Failure

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Abstract
A method for determining optimal inspection schedules of equipment is discussed, in which failures of equipment are detected only by inspection. The inspection density function, which generates inspection schedules, is employed in a minimization problem. Two types of objective are considered: the expected cost per cycle, and the expected cost per unit time. An optimal inspection density function is derived by the variational method. The proposed method can generate optimal inspection schedules when failure distributions of equipment are completely unknown. Optimal inspection density functions and optimal sequences of inspection times are obtained explicitly for some cases that failure distributions are completely unknown.

Keywords:
Inspection; Variational Method; Inspection Density Function

1 INTRODUCTION

Inspection is carried out at various stages in the life cycle of equipment. In this study, inspection performed in an operational phase is considered for optimization. Inspection is considered as a means of confirming whether equipment operates normally or whether it works correctly when needed. An increase in maintenance cost results when the inspection interval is short since cost accompanies inspection. On the other hand, failure of equipment may arise or loss generated by failure of equipment may increase when the inspection interval is long. Therefore, it is important to determine appropriate inspection schedules in order to reduce maintenance cost.

Optimal inspection schedules for a single-unit system whose time to failure is described by a probability distribution, in which loss caused by its failure is limited to a linear loss rate function, were derived on the basis of the variational method [1][2][3]. Moreover, optimal inspection schedules were examined on the assumption that the probability distribution of the time to failure is unknown; however, the loss rate function was limited to a linear type [1][3]. Okumura [4] discussed inspection schedules by the variational method, in which equipment has a general type of loss function after its failure and the objective is the expected cost per cycle. A criterion of the expected incurred cost per unit time over an infinite time horizon has not been treated.

In this paper, the cases in which the probability distribution of the time to failure is given and unknown are considered when inspection schedules are optimized. The objective in this paper is the expected cost per cycle and the expected incurred cost per unit time. For the case in which the probability distribution is given, a conditional equation that optimal inspection schedules should satisfy is derived, in which the loss rate function is in a general form. When the probability distribution is assumed to be unknown, a differential equation that optimal inspection schedules should satisfy is obtained.

2 FORMULATION

2.1 Assumptions

(1) Equipment is a single-unit system.

(2) When a system fails, the failed state is detected only by inspection with probability 1.

(3) Inspection is conducted at time t_k ($k = 1, 2, \ldots$) with negligible time for an inspection.

(4) A probability density function and a cumulative distribution function of the time to failure of a system exists, which are denoted by $f(t)$ and $F(t)$ ($t \geq 0$), respectively. A failure rate function is denoted by $\lambda(t) = f(t)/\overline{F}(t)$ ($t \geq 0$), where $\overline{F}(t) \equiv 1 - F(t)$.

(5) The time-to-failure distribution is not influenced by inspection.

(6) Loss, which is characterized by a loss rate function $L(t)$, is incurred from the moment the system fails until the time when it is detected.

(7) A continuous inspection density function $n(t)$ exists, which gives the approximate number of inspections per unit time [1]. Herewith, the inspection interval is approximately given by $1/n(t)$. If $n(t)$ is identified, t_k are determined since we have the relation $\int_0^{t_k} n(t)\,dt = k$ [2]. Here, inspection time is given by

$$t_k = N^{-1}(N(0) + k), \quad k = 1, 2, \ldots, \tag{1}$$

where $N(t)$ is the primitive function of $n(t)$.

(8) An inspection cost is denoted by c.

2.2 Objective

We consider two types of objective: expected incurred cost per cycle and expected incurred cost per unit time.

(1) Expected incurred cost per cycle

The sum of the expected costs, whose elements are inspection cost and loss cost, is approximately given by

$$EC_1 = c\int_0^\infty \overline{F}(t)n(t)\,dt + \int_0^\infty \left(n(t)\int_0^{1/n(t)} L(x)\,dx\right) f(t)\,dt, \quad (2)$$

which arises in a sequence of time: an as-good-as-new state that begins at $t = 0$, a failed state whose time of occurrence is characterized by $F(t)$, and duration of the failed state until the failure is detected by inspection[4].

(2) Expected incurred cost per unit time

The sum of the expected costs, whose elements are inspection cost and loss cost, is approximated by

$$EC_2 = c\int_0^\infty \overline{F}(t)n(t)\,dt + \int_0^\infty \left(\int_0^{1/n(t)} L(x)\,dx\right) f(t)\,dt. \quad (3)$$

The expected length of a cycle is given by

$$ET = \int_0^\infty \overline{F}(t)\,dt + \int_0^\infty \frac{f(t)}{n(t)}\,dt. \quad (4)$$

Therefore, the expected cost per unit time over an infinite time horizon is expressed as

$$\frac{EC_2}{ET}. \quad (5)$$

2.3 Optimal inspection density function when time-to-failure distribution is given

(1) Objective: Expected incurred cost per cycle

The Euler equation is derived in order to find $n(t)$ which minimizes equation (2):

$$\frac{1}{n(t)}L\left(\frac{1}{n(t)}\right) - \int_0^{1/n(t)} L(x)\,dx = \frac{c}{\lambda(t)}. \quad (6)$$

Nonlinear equations for $n(t)$, which are derived by substituting potential $L(t)$ into equation (6), are solved.

(a) $L(t) = c_1 t^p + c_2$ (p, c_1, c_2: positive constant)

$$n_1^*(t) = \left(\frac{c_1 p}{c(p+1)}\lambda(t)\right)^{1/(p+1)} \quad (7)$$

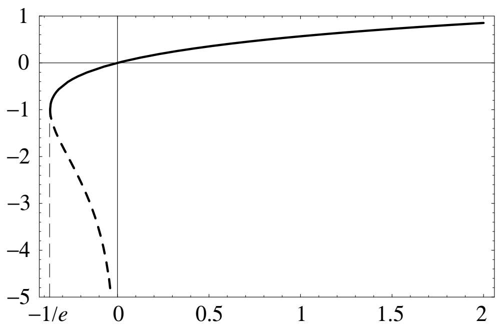

Figure 1: The real values of the Lambert W function (the solid line: $W_0(x)$, the dashed line: $W_{-1}(x)$).

(b) $L(t) = c_1 t^2 + c_2 t + c_3$ (c_1, c_2, c_3: positive constant)

$$n_2^*(t) = \frac{k_1\lambda(t)}{G(\lambda(t))} + G(\lambda(t)), \quad (8)$$

where $G(x) = \{x(k_2 + (k_2^2 - k_1^3 x)^{1/2})\}^{1/3}$, $k_1 = c_2/6c$, $k_2 = c_1/3c$.

(c) $L(t) = c_1(\exp[c_2 t] - 1) + c_3$ (c_1, c_2, c_3: positive constant)

$$n_3^*(t) = \left[\frac{1}{c_2}\left\{1 + W_0\left(\frac{1}{e}\left(\frac{cc_2}{c_1\lambda(t)} - 1\right)\right)\right\}\right]^{-1} \quad (9)$$

is derived, where $W(\cdot)$ is the Lambert W function as shown in Figure 1, which is the complex-valued function that satisfies $W(x)\exp[W(x)] = x$ for all $x \in \mathbb{C}$.

Note that the increasing and decreasing properties of $n_i^*(t)$ ($i = 1, 2$ and 3) correspond to those of $\lambda(t)$ at every $L(t)$.

(2) Objective: Expected incurred cost per unit time

The following Euler equation is obtained:

$$\delta EC_2 \cdot ET - EC_2 \cdot \delta ET = 0, \quad (10)$$

which yields

$$\left\{\frac{c\,n(t)}{\lambda(t)}\right\}^2 + \left\{2c - \frac{1}{n(t)}L\left(\frac{1}{n(t)}\right)\right\}\frac{c\,n(t)}{\lambda(t)} + c\left\{\int_0^{1/n(t)} L(x)\,dx - \frac{1}{n(t)}L\left(\frac{1}{n(t)}\right)\right\} = 0. \quad (11)$$

Optimal inspection density functions are derived by substituting potential $L(t)$ into equation (11).

(a) $L(t) = c_1$ (c_1: positive constant)

$$n_4^*(t) = -\lambda(t) + \sqrt{\frac{c_1}{c}\lambda(t) + \{\lambda(t)\}^2} \quad (12)$$

(b) $L(t) = c_1 t^p + c2$ (p, c_1, c_2: positive constant)

The following equation should be solved:

$$n^{p+3} + 2\lambda n^{p+2} - \frac{c_2\lambda}{c} n^{p+1} - \frac{c_1\lambda}{c} n - \frac{c_1 p \lambda^2}{c(p+1)} = 0, \quad (13)$$

where $n := n(t)$, $\lambda := \lambda(t)$.

When $L(t) = c_1 t^2 + c_2 t + c_3$ and $L(t) = c_1(\exp[c_2 t] - 1) + c_3$ we cannot obtain an optimal inspection density function in algebraic form.

2.4 Optimal inspection density function when time-to-failure distribution is unknown

When $\lambda(t)$ is given, optimal inspection density function $n^*(t)$ which minimizes EC_1 or EC_2/ET can be derived. If $\lambda(t)$ or $F(t)$ is unknown, a minimax solution, i.e., $\max_{F(t)} \min_{n(t)} EC_1$ or EC_2/ET, is considered, by which conservative inspection schedules can be obtained.

We can see that the optimal inspection density function is denoted by $n^*(t) = q(\lambda(t))$ from equations (6) and (11); therefore, $\max_{F(t)} \min_{n(t)}$ is equivalent to $\max_{\lambda(t)} \min_{n(t)}$.

(1) Objective: Expected incurred cost per cycle

The Euler equation for $\max_{\lambda(t)} \min_{n(t)}$ is given by

$$\begin{aligned} &\{(\lambda^2 - 2\lambda')q' - \lambda\lambda' q''\}\left\{q \int_0^{1/q} L(x)\,dx - L\left(\frac{1}{q}\right)\right\} \\ &\quad - cq(q - \lambda q' + \lambda' q'') - \lambda\lambda'\left(\frac{q'}{q}\right)^2 L'\left(\frac{1}{q}\right) = 0, \end{aligned} \quad (14)$$

since we have the relations $F(t) = 1 - \exp[-\int_0^t \lambda(t)\,dt]$ and $f(t) = \lambda(t)\exp[-\int_0^t \lambda(t)\,dt]$, where $q := q(\lambda(t))$, $q' := q'(\lambda(t))$, $q'' := q''(\lambda(t))$, $\lambda := \lambda(t)$, and $\lambda' := \lambda'(t)$.

When $L(t) = c_1 t^p + c_2$,

$$q_1(x) = \left(\frac{c_1 p}{c(p+1)} x\right)^{1/(p+1)} \quad (15)$$

from equation (7). Then equation (14) becomes

$$\lambda_1'(t) - (p+1)\{\lambda_1(t)\}^2 = 0. \quad (16)$$

If $\lambda_1(0) = a$ is assumed to be an integration constant,

$$\lambda_1(t) = \frac{a}{1 - (p+1)at} \quad (17)$$

is derived from equation (16). Then, we have

$$\begin{aligned} n_1^{**}(t) &= q_1(\lambda_1(t)) \quad (18) \\ &= \left(\frac{c_1 p}{c(p+1)} \cdot \frac{a}{1-(p+1)at}\right)^{1/(p+1)} \\ &\qquad 0 \le t < \frac{1}{a(p+1)}, \quad (19) \end{aligned}$$

$$\max_{\lambda(t)} \min_{n(t)} EC_1 = \left\{\frac{c_1}{p+1}\left(\frac{c}{ap}\right)^p\right\}^{1/(p+1)} + c_2. \quad (20)$$

We cannot obtain explicit solution of equation (14) when $L(t) = c_1 t^2 + c_2 t + c_3$ and $L(t) = c_1(\exp[c_2 t] - 1) + c_3$.

(2) Objective: Expected incurred cost per unit time

The Euler equation for $\max_{\lambda(t)} \min_{n(t)}$ is derived as

$$\begin{aligned} &\{(\lambda^2 - 2\lambda')qq' + 2\lambda\lambda'(q')^2 - \lambda\lambda' qq''\} \\ &\quad \cdot \left\{\int_0^{1/q} L(x)\,dx - \left(\frac{1}{\lambda} + \frac{1}{q}\right) L\left(\frac{1}{q}\right)\right\} \\ &- q^3\left\{c - \int_0^{1/q} L(x)\,dx\right\} \\ &+ cq^2\left\{q'\left(q + 2\lambda - 2\frac{\lambda'}{\lambda}\right) - q''\left(\frac{q\lambda'}{\lambda} + 2\lambda'\right)\right\} \\ &+ 2c\lambda' q(q')^2 \\ &- \lambda'(\lambda + q)\left(\frac{q'}{q}\right)^2 L'\left(\frac{1}{q}\right) = 0. \end{aligned} \quad (21)$$

When $L(t) = c_1$

$$q_4(x) = -x + \sqrt{\frac{c_1}{c}x + x^2} \quad (22)$$

from equation (12) yields

$$\lambda_2'(t) + 2\{\lambda_2(t)\}^2\left(1 + \frac{c}{c_1}\lambda_2(t)\right) = 0 \quad (23)$$

for equation (21). Since $\lambda_2(t)$, c, $c_1 > 0$, then $\lambda_2'(t) < 0$; $\lambda_2(t)$ is a nonincreasing function when the objective is EC_2/ET. Whereas $\lambda_1(t)$ is a nondecreasing function when the objective is EC_1.

3 SOME EXPLICIT RESULTS

3.1 When time-to-failure distribution is given

(1) Objective: Expected incurred cost per cycle

Equations in a closed form for (1) the number of inspections, (2) optimal inspection time, and (3) the condition that the number of inspections is m ($m = 1, 2, \ldots$) are derived.

(a) Failure distribution: the Weibull distribution

When $L(t) = c_1 t^p + c_2$ and the time to failure is provided by the Weibull distribution $\lambda(t) = \beta/\eta \cdot (t/\eta)^{\beta-1}$, the following is obtained in the range of $\{t \mid F(t) \le 1 - \varepsilon\} \iff \{t \mid 0 \le t \le \eta(\ln \varepsilon^{-1})^{1/\beta}\}$, where ε is a small positive constant.

- Number of inspections:

$$\begin{aligned} n_I &= \left\lfloor \int_0^{\eta(\ln\varepsilon^{-1})^{1/\beta}} n_1^*(t)\,dt \right\rfloor \quad (24) \\ &= \left\lfloor \frac{\eta(p+1)}{(p+\beta)} \left(\frac{c_1 p}{c(p+1)} \cdot \frac{\beta}{\eta}(\ln\varepsilon^{-1})^{p/\beta+1}\right)^{1/(p+1)} \right\rfloor, \end{aligned} \quad (25)$$

where $\lfloor x \rfloor$ denotes the greatest integer less than or equal to x.

• Optimal inspection time:

$$t_k = \left\{ \eta^{\beta-1} \left(\frac{c_1 p}{c(p+1)} \cdot \frac{\beta}{\eta} \right)^{-1} \left(\frac{k(p+\beta)}{p+1} \right)^{p+1} \right\}^{1/(p+\beta)}, \quad k = 1, \ldots, n_l. \tag{26}$$

• Condition that the number of inspections is m:

$$r_1(m+1) < \frac{c_1}{c} \leq r_1(m), \tag{27}$$

where

$$r_1(m) = \left(\frac{m(p+\beta)}{\eta(p+1)} \right)^{p+1} \left(\frac{p}{p+1} \cdot \frac{\beta}{\eta} (\ln \varepsilon^{-1})^{p/\beta+1} \right)^{-1}. \tag{28}$$

For $L(t) = c_1 t^2 + c_2 t + c_3$ and $L(t) = c_1(\exp[c_2 t] - 1) + c_3$, when $\lambda(t)$ is the Weibull distribution, it is difficult to derive explicit results. However, if the time-to-failure distribution is a negative exponential, i.e., $\beta = 1$, $\lambda(t) = 1/\lambda$, it is possible to derive some equations in a closed form.

(b) Failure distribution: negative exponential distribution

When $L(t) = c_1 t^p + c_2$, the results are the same as those substituted $\beta = 1$ into equations (25), (26) and (28).

$$n_l = \left\lfloor \eta (\ln \varepsilon^{-1}) \left(\frac{c_1 p}{\eta c(p+1)} \right)^{1/(p+1)} \right\rfloor \tag{29}$$

$$t_k = k \left(\frac{\eta c(p+1)}{c_1 p} \right)^{p+1} \tag{30}$$

$$r_1(m) = \frac{\eta(p+1)}{p} \left(\frac{m}{\eta \ln \varepsilon^{-1}} \right)^{p+1} \tag{31}$$

When $L(t) = c_1 t^2 + c_2 t + c_3$ and $\lambda(t) = 1/\eta$ the following equations are derived.

• Number of inspections:

$$n_l = \left\lfloor \int_0^{\eta \ln \varepsilon^{-1}} n_2^*(t)\, dt \right\rfloor \tag{32}$$

$$= \left\lfloor \frac{\{k_1 + \eta \{G(1/\eta)\}^2\} \ln \varepsilon^{-1}}{G(1/\eta)} \right\rfloor. \tag{33}$$

• Optimal inspection time:

$$t_k = \frac{k}{G(1/\eta) + k_1/\eta\, G(1/\eta)}, \quad k = 1, \ldots, n_l. \tag{34}$$

• Condition that the number of inspections is m:

$$r_2(m) \leq \eta < r_2(m+1), \tag{35}$$

where

$$r_2(m) = \frac{m \left\{ (9k_1^2 \ln \varepsilon^{-1} + 8k_2 m)^{1/2} - 3k_1 (\ln \varepsilon^{-1})^{1/2} \right\}}{4k_2 (\ln \varepsilon^{-1})^{3/2}}. \tag{36}$$

If $L(t) = c_1(\exp[c_2 t] - 1) + c_3$, the following is obtained.

• Number of inspections:

$$n_l = \left\lfloor \int_0^{\eta \ln \varepsilon^{-1}} n_3^*(t)\, dt \right\rfloor \tag{37}$$

$$= \left\lfloor \left[\frac{1}{c_2 \eta \ln \varepsilon^{-1}} \left\{ 1 + W\left(\frac{1}{e} \left(\frac{c c_2 \eta}{c_1} - 1 \right) \right) \right\} \right]^{-1} \right\rfloor. \tag{38}$$

• Optimal inspection time:

$$t_k = \frac{k}{c_2} \left\{ 1 + W\left(\frac{1}{e} \left(\frac{c c_2 \eta}{c_1} - 1 \right) \right) \right\}, \quad k = 1, \ldots, n_l. \tag{39}$$

The condition that the number of inspections is m and the condition that inspection is effective cannot be easily derived in a closed form.

(c) Failure distribution: uniform distribution

When $L(t) = c_1 t^p + c_2$ and time to failure distribution is provided with a uniform distribution in the range of $[0, T]$ the following results are obtained.

• Number of inspections:

$$n_l = \left\lfloor \int_0^{T} n_1^*(t)\, dt \right\rfloor \tag{40}$$

$$= \left\lfloor \left\{ \frac{c_1}{c} T^p \left(\frac{p}{p+1} \right)^{p+2} \right\}^{1/(p+1)} \right\rfloor. \tag{41}$$

• Optimal inspection time:

$$t_k = T - \left[T^{p/(p+1)} - k \left\{ \frac{c}{c_1} \left(\frac{p+1}{p} \right)^{p+2} \right\}^{1/(p+1)} \right]^{(p+1)/p}, \quad k = 1, \ldots, n_l. \tag{42}$$

• Condition that the number of inspections is m:

$$r_3(m) \leq T < r_3(m+1), \tag{43}$$

where

$$r_3(m) = \left\{ \frac{c}{c_1} \left(\frac{p+1}{p} \right)^{p+2} m^{p+1} \right\}^{1/p}. \tag{44}$$

When $L(t) = c_1 t^2 + c_2 t + c_3$, every result is difficult to write in a closed form; however, when $L(t) = c_1(\exp[c_2 t] - 1) + c_3$, the following is derived.

• Number of inspections:

$$n_I = \left\lfloor \int_0^T n_3^*(t)\,dt \right\rfloor \tag{45}$$

$$= \left\lfloor \frac{c_1}{c}\left\{\exp\left[1 + W\left(\frac{cc_2 T - c_1}{ec_1}\right)\right] - 1\right\}\right\rfloor. \tag{46}$$

• Optimal inspection time:

$$t_k = \frac{c_1}{cc_2}\left(w - \frac{ck}{c_1}\right)\left\{1 - \ln\left(w - \frac{ck}{c_1}\right)\right\} + \left(T - \frac{c_1}{cc_2}\right), \quad k = 1, \ldots, n_I, \tag{47}$$

where

$$w = \exp\left[1 + W\left(\frac{cc_2 T - c_1}{ec_1}\right)\right]. \tag{48}$$

• Condition that the number of inspections is m:

$$r_4(m) \le T < r_4(m+1), \tag{49}$$

where

$$r_4(m) = \frac{1}{cc_2}\left\{(mc + c_1)\ln\left(\frac{mc}{c_1} + 1\right) - mc\right\}. \tag{50}$$

(2) Objective: Expected incurred cost per unit time

(a) Failure distribution: negative exponential distribution

When $L(t) = c_1$ the following equations are obtained.

• Number of inspections:

$$n_I = \left\lfloor \ln\varepsilon^{-1}\left(\sqrt{\frac{c_1\eta}{c} + 1} - 1\right)\right\rfloor \tag{51}$$

• Optimal inspection time:

$$t_k = \frac{k\eta}{\sqrt{\frac{c_1\eta}{c} + 1} - 1} \tag{52}$$

• Condition that the number of inspections is m:

$$r_5(m) = \frac{m(m + 2\ln\varepsilon^{-1})}{\eta(\ln\varepsilon^{-1})^2} \tag{53}$$

3.2 When time-to-failure distribution is unknown

When the objective is the expected incurred cost per cycle some explicit results are obtained. However, the objective is the expected incurred cost per unit time, no explicit equations are derived. If $L(t) = c_1 t^p + c_2$ and $a = \lambda(0)$ for the objective of the expected incurred cost per unit time the following results are obtained.

• Number of inspections:

$$n_I = \left\lfloor \int_0^{1/a(p+1)} n_1^{**}(t)\,dt \right\rfloor \tag{54}$$

$$= \left\lfloor \left(\frac{c_1}{c(p+1)} \cdot \frac{1}{(ap)^p}\right)^{1/(p+1)} \right\rfloor \tag{55}$$

• Condition that the number of inspections is m:

$$r_5(m+1) < a \le r_5(m), \tag{56}$$

where

$$r_5(m) = \frac{1}{p}\left(\frac{c_1}{c(p+1)}\right)^{1/p} m^{-(p+1)/p}. \tag{57}$$

• Optimal inspection time:

$$t_k = \frac{1}{a(p+1)}\left[1 - \left\{1 - k\left\{\frac{c(p+1)}{c_1}(ap)^p\right\}^{1/(p+1)}\right\}^{(p+1)/p}\right], \quad k = 1, \ldots, n_I. \tag{58}$$

4 NUMERICAL EXAMPLES

Optimal inspection schedules to a virtual maintained system are discussed. Table 1 shows the optimal inspection schedules when density function $f(t)$ is the Weibull distribution (mean 15 [year], coefficient of variation: c.v. $= 1/3$ and 2/3) and a negative exponential distribution (mean 15 [year], c.v. $\equiv 1$). Shape and scale parameters of the Weibull distribution are (shape parameter, scale parameter) = (3.30, 16.72) for c.v. $= 1/3$, (1.53, 16.65) for c.v. $= 2/3$, and (1, 15) for c.v. $= 1$.

Loss rate functions evaluated in this study are $L_1(t) = 1$, $L_2(t) = t$, $L_3(t) = t^2$, $L_4(t) = t^2 + t$, and $L_5(t) = (\exp[2t] - 1)/2$, each of which is a typical example of the functions. The examined loss rate functions have the following characteristics if time-to-failure distribution is known. When EC_1 every loss rate function except $L_1(t)$ gives an explicit form of optimal inspection density function. Then $L_1(t)$ when EC_1 does not produce optimal inspection times. When EC_2/ET loss rate functions $L_1(t)$ and $L_2(t)$ yield an optimal inspection density function in an explicit form; however, $L_i(t)$ ($i = 3, 4, 5$) do not produce an explicit optimal inspection density function. If time-to-failure is unknown and objective is EC_1 loss rate functions $L_2(t)$ and $L_3(t)$ give explicit solution of optimal inspection times. On the other hand, $L_1(t)$ is the only loss rate function which yields optimal failure rate and inspection density functions when EC_2/ET.

The optimal solutions are calculated in the range of $\min(20, \{t \mid F(t) \le 1 - 10^{-6}\})$, and rounded to the nearest integer. We can see that the inspection interval shortens with time when c.v. $= 1/3$, whereas the interval is a constant value when c.v. $= 1$ and optimal inspection times are not rounded. The first inspection is conducted at an earlier time and inspection

Table 1: Optimal inspection schedules when time-to-failure distribution is given.

Loss rate	c.v.	Optimal inspection time when EC_1	Optimal inspection time when EC_2/ET
$L_1(t)$	1/3	—	{10, 14, 18}
	2/3	—	{6, 12, 16}
	1	—	{5, 10, 15, 20}
$L_2(t)$	1/3	{11, 15, 18}	{6, 10, 12, 14, 17, 18, 20}
	2/3	{7, 13, 17}	{4, 6, 9, 12, 14, 17, 19}
	1	{5, 11, 16}	{3, 5, 8, 11, 13, 16, 19}
$L_3(t)$	1/3	{7, 10, 13, 15, 17, 19}	{5, 8, 10, 12, 14, 15, 17, 19, 20}
	2/3	{4, 7, 10, 13, 15, 18, 20}	{3, 5, 7, 9, 11, 13, 15, 17, 19}
	1	{3, 6, 8, 11, 14, 17, 20}	{2, 4, 6, 8, 10, 12, 14, 16, 18, 20}
$L_4(t)$	1/3	{7, 10, 12, 14, 16, 18, 20}	{5, 7, 9, 11, 13, 14, 16, 17, 19, 20}
	2/3	{4, 7, 9, 12, 14, 17, 19}	{2, 5, 7, 8, 10, 12, 14, 15, 17, 19, 20}
	1	{3, 5, 8, 10, 13, 16, 18}	{2, 4, 5, 7, 9, 11, 13, 15, 16, 18, 20}
$L_5(t)$	1/3	{3, 6, 8, 10, 11, 13, 14, 15, 17, 18, 19, 20}	{3, 5, 7, 8, 10, 11, 13, 14, 15, 16, 18, 19, 20}
	2/3	{2, 4, 6, 7, 9, 11, 12, 14, 15, 17, 18, 20}	{2, 3, 5, 6, 8, 9, 11, 12, 14, 15, 16, 18, 19, 20}
	1	{2, 3, 5, 7, 8, 10, 11, 13, 15, 16, 18, 20}	{1, 3, 4, 6, 7, 9, 10, 11, 13, 14, 16, 17, 19, 20}

c.v.: coefficient of variation

Table 2: Optimal inspection schedules when time-to-failure distribution is unknown.

Loss rate	Condition $\lambda(0)$	Optimal inspection time when EC_1	Optimal inspection time when EC_2/ET
$L_1(t)$	10^{-2}	—	{12}
	10^{-3}	—	{∅}
	10^{-4}	—	{∅}
$L_2(t)$	10^{-2}	{13}	{5, 10, 15, 20}
	10^{-3}	{∅}	{10, 20}
	10^{-4}	{∅}	{∅}

interval shortens as coefficient of variation increases or a loss rate function has a sever property for both objectives. Objective EC_2/ET gives more number of inspection, which means safer side solution while inspection cost increases, compared with objective EC_1.

The optimal inspection schedules when the time-to-failure distribution is unknown are shown in Table2 in the range of $\min(20, \{t \mid F(t) \leq 1-10^{-6}\})$. Even though time-to-failure distribution is unknown optimal inspection time is derived if initial failure rate is given. No inspection policy can be effective if failure rate at time 0 has a smaller value.

5 CONCLUSIONS

Optimal inspection schedules for a single-unit system whose deterioration is discontinuous as well as continuous were discussed. The approximate expected cost per cycle is the objective where the loss rate function is treated in a general form. The variational method was used to optimize the inspection schedules. Then, optimization problems were classified from the point of whether failure distribution is given or not. When the time-to-failure distribution was given, some optimal inspection densities were derived in a closed form for every potential loss rate function. When the failure distribution was unknown, a differential equation that the optimal inspection density function satisfies was derived. Numerical examples were shown and characteristics of optimal solutions were discussed.

One of the objectives of the optimization problem in this paper is the expected cost per cycle, in which the functional is non-fractional, and absolute term of the loss rate function and replacement cost do not influence optimal inspection schedules. If a criterion is the expected incurred cost per unit time over an infinite time horizon, in which the functional is fractional, the optimal inspection schedules may differ. Then, the effect on the incurred cost per unit time on optimal schedules was investigated. Numerical examples shown in this study is for a virtual system because the primary aim of the examples is to demonstrate the validity of the developed technique. Our future work is to apply the method to a real system and examine the effectiveness of the proposed method.

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Sustainable Machine Tool Reliability based on Condition Diagnosis and Prognosis

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Abstract

Current trends in mechanical engineering show the growing importance of costs for machine tool life cycles. Since major customers increasingly focus on machine tool reliability and costs, even small and medium-sized companies that usually supply machine tools need to pay more attention to their products' life cycle. Taking these requirements into account, the manufacturers can concentrate on their current service activities and improve their long-term customer retention. The objective of the presented research project is the development of a machine tool diagnosis and prognosis system that facilitates the improvement of maintenance activities.

Keywords:

Life Cycle Engineering, Maintenance, Machine Diagnosis

1 INTRODUCTION

1.1 Motivation

Current trends in mechanical engineering show the growing importance of costs for machine tool life cycles. The manufacturers that usually supply these machines need to focus on machine tool life cycles since more and more contracts include guaranteed availabilities and costs, e.g. the "Total Cost of Ownership" (TCO) for operating companies [1, 2, 3, 4].

Besides helping the company to comply with cost and maintenance requirements, diagnosis and prognosis systems for machine tools can give the operating company the following additional advantages: As rising complexity is one of the current trends in business relations, an integrated additional system may help to support the operators in dealing with these complex structures. Additional information monitored at the machine tool will facilitate a company's day-to-day business and – in case of failures – provide measures to reduce the number of affected components or functions in the machine tool. If the root cause can easily be remedied, the diagnosis system will communicate the corresponding measures to the operator or the local maintenance team.

The launch of machine tools that have got supporting functions improves a product's serviceability and may be less demanding in terms of operator requirement. Therefore, it can be regarded as a way for companies to increase their competitiveness and offer special services [5].

By incorporating these diagnosis features into existing machines the manufacturer has the opportunity to use standard internet technologies to monitor a machine's condition and failure messages via a central web server. The standardized interfaces ensure secure data exchange, and current server structures provide different functions to predefined user groups, such as reading failure messages, downloading corresponding measurement data or receiving failure warnings. The manufacturer's service team can use the data to identify the potential for a continuous improvement process and then report their findings to Engineering and Construction.

After completing the process, the machine tool's design and its integrated components will be continuously adapted in accordance with field data and operating experience. As a consequence, the key figures (e.g. availability, costs) will be based on solid long-term data and be more accurate. The consistent monitoring of the machine tool's condition may directly improve service activities and have an impact on long-term customer retention. Tele-service based on current machine tool data will reduce traveling and transportation costs and the number of required and shipped spare parts so that spare parts logistics can be simplified and will be easier to plan [6].

The presented research project ZuprogOn provides a new approach to life-cycle engineered machine tools including condition diagnosis and prognosis based on a manageable system for machine tool manufacturers [7].

1.2 Starting point

Additional systems for machine diagnosis have already been developed and implemented for large-scale plants. These solutions for cost-intensive projects, which are often tailored to the respective project, monitor the state of applications in the energy sector, for example (power plants, mining applications and wind energy plants) [8, 9, 10].

By contrast, the mainly limited-lot production of machine tools currently does not follow standardized and consistent systems. In the field of monitoring solutions, there already are exemplary solutions for availability increase by means of troubleshooting support systems. Such a system has already been already developed at the Institute of Production Science (wbk) in the form of a diagnostic tool for electro-hydraulic machine tools [11, 12].

Another approach to monitoring the condition of machine tools consists in uploading machine data from the control to a central web server, like the ePS-system does. Special testing procedures can be configured and run at predefined times. The diagnosis is then carried out by experts checking the data and comparing it to former runs [13].

1.3 Aim and procedure

In line with the above-mentioned motivation and starting point, the aim is to develop a machine tool integrated diagnosis and prognosis system designed for small and medium-sized companies. The developed system will be integrated into the machine tool periphery and connected to the internet. Failures and key figures will be monitored via a central web server.

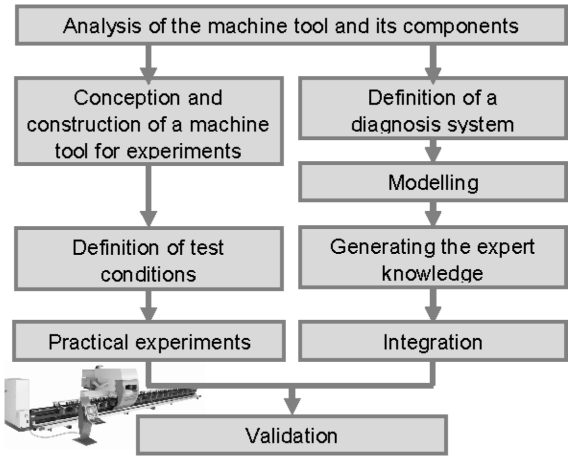


Figure 1: Development approach.

After analyzing the machine tool's structure and properties including all components, a sample machine tool is designed and built. Defined testing conditions are the basis for practical experiments which provide data on a faultless or faulty condition of the machine tool (fig. 1).

Besides, all the individual properties are integrated into a SQL database in the form of attributes. Therefore, the given machine tool structure is represented and put in relation to the information that has been gathered. Finally, the data is exported to an embedded hardware system and then integrated into the machine. Experiments with the machine tool will help to modify the deposited attributes and validate the entire system.

2 APPROACH

2.1 System infrastructure

In order to facilitate machine diagnosis and prognosis on the basis of the machine tool, the required expert knowledge and the monitoring conditions need to be integrated into the machine tool's periphery as can be seen from figure 2.

The infrastructure is based on the results of a failure mode and effects analysis (FMEA) and a central database. Using a converter, all the necessary information from the database can be converted into an exchange file and read by embedded hardware for machine diagnosis. The PROFOXY system by Kröhnert Infotecs GmbH is designed for machine diagnostic applications and provides interfaces to most of the control units that are currently in use. It carries out data recording, data analyses and provides a platform for server operation, where detected failures can be monitored.

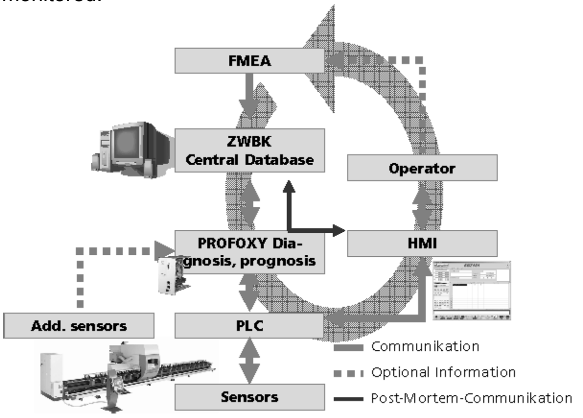


Figure 2: Defined and implemented infrastructure.

The measurement values fed into the system directly result from the inputs/outputs of the control unit. Since the amount of additional sensors is supposed to be kept to a minimum, measurands from machine tool integrated sensors are used for the project. In order to gather more information on the machine condition, information from the drives will also be used, e.g. the motor current.

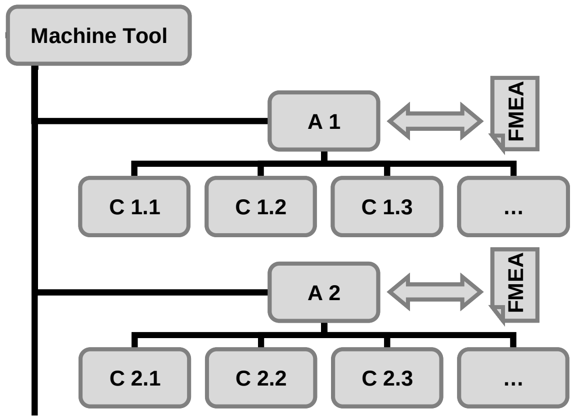
Messages are displayed on a standard HMI by means of the interface between the diagnosis hardware and the PLC. Measures for fault repair or for the reduction of failure causes are indicated to the operator, and testing procedures can be confirmed or rejected, which leads on to the next stage.

Field data from machines with an optional diagnosis system will be monitored from a web server and analyzed by the manufacturer's Service and Construction Center. Deviations in the database will be corrected in order to continuously improve the quality of the data.

2.2 Machine tool and component analysis

Beginning with a systematic analysis of the entire machine tool structure, the expert knowledge of the manufacturer's employees from different departments was analyzed by means of a failure mode and effects analysis (FMEA). This standardized method was selected as a proven standardized and objective tool for failure analysis [14, 15, 16, 17, 18]. There is another benefit apart from the collection of data for diagnosis and prognosis, i.e. the identification of potential in the areas of product design, assembly or quality. The FMEA team can directly develop solutions for machine tool optimization.

Breaking the machine structure down into assemblies and components and mapping their potential failures generates expert data and information for the diagnosis system (fig. 3). The focus on diagnosis and prognosis is reflected by additional fields in the standard FMEA table which provides the required data. The potential chaining of component failures is of particular importance. In order to avoid incorrect diagnoses, the interaction of different components or assemblies is also taken into consideration during that phase of analysis. Failures may be caused by other failures which may have different root causes (error propagation).



(A) Assemblies (C) Components

Figure 3: Structure of the machine tool (extraction) in relation to the failure mode and effects analysis (FMEA).

After a failure has been diagnosed, the diagnosis system needs to trigger reactions that provide a safe state of the machine tool. Therefore, different possible reactions can be defined and displayed on the HMI. Depending on the potential impact the failure may have, the machine tool may need to be stopped immediately. In less important cases, it may be sufficient to send a failure message to the operator and to monitor those failures via the web server.

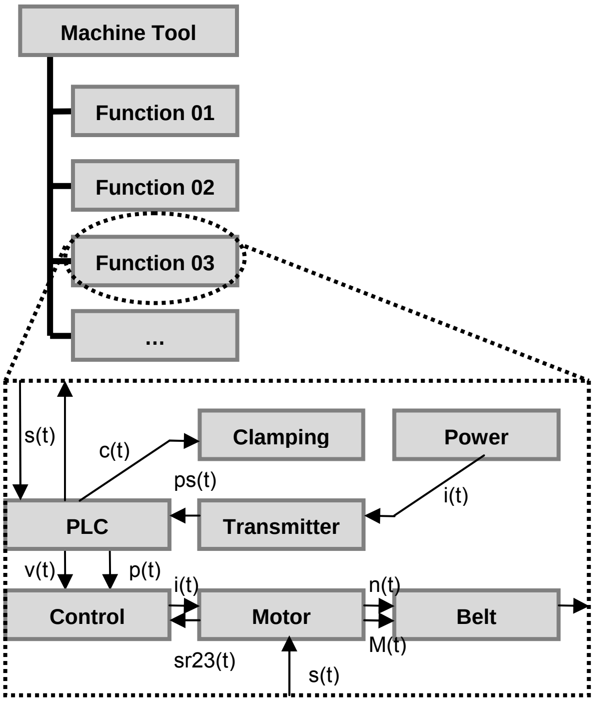


Figure 4: Functional interrelation between different components belonging to one superordinate function (extract).

Methods to fix the failure state will be displayed in these situations, too. The range includes measures completely conducted by the operating company (maintenance), spare part orders, and organizing the manufacturer's service, for example. Therefore, additional information such as data on test procedures or action items to fix defects has been added to the FMEA template.

The predefined structure of the failure mode and effects analysis with the above-mentioned modifications allows for the comprehensive mapping of a machine tool. The attributes required for diagnosis will directly be generated from the FMEA data.

2.3 Functional analysis

After breaking the machine structure down into assemblies and components, the functional chains need to be examined. In addition to the error propagation from the FMEA, it is essential to know all sensors and all physical quantities that can be measured in between the components of such a functional chain.

As shown by the extract of the functional interrelation of components depicted in figure 4, the connections between subsystems may vary and effect several measurements in the global machine tool's functions.

An analysis of all superordinate machine tool functions provides the data to generate another tree that visualizes all functions and links them to integrated components. Every function may affect different components and can result from different starting conditions (e.g. no emergency stop AND machine tool in home position).

Every function needs to be described by means of attributes focusing on equations to monitor the state of the functions and their components. Moreover, response from the machine tool, required receipts and recorded data are required for a description of the functional state.

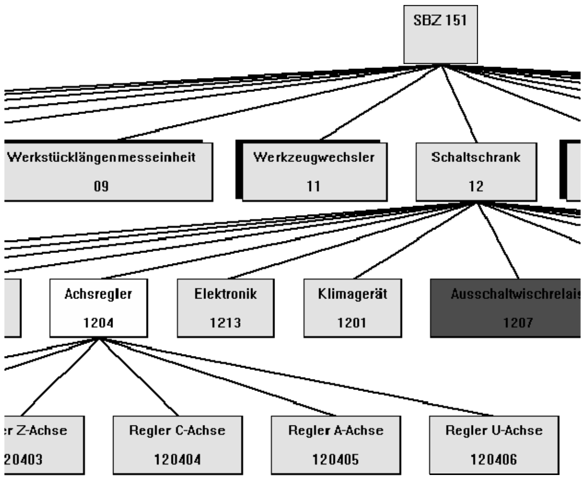


Figure 5: Visualization of the database (extract).

2.4 Configuration of the database

In accordance with the machine tool's structure, the expert data is mapped in a database. The structural approach to the machine tool's data breaks the entire system down into assemblies and components. The modular structural tree used allows for simple ways to generate different machine tool options. Furthermore, reconfigurations of components used in the machine tool can be displayed and transformed into data.

Every component has got its attributes and potential failures generated from the FMEA (input and output data, e.g. speed). All information generated from the FMEA is included and can easily be accessed. In case of new field experience or newly designed assemblies, the information included in the system can be updated by the Construction. As can be seen from figure 5, different color codes facilitate the handling and configuration of the software tool.

The functional interrelations are also integrated in form of a tree, and linked to the integrated components. Based on the requirements explained in section 2.2, every function has got a starting condition which ensures that only operable functions will be monitored. The link to the components is realized by means of functional chains mapping the respective piece of information (fig. 6).

The implementation of the continuous improvement process (CIP), i.e. integrating information from sold machine tools into the system guarantees the sustainable backflow of field data.

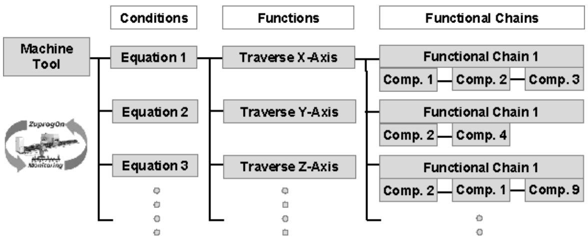


Figure 6: Defined functional chains combining functions and different components.

2.5 Practical experiments

First, the integration of the diagnosis system and the verification of the required interfaces need to be ensured. Practical experiments are required in order to validate the potential failures and testing procedures.

In order to enable the diagnosis system to differentiate between faultless and faulty conditions, it is essential to analyze and classify the nominal condition of the machine tool. Based on the results of the FMEA, failure modes can be detected and then distinguished from the nominal conditions. For an application of the Fast Fourier Transformation to the diagnosis system, frequencies are analyzed and related to rotational speeds. Frequency-independent effects must be separated from failure consequences, e.g. harmonics.

The focus of the practical experiments lies on the data directly available at the machine tool and on the existing sensors, the data in the PLC/CNC and the information from the drives [19]. Additional sensors such as accelerometers are used to verify the experimental studies and to validate the developed methods.

Worn out or partly broken parts from customers are examined with the sample machine tool. Additional sensors in different locations may sustainably improve data quality and diagnosis performance. As sensors were added in a gearbox, strains can be measured directly where they emerge.

3 RESULTS

First results show that the diagnosis system has been successfully integrated into the machine tool's periphery and connected to the control unit and to the internet. The expert data has been gathered in several stages analyzing all assemblies and components of the machine tool. The central database is developed and filled with data from the FMEA. In a second step, data from experimental studies is added and the virtual machine tool's model can be continuously improved.

The database generates exchange files with all the required attributes. These attributes are based on experimental studies and provide the system with equations containing static or dynamic limits. An implemented Fast Fourier Transformation supports a vibration analysis of the system frequencies. Furthermore, additional sensors, e.g. for gearbox-integrated measuring of forces, have been implemented and tested considering cost-benefit analyses also.

The modular structure of the developed database allows machine tool manufacturers to make use of that system even for limited-lot production. Particularly, wide varieties of machine tools with different option part lists can be easily configured with the predefined modules. The added value for machine tool manufacturers consists in the possibility to use the system as a simplified procedure for the configuration of different types of machine tools using an intuitive access to a graphical user interface. Changing constraints can directly be adapted to by using the machine tool tree from the database.

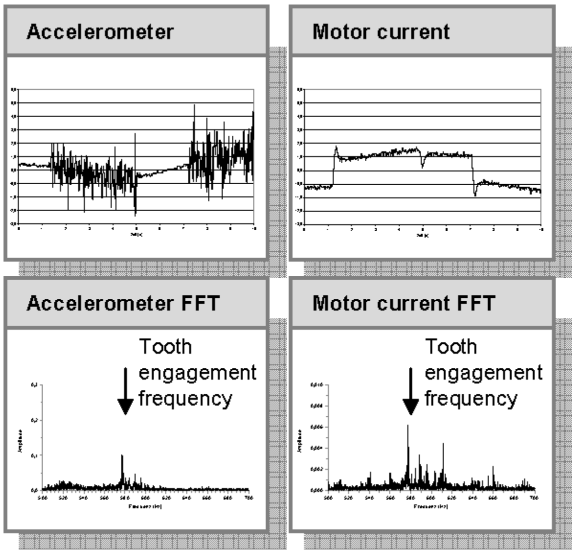
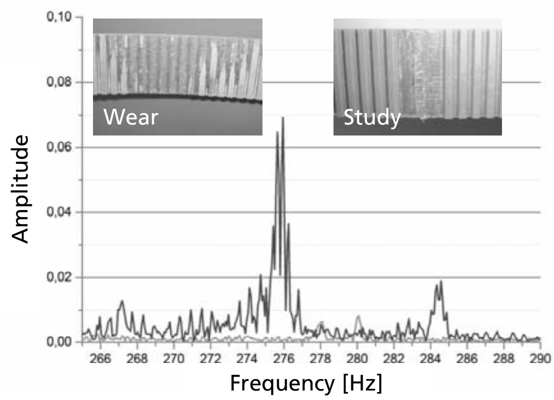


Figure 7: Characteristic frequencies seen in the accelerometer and motor current diagrams.



(red) worn out belt (green) faultless belt

Figure 8: Failure study with a worn out/manipulated belt.

The measurements show that characteristic frequencies can be found in the signals from both the accelerometer and the motor current (fig. 7). A comparison indicates that there are additional effects in the motor current which need to be analyzed and separated from the recorded original signals.

The shown analysis illustrates that vibrations of the power train may be taken into account without having to add accelerometers to the machine tool.

Experimental studies using worn out or manipulated components show the functional capability of the entire system. The diagram in figure 8 illustrates that failures can be detected by analyzing the frequencies and by relating them to rotational speeds. Special failure frequencies for different components were integrated and validated in test runs.

As depicted in figure 9 changes of the machine tool behaviour can be monitored using the programmed (rotational) speed and the recorded motor current. All relevant data is recorded by the diagnosis and prognosis system. The implemented Fast Fourier Transformation then supplies the diagnosis system with the amplitude of critical frequencies of the machine tool or its components.

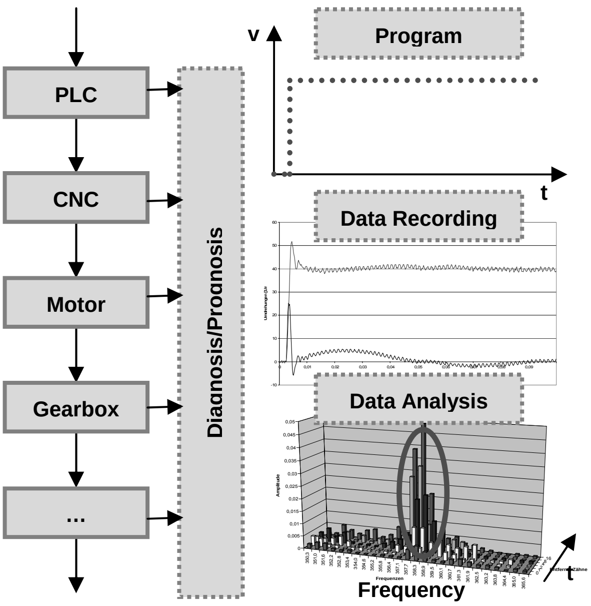


Figure 9: Signal processing associated with the power train (analysis of the motor current).

As the modules of the current database may be applicable to different types of machine tools, the recorded failure information can be used for a wide range of configurations. As more and more field data will be entered into the system, the tool can be used in an increasing number of company departments, which improves its quality and accuracy.

4 OUTLOOK

On the basis of the implemented inline diagnosis, additional attributes will be realized for the description of the expected maintenance history in order to provide sustainable prognosis of potential breakdowns or malfunctions. Before it becomes necessary to replace a component, the web server generates an alert message. The operating company can then order spare parts or request a service technician for a specific date. The actual use of such a component may still exceed the estimated lifetime, but the operating company will be able to cope with any breakdown caused on component and machine tool level.

As explained before, the loop depicted in figure 5 can be closed manually. In order to facilitate fast data improvements and make the calculation of required key figures more accurate, an automated field data feedback should be integrated into the database. As key characteristics are absolutely vital for tender preparation, they need to be calculated on a sustainable basis (e.g. MTBF, MTTR) [20].

5 SUMMARY

Motivated by the necessity to improve machine tool availability and reduce costs for their operation, machine manufacturers try to improve their availability and worldwide after-sales service. In line with these objectives, diagnosis and prognosis systems offer direct support and provide the possibility to monitor the machine tool's condition.

As even small and medium-sized companies need such a system or at least need to be able to react to the changing market requirements, the ZuprogOn project has developed a diagnosis system focusing on machine tools manufacturers.

The designed and developed diagnosis system has been successfully integrated into the machine tool's periphery and connected to the control unit and to the internet. All the expert data required was generated in several stages analyzing all machine tool assemblies and components by means of a modified version of the standardized failure mode and effects analysis (FMEA). The central database has been developed and filled with data from the FMEA and with service data. In a second step, data from experimental studies was added, facilitating an improved virtual reproduction of the machine tool.

The database generates exchange files with all the required attributes. These attributes are based on experimental studies and provide the system with equations containing static or dynamic limits. An implemented Fast Fourier Transformation supports a vibration analysis of the system. Furthermore, additional sensors, e.g. for gearbox-integrated measuring, have been implemented and tested considering cost benefit analyses also.

The implementation of a continuous improvement process (CIP), i.e. integrating information from sold machine tools into the system guarantees the sustainable backflow of field data. After completing the process, the machine tool's design and its integrated components will be continuously adapted in accordance with field data and operating experience. As a consequence, the key figures (e.g. availability, costs) will be based on solid long-term data and be more accurate.

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Optimizing the Life-Cycle-Performance of Machine Tools by Reliability and Availability Prognosis

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Abstract
The Life-Cycle-Performance of machine tools is a key figure concerning aspects of cost and benefits such as a high reliability and availability [1]. The dependence of production facilities on a high and constant availability increases with the degree of utilization. Hence, the availability of machine tools is substantial for the economic success of a manufacturer. The configuration of equipment elements in line with adapted product-accompanying services decisively contributes to the availability assurance. Thus, the aim of the article is to present a comprehensive calculation model to optimize the Life-Cycle-Performance of machine tools by a suitable reliability and availability prognosis considering the availability contribution of alternative machine equipment options and product accompanying services.

Keywords:
Reliability; Availability; Life Cycle Cost

1 INTRODUCTION

In the present time breakdowns in production cost the companies millions of euros. Furthermore, due to increasing plant utilization operators depend on a high and constant availability of their machines as one of the most important quality aspects. Thus, it is absolutely necessary to adopt efficient activities to assure a specified availability level across the machine's lifetime. Manufacturers of machine tools can strengthen their position in market by an adequate quality and reliability of their products. However, it is very difficult to discuss those factors with an operator's purchase department in the early phase of machine acquisition. Therefore, operators of production facilities and especially those of the automotive sector demand broad information and guarantees concerning well defined reliability and availability targets and the resulting Life Cycle Costs (LCC). In doing so, they try to compare not only the LCC but much more the Life-Cycle-Performance (LCP) of machines of different suppliers [1, 2]. For a manufacturer such guarantees are associated with high risks. These concern higher costs especially for after sale services to achieve a certain availability level. The replacement and improvement of weak components to the point of balancing the operator's costs for production breakdowns are common in many cases. Hence, it is very important to determine those risks very accurately and to compare them to the costs of availability assurance.

Basically, there exist two possibilities to influence the machine's availability provided that the design is defined during tender negotiation. The configuration of equipment elements in line with adapted product-accompanying services decisively contributes to the availability assurance. Thereby a complex decision model depending on the desired business model by the customer is generated. The more comprehensive the performance bonds by the manufacturer the more intensive the integration of his service department in the customer's processes of availability assurance. In the case of a manufacturer's participation in corrective maintenance activities it is necessary to analyze the administrative and logistical aspects of a machine's downtimes and therefore the operational availability. Availability is identified as the period of time in which the machine can actually be used for production purposes. Operational availability in that sense takes into account times of technical, administrative, organizational and logistical disruptions of production. In consequence, operational availability is, in essence, determined by the three factors reliability, maintainability of the machine and maintenance supportability of the service organization [3, 4]. These three aspects in turn have their own influence factors like the environment, age or load. For this reason, operational availability relates to all relevant periods that can be directly influenced by the maintenance department. Since most services have an impact on those time proportions, the service benefit can be expressed by the improvement of the operational availability. Aspects of key figures and dimensions of operational availability regarding reliability [5, 6], maintainability [7, 8] and maintenance supportability [9, 10] are discussed in current literature.

2 RESEARCH OBJECTIVES

This article presents the results of a research project funded by the German Research Foundation (DFG). The aim is to present a method to optimize the Life-Cycle-Performance of machine tools by a suitable reliability and availability prognosis. The consideration of the availability contribution of alternative machine equipment options and product accompanying services in dependence on the operating conditions is the central point of the comprehensive calculation model. Additionally, the resulting costs have to be calculated (see Figure 1).

The initial point of the method is a reliability model of the machine's technical structure representing the characteristics of components and alternative equipment options with regard to their failure behavior. Both mutual failure influences and cause-and-effect relationships are taken into consideration. The reliability model is expanded with algorithms for the availability contribution of single and bundled service measures, which can be determined by field data analysis and expert rating. Subsequently, service processes are scrutinized to reveal service cost structures to be reflected against the respective failure cost. Facing the complexity of the calculations the method is finally to be transferred into a software prototype.

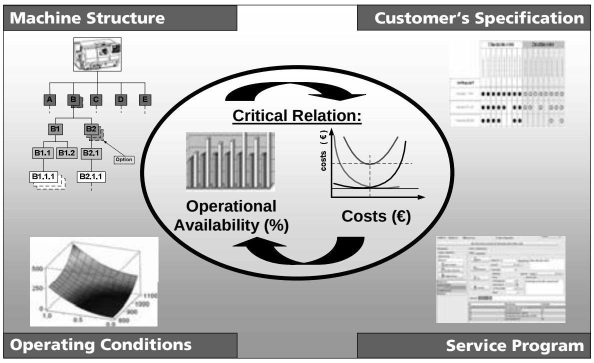

Figure 1: Relation between operational availability an costs.

3 ANALYSIS OF THE MACHINE'S BREAKDOWN BEHAVIOUR

The analysis of the machine's breakdown behavior is an essential element of the comprehensive calculation method. This consists basically of two parts. On the one hand an accurate reliability analysis and prognosis of the machine and its components has to be carried out. On the other hand the analysis of the specific downtime units is very important for the latter classification and optimization of the services as well as for the calculation of the availability.

3.1 Reliability analysis and prognosis

Integrating calculations for an expected and required reliability into the design phase of a machine tool is essential to obtain high reliable products. But this requires dependable and practically approved failure rates and mathematical models allowing a correct conversion of those values to the boundary conditions. Therefore, a clear structure in the analysis and detailed information in terms of customer requirements and field data is important.

The basis for the reliability analysis is a machine structure model in which all relevant information of the items is lodged. Basically, the model consists of a hierarchical tree structure of the considered items regarding the whole system, components and single elements. Therewith, it abuts to the known fault tree analysis [5]. The underlying data for the reliability analysis have to be brought together and assigned to the respective items diligently, because they determine the outcome of the calculation to a great extent. Generally speaking, incoming information for reliability and availability calculations are afflicted with uncertainties. Due to the fact, that units from different production technologies and operational conditions are aggregated, some failure causes and their interdependencies remain unconsidered and control samples are coincidental. Thus, the consistent gathering and use of information about the machine's operational behavior is an essential success factor for the analysis [11, 12]. All available data sources both on the operator's and on the manufacturer's side should be reviewed in regard to the appropriation for the reliability analysis. Especially for electronic components and to a certain extent for mechanical components as well, it is possible to use special catalogs of failure rates [13, 14].

Optional machine configurations are taken into account by the reliability model as already mentioned before. Optional items can influence the machine's availability in terms of failure tolerance, maintainability, diagnosis and different lifetimes [15]. They are necessary to customize the machine to the individual needs and to the boundary conditions of an operator or to augment the availability systematically. In this model the term machine option describes technical items in different aggregation levels i.e. single elements or components as well as auxiliary equipments. Finally, the user will be able to customize his machine according to the specifications and to analyze the reliability for the whole machine including the options.

In this model the two parametrical Weibull distribution is used for the description of the breakdown behavior of the single items due to its adaptivity to different breakdown characteristics by variation of its parameters β (shape parameter) and η (characteristical lifetime) [5]. If acceding failure rates cannot be proved it is reduced to the common exponential distribution. Reliability models have to integrate life cycle variations because of ageing, wear and other effects [16]. Therefore the method takes into account early failures and increasing failure rates in the wear-out zone. A special factor for early failures represents deviated failure rates during the first months after ramp-up. In view of dissimilar stress loads and ambient conditions, further correction factors are introduced. They are used if operating conditions and resulting reliability deviation of an item can be properly identified.

The reliability model considers each individual item separately and links it with the failure behavior of the whole system. Reliability of a machine is characterized respectively by its failure frequency and failure behavior with its key figures like the failure rate $\lambda(t)$ and the mean time between failures (MTBF). Besides these key figures further information is lodged to the items [17]. For example this information concerns mean repair times (MRT), mean administrative downtimes (MAD), failure causes and effects as well as spare parts costs (see Figure 2).

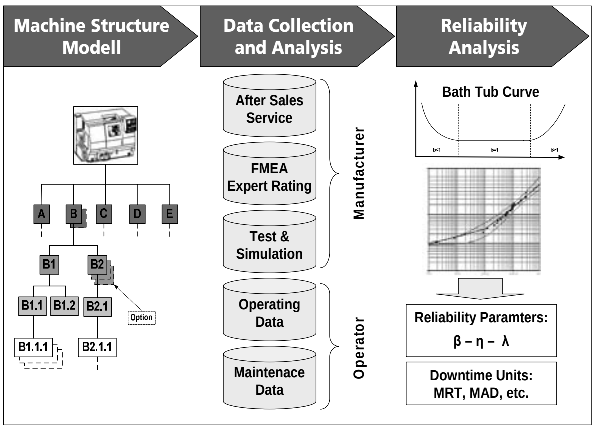

Figure 2: Reliability Analysis.

After the determination of the parameters of the breakdown functions the failure rates *λ(t)* of each operating phase are converted into constant failure rates *λ*. This linearization is necessary to reduce the complexity of the subsequent steps. Additionally, performance agreements between an operator and a manufacturer often define static availability levels for a certain year or over the whole contract duration. Figure 3 displays three different types of linearization of the item's breakdown behavior which are used in the model. The basic failure patterns are divided into typical usage phases *(P_i)*. Reasonably, the fist phase should encompass the ramp-up time, in which early failures occur and production processes are not sufficiently robust yet. The second phase covers the rest of the warranty period, where failure rates are mostly stable. The third phase covers the period, where ageing induces increasing failure rates for many items. It closes with the end of life of the production system or with the planning horizon for availability assurance. At this stage, additional services can sustain the specified availability target that would probably be missed otherwise. Within each usage phase, we assume a constant failure rate. This is expedient, as far as availability targets apply to the usage phases and as service configuration is supposed to be unaltered within each usage phase.

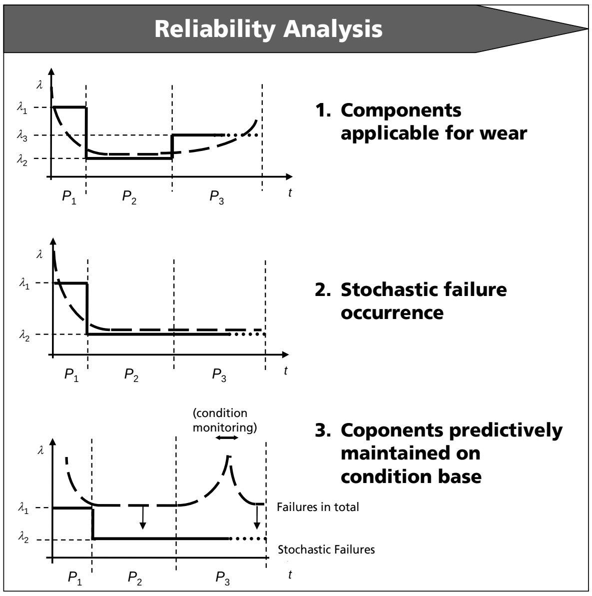

Figure 3: Failure rate in different life cycle stages.

In figure 3 the first type of linearization characterizes items which are applicable for wear and therefore have an increasing failure rate. This form is described by the classical bath tub curve. Considering early failures as well, this type consists of three usage phases, each with a constant failure rate. The second type describes a stochastic failure occurrence with a similar failure rate in the last two periods. Merely early failures of the first period are considered. The last type finally covers items with condition monitoring which can be predictively maintained if necessary. Again, the failure rate of the last two periods is equal due to the fact that no period of time with a higher failure occurrence can be determined if the items are repeatedly changed. The necessary analysis covers the stake of stochastic failures which cannot be avoided by predictive maintenance.

3.2 Analysis of the machine's downtimes

To calculate the operational availability, losses of time due to maintenance during planned machine busy times have to be recorded. These losses of time are caused by machine failures. Their duration depends on the maintainability, the reaction time and on the service performance of the maintenance department (Figure 4).

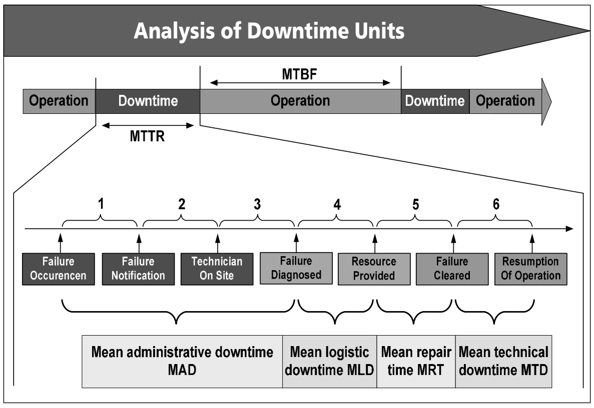

Figure 4: Analysis of downtime units.

Disaggregating the MTTR (mean time to repair, downtime interval) leads to the individual time units (1,…, 6) (Figure 4). Each characteristic time unit corresponds to an individual phase during the maintenance process. Basically, these phases do not have a particular order. Thus, the diagnosis of the problem for example can take place prior to the error message by the customer, just after the error message by means of teleservice or local customer service. Crucial to the disaggregation is that each activity and idle time can be distinctly associated with a single phase and that either the manufacturer's service or the customer himself is responsible. If required, the main phases should be partitioned into subordinate activities. The 6 exemplary time units in figure 4 include:

- Administrative stand by time (1 to 3) defined as latency caused by communication and assignment processes in addition to non-reachability issues. Since failure diagnosis is a cooperative process between a customer and a manufacturer it is part of this category.
- Logistical stand by time (4) for the preparation and provision of all necessary resources for repair. They do not occur in every service case.
- Component-dependent downtimes (5 and 6) due to technological reasons.

The maintenance process is not completed with the return to operation. In addition to the specific downtime units, time and effort of the customer's service for documentation, traveling etc. accrues. Even though these factors are not relevant for the calculation of availability, they should be considered at this stage as essential for the determination of resource demand later on.

The calculation of the probability distributions for the duration *(ξ_i)* of the individual time units can be carried out according to the reliability analysis of the items. Again the underlying data influences the outcome of the calculation to a great extent. Therefore broad expert rating is crucial. Initially, the determination of the durations and the probability of occurrence of the individual time units is carried out in the case that no services are offered or as the case may be only a minimal configuration. The lognormal distribution with its parameters μ (mean) and σ^2 (variance) according to [18] is used for the description of the individual administrative and logistic time units. The determination of the impacts of services on the individual time units and the probability distributions for their duration *(ξ_i)* can be accomplished right after the analysis of the product accompanying services described in section 4.

4 TECHNICAL SERVICES

For an optimization of a machine's Life-Cycle-Performance in terms of reliability and availability it is necessary to analyze the impacts of technical services on the availability next to the reliability prognosis. First of all, it is crucial to analyze and structure the service program, offered by a manufacturer of production machines. Afterwards the impacts on the availability and an optimal combination of single services can be scrutinized.

4.1 Classification of a service program

Attaining a clear classification and structure of a service program, it is necessary to acquire both services already offered by a manufacturer and further possible elements. If they do not have a specific influence on the availability they are taken out of the consideration. Out of the remaining service elements different types are identified and combined to service groups with characteristically specifications. The quality of the specification has to be exactly defined in terms of the dimension of its potential, process and result. For example this concerns the extent of the operator's training or the elements of a spare part package. Above all, it is important to consider the strategic company intentions next to the technical requirements when setting up a service program [19]. Normally an operator of production machines has already implemented a specific service program and is not willing to accept great changes. That is why manufacturers should consider those specifications when adjusting a service portfolio for a machine tool during the early phase of tender preparation.

4.2 Impacts on the availability

After the service program is structured, it is possible to analyze the impacts of the individual elements on the availability. In order to measure the influences on the operational availability, a key figure called availability contribution of a service element is introduced. This key figure describes the reduction in time during a machine breakdown by a specific service element. Admittedly, the extent of the availability contribution depends on simultaneously adduced services.

Determining the availability contribution of a specific service element, it is essential to identify the interdependencies between different services concerning their contribution. To achieve this, the groups of services are arranged in a two dimensional matrix. Afterwards the interdependency of each pair is estimated for every downtime unit described in section 3.2. Predominantly, the estimation is based on the expert rating of the manufacturer's service department. It is defined if the availability contribution *(y_i)* of two service groups *(k, l)* meet the following criteria (Figure 5):

- The interaction is neclegtable and therefore the availability contribution of services can be just added:

$$y_{kl} = y_k + y_l \tag{1}$$

- The services interact and one service dominates the other so that the latter does not have an additional influence on the availability:

$$y_{kl} = max(y_k ; y_l) \tag{2}$$

- The services interact subsidiarily. The concerted availability contribution normally is between the higher availability contribution and the sum of both. In this case further analysis of the exact concerted availability contribution is necessary:

$$max(y_k ; y_l) < y_{kl} < y_k + y_l \tag{3}$$

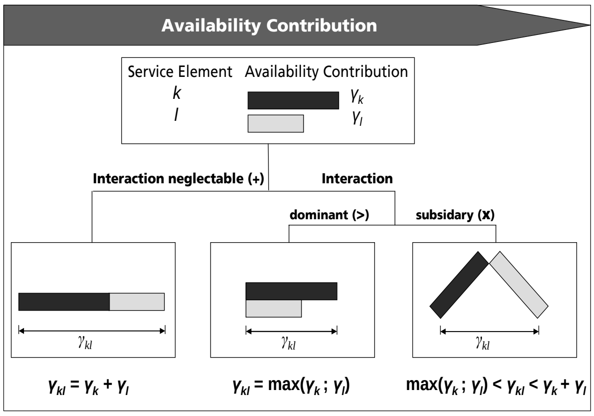

Figure 5: Interaction of different service elements.

If necessary this approach for service pairs can be also expanded for triples. But the practical use has shown that on the base of the characterstical time units the interdependencies are decertelized satisfactory and therefore the examination of service pairs is adequate.

The requirement of an universal application of the method demands to distinguish between the authorities who render the service, particularly in the case of corrective maintenance. This distinction can be achieved by defining the availability assuring activities which are not carried out by the manufacturer as additional service elements in the model. However, the process of corrective maintenance basically requires a separate analysis for each authority rendering the service, for example the service department of the manufacturer or the one of the operator, third parties like local service providers or as the case may be the machine's operator himself. The proportion for each authority is used with the corresponding emphasis in the calculation.

The final calculation of the availability contributions of individual services and their combination is afflicted with uncertainities, due to the fact that this analysis is mainly based on expert rating. Therefore, the analysis of the impacts of services on the individual downtime units has to be carried out very accurately as already described at the end of section 3.2. At this stage it is possible to analyze the impacts of services on the downtime units and to compare them to those cases where no service is provided.

5 AVAILABILITY CALCULATION ON SYSTEM LEVEL

Finally the availability of the machine as a whole system can be calculated based on the failure and maintenance rates of the individual components. This calculation has to be carried out for each operating period individually (cp. section 3.1). Based on the analysis of the machine's reliability and the impacts of services described in the previous sections, the following results are acquainted:

- The expected time (T_F) to breakdown:

$$E(T_F) = MTBF = \lambda^{-1} \quad (4)$$

- The expected time (T_R) to maintenance:

$$E(T_R) = MTTR = \sum_i \xi_i = \sum_i e^{\mu_i + \sigma_i^2/2} \quad (5)$$

The availability calculation of the whole system consisting of all relevant components with an individual failure and maintenance behavior is very complex. Initially, the availability of each component (AC) and not the availability of the whole system (AS) is calculated because the availability and cost analysis in the model is predominantly focused on component level. The availability of a single component (Ac) can be calculated as:

$$A_C = \frac{E(T_F)}{E(T_F) + E(T_R)} \quad (6)$$

The availability of the whole system (As) modeled as a serial structure can be calculated as:

$$A_S = \prod_C A_C \quad (7)$$

But there does not exist a probabilistic guarantee that this static system availability can be obtained [20]. Therefore oftentimes the value Aγ for P(A ≥ Aγ) = γ with an arbitrary chosen 0 ≤ γ ≤ 1 is of special interest. This may be the case if availability commitments are made for single weeks or months. Special solutions for this problem are given by [20] which are based on single breakdown-repair-cycles or by [21] and [22] for several circles or for an arbitrary interval. But it is difficult to allegorize those solutions for a highly complex system in an analytical way. For the derivation of information in terms of the risks of a guaranteed availability level it is necessary to use numerical methods or approximations [23].

6 COST MODEL AND SOFTWAREPROTOTYPE

Beside the analysis of the reliability and availability of the machine tool with its equipment options and accompanying services, the associated costs are calculated. The cost model considers different types of costs depending on their accruement. Furthermore, a calculation of failure cost or even contract penalties is accomplished. The costs for availability relevant equipment options are predominantly known and can be allegorized as fixed costs. Whereas the cost concerning maintenance and other technical services are mostly intransparent and variable. Therefore, it is necessary to analyze the characteristics of the service portfolio described in section 4 concerning their potentials. The single service elements or the service groups can then be broken down into their single steps and be modeled as activity based costs. Special service potentials can then be modeled as supply or usage costs. Due to the fact that needs and costs of availability assuring service elements vary across the machine's lifetime it is essential to calculate the costs for an accurately defined time period.

Facing the complexity of the calculation and the huge amount of necessary data for the statistical fuse of the results, it is indispensable to transfer the method into a software prototype. Impacts of alterations in equipment elements or services are immediately calculated and visualized in terms of availability contribution and costs. After the definition of the customer's needs and boundary conditions, the machine structure and the service program, the availability is calculated for each usage phase. Currently, the method is implemented by a manufacturer of machine tools and is evaluated concerning its accuracy. The comparison of the results of the prognosis to the actual values is satisfactory within the first verifications.

7 SUMMARY

The aim of the presented approach is to optimize the Life-Cycle-Performance of machine tools by a suitable reliability and availability prognosis. The method analyzes the influence of optional machine configurations and technical services on the reliability and availability of production machines. A central objective of the approach is the quantification of the impacts of services on the operational availability in terms of the reduction of the downtime units.

The deceived prognosis method calculates the expected operational availability for each combination of machine equipment, service elements and boundary conditions. Furthermore, the resulting costs are displayed in the comprehensive calculation method. Initially, the machine's reliability on the base of different data sources and boundary conditions is calculated. By establishing an appropriate reliability model different components and single elements of the machine can be analyzed individually. Afterwards the individual failure rates can be aggregated to the failure rate of the whole system. Depending on the defined services it is possible to calculate the availability contribution as well as the operational availability of the whole system.

In the next phase of the research projects it is necessary to advance the described calculation algorithms and the functionality of the software prototype. The latter should support the user by an appropriate reliability and availability prognosis of a machine by easy handling and visualization possibilities. The aim is to examine the following optimization problem in the early phase of tender preparation:

- Maximization of the machine's availability by a given budget.
- Minimization of the costs for achieving a certain availability level.

8 ACKNOWLEDGMENTS

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The Role of Warranty in the Reuse Strategy

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Abstract
In the reuse strategy the role of warranty to deal with quality uncertainty is critical to ensure market acceptance and the economic feasibility of reuse itself. However, up to now there are only a few studies investigating this role. This paper will elucidate the role of warranty in the reuse strategy by reviewing the functions of warranty and putting them into a reuse context. Since warranty analysis is heavily based on reliability and leads to potential additional future costs, a model for analyzing the reliability of reused products and the cost consequences will be presented. An example focusing on a renewing Free Replacement Warranty (FRW) policy will be given.

Keywords:
Reuse; Warranty; Reliability

1 INTRODUCTION

The reuse of components, sub-assemblies, or entire products is considered as one of the most efficient strategies as it preserves materials and energy while maintaining the functional properties of the product [1-2]. Although reuse has been successfully implemented in some product types such as copying machines, toner cartridges, and power tools, its implementation still needs to be expanded to more product types and to broader regions. This is not easy, as the reuse strategy is hindered by many concerns, particularly the quality of used products at the end of the first life [1-3].

At present a variety of research works are carried out to investigate the potential reusability of old products and to increase the possibility of reuse in the next generation of products. Nevertheless, the success of the reuse strategy also greatly relies on market acceptance of reused products that eventually will justify the economic feasibility of reuse. Given that market acceptance is formed by consumer acceptance, the attitude and perspective of consumers toward reused products need to be explored further.

In general most consumers view reused products as having less quality or being second-class quality products [3]. This significantly affects the market for reused products. However, this belief is completely in contrast to the spirit of reuse, which aims at offering as-good-as-new or even better quality products [1]. To unravel this misunderstanding, producers must communicate the quality of reused products to the consumers. Some researchers in the area of marketing and life cycle management highlight different instruments that are currently used by companies to convey product quality to consumers, such as advertisement, price, and warranty [4-5]. These instruments become critically important in promoting reused products, since reused products have not been on the market for a long time, and thus customer's experience associated with reused products is still limited. Literature suggests that the role of warranty is considered as one of the best ways to convey product quality to consumers. The reason is that customers could not explore the quality of the products prior the purchase, and thus warranty would provide a 'peace of mind' and give confidence to consumers to make a purchasing decision. Unfortunately, up to now there are only a few reported studies investigating the role of warranty as one of the potential strategies to deal with quality uncertainty in the reuse strategy.

This paper will elucidate the role of warranty in the reuse strategy by reviewing the current functions of warranty and putting them into a reuse context. Since warranty analysis is heavily based on reliability, and warranty leads to potential additional future costs, a model for analyzing the reliability of reused products and the cost consequences will be presented. The impact of potential warranty costs on the total profitability of reuse will also be discussed and an example focusing on a renewing Free Replacement Warranty (FRW) policy will be given.

2 AN OVERVIEW OF WARRANTY

2.1 The definition

Literature defines a warranty as "a written assurance that the manufacturer of a product will guarantee the quality and reliability of a product in terms of correcting any legitimate problems with the product at no additional cost, for some expressed or implied period of time or use" [6]. Although regulations seem to be the reason for manufacturers to offer warranty, literature reveals that warranty is dictated more by customer and market competition [6-7].

2.2 The policies

Any warranty policy is generally characterized by a combination of the following elements [7]:

- One-dimensional or two-dimensional policy.

  One-dimensional warranty is a warranty that is based on calendar time alone. Two-dimensional warranty is a warranty that is limited by the age and the usage of the product.

- Free-replacement, pro-rata, or rebate policy

  In a free-replacement warranty (FRW), manufacturers will repair or replace the failed items free of charge up to some specified period from the initial purchase. In contrast, under a pro-rata warranty (PRW), manufacturers will refund a fraction of the purchase price or will replace the failed item with a new one at a prorated price, if an item fails under warranty. Under a rebate policy manufacturers agree to refund an amount to the maximum of the selling price if an item under warranty fails. “Money Back Guarantee” is a classical example of this policy, which happens if the refund is the same as selling price.

- Renewing or non-renewing policy

  Under a renewing policy, if an item fails within the warranty period, it will be replaced by a new item with a new identical warranty, replacing the old one. In other words, a new warranty period begins with each replacement. On the contrary, the non-renewing policy will replace the failed item but will not add another period of warranty. Under this policy, the warranty time after the replacement is only the time remaining in the original warranty period.

The most popular warranty policy for typical consumer goods is FRW and "Money Back Warranty” [6-7]. The FRW could be renewing or non-renewing, whereas the rebate warranty is logically a non-renewing policy.

2.3 The roles

Through time, the perceived role of warranty in society has changed [8]. Warranty serves not only the buyer but also the producer, government, and the society as a whole [7].

Consumer’s point of view

The average consumers are unable to judge the quality of products they are buying and unfortunately they have no chance to experience the quality of the product prior the purchase [9]. Therefore, they need an instrument that could tell them the quality of the product and at the same time protect them from purchasing a poor quality product [7].

Therefore the first role of warranty is to protect consumer rights. A warranty is a means of redress if the item, when properly used, fails to perform its intended function. Specifically, the warranty will assure that a faulty item will either be repaired or replaced at no cost or reduced cost.

Secondly a warranty is a good indicator of a product’s reliability. This concept proposes that, if a manufacturer offers a better warranty than a competitor, then the reliability of the product should also be better. In this sense, warranty becomes an informational instrument that helps the consumer to make a purchasing decision.

Producer’s point of view

Essentially, warranty is also a protection for producers [7]. This refers to the use and conditions of use for which the product is intended. Consequently, misuse or improper use of the product will cancel the coverage of warranty.

In addition, because of the signaling characteristic, warranty can be used as a marketing tool to promote sales and to be highlighted as an important product feature. These roles eventually aim to build a long-term image and relationship with customers, thus retaining business even after the warranty period expires.

When setting the warranty length, manufacturers have to target zero defects during the warranty period, because they do not want to spend the warranty costs. More importantly, producers try to satisfy their customers as it is far cheaper to keep an existing customer than to get a new one.

2.4 Warranty cost

A warranty will certainly induce additional costs. These costs are unpredictable future costs and they have a significant impact on the total profits of a manufacturing business. Logically, warranty costs depend on product reliability and warranty terms [4,7]. Warranty terms include the length of the warranty period and the features of the warranty policy. Therefore producers have to analyze the product’s reliability and the associated warranty cost carefully before offering any warranty.

2.5 Warranty in a reuse context

Similar to buying a new product, before making a purchasing decision for a reused product, customers want an assurance that the reused product will perform satisfactorily during the useful life. To respond to this requirement, manufacturers not only need to make sure that reused products will have a good quality, but they also need to provide assurance to the customer. Considering the uncertainty of the quality of reused products, the role of warranty in reuse will be even more critical than in new products. Without a suitable warranty, market acceptance for reused products will be limited, and the economic feasibility of reuse itself will be jeopardized.

In this research warranty is considered as an expression of social responsibility, offered by the company to protect the customer’s rights for getting a good product. Being an environmentally conscious company does not mean that the company can neglect the responsibility to provide a good quality product. The tenet highlighted in this research is that reused or remanufactured products must carry the same protection, if not better, to the customers in terms of quality.

The above comments on the role of warranty have led to the conclusion that warranty can play a significant role to enhance the attractiveness and the market acceptance of reused products. However, the inclusion of warranty in the reuse strategy will usually entail a higher warranty cost as the ‘older’ products will generally have a higher failure probability. Even if the length of the warranty is the same as for new products, the risk of having higher claims is understandable [10]. Therefore, a cost exercise is needed to plan for a suitable warranty policy for reuse.

Research in this area is still limited. Therefore this paper will provide a methodology to assess the warranty cost reserved by manufacturers in the reuse strategy and how this additional cost influences the profitability.

3 QUALITY ASSESSMENT IN A REUSE CONTEXT

3.1 The scope of quality

In this research, quality is divided into three dimensions; the technology, the functionality, and the reliability. If the speed of technology development in a particular application is very fast, the technological assessment of a current product in that application will be lowered due to the emergence of new technology products. In this situation the reusability of the current product will decrease. Reuse is only suitable for products that are mature in technology and have slow to moderate changes in technology.

For technologically stable products, functionality and reliability become the quality dimensions that need to be addressed. Functionality represents how well a product can perform its intended functions at the beginning of its life. For reused products, it represents the condition of the product at the beginning of the second life. Reliability represents the ability of a product to perform its function in an acceptable way during a given period of time, which is a normal usage period. In the reuse strategy, reliability of a used item must be assessed based on the probability of its survival during the second life. A product with high quality should be functioning properly and working reliably during a normal usage period. Therefore, in a reuse context, reused products should deliver the same quality as new products.

Normally the functionality assessment of used products can only be done after collection and disassembly. However, for economic reasons it would be more effective to assess the product's remaining life before collection. Graphically, the flow of assessment is shown in Figure 1. Used products that have no remaining life at all do not need to be disassembled and can be collected for recycling or disposal purposes.

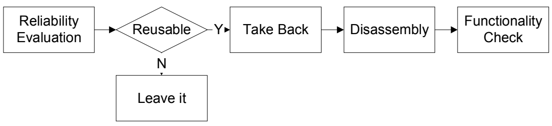

Figure 1: The flow of assessment.

3.2 Remaining life assessment

In regard to reliability, most products follow a bathtub curve over their life (Figure 2) that consists of three different phases: setting phase, useful life phase, and wear-out phase [2]. Products in the market usually have passed their setting phase and commence their stabilized phase. Reuse is only applied when the product is still in the useful life phase, since the failure rate at this stage is constant.

While there are many ways to assess the remaining life of products [2], this research will use life data analysis using statistical approaches. This method has been widely used in many previous researches and has some strong points compared to other methods [2]. One of the most prominent advantages is due to the fact that this method can use current data available in most companies, thus it does not need new investment.

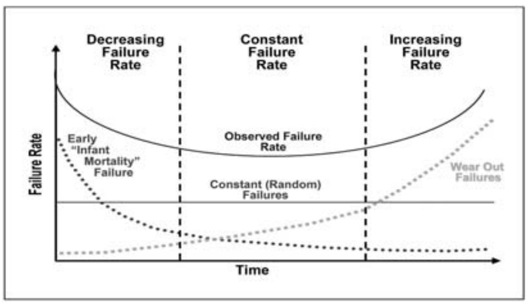

Figure 2: The bathtub curve [11].

In brief, the steps of this assessment can be seen in Figure 3. The first step in this assessment is to determine the reliability distribution of the products. By utilizing life cycle data, either from accelerated life testing data or field data, this step yields reliability distribution and reliability parameters that characterize the life of the product under investigation.

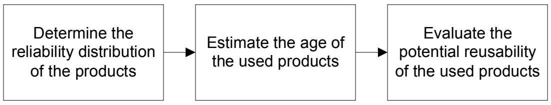

Figure 3: The steps of reliability assessment.

There are some common lifetime distributions that can be used to best represent the reliability of a product. Among those, the Weibull distribution is the most flexible distribution that can characterize the three phases in the bathtub curve.

The Weibull distribution is characterized by two parameters, a scale (η) and a slope (β). The scale parameter (η), also known as the characteristic life, is defined as the life of the product at which 63.2% of all units will fail, while the slope parameter (β) is defined as the mode of failure. Referring to the well-known bathtub curve (Figure 2), β<1 indicates a decreasing failure rate at the setting phase, β=1 is a random failure during the useful life, and β>1 is an increasing failure rate at the wear-out phase.

The cumulative distribution function, *F(t)*, in the Weibull distribution can be determined by using Equation (1) to represent the cumulative probability of units failing at a particular time *t*.

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \qquad (1)$$

Furthermore as the number of survival at time *t*, *R(t)*, can be determined by *1 – F(t)*, the reliability can be calculated by using Equation (2).

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \qquad (2)$$

The second step is to estimate the age of the used products at the end of their first life. It can be done through different techniques as well, ranging from the most sophisticated one, which is the use of an electronic data log mounted in the product, to the most common one, which is the use of the historical data of the product, kept by production, maintenance, or marketing departments within the company. The estimation can be very accurate or less accurate depending on the applied method and the quality of the data. Based on the age estimation, the reliability of the used products can be determined and the reuse evaluation can be conducted.

In the third step, manufacturers have to determine the threshold value for the reliability of the reused products. Literature suggests that the most common measure is the Mean-Time-to-Failure (MTTF), which indicates the average life of a product or the time when around 50% of products will fail. However, this is the worst-case scenario and most manufacturers want to have a higher threshold than 50%.

3.3 Reliability-based decision for reuse

Ideally, manufacturers want to provide 100% reliability to their customers. However, some failures are unavoidable and they will happen to most sold products during the average life. It can be said that there is no 100% reliability for the whole lifetime, neither for new items nor for reused items. Therefore, instead of using 100% performance as a target, manufacturers have to determine a threshold which represents an acceptable number of failures during the product's life time.

The acceptable number of failures is the maximum number of failures allowed for the total number of products considered during their average life. The setting is subjective, depending on the marketing strategy of the manufacturer, including factors such as company image, market competitiveness, and targeted customers. As an example, if a manufacturer allows only 10 units to fail among 100 units sold during the product's life, that means the selected reliability threshold is 90%. The manufacturer then will try to achieve this target through material and process selection. If the accelerated test and the empirical maintenance data show that this target has not been achieved, the manufacturer will examine the design and undertake redesign exercises.

The desired reliability level during the product's life is denoted as R^*, while the maximum time of concern related to the selected reliability threshold is denoted as T^*. T^* can be calculated using a specific function in the Weibull distribution, called percentiles, t_p, or *BX* life (Equation 3). B10 life is usually used in industry as a criterion for the lifespan of new products.

$$t_p = \eta(-\ln R)^{\frac{1}{\beta}} \quad (3)$$

Based on R^* and T^*, the reusability evaluation of used products is possible. Two additional factors that affect the decision are the age of used items at the end of the first life, signified by t_1, and the estimated time for the second life, signified by t_{02} (the index 02 indicates that it is an estimated time and not a real time) In the evaluation, used items will be categorized as potentially reusable without remanufacturing only if their reliability at the end of the second life, $R(t_1 + t_{02})$, is still greater than R^* (see Figure 4). By adopting this concept, statistically manufacturers would offer reused products with the same performance as new ones.

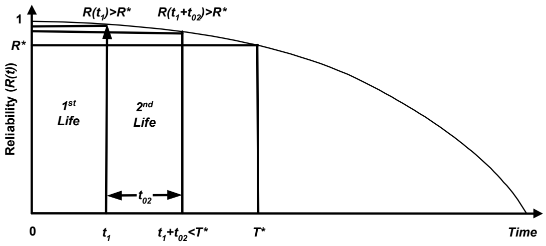

Figure 4: Reliability of products with potential reusability.

If $R(t_1 + t_{02})$ is less than R^*, manufacturers should consider remanufacturing as the best option. Remanufacturing will reset the life of the used product and bring the reliability back to the maximum. Based on the above guideline, the idea of reuse and remanufacturing will be achieved since the reused products will perform within the range of acceptable reliability in the same way as the new products.

As the purpose of this paper is only to present the role of warranty in the reuse strategy, a discussion on the remanufacturing option will not be presented here.

3.4 Warranty analysis

The reliability curve in Figure 4 indicates that the probability of survival is a function of time. Thus the probability of failure will increase as the age of the product increases. As a baseline, the warranty cost for the first life has to be calculated first. Then, the warranty cost for the second life can be calculated based on several factors such as the reliability threshold, the age of the used product, and the length of the warranty period.

In this paper, the analysis will be focused on renewing FRW. Under this policy, a failed item is replaced at no cost to the buyer if the failure occurs within the warranty period. The replacements are given full warranty coverage as the original item. This type of warranty is often called an unlimited warranty or unlimited free-replacement warranty. Equation 4 can be used to determine the estimated average cost to the manufacturer per item [12].

$$C_w = E[C_w(t_w)] = PLCC \times \frac{F(t_w)}{1 - F(t_w)} = PLCC \times \frac{F(t_w)}{R(t_w)} \quad (4)$$

Where:

C_w = total warranty cost per unit reserved by producers.

$E[C_w(t_w)]$= producer's expected warranty cost .

t_w = the length of warranty period.

PLCC = warranty cost per failure paid by producer, in this case it is the Product Life Cycle Cost (PLCC) including production cost, administration cost, labor cost, and other costs associated with providing the item to the customer.

$F(t_w)$ = the cumulative distribution function.

$R(t_w)$ = the reliability function.

Index *i* = 1, 2, … = the i^{th} life, e.g. *i = 1* for the 1^{st} life and i = 2 for the 2^{nd} life.

Considering that C_{w2} would potentially increase the total life cycle cost of the product, a maximum value must be set as a basis for evaluating whether the additional warranty cost for the second life still justifies the required profit margin. If *MP* represents the market price and *PLCC* represents the total product life cycle cost, then the desired profit margin, *PM*, can be determined by using financial figures for a new product (Equation 5). This *PM* is the reference point to evaluate the maximum additional warranty cost for the second life, ΔC_{w2}. In other words, a reused product must attain at least the same *PM* as a new product (Equation 7). By solving Equation 7, the maximum additional warranty cost can be determined by using Equation 8.

$$PM = \frac{MP_1 - PLCC_1}{PLCC_1} \quad (5)$$

$$\Delta C_{w2} = C_{w2} - C_{w1} \quad (6)$$

$$PM \le \frac{MP_2 - (PLCC_2 + \Delta C_{w2})}{(PLCC_2 + \Delta C_{w2})} \quad (7)$$

$$\Delta C_{w2} \leq \frac{MP_2 - PLCC_2(1+PM)}{(PM+1)} \quad (8)$$

4 A CASE STUDY

4.1 Description

As part of an ongoing research project on the reuse of appliances, the compressor of a domestic refrigerator has been selected to demonstrate the analysis of the proposed method. Normally, the useful life of refrigerators ranges from 10 to 15 years, while the compressor is expected to have a longer life. The typical warranty period for a compressor varies from 1 to 5 years and the warranty coverage usually includes replacement and labor costs.

4.2 Reliability analysis

This case study utilizes real field data collected from a leading manufacturer of home appliances. The nature of the data includes time-to-failure data recorded by the maintenance department, the number of surviving products from sales data, and the distribution of the product in the market region.

The data of the observed compressors were analyzed by using the Weibull distribution to reveal the main parameters as summarized in Table 1. Based on these reliability parameters, reuse evaluation and warranty analysis were conducted.

Table 1: Results of Weibull analysis for a compressor.

Shape Parameter (β)	1.4724
Scale Parameter (η)	84.65 years
Mean life or MTTF	76.6 years

4.3 Reuse evaluation and warranty scenarios

To demonstrate the applicability of the proposed model, the potential reusability of the compressor will be assessed under four different threshold values, i.e. 95%, 90%, 75%, and 50%. The first is selected to represent a strict performance policy, while the latter represents a common practice related to the use of mean life or MTTF as the basis for remaining life estimation [2]. With regard to the selected values of R^*, the associated T^* has been calculated and the results are presented in Table 2.

Table 2: Threshold values.

BX	*R**	*T** (days)	*T** (years)
B5	0.95	4110.08	11.26
B10	0.9	6701.42	18.36
B25	0.75	13257	36.32
B50	0.5	24089	66

In order to perform the warranty cost analysis, a set of cost data has also been collected, which is summarized in Table 3. The cost data has been simplified in order to avoid disclosure of confidential company information, but it still represents a realistic situation. As explained in the model, the desired *PM* is set, based on the economic performance of the new product. Furthermore, this case study will examine two scenarios in terms of the setting of *MP* for reused items. In the first scenario, reused items will be sold at the same *MP* as new items ($MP_2 = MP_1$). In the second scenario, reused items will be sold at a reduced price. In this case it is set at only 60% of the new items' *MP*.

Table 3: Cost data.

New Products		Reused Products			
		Scenario 1		Scenario 2	
MP_1	\$180				
$PLCC_1$	\$128.57	MP_2	\$180	MP_2	\$108
PM	40%	$PLCC_2$	\$51.43	$PLCC_2$	\$51.43

Five different warranty periods are considered in the analysis to cover the real situation in the market where most manufacturers offer 1 to 5 years warranty. For each warranty period, the warranty cost for new products has been calculated and will be used as the baseline value. The maximum additional warranty cost permitted for each scenario has also been calculated using the cost data presented in Table 3. These values will be used to justify whether the additional warranty cost triggered by the increased failure probability in reused items is still acceptable and does not diminish the overall profitability.

Table 4: The baseline results.

	Warranty period (years)				
	1	2	3	4	5
$F(t_{w1})$	0.001	0.004	0.007	0.011	0.015
$R(t_{w1})$	0.999	0.996	0.993	0.989	0.985
$F(t_{w1})/R(t_{w1})$	0.001	0.004	0.007	0.011	0.016
C_{w1}	\$0.19	\$0.52	\$0.94	\$1.44	\$2.01
Max ΔC_{w2} for Scenario 1			\$77.14		
Max ΔC_{w2} for Scenario 2			\$25.71		

The baseline results suggest that the performance of the compressor is very good and the risk of having failed products within the warranty period is very low, even under the 5-year warranty. The baseline results also highlight that the reduction of *MP* will significantly cut down the allowance of additional warranty cost, as expected. Hence if ΔC_{w2} is still justified under the second scenario, the reused products will be much more attractive as they can be sold at a cheaper price with the same warranty as the new items.

By setting t_1 from 1 to 15 years and by assuming that t_{02} will be 10 years on average, the reusability potential of used products and the additional warranty cost required by the reused products can be analyzed. For further analysis, two longer warranty periods, set to be 10 years and 15 years, are added to investigate the cost consequences of offering longer warranty for reused items. Some of the results are presented in Table 5.

The results suggest that under the strictest threshold 0.95, the used items will not be reusable if they have been used for more than 2 years. For the threshold of 0.9, direct reuse without remanufacturing will not be possible when t_1 exceeds the value of 9 years. However, the cost exercises show that even after 15 years of use, the failure probability is still justified and the additional warranty cost (if $t_{w2} = t_{w1}$) is less than the maximum allowable limit for both scenarios. Conclusively, the analysis highlights that the manufacturer could reconsider the threshold setting and relax the target without jeopardizing the performance.

Table 5: The additional warranty cost for the second life.

t_{w2} (year)	The Age of used products at EOL (t_1)						
	1	2	3	…	10	15	25
1	0.33	0.76	1.26	…	6.35	11.37	24.53
2	0.43	0.93	1.49	…	6.93	12.16	25.75
3	0.50	1.07	1.69	…	7.47	12.91	26.92
4	0.57	1.19	1.87	…	7.97	13.62	28.05
5	0.63	1.31	2.04	…	8.45	14.31	29.16
10	4.52	5.44	6.40	…	14.31	21.20	38.25
15	9.54	10.67	11.84	…	21.20	29.16	48.55

Under the same warranty policy, providing the same warranty period for reused products seems to have no risk at all. The value of ΔC_{w2} is greater than \$25.71 only if the used items age more than 25 years, which is unlikely to happen. Recall that the extreme usage life of refrigerators is only around 15 years, thus the collection time of compressors would be around 15 years as well.

Table 6: An example of different warranty length analysis.

t_1 = 12	t_{w1}				
t_{w2}	1	2	3	4	5
1	8.23				
2	9.23	8.90			
3	10.28	9.94	9.52		
4	11.37	11.03	10.61	10.11	
5	12.50	12.16	11.74	11.24	10.67
10	18.77	18.44	18.01	17.51	16.94
15	26.08	25.75	25.33	24.82	24.26

Since all ΔC_{w2} are less than the maximum ΔC_{w2} for scenario 1, a cheaper *MP* with the same warranty coverage can be blended into a single strategy that certainly will strengthen the attractiveness of reused products. To support this argument, a further investigation has been conducted to identify the cost consequences if manufacturers offer a longer warranty period for reused products compared to new products. An example of this analysis is presented in Table 6, where the age of the used items is 12 years and $t_{w2} \geq t_{w1}$. Assuming that on average manufacturers offer 3 years warranty for new items, the results suggest that up to t_1 = 10 years, it is still economical for manufacturers to offer longer warranty periods up to 10 years. In this sense, the role of warranty as a protection and a promotional instrument can be achieved. From the customer's perspective, the warranty is also viewed as an advantage. However, offering a lifetime warranty of 15 years is only affordable if the age of the old items is less than 11 years.

5 CONCLUSIONS AND FURTHER RESEARCH

In this paper, the roles of warranty in a reuse context have been discussed and a model to assess the potential reusability and to analyze the additional warranty cost has been proposed. A case study on compressors has confirmed the applicability of the model and revealed that it is possible to provide a longer warranty for reused products without reducing the targeted profit. Although tied to a particular data set in the case study, the same steps can be used as a guideline for other applications.

In a nutshell, it can be concluded that the reliability pattern, the selected threshold, the age of old products, and the warranty length have influence to the feasibility of direct reuse. There are plenty of rooms for further research, such as the effect of different warranty policies in the model, the reliability behavior of reused products, and how to find out the optimum warranty length from both company and consumer's perspective.

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Lifetime Modelling of Products for Reuse: Physical and Technological Life Perspective

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Abstract
Reuse of products and their components can be an economically and environmentally superior alternative to material recycling. One of the main obstacles in implementing a reuse strategy is the lack of reliable methods to assess the reliability of used parts, which should take the physical and technology life into account. This paper presents a lifetime simulation model to predict the remaining life of components for reuse based on the Weibull method and the S-curve technique to represent the physical and technology life of components. The model was tested by using a Cathode Ray Tube (CRT) television.

Keywords:
Reuse; Lifetime Modelling; Physical Life; Technological Life

1 INTRODUCTION

The contemporary society is confronted with a global environmental challenge. The responsibility in sustainable development is expanded to include manufacturing firms and the society as a whole with a focus to achieve vast reductions in resource use and waste generation. This introduces the concept of closed loop manufacturing which aims to develop strategies to enhance product take-back and recovery activities. While material recycling is widely used as an instrumental End-of-Life (EOL) option, reusing the products and components can be an economically and environmentally superior alternative for many products [1].

When a product is discarded, it is generally due to the product's obsolescence which can be grouped into two categories. The first one is the technical obsolescence, in which a product is discarded due to its physical limits e.g. aging or wear and tear. The latter obsolescence is due to those factors which also influence the usage lifetime of a product in terms of value changes. The value of a product may be justified by its technology features, aesthetic appearance, performance per unit dollar, level of environmental impact, and emotional value [2]. These factors have a different impact on different users or market and considerably change over time in relation to the technology progress of a particular product. However, regardless of the category of obsolescence, it is observed that a discarded product often contains some component that offers potential for reuse. This is because the average lifetime of components can be longer than the lifetime of the entire product. For example, Mazhar et al [3] provides empirical evidence that the lifetime of an electric motor often exceeds the life time of the product which it is installed in. There is fundamentally very little information available on the remaining lifetime of used products and their components.

Past researches [4, 5] have discussed two alternative techniques to assess the potential lifetime of used products and their components: (a) End-of-Life testing of the product/components and (b) Analysis of the operational data collected during the intial life. However, these techniques are time-consuming in collecting and analysing the data and require disassembly which is not valid for stationary components.

The disadvantages of these empirical alternatives together with the technological developments that lead to products and components being progressively obsolete are the basis for this paper which proposes an integrated methodology for estimating the remaining lifetime of used product and their components. The methodology and results should benefit designers and manufacturers in selecting components for reuse. In addition, it works as a decision support tool that assists in product end-of-life selection.

The study employs non-empirical techniques that focus on fundamental lifetime boundaries of physical and technological aspects respectively. The methodology was tested by using a Cathode-Ray-Tube (CRT) television as a case study.

2 INTEGRATED METHODOLOGY

In order to estimate the remaining life of used components, the two aspects, physical and technology life must be integrated so that the aforementioned category of obsolescence can be taken into account.

2.1 Physical Lifetime

The first step in the methodology is to estimate the reusability of products and its components based on their physical life-limit as shown in Figure 1. In order to achieve this, the remaining physical lifetime, T_p, is calculated as a difference between the physical life of the product, T_f, and the intensity with which the object has been used, T_u. This relationship can be shown as follows:

$$T_p = T_f - T_u \qquad (1)$$

The lifetime of products is commonly measured in hours, cycles or in any other unit that applies to the period of successful operation of a particular product. The parameter T_f, is an estimation of failure datum, which was assumed to be the Mean-Time-to-Failure (MTTF) instead of B10 life that is used in industry. This assumption was made in order to test the worst case scenario. In this study, this was obtained by using the Weibull analysis of collected data from a manufacturer [6] and the evaluation of statistical properties using Arena simulation software. The age of a product, T_u, is also a critical parameter that indicates how long a product has been used. This is different from the calendar year, which is often calculated from the date of manufacture to the date of disposal of the product. In this study, the usage life of product, T_u, was estimated based on its usage intensity over time.

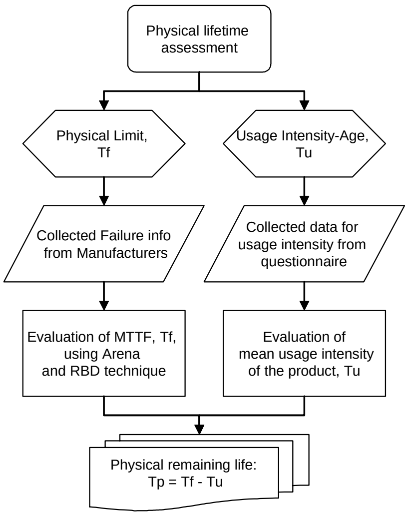


Figure 1: Method of estimating remaining physical lifetime

This is more realistic than methodologies presented in the literature, which tend to estimate the usage life as constant throughout its lifespan [10]. In fact, the usage conditions and level of intensity may change and depends on the obsolescence with respect to time. For example, the frequency and duration with which a ten year old television may be less than a two year old television in the one house hold due to a preference for the newer model. For instance, due to the new features and attractive design that the new television has over the ten year old with malfunctions and inefficient energy consumption.

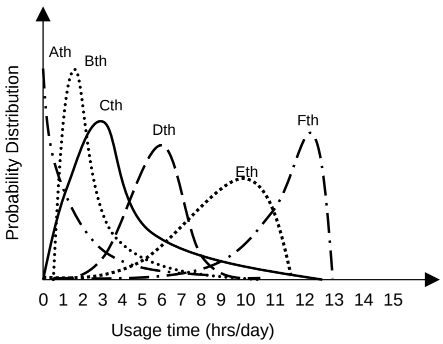


Figure 2: Made-up probability distributions of usage intensity of a product at different age.

In this study, a survey was designed to collect data from users, which was then statistically analysed in order to estimate the frequency and the duration that a television spends in active mode at different ages. The results provided a meaningful representation of the usage life as shown in Figure 2.

The probability distributions, as shown in Figure 2, are non-symmetric, and may vary from right to left skewed. If it is assumed that a product is likely to spend X_1 hours per day in active mode during its *1*st year, X_2 hours per day during the *2*nd year, X_3 hours per day during the *3*rd year and so forth, until the *jth* year of its service life, where the estimated total hours, T_u, that a product has been used before being disposed, can be calculated using Equation (2).

$$T_u = \sum_{i=1}^{j} X_i \times 365 \quad (2)$$

Since the statistical variable X_{ij} returns pseudo-random values governed by the probability distributions, the result T_u can be different for each unit of product. The value of the average is therefore an absolute T_u of product at that particular age. Moreover, the T_u of the components is simply equal to the T_u of the product itself.

Simulation Modelling

In the area of life cycle engineering, there are many studies on product life cycle that use simulation-based methodologies for evaluating life cycle issues - from product design, materials and energy flow, use and operation, to selection of end-of-life options [7]. Simulation model of products are particularly used to represent how product s function and reflect changes in operational condition due to the malfunction of components or subsystems. In this research, computer simulation is used for evaluating physical failure distributions and MTTF of a product and components from the available statistical properties.

It is generally difficult to use statistical calculations to assess the random failures and find an estimate of MTTF of components. However, a computer simulation may be used to predict the MTTF with a high degree of confidence. The tool chosen for the simulation model is Rockwell Software’s Arena V8. It is a system modelling package that combines the ease of use found in high-level simulators with the flexibility of simulation languages. The key feature is that it contains a set of built-in functions for evaluating random variables from commonly used probability distributions.

A simulation model in this study was developed based on the Reliability Block Diagram (RBD) representation, an analysis technique supporting the study of system failure and reliability [8]. The technique uses a probabilistic scheme to demonstrate the reliability relationship of a system. An advantage in using RBD is that it overcomes the complexity of the functional layouts as well as their inter-relationships in normal block schematic diagrams [9]. This reduces an overall system to a simple system in series or parallel arrangements of the products components. The following assumptions were made to represent the system:

- The components have independent failures of each other enabling individual failure probability distributions furthermore where failure is instantaneous.

- Components which contribute to the same functional output were grouped together under a sub-system block diagram in order to simplify the system.
- Components fail independently according to the assigned failure probability distribution.
- When a product malfunctions due to failure of one of the sub-systems, then every component within that sub-system is assumed to have failed.
- Each replication of the simulation represents a lifetime period of one unit of product.

2.2 Technological Lifetime

The second classification of product obsolescence is mainly due to the technological progress of improved products. There has been little research done to measure the change particularly at the early stages of launching technological products [11]. In this paper, a mathematical model for technology substitution was used. Figure 3 shows the remaining technological lifetime estimation. Note that the value of T_t of a particular product technology is estimated as when its market share drops to a certain limit.

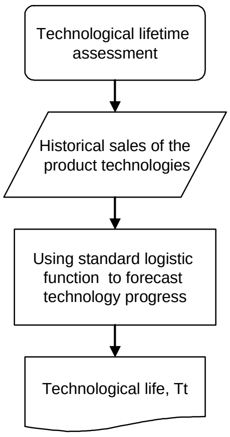


Figure 3: Remaining technological lifetime assessment

This model forecasts a point in time when a generation of product technology is being replaced partially or completely by another in terms of market penetration. The substitution tends to take the form of an S-Shaped curve that has been supported empirically by many researchers, including Fisher and Pry [12].

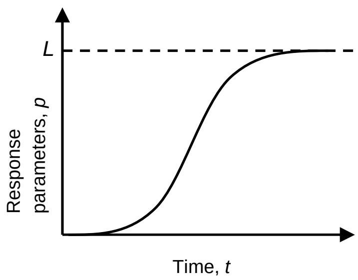


Figure 4: Logistic curve (S-curve)

As seen in Figure 4, the characteristic S-shape shows that the curve begins with slow initial growth, followed by subsequent rapid growth at first, but because of new competitive technology and limitation on the size of the underlying market, eventually grows more slowly and then level off. An S-shaped growth curve of a product was modelled using a standard logistic function. It particularly follows the logistic law of growth that assumes an exponential growth until an upper inherent limit, L, in the system is approached.

In the normal exponential growth model, the growth rate of a population, $P(t)$, is proportional to the population at time t.

$$\frac{dP(t)}{dt} = bP(t) \tag{3}$$

The logistic function adds to the above equation a feedback term that slows the growth rate of the system as the population L is reached.

$$\frac{dp}{dt} = \left[\frac{b}{L}\right] p(L-p) \tag{4}$$

Therefore, a standard logistic function can be defined by the following mathematical equation:

$$p = \frac{L}{1 + ae^{-bt}} \tag{5}$$

, where p is the value of the technological parameter; in this instance it is the percentage of market penetration, t is the time unit in year, L is the natural limit, a is a constant scale parameter, and b is a shape parameter. Note that the value of a yields p when t is zero and b adjusts how quickly the response changes with changing t a single unit.

2.3 The Integrated Approach

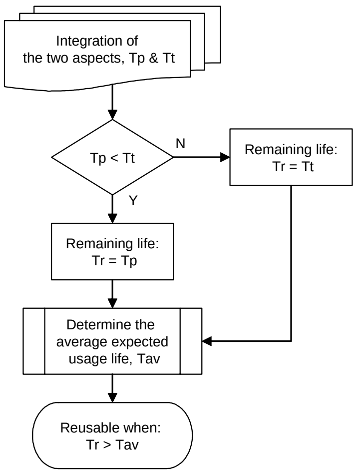


Figure 5: Integrated remaining lifetime assessment.

Figure 5 summaries the steps of the integrated methodology from the two aforementioned aspects, namely physical and technological life. The comparison of the values of T_p and T_t gives an estimation of the remaining lifetime for a particular product or component. If the technological lifetime is shorter than the physical lifetime, then the remaining lifetime of the product is governed by the value of the technological lifetime itself, and vice versa. Moreover, this points out the importance of an average service life, T_{av}, of a particular product. In order for a component to have reuse potential, the remaining life must be greater or equal to this expected service life.

3 APPLICATION OF THE METHODOLOGY

In order to demonstrate the validity of the proposed methodology, a Cathode Ray Tube (CRT) television was used. An evaluation of the remaining lifetime of the product and its components was performed based on the following assumptions:

Failure modules of the product and its components

The model assumes that a product can be simulated as a series of independent components. If there are multiple identical components (e.g. a CRT with 130 capacitors), then it was assumed that all components fail at the same time when the product (i.e. CRT) fails. This implies that all the identical components share a single failure distribution.

Technological progress

Breakthrough technology was the type technological progress addressed in this paper, while products in similar technology groups (e.g. curve-screen CRT, flat-screen CRT, slim-panel CRT, etc.) were not considered. Additionally, it was assumed that every component in a product is only eligible for reuse within its own technology group.

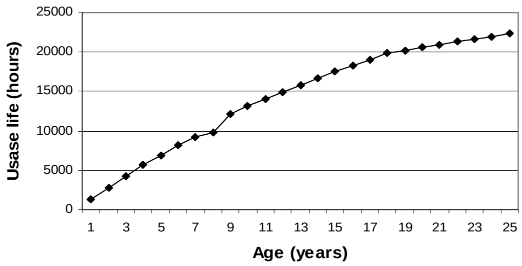
Time axis

The physical lifetime of a product and its components were measured in hours whereas technological lifetime was measured as elapsed-time measured in years. Therefore in order to integrate these two aspects, the latter was converted to hours in order to have consistency of units.

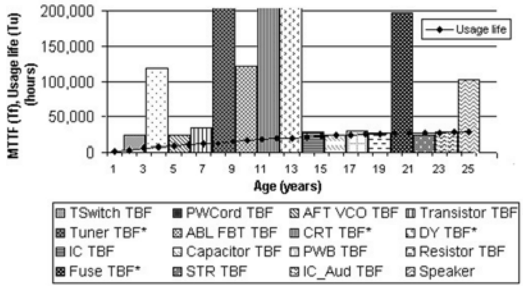
3.3 Results of the case study

An RBD representation of a CRT television was first created. Definitions of selected components are given in Appendix A. The diagram consists of five sub-systems namely, power input and switches, signal receivers and encoding devices, electronic circuit devices, picture encoding and display devices, and audio devices. Then these five sub-systems were converted to a simulation model to simulate the physical life time of the CRT television and its components. Figure 6a and 6b show the average lifetime of individual components within a CRT television. The results indicate that they are relatively long in comparison to the estimated usage life. This is particularly the case with the tuner, CRT, DY, and Fuse (marked with an '*'), which can potentially last longer than 200,000 hours. Note that the standard deviations of average lifetime of all the components are within 10%.

A comparison of the market shares between different television technologies was carried out for the remaining technological lifetime. These include Cathode Ray Tube (CRT) TV, Liquid Crystal Display (LCD) TV, Plasma Display Panel (PDP) TV, and Rear Projection Television (RPTV). Figure 7 shows a significant decrease in market share of CRT televisions due to the growth in the market segment of LCD and PDP televisions.



(a) Usage life of a television and its components in hours with respect to its age



(b) Comparison of the physical limit and the used life of television components

Figure 6: Estimated used life of a television at different ages

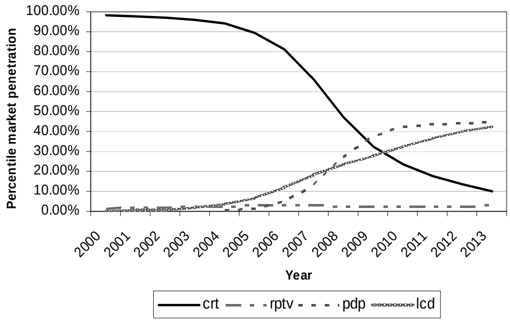


Figure 7: The forecast of television's market penetration for different technologies

Figure 7 illustrates that the product and its components are eligible for reuse in terms of their technology until the year 2010. This result is based on the fact that the technological lifetime of CRT TV ends when its market share drops to 30% as used by the TV manufacturers.

The results discussed so far, indicate the importance of integrating the two lifetime aspects. Figure 6(b) suggests that most of the components in a television have potential for reuse on the basis of its physical lifetime as a stand-alone factor. However, the integrated approach shows a different trend as shown in Table 1. Since the remaining technological lifetime, T_t, of every component is less than their remaining physical life, T_p, the total remaining lifetime, T_r, of the components are thus governed by the value of T_t. In addition, this is noticeably shorter than an expected service life, T_{av}, of a television, which is 10 years or 13,190 hours. Consequently, none of the components appear to have a reuse potential.

Component	Capacitor	PWB	Resistor	Fuse	STR
Physical Limit, *Tf*	24,012	28,996	26,483	197,719	24,310
Used life @ 15 yrs, *Tu*	17,522	17,522	17,522	17,522	17,522
Remaining Physical life, *Tp*	*6,490*	*11,474*	*8,961*	*180,197*	*6,788*
Remaining Technology life, *Tt*	*5,110*	*5,110*	*5,110*	*5,110*	*5,110*
Total Remaining life, *Tr*	5,110	5,110	5,110	5,110	5,110
Expected service life, *Tav*	13,190	13,190	13,190	13,190	13,190
Reuse Potential	No	No	No	No	No

Table 1: Example of estimated remaining lifetime and reuse potential of some components in CRT television

4 CONCLUSIONS AND FUTURE WORK

The integrated methodology presented in this paper provides a useful tool for estimating the remaining life of product components without time consuming disassembly and testing operations. This methodology is applicable to different type of products. The validity of the model was demonstrated by using a CRT television. The results indicate that the proposed model provides promising tool for EOL decision making and benefit designers and manufacturers in selecting components for reuse.

The continuation of this work includes further validation of the methodology using other types of technology diffusion as well as with different products and failure modes.

5 ACKNOWLEDGEMENT

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7 APPENDIX A – A Brief Description of Parts [6]

1. Auto Beam Current Limit Flyback Transformer (ABL FBT) is a component that functions for adjusting and controlling picture brightness as received by signal or antenna.
2. Automatic Fine Tuning Voltage Controlled Oscillator (AFT VCO) COIL is used to control the accuracy of signal receiving.
3. CAPACITOR is used to filter DC voltage.
4. CRT is the screen to display picture.
5. DEFLECTION YOKE (DY) works to control the horizon and vertical width of the picture in the screen.
6. FUSE is a component that locates any electrical failure.
7. IC is an integrated component
8. POWER CORD is used to distribute electricity.
9. PWB (Panel Wok Board) is a board where parts that perform a function assembled.
10. RESISTOR is used to adjust the electricity from power source to fit TV system requirement.
11. STARTING RESISTOR (STR) is a resistor that component works only when TV is turned on.
12. TOUCH SWITCH is a component that temporally turns on and off the electricity.
13. TRANSISTOR is a component that boost receiving signal.
14. TUNER is a signal receiver.

Tackling Adverse Selection in Secondary PC Markets

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Abstract
The work presented in this paper addresses the issue of adverse selection in the secondary PC market and aims to raise consumer confidence with regard to the purchase of second hand personal computer systems. The solution adopts the concept of signalling from economic market theory and utilises existing on-board Self Monitoring and Reporting Technology (SMART) sensors to capture real-time usage data for the provision of a comprehensive signalling dataset on the product.

1 INTRODUCTION

There have been numerous studies which present strong evidence that lifetime extension through second hand use and re-use of certain electronic systems and components is among the optimal methods of mitigating environmental impacts through reduction of their per annum environmental impact.[1-3] Computer system manufacture has been identified as a major environmental burden when compared to other electronic products, due to the low entropy nature of its subassemblies.[4-5] This highlights the requirement for adoption of re-use activities through reselling, refurbishing or remanufacture to reduce the life cycle impact of the PC .

There is much speculation that legislation at various levels could enforce re-use targets to counteract the growing waste stream of used PCs as well as other end of life consumer electronics. In Europe, the European Commission has instigated a review of the WEEE directive and is examining the possibility of setting re-use targets in the future revision of the WEEE legislation. Numerous uncertainties remain about implementing this, the most prominent being how exactly legislation will quantify re-use targets. For example, the practice of second hand use through reselling is obviously unquantifiable in any meaningful way.

It is considered a truism that markets for remanufactured and refurbished computer systems are already well developed and beginning to flourish, in particular in relation to the business to business (B2B) sector. [6] Remanufacturing and re-use of products and systems allow OEMs to generate a considerable financial benefit, maximising the value return for returned or excess products. It permits a high degree of channel control with the provision of second life products and also a supply of service parts, which may be critical to customer needs. Remanufacturing and re-use programs also prevent millions of tonnes of waste from entering landfills each year. [7]

However incorporating remanufacture into the business to consumer (B2C) PC life cycle would require an extensive change to the design and manufacturing process as well as the incorporation of appropriate business models and these type of lease based models are generally not applicable to your average PC home user. The practice of refurbishing for resale is also generally avoided. For lower end systems, the price of a new motherboard and hard disk is generally high compared to the price of a new system. This coupled with changes in the physical design of the case, components and sometimes even the internal communication structure, means upgrading is also unattractive.

It has been reported that there has been an upsurge in the PC penetration rate in the developed nations in recent years. In Europe, Ireland has seen large growth from 18.6% in 1998 to 54.9% in 2005. [8] Other countries in Europe have shown similar trends. Sweden has already showed that a penetration rate as high as 82% is attainable.[9] With numerous government and other initiatives to bridge this digital divide, the increasing demand for home computer systems in these developed countries is inevitable, in terms of both first time buyers, as well as buyers wishing to change to new higher specification systems. The upcoming release of Microsoft's new operating system,"Windows Vista" will result in a significant portion of users changing or upgrading in order to satisfy Vistas hardware requirements. [10] Analysts have predicted that 100 million PCs will be running Vista by the end of 2007.[11] Even with Windows Experience Index(WEI), [12] this could potentially leave behind a large number of perfectly functioning units. The increased accessibility to broadband is likely to further escalate new computer system sales. The manufacturing burden posed by this demand will have considerable environmental implications and it is vital that we find a more sustainable solution then simply the manufacture of more and more PCs. The development of B2C and C2C secondary PC markets is the only means of nullifying a large portion of the manufacturing burden needed for this demand.

There is the argument that with the advent of gaming and high performance multimedia applications there simply isn't a market for older systems. However, for many people, their most fundamental computing needs still remain unchanged. This is recognised in the recent preliminary draft for the Energy Star review where classification of various specifications of systems will be reflected in future energy star labels. [13] We have an obligation to address the barriers in our secondary PC markets to ensure basic needs, typically access to information and also the communication medium provided by the web, are available to everyone.

This paper proposes an alternative approach to the current selling of used computer systems by incorporation of a comprehensive signalling strategy. This can facilitate a more credible means of information exchange between the buyer and the seller in used PC markets thus increase market efficiency, maximise profitability and reduce the life cycle impact of the PC.

CONTRIBUTIONS

- A brief background on the current economic models on which our research is based is provided.
- In Section 3 we discuss how provision of usage information on the PC life cycle can be used to address the problems associated with adverse selection in secondary PC markets. This includes a section on currently accessible criteria that could facilitate customer acceptance of the used equipment
- A case study of a personal computer is presented in Section 4. This is a continuation of previous work. This methodology adopts a health monitoring approach utilising existing on-board Self Monitoring and Reporting Technology (SMART) sensors for the purpose of capturing real-time environmental and usage data
- Finally, some suggestions are offered on how integration of sensing technologies during the design phase can potentially enhance signalling between the seller and the buyer in future products.

2 SECONDARY MARKETS

Secondary markets have long been criticised by economists with one of the main barriers to efficient operation being lack of credible information exchange between the buyer and the seller. George A. Akerlof and Michael Spence in conjunction with Joe Stiglitz explained how agents with differing amounts of information affect many different kinds of markets. Their theories on these concepts were the subject of the Nobel Prize in Economics in 2001. [14]

Akerlof initially recognised the existence of adverse selection in secondary markets[15] and analysed its repercussions on the secondary automobile market. The used automobile market is similar to the used PC market and is a typical example of where only the seller has true knowledge of the car's actual worth. In this market, sellers of below average quality second hand cars i.e. “lemons” will willingly sell their vehicle and take whatever profit they can get. On the other hand, owners of above average quality second hand car owners are unwilling to sell their product as it is impossible for them to obtain their products actual worth. This reduces the efficiency of this market, with the higher quality second hand cars usually being driven out of the market by substandard “lemon” equivalents. Although repeat sales and reputation may partly resolve the problem, the net effect is essentially the flooding of the market with “lemons” and driving the superior quality second hand cars out of the market. This imbalance of information can be applied to most secondary durable markets and its effect significantly devalues these otherwise perfect markets. [15] This is manifesting itself as the “Closet Effect“ in the PC market where it has been reported that older systems typically spend 2.8 years unused in closets before next disposition. [16]

Michael Spence showed that under certain conditions well-informed sellers can improve their market outcome by "signalling" their private information to those who are less well informed. His signalling models demonstrated how information could be used to communicate a superior position. He focused specifically on how individuals use signalling to communicate their abilities in the labour market. [17]

This idea of signalling can again be observed in secondary durable markets where its inclusion is an obvious means of qualifying products merchantability. The second hand car market has incorporated numerous signals, the most distinguished being the provision of accumulated mileage together with the full vehicle service history in second hand transactions. Online services such as the widely renowned “Kelley-blue book” service have been developed standardise pricing schemes in the US. [18] Another recognised signal in this market is the “One Lady Owner” tag. Even the presence of a “towbar” can influence a potential buyer’s decision.

No such signals exist for consumers in the secondary PC market. Clearly this is a concern from an environmental standpoint alone. While the ratio of embodied fossil fuels in production to the weight of the final product is approximately two for automobiles, It has been reported that PC manufacture consumes roughly 12 times the weight of the machine in fossil fuels. [19] Another Life Cycle Assessment (LCA) has estimated carbon dioxide emissions for PC manufacture at 103kg/desktop system. [20] The absence of a second hand market is clearly driving excess demand for the manufacture of new systems.

Figure 1 depicts a conceptualised view of the value placed on a second hand computer over time by the original buyer of the equipment (Buyer1) and a potential subsequent buyer (Buyer2).

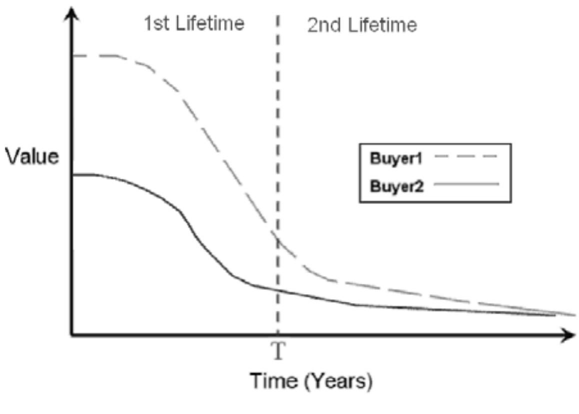

Figure 1: Asymmetric Information: Market Failure!

At time 0 Buyer 1 is after buying a new system. At this time Buyer 2 places a lower value on the system. This may be due to Buyer 2's current financial situation. (Simply not having enough money to afford a new PC) After time T has elapsed buyer 1 has opted to buy a new system as his present model no longer satisfies his needs. This is common among the gaming community and other early adopters of new technologies, where new systems maybe purchased as timely as one year after original purchase. [16] These computer users desire fast moving games, high resolution graphics, high end multimedia and other high performance applications. Buyer 1 places his own value V1 on the used system. Buyer 2 is interested in the system as it satisfies his needs for the applications he requires and subsequently places a value V2 on the system. In most cases V1 is much greater than V2. Information asymmetry causes Buyer 2 to have a lower value than Buyer1. At all times, Buyer 1 places more value on his used system then buyer 2 and therefore any "value creating trade" [21] is impossible. Buyer 1 subsequently stores his old system away. This is more commonly known as the "closet effect" [16] and is seen to significantly devalue the market.

Figure 2 shows the conceptualised view again with provision of signalling by Buyer1 in the market transaction. In this scenario, the value buyer 1 place's on the system remains unchanged. However the signal provided by buyer 1 raises buyer 2s confidence in the value of the used machine. This considerably enhances the probability of occurrence of a "value creating trade" between the 2 parties involved. The result acts to counteract the "closet effect", thus prolong system useful life.

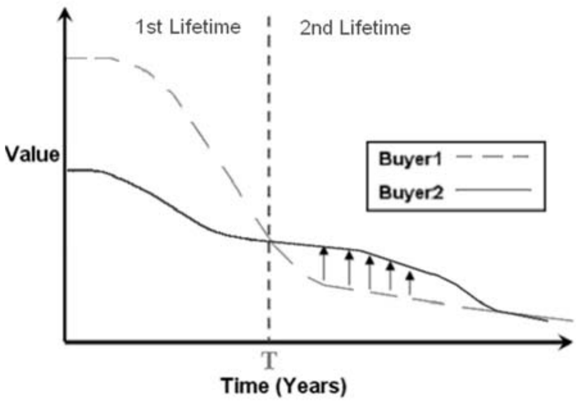

Figure 2: Asymmetric Information: Market Success!

The net effect is ultimately to increase both the pc penetration rate and economic value without incurring the environmental costs associated with computer system manufacture.

This concept of signalling is even more crucial when dealing with products such as computers as reselling is carried out through an online medium. Although online systems eliminate barriers to market entry, on the Internet there is no real guarantee of quality. Consumers don't know if they are getting value for money until after the transaction is completed. As a result, we expect people to pay less in general for online goods. This is reflected in pricing and standards for Internet commerce which tend to be lower than those of traditional business models. The adoption of a signalling strategy could facilitate a competitive advantage for a business competing in an online marketplace. Indeed signalling may be necessary to prevent widespread adverse selection on the internet.

3 CUSTOMER ACCEPTANCE

Reliability is a key criterion for determining re-use potential and must be adequately conveyed in signalling when it comes to remarketing of used products. Reliability is the ability of a product to fulfil the required functions over a certain time while experiencing usage loads.

While there is a large void of information on reliability of PC systems, there exists strong evidence that the reliability of semiconductor technologies is improving. The traditional bathtub curve for electronics reliability is well known. It is believed that modern semiconductor designs, manufacturing processes and process controls have improved so much that the infant mortality and useful life regions of the traditional bathtub curve have failure rates so low that the bathtub "no longer holds water".[22] It is recognised that for a device operating within specification limits, the wearout portion of the curve is delayed well beyond useful life.[23][34] It is also common for OEMs to offer up to 4 year extended warranties on most of their systems. This further highlights manufacturer confidence in the reliability of computer products.

In recent years critical computer components have also been designed with built-in temperature sensors that monitor these components as to how they are being used. The rate of hard faults occurring in the useful life of components is tightly coupled with the increasing temperature. [24]Temperature sensors are currently incorporated in all modern processors and certain high performance graphics cards. These sensors are all software visible and are accessible while the system is in operating mode.[25] Current hard drives also incorporate SMART technology that permit the end user to determine the health of their various mechanical and electrical attributes. Predictable failures are characterized by degradation of a certain attribute over time before the disk drive fails. Mechanical failures and other certain electronic failures are considered predictable because they show a degree of degradation before failing. [26]

Despite the investment into all these efforts, much of this information is being underutilised or not utilised at all. The following potential dataset could serve as a valuable set of signals when it comes to remarketing used computer products. This dataset can increase customer acceptance in the value of the used equipment. It should be noted that this dataset is non exhaustive and market research is currently ongoing to determine what consumers actually perceive reliability to be.

3.1 Operating time

The total system operating time is easily calculated and is an obvious signal. However, it must be evaluated in the context of how the equipment was used. For example, some people, known as "Over-clockers", operate their machines at increased clock frequencies and subsequently higher temperature levels than their more sedate counterparts not withstanding the fact that both machines may have accumulated the same operating time.

3.2 Operating Temperature

Operating temperature is also a very important signal. Temperature, in terms of either spatial or temporal gradients, or absolute temperature, can seriously influence the reliability of electronic systems [27]. Many integrated circuit packaging failure mechanisms have been found to have multiple temperature dependencies. [27] The following is a summary of the main temperature effects we can provide, that affect the lifetime reliability of both the central and graphics processing units.

Individual failure mechanisms are not discussed in detail here. The purpose of this section is to simply summarise the individual thermal effects that eventually lead to intrinsic hard failures that render the system non functional.

Steady State Temperature

Steady-state temperature was traditionally considered the only stress parameter that affected device reliability. Conventional reliability prediction methods used in “Burn-in” and device qualification assumed that the failure rate of a device was independent of time so as a result utilised solely Arrhenius based models to predict influence of temperature on electronic-device failure rate or MTTF. [28]

Time Dependent Temperature Changes & Gradients

Time dependent temperature changes are a major contributor to electromigration stress build-up, one the most common causes of IC failure. [31] Significantly shorter electro-migration lifetimes are also observed in the presence of a temperature gradient. [30] Temperature gradient is a physical quantity that describes in which direction and at what rate the temperature changes. Both temperature phenomena are also applicable to temperature-related gate-oxide breakdown. [31]

Temperature Cycles

Temperature cycles can also lead to fatigue failures. Damage accumulates every time there is a cycle in temperature, eventually leading to failure. These effects are most pronounced in the package and die interface (for example, solder joints) [32] Both the CPU and the GPU go through two types of thermal cycles.

- Large thermal cycles occur at low frequency (a few times a day). Examples include powering up and down, or going into low power or stand-by mode. [33]
- The second types are small cycles which occur at a much higher frequency. Small thermal cycles are invoked by changes in workload behaviour and context switching. [33] Aggressive power management schemes can be a major contributor to these types of cycles. [24]

3.3 Operating Voltage

Operating voltage is another important signal. The actual deviation of system voltages from nominal is an important indicator of the health status of the power supply. Over-volting of CPUs is common amongst power users as a means of enhancing stability while overclocking. Higher clock frequencies also generate more heat, which further contribute to the temperature degradation effects previously described.

3.4 Hard Drive SMART Attributes

The information currently available from current hard disks could also be used by a seller to signal a system’s quality in the secondary market. All modern hard disks currently provide a set of operating variables which allow the user to evaluate the probability of predictable failures at any given instant. Predictable failures correspond to degradation of an electronic or mechanical attribute over time and account for 60% of all hard disk failures [26] A “normal value“ is usually chosen for each attribute and any deviation from this value obviously corresponds to a certain level of degradation in the drive. Examples of attributes set by drive manufacturers include read error rate, throughput performance, power-on hours, uncorrectable sector count as well as a host of others. [26] An internal temperature reading is normally specified. Power Cycling is also considered to affect the reliability of hard disks. This misconception comes from the fact that in the past, hard disks did not automatically park their heads when shut off. Frequent on-off cycling could damage such hard disks. Modern hard disks have addressed this issue are not significantly affected by frequent shut-downs. [35]

When the system is being resold at End of Life the provision of a comprehensive usage dataset, quantiying the profile of the user in terms of all the runtime variables and attributes described can provide the buyer with all the information necessary to make a better informed purchasing decision. A non functioning system does not mean it isn’t of value. When certain buyers with appropriate levels of expertise observe that all a PC requires is, for example-the installation of a new hard drive with the result being a perfectly functioning PC, a “value creating trade“ maybe accomplished. This will largely depend on the expertise of the buyer. Usage information must also be readily available on the system.

4 EXPERIMENTS

This section describes a continuation of previous work on data acquisition for the purpose of Life consumption monitoring[25] and can be utilised in the signalling model described in section 2. The non taxing nature of office applications compared to the severe nature of numerically intensive applications running concurrently on the system has already been demonstrated in previous work. [25] While CPU intensive benchmarks provide useful data when measuring processor innovations these workloads rarely represent the day to day usage of many computers in both office and home environments. These sample of tests represent a sample of those applications and their execution result in the phenomena relating to computer system reliability outlined in Section 3. RRDTool (Round Robin Database Tool) was used to display the time series temperature data. [36]

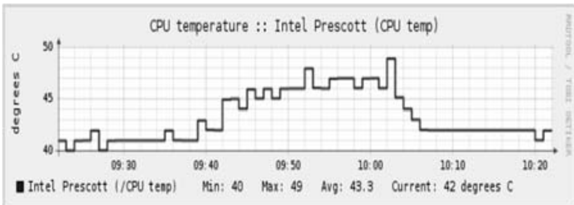

Figure 3: Playing a DVD

The thermal specification for the Pentium 4 Prescott used in this study is 69.1C.[37] Although the temperature never exceeded this limit the processor did exhibit both time dependent temperature changes and temperature gradients while executing all of these applications. These were most severe in the case of ripping a dvd with the processor exhibiting a positive temperature gradient of 0.183C/sec. This process demanded a relatively high CPU utilisation of 52%, a factor of 2 greater than that of playing the actual dvd. (Figure 3)

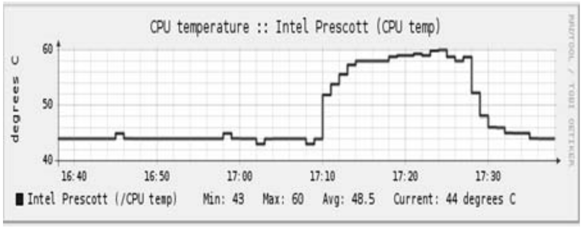

Figure 4: Ripping a DVD

A software package called “Gimp“ was used to generate the temperature data captured in Figure 5. Gimp is a software package used for tasks such as photo editing, image composition and image authoring. A selection of scripts from the Gimp “Script-Fu“ users library invoked this particular sample of time series temperature data. The execution of this type of interactive application is seen to exhibit a high degree of temperature cycling.

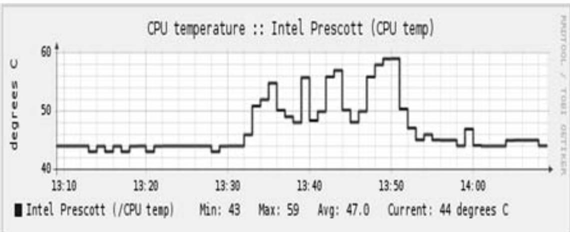

Figure 5: Digital Photo Editing

Another interesting observation was the temperature gradient exhibited by the execution of various screensavers on the system. (Figure 6) The ubuntu operating system used incorporated screensaver cycling functionality which allowed the user to specify the periodic excecution of various screensavers at a designated interval. The most significant gradient from this sample was found to be 0.1667 C/sec and is illustrated in Figure 6.

The temperature variations experienced by the hard disk over the the course of a 6 day period are shown in figure 7.

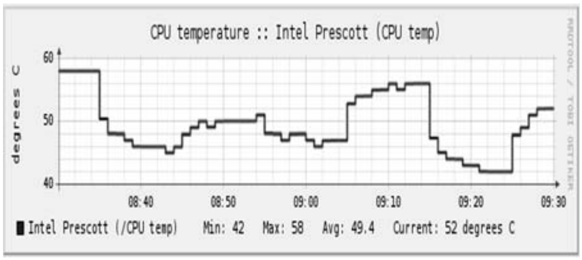

Figure 6: Screensaver

The series of peaks and troughs represent typical office usage during that period.

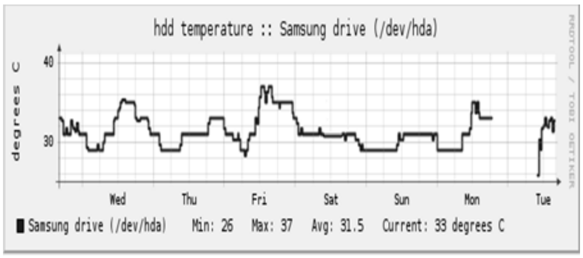

Figure 7: Hard Disk temperature variations

The discontinuity in the graph is as a result of the system being powered down on monday evening. The most significant gradient experienced by hard disk was as a result of the subsequent power up, the following morning.

We are unable to carry out direct temperature measurement with regard to large temperature cycles.(Section 3) This is a limitation of our SMART monitoring methodology. [25] However, we are able to monitor the frequency of these temperature cycles and it is important these are also included in the signalling dataset when it comes to reselling the system. We are also currently unable to provide samples of temperature affects on the graphics processing unit. Our system does not currently incorporate a GPU with integrated SMART technology. This card will be incorporated for future work.

Ultimately, we intend to collate this data into clear signals, which consumers can use to derive their own quality interpretation from.

5 SIGNALLING IN FUTURE MARKETS

It is important that we integrate comprehensive self monitoring systems into future computer products to enable monitoring of other critical parameters of their life cycle environment. Both humidity and vibration loads can also have a large influence on the lifetime of these products.[38] With the emergence of multicore processors, the incorporation of sensors that allow monitoring of each independent core is necessary for more accurate determination of reliability and re-use potential. The usage information provided by these sensing technologies can facilitate perfect information exchange between buyers and sellers. The end result is better informed buyers and the eradication of the problems associated with adverse selection ultimately leading to increased market efficiency. The incorporation of policing polices to ensure this reliability information is not tampered with, is another important consideration. Raising customer awareness on the high environmental impact caused computer product manufacture can further serve to increase efficiency in these markets.

There are also more questions to be answered regarding consumer attitudes to both buying and selling used equipment. The perceived rate of devaluation by sellers on purchased equipment needs to be established. This is necessary in order to accurately determine the optimal time “T” at which a successful market transaction can occur. From a buyer’s point of view, we need to understand what exactly the average consumer perceives as quality. This can serve to provide a list of criteria that will be essential when it comes to remarketing and reselling the product. This research is being carried out at this present time.

6 CONCLUSION

A new approach to marketing of personal computers has been proposed. This approach utilises the concept of signalling from economic market theory. The provision of signalling in the form of a comprehensive dataset on the useful lifetime of computer products can serve to raise customer confidence in the value of used equipment thus increase market efficiency, maximize profitability and ultimately serve to create a more sustainable solution to increasing PC penetration in a given population.

7 ACKNOWLEDGEMENTS

This work was supported by the Irish Research Council for Science Engineering and Technology (IRCSET) and in part by Microsoft Research through the European PhD Scholarship Programme.

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Simulation of Network Agents Supporting Consumer Preference on Reuse of Mechanical Parts

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Abstract
To achieve sustainable development, mechanical parts should be reused repeatedly. For the effective reuse of parts, each reusable part is required to be under an appropriate management. For this purpose, we are proposing a system that is a combination of network agents called "Part agents" and radio frequency identification. A scheme is proposed in which Part agents generate advice for the consumer on the adequate activity of maintenance of the part based on their preference and the degradation status of the part. A simulation system of Part agents is developed to show that the proposed Part agent system would promote the reuse of parts.

Keywords:
Reuse; Network agent; Consumer's preference

1 INTRODUCTION

The effective reuse of parts is considered to be a requisite for developing a sustainable society [8]. For this purpose, the authors are proposing a system that is a combination of network agents and radio frequency identification (RFID); in this system, the network agent is assigned to a particular part to which a RFID chip is attached and is programmed to follow the part wherever it goes. We call this agent a "Part agent" [1][6].

Behavior of users or consumers is a hindrance to the circulation of reused parts. The flow of reused parts around the user is uncontrollable and unpredictable despite the significant effort of the manufacturer. The cause of such instability may include the user's inability to manage all the parts in his products as well as his lack of access to correct information on their maintenance.

The objective of our proposal of the Part agent is to provide users with appropriate advice on the reuse of parts and to promote the circulation of reused parts. In a previous work [2], it has been shown by the simulation of Part agents that advice can be generated by considering the user's preference and the operation histories of products. In this paper, a mechanism with which a Part agent makes necessary decisions is discussed. A simulation model for the Part agent is developed to show the Part agent's effectiveness in supporting the preference of users or consumers.

First, the concept of a Part agent is described in section 2. In section 3, the consideration of the user's preference in maintenance is discussed. The model and scenario for the simulation are discussed in sections 4 and 5; these sections deal with how Part agents make a decision on maintenance of parts and provide advice to users. Preliminary results of the simulation using these mechanisms are presented in section 6. Remaining issues related to the realization of the Part agent are discussed in section 7, and section 8 summarizes the paper.

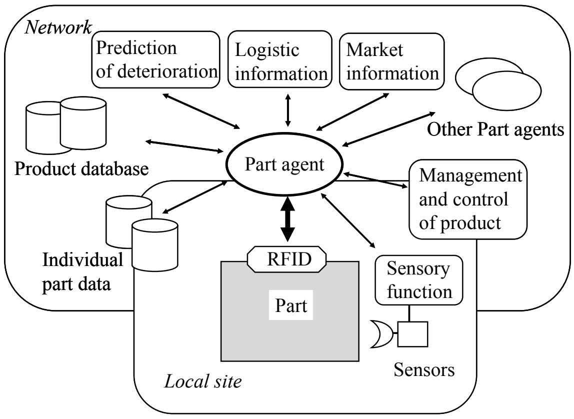

Figure 1: Conceptual scheme of Part agent [2]

2 LIFE-CYCLE SUPPORT OF PRODUCTS USING NETWORK AGENT

We are proposing a Part agent system that manages the life cycle of mechanical parts by using network agents and RFID. The system should manage all the information on an individual part throughout the part's life cycle on the assumption that the network environment is available ubiquitously.

2.1 Concept of Part Agent

The concept of the Part agent is shown in Figure 1. In our scheme, the Part agent has the following functions.

(a) It tracks the corresponding part through the network. The Part agent uses an RFID tag [5] attached to the part as the key to find and identify the corresponding part.

(b) It obtains the design information that is provided by the manufacturer for the part from the product database in the network.

(c) It manages the current information on the corresponding individual part, including assembly configuration, historical records, deterioration level, and environmental status, that may be stored in databases in the network, at the local site, or in the RFID tag.

(d) It may activate the sensors at the local site and obtain information on the part, such as the applied load and wear and environmental information like the temperature.

(e) It uses applications in the network to decide the action of the part. We assume that applications that provide Part agents with information such as prediction of deterioration, logistic information, and market information are available. The Part agent uses the information as well as the current status for its decision.

(f) Based on the decision, it requests the operator or function that controls the product to take the necessary action.

By combining these functions, the Part agent autonomously and intelligently supports the life cycle of the part. Based on this concept, we are currently developing functions using network agents and RFIDs to realize a Part agent system.

2.2 Part Agents to Support User's Activity

A prototype Part agent system was developed based on the agent function of the CORBA system Voyager [3]. The developed system has the ability to communicate RFIDs, but we are still investigating the information that should be stored and the mode of its storage. A preliminary experiment without using RFIDs has been successfully performed with approximately 20 Part agents moving in a network of 5 sites installed in separate computers [1].

While parts and products are under manufacturer's control in shop floors or stores, they are managed precisely and efficiently avoiding any waste of resources. However, once they are shipped to consumers, they may be used with heavy load, may be used in a severe environment without maintenance, may be idle for a long period or may be discarded even if they still have enough ability. This unpredictable and uncontrollable user's behavior makes it difficult to foresee the flow of take-back parts and, hence, is a hindrance of circulation-oriented society. The Part agent is employed to provide users with advice on the maintenance of parts, which will promote the circulation of reused parts.

To investigate the ability of Part agents to support users, a simplified simulation was developed and the following results were obtained [2][7]:

- Part agents having the ability to decide their own behavior were implemented.
- Information agents that collect the necessary information from the network for the Part agent were implemented.
- A simple model was developed and used in the simulation to provide the deterioration level, operation cost, and environmental load of a part during its life cycle. Using these models, the simulation of Part agents was performed based on the current and predicted values of these parameters.
- A mechanism that utilizes the operation history of the part's assembly for the maintenance of the part was developed. Additionally, because it is required for every part to know its entire life history for its maintenance, a function was developed for a reused part to collect the operation history of the assembly to which the part previously belonged.

3 MAINTENANCE BASED ON CONSUMER PREFERENCES

Parts or products that are reused through a used-parts market, such as cars or small computers, have a difficulty in reducing the total environmental burden during their entire life cycle. For manufacturers, it is difficult to predict the behavior of their customers. This prediction leads to the information on the quality and quantity of take-back parts that is required for an efficient and effective circulation-oriented production.

For the users of products, it is not easy to behave truly in favor of the environment, as firstly, it is difficult to give adequate maintenance to each part of every goods they are using. Secondly, users may not know the precise deterioration level of their products or the available options for their maintenance. Thirdly, it is also difficult to decide what is beneficial for the environment, as they do not have a measure to evaluate the environment friendliness of a specific option. Furthermore, users may want an option for employing their own strategy. Some users may prefer a newer version of products, while others may prefer to use a product for a longer duration.

We consider that the behavior of users is an essential factor for reducing the environmental burden during the total life cycle of products and that it is important to provide adequate assistance to the users.

Preliminary results from a previous research [2] suggest that when consumers have various options for maintenance, the adequate support of their preference promotes the effective reuse of parts.

It is necessary to develop a simulation system to investigate the ability of the Part agent to provide effective maintenance support to users in order to promote the reuse of parts.

4 SIMULATING THE BEHAVIOR OF PART AGENTS

To evaluate the proposed Part agent system and the effectiveness of the scheme to support users, a simulation system is developed.

4.1 Requirements of the Simulation

The purpose of the simulation is as follows:

- To estimate the applicability of the Part agent system to the real world where numbers of mechanical parts are used.
- To develop a mechanism for the maintenance of parts based on their user's preference.
- To evaluate the effectiveness of the approach.

For these purposes, a simulation system is developed to fulfill the following requirements:

- Each individual part is treated separately using its own history.
- The behavior of parts and Part agents can be simulated during their life cycle, including the reuse period.
- Any number of parts and their corresponding Part agents can be created within the limits of computer capacity.

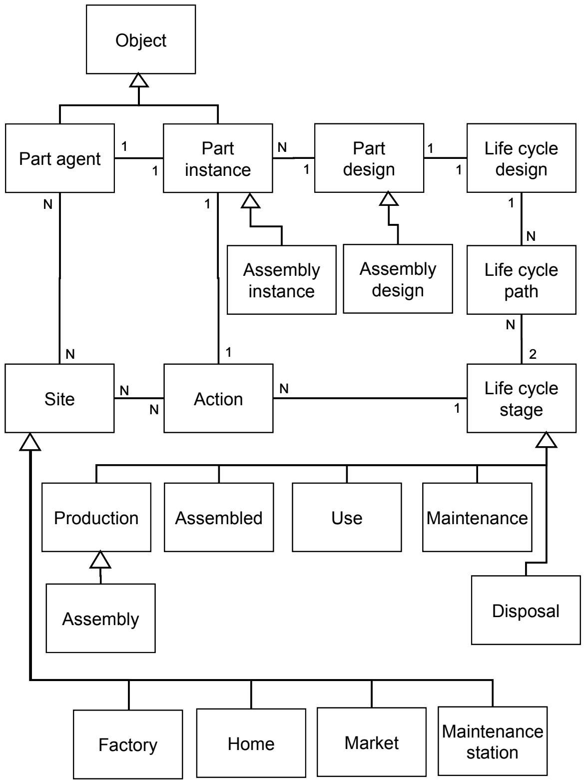

Figure 2: Simplified model of Part agent system

- The representation of user's preference should be provided for the maintenance of his/her parts.

4.2 Model of Parts and Part Agents

The overall configuration of the elements developed for the simulation is shown in Figure 2. The diagram is presented in a UML-like representation. The rectangles represent the elements indicated by the labels in them. The lines represent the relationship between the elements. Lines with an arrow at one end represent a class inheritance relationship in which the rectangle at the arrow end is the superclass. Other lines are simple relationships with their cardinality shown on their side. For example, the relation between Part instance and Part design is shown in the figure with the letter N on the side of the former and the numeral 1 on the side of the latter. This indicates that a single Part design exists for each Part instance, while many Part instances may exist for each Part design.

Each individual part is represented as a Part instance in the figure. Part instance and Part agent are the two main elements in this simulation. The common superclass of these elements is named Object. A Part instance has a reference to a Part design that represents the design information of the part.

A Life-cycle design is assigned for each Part design of a part. A Life-cycle design that is an expected life cycle of the part is represented as a network of Life-cycle stages. Each Life-cycle stage represents a stage in the life cycle, such as production, use, and maintenance, as shown in the figure.

Assembly is represented as a class of part for both Part instance and Part design. Although not shown in the figure due to space limitation, Assembly instance and Assembly design are associated with multiple Part instances and Part designs, respectively, that represent their components.

An Action is the information that represents the current location of a Part instance and its action. Each Part instance has an Action that refers to a Life-cycle stage representing its status and to a Site representing its location.

Note that Figure 2 is simplified for a better understanding of the overall configuration of the simulation. In fact, more elements and relations exist for representing the detailed information.

With this model, the behavior of parts and their corresponding Part agents can be precisely simulated throughout their life cycle.

5 CONSUMER PREFERENCES

Consumers would like to provide for the maintenance of the parts of their products based on their preferences. Some would like to use their parts until they are broken. Others would like to continue purchasing the latest version to replace their current part. However, in spite of their preference, most maintenance services are based on breakdown or in a manner predefined by the manufacturer. This is because it is difficult and cumbersome for consumers to keep checking the status of all their parts. It is also difficult for them to know what the best course of action for the maintenance of their preference is. It is expected that Part agents can support the consumers in solving these problems.

In the simulation, the consumer's preference is simulated in the following way. The Part agent in the Use stage calculates the value *D* as shown in the following equation (1), based on the variables for the corresponding part:

$$D=\alpha_0\cdot(1-V_h)+\alpha_1\cdot V_t+\alpha_2\cdot V_u+\alpha_3\cdot(1-V_p) \qquad (1)$$

where V_h is the level of health of the current part; Vt, the trade-in price of the current part; Vu, the level of health of the used part that may replace the current part; Vp, the price of the replacing part; and α_0, ..., α_3, the weighting coefficients for the variables.

The level of health is initially 1 for a newly produced part and it decreases as the part deteriorates. Note that all the variables are normalized to 1 and

$$\sum_{i=0}^{3}\alpha_i = 1.0 \qquad (2)$$

Some of these variables are acquired by obtaining information from the used-parts market. The value *D* represents the benefit of replacement. If it is larger than a predefined threshold value, a recommendation is made to the consumer to replace the current part with the used part. The set of weighting coefficients α_0, ..., α_3 is assigned by each consumer and represents his or her preference for maintenance.

6 EFFECTS OF THE SUPPORT OF THE CONSUMER

A simulation software is developed based on the above-described model.

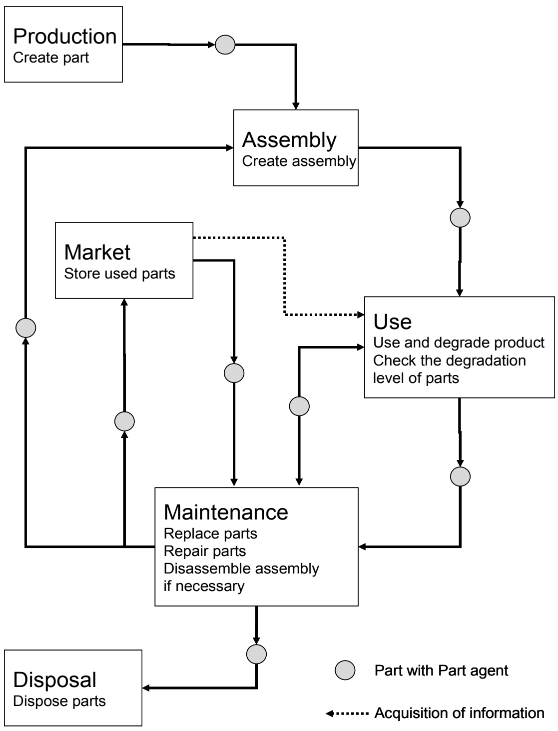

Figure 3: Simulated life cycle of parts

6.1 Simulation Scenario

For each time step, every Part agent performs the required actions specified in its current Life-cycle stage. Subsequently, based on the result of the action, the Part agent changes its own Life-cycle stage and Sites. A typical life cycle of parts is shown in Figure 3 and is as follows.

A Part is created in the Production stage and is then transferred to the Assembly stage where an assembly is constructed from the component parts.

In the Use stage, the degradation of the part is basically estimated according to the elapsed time steps. Information on used parts is collected from Market, where used parts are stored. If a failure is found in the part or if it is decided that a part should be replaced based on the degradation information from Market, the assembly that includes the part as its component is transferred to the Maintenance stage. As described previously, the decision for replacement is made based on the consumer's preference.

In the Maintenance stage, when a replacement is ordered from the Use stage, the component part is replaced and the assembly is sent back to the Use stage. When the part is defective, the degradation level of the part is lowered, or in other words, the part is repaired in the Maintenance stage. If as a result of the repair every component part in the assembly is determined to be functional, the assembly is sent back to the Use stage. If any defective part still exists, then the assembly is disassembled and the functional component parts are sent to the Assembly stage or Market stage, and the failed ones are sent to the Disposal stage.

The configuration of the assembly used in the simulation is shown in Figure 4. It consists of 4 components, two of which comprise a subassembly.

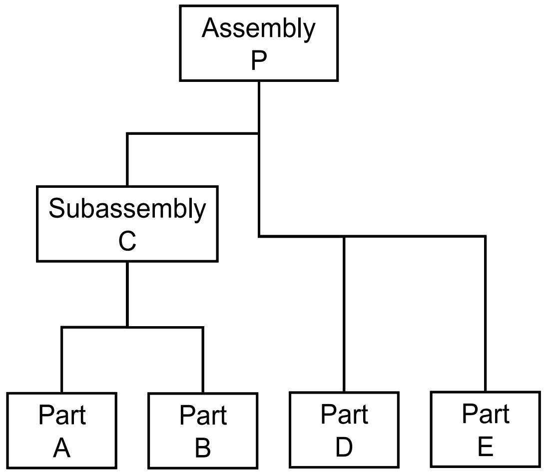

Figure 4: Configuration of simulated assembly

6.2 Results of Use of Operation History

The simulation is performed based on the above scenario. For each of the four types of a part, a factory is set up in the Production stage and produces 100 parts. Two assembly factories are set up in the Assembly stage to assemble these parts to produce 100 assembly products. These products are distributed to 20 homes that are prepared to represent 20 consumers corresponding to the Use stage of the part's life cycle.

The parts in the Use stage randomly deteriorate at each step of time. When the accumulated degradation level exceeds 70% of the initial level of health of the part, the part is determined to be defective. In the Market stage, the price of reusable parts is discounted according to the degradation level.

The simulation is performed using the four types of preferences shown in Table 1. First, cases in which all the 20 homes have the same preference are simulated. Subsequently, the homes are divided into four groups that have different preferences, with each group consisting of five homes.

Table 1: Coefficients of preferences

	Type	Current part		Replacing part	
		State	Trade-in price	State	price
1	State of current part and replacing part	0.5	0.0	0.5	0.0
2	Cost of current part and replacing part	0.0	0.5	0.0	0.5
3	Both state and cost	0.25	0.25	0.25	0.25
4	State of current part	1.0	0.0	0.0	0.0

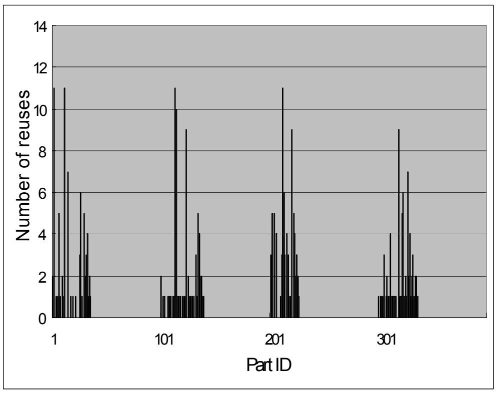

Figure 5: Number of reuses of each part with all the consumers having type-4 preference

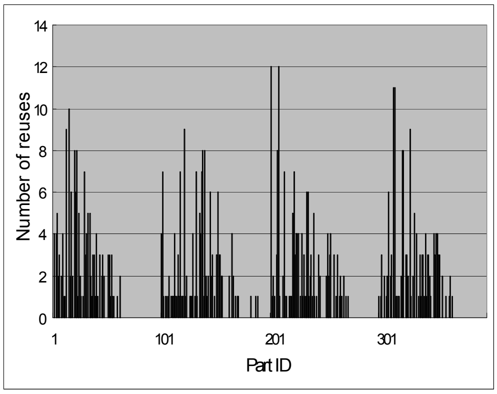

Figure 7: Number of reuses of each part with four groups of consumers having different types of preferences

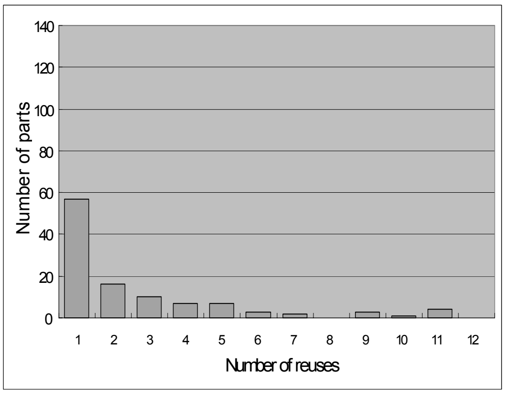

Figure 6: Part number against the number of reuses with all the consumers having type-4 preference

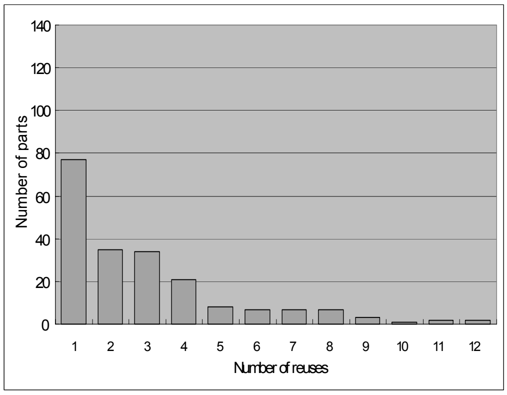

Figure 8: Part number against the number of reuses with four groups of consumers having different types of preferences

Figures 5 and 6 show the result of the simulation when all the 20 homes have type-4 preference. This corresponds to the case in which parts are sent based only on the deterioration level; this means that consumers do not accept any advice of the part agent relating to maintenance. Figure 5 shows the number of reuses for each part, and Figure 6 shows the number of parts against the number of reuses. The total number of reuses is 295.

Figures 7 and 8 are the results of the simulation when the consumers are divided into four groups with different types of preferences. As observed in Figure 7, the parts are reused more as compared to the single-preference case shown in Figure 5. Figure 8 also shows the same tendency. There are a total of 603 reuses.

Though it is confirmed that multiple preferences lead to an increased reuse, an increase in the number of required products was also observed. At step 80, the simulation considering a single type of preference (type 4) shows that 32 new products remain unused and 125 used parts are in the Market stage, whereas the simulation using the four types of preferences shows that only one new product remains unused and 194 used parts are in the Market stage. As 100 new products are produced initially in both the cases, it seems that the former case with a singe preference requires fewer products during the same period. However, because the total amount of activity performed by the product is not evaluated in the simulation, it is not determined whether the former case shows larger effectiveness.

For more precise simulation, we are now developing a function to evaluate the activity and related cost.

7 REMAINING ISSUES

The initial results of the simulation of Part agents are described above. Using this simulation system, we will further investigate the following issues.

- What is the essential factor for the promotion of the reuse of parts? Because of the interrelated distributed nature of the problem, it will be difficult to describe the best way for promoting the reuse of parts.
- What is the level of detail required for representing the real world? This is a question valid in any simulation; however, for the life cycle of products, it appears to be more important.

We hope that the simulation is used as a basic tool for designing a Part agent and the corresponding part with its life cycle.

For the Part agent system, the following issues are identified.

Security is one of the major issues for the Part agent system. A mechanism that ensures the valid motion of agents must be

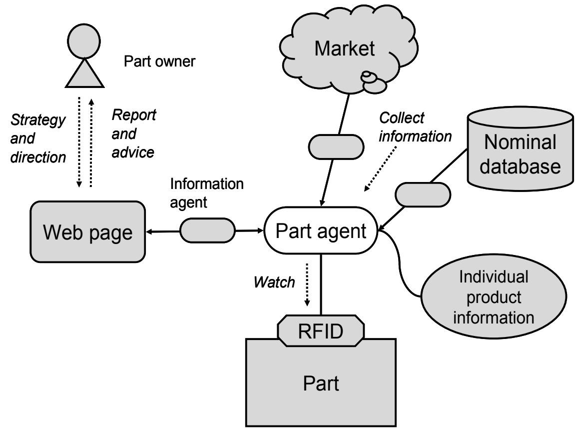

Figure 9: Communication between part owner and Part agents

developed. The effective encrypting of the information on agents or RFIDs is also required to avoid theft.

There is also the privacy issue [4] with regard to the treatment of the operational information on parts, including the degradation level and the user's preference with regard to maintenance. The users may not accept the operation history of his or her product being transferred to another person. Careful management is also required for retaining information on discarded assemblies.

A method is required for users to easily communicate with the Part agent. For this purpose, we are developing web-based communication between users and the part agent, as shown in Figure 9. The Part agent sends a subordinate information agent to the Web site. A report and advice from the Part agent is provided via a Web page to the user. Conversely, the user can send the preferred maintenance strategy or instructions to the Part agent through this mechanism.

8 CONCLUSION

To achieve the effective reuse of parts, a Part agent system is proposed to help users with regard to the maintenance of parts. A simulation system is developed to study the behavior of the Part agent throughout the life cycle of the corresponding part. Though the simulation is still premature, the initial result shows the effectiveness of the scheme.

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Perspectives for the Application of RFID on Electric and Electronic Waste

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Abstract

Concerning the End of Life (EOL) of Waste of Electric and Electronic Equipment (WEEE), the idea of a wireless ID or wireless information attached to WEEE devices, may enable numerous concepts for increased traceability and increased recycling efficiency. Technologically RFID is already capable of realizing several of these theoretical options. The ongoing development towards more powerful, reliable and cheaper RFID transponder technology will enable more and more of these theoretical options. This paper will introduce different concepts and a three-generation perspective for the application of RFID to WEEE.

Keywords:
RFID; WEEE; EOL

1 INTRODUCTION

Radio frequency ID (RFID) is one of the approaching technologies, which can be expected to have a big impact on our lives. RFID and its ability to extend networking from computers to basically any object is seen as the next revolution of daily life. The “Internet of Things” could provide vast possibilities, which can be promising and worrisome at the same time. Even though this idea of an “Internet of things” is still far away from a real break through, it is progressing with, for example, several RFID ISO standards on the way.

On the other hand, waste management is a major topic among environmental issues today. E-waste especially is a major concern because of its rapidly increasing amount and special composition of hazardous and precious substances. Proofs of this are the different new e-waste laws, which are under way around the globe. One of the global leaders is Europe with the Waste of Electric and Electronic Equipment (WEEE) directive.

There are already different studies about the application of RFID to the waste stream. Examples would be the possible use of RFID on PET or glass bottles, to increase the sorting and manage the re-use of them. Among these approaches to the use of RFID for recycling applications, WEEE seems to be a good choice. Studies like Quirici[1] show that, among the different waste factions, WEEE seems to provide the best possibilities for the application of RFID. The high amount of valuable and hazardous substances included in electronic devices, combined with the sheer and still increasing amount of WEEE, seems to enable some possibilities for RFID.

2 APPLICATION CONCEPTS

There are various possible concepts for the application of RFID to WEEE. Visibility networks can be built and the additional information can help to make end of life (EOL) decisions[2]. Hereafter, a few of these concepts will be introduced and explained

2.1 Enhanced Traceability

RFID in many cases is a tool used to increase the traceability of materials and products throughout complex transport chains. For WEEE, hazardous substances in certain devices, or even all WEEE could be traced and proper treatment could be guaranteed. In this context, applications without a transponder on every single device are possible as well. Containers or other accumulations of WEEE could be tagged and traced. Even the use of GPS supported transponders is possible.

2.2 Enhanced Waste Collection

According to European legislations for WEEE, the devices should be returned separately and free of charge to collection points (municipal waste companies or retailers, depending on the system). In general, uncontrolled treatment of WEEE should be avoided whenever possible. To achieve this, RFID could be used in different ways.

One way could be to install automatic points of return (POR). These could pre-sort the devices and register them in a database. Such automatic points of return could help to increase return rates. In addition, the negative effect of a significant destruction and the co-mingling of the devices could be avoided. Furthermore, devices could be registered by the consumer and receive a transponder at the POR. This would make several of the following applications possible.

Another way to use RFID to reduce uncontrolled treatment would be RFID auto-recognition for WEEE in the residential waste. One problem with the return of WEEE is that a certain amount still ends up either in the residential waste or is disposed uncontrolled into the environment. There are no reliable statistics regarding uncontrolled disposal of WEEE, but there are some available concerning residential waste. Studies[3] in Germany indicate an amount of about one kg/capita per year. However, regional differences are highly likely. RFID transponder on the WEEE could be used to enable an auto-recognition system for WEEE and start some kind of exception handling. This auto-recognition could already start when the municipal waste company is picking up the waste. The exception handling could be used to separate the WEEE from the other waste, possibly at an additional charge, to the related citizen. Another option could be to just deny accepting waste with such undesignated contents. In the case of the uncontrolled disposed waste, increased traceability through the use of a consumer-device link could be a solution.

2.3 Enhanced Sorting

A device could be recognized and registered as WEEE. Furthermore, the unique device ID could be used to organize the following disposal process. An automated model of preferences can optimize the sorting and transport process and also lead to an increased efficiency of the recycling and recovery. This automated system could function as guidance system for every single device. It could lead every device to the most eligible recycling facility. It could also direct the separation process to minimize and optimize the necessary separation.

2.4 Smart Disassembly and ReUse

In the final stage, RFID could also be used for different applications to increase the efficiency of the recycling processes.

-Information for the disassembly could be provided to increase disassembly speed.

-Valuable and hazardous substances could be marked to increase recycling percentages and guarantee the right treatment for each device.

-Complete "lists of contents" could increase flexibility and make it easier to react to changed material prices.

LCID-CU Concept

RFID could be combined with embedded information modules, the so called life cycle units[4] (LCU's). The LCU can deliver information about the "stress" a device or part may have experienced during its life. The original target of a LCU is to predict failures and trigger maintenance measures, when they are really necessary. Combining a LCU with a life cycle ID (LCID) to a LCID-CU (life cycle id-control unit) could lead to more efficient maintenance processes, saving resources and money during the life cycle. At the EOL such a LCU could support the recycling, re-use and future product development, by providing information of the function and condition of the whole device or even specific parts of the device. The LCU would serve as a data acquiring device, while the RFID would work as central storage and communication platform.

Such a system could work on bigger home appliances, like washing machines or refrigerators. It would not make much sense to put transponders on every part of a washing machine, but a central system could be a good solution. All necessary information about replacements or maintenance measures should be stored on one central transponder. A central LCU could provide additional information about the state of the application and could enable direct re-use of the whole application. Today the problem with such a direct re-use of the device is the economic feasibility of testing all the disposed devices. With LCU supported information and a reasonable percentage of devices that really can be re-used, such control could become feasible. Possibly such a control could also identify easy to repair devices, which could be fixed for re-use or re-usable parts.

3 CHALLENGES

3.1 Cost

For a not legally anchored system cost and ROI are central questions. Due to the decrease of RFID transponder and interrogator prices in recent years, RFID is getting closer to becoming a feasible solution for all fields. The increasing production numbers also support decreasing prices.

On EOL applications, RFID could take advantage of LCID's, which are already in place and could be "re-used" at the EOL.

For governmental regulations, there are mainly two paths. For certain products a transponder could just be required, for example, as part of the CE marking in Europe, and with this, rule out cost as killer criteria. The other path would be that the government finance, or at least financially support the use of RFID to make it cost efficient. The third and maybe most likely way would be a combination of both.

3.2 Readability

The question of readability is first a question of what distance and average read percentage is necessary. For an effective system, the read percentage should in any case reach read rates very close to 100%. The distance varies from application to application, but for most passive systems, a realistic distance would be below 3 meters.

The second question towards readability is the surroundings and the conditions under which these distance and read percentages have to be reached. Again this varies a bit from application to application, but in most cases, WEEE will include metal surroundings and undefined positions. Since both metallic surroundings and unclear positions, have a highly negative impact on reading rates, this has to be closely considered in RFID applications.

3.3 EcoEfficiency

In order to implement RFID for ecological reasons, the eco-efficiency of RFID must be proved as well as the economical feasibility. In the case of the re-use of LCID's, eco-efficiency for WEEE treatment is not the problem; however, an analysis of the life-cycle eco-balance of such an LCID may be necessary. For WEEE only transponders, the eco-efficiency must be proved for each scenario, one by one. The increased amount of material and energy consumption for RFID must be compensated by the increase of recycling quality.

4 APPLICATION SCENARIOS

4.1 Life Cycle ID

RFID transponders are already used for applications at the start of the life cycle, like supply chain management and others. Furthermore, RFID holds capabilities for many other applications and decisions as well[5]. Considering this it seems logical to create one transponder, which can be a solution for all or most of the possible applications. The most applications would only require a unique ID. So it makes absolutely sense, to rely on ID solutions, instead of data on transponder solutions.

Concerning EOL applications, such a full LCID can help to secure the producer responsibility requested in the EU, by enabling a direct connection between the producer and the WEEE device. In addition, that the ID is already in place before the collection enables different possibilities at the point of collection. Auto-recognition and guided sorting could be realized. Furthermore, the amount of information related to the device can be expected to be much more detailed, then if the transponder would be attached at the EOL.

A short term problem for the introduction of such a LCID system for EOL applications lies in the long life cycle of some electronic devices. Even if every new device were to contain a RFID transponder today, it would take another 10 to 20 years for a full deployment of these transponders to the EOL to take place. Even then, there would still be a certain amount of devices, which are too old to carry an ID, lost it during the life cycle or carry a malfunctioning ID. So in any case, the deployment of this system requires not only time but also a solution for the combined treatment of LCID carrying and LCID less devices. A possibility could be to attach EOL ID's to the LCID less devices or use applications that do not necessarily need a transponder in place to be efficient.

Transponder

The transponder, in combination with the interrogator, must provide certain read rates and ranges. The obvious selection for the transponder would be the extension of the RFID supply chain management technologies, onto the whole life cycle. This would involve using ISO 18000-6 (EPCglobal) transponders. The transponders should be attached in a way that allows them to be used for supply chain management, but prevents them from being removed by the retailer or the customer. This means the transponders must be integrated into the product. To incorporate an ISO 18000-6 transponder into a product will cause some problems with read rates, but with ongoing technological development and a design for product integrated readability, it is possible for these problems to be solved. Since a LCID should be on the device for the whole life cycle, other problems could involve privacy. These privacy issues could be solved through software solutions (for example temporary deactivation) or hardware approaches. A possible hardware approach could be a Switch-Chip.

Such a Switch-Chip would provide the possibility to switch between two modes. The first and default one would be the full mode, which would enable the full functionality of the transponder. The second mode would reduce the functionality to a simple EAS-like (electronic article surveillance) transponder.

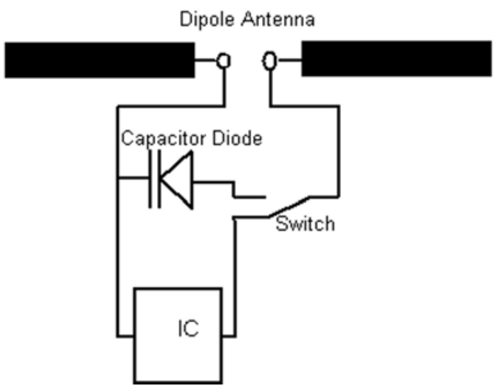

Figure 1: UHF Switch-Chip

A non-linear component attached to a dipole antenna results in reflections at the harmonics.

This Switch-Chip could be used for a 1-Bit Plus system. Such a system would basically require only a 1-bit recognition of WEEE devices, or depending on the deactivation, possibly just a certain bigger group. A bigger group in this context could be the recycling groups in the European WEEE directive. Even though the basic function of such a 1-Bit system would only require limited information, more complex information could be used to trigger enhanced treatment. In the case of Switch-Chip's, even the possibility of switching the chip back exists and with this, the possibilities of enhanced treatments may open up.

Concerning transponder technology, other standards could be used as well. Lower frequencies technologies, using inductive coupling, could be a good solution to increase the read rates especially among metals. In this context, the new upcoming RuBee standard could be the solution for the future. RuBee is still under deployment by the ISO and is currently being discussed under P1902.1. RuBee provides the advantage of passive and active possibilities, which could be a good combination for simple RFID applications and complex smart home or applications. Furthermore, the active transponder could possibly be read as a passive one at the EOL, even after the battery is used up.

Another possibility is to incorporate a combined RFID/bar code solution. The bar code could help to decrease costs. In some places where remote or fast reading is not a factor, cheap bar code readers could be a replacement. In case of a malfunctioning RFID, a bar code also can serves as a back up.

ID

Concerning different applications during the life cycle, the ID should be deployed as a full ID. 1-Bit or sub-ID could not provide the necessary information for many applications, like for example, warranty's. For instance, in the case of transponder technology, the easiest solution would be to adopt the EPCglobal framework, which provides adoptions of different coding schemes, like the SGTIN (Serial General Trade Item Number). These would enable unique identification of every single device. Also EPCglobal provides certain compatibility between different coding schemes. EPCglobal provides some ready to use solutions, but other solutions are possible as well. In any case, the transponder should be capable of carrying a unique identifier (UID).

Infrastructure

To enable a function system, an adequate interrogator and database network has to be available. To reach a certain economical feasibility, the interrogators shouldn't be too expensive. Especially standard conflicts should be avoided if possible. Multiple standards would lead to the need of multi system interrogators, and by this, could lead to a noticeable increase of the interrogator cost. To enable a functioning ID system, a well-developed database structure is also absolutely necessary. The database has to contain all necessary information for all applications. Possibly sub-net's could provide closed information systems for data, which should not be provided to all participants. Furthermore, such a database can provide differentiated access rights and safe data storage.

4.2 End-of-Life-Tracing (Recycling Logistics)

RFID could serve as an asset to increase and guarantee the traceability at the EOL and increase progressing speeds. In Germany, the producer usually assigns the recycling of the required amount of WEEE to contractors. To trace the amount of WEEE each contractor has received for further treatment and to determine what each contractor is actually doing with the WEEE, a monitoring system, possibly RFID supported, is necessary. In Japan the recycling system for home appliances is already using a paper manifest system combined with a central database. The Japanese system enables a clear traceability of the amount and type of device each recycling facility has received. Another advantage of the Japanese system is that every user can access the database through the Internet and see where his or her disposed device ended up for final treatment. The advantage of an RFID would be the same as in the supply chain management, where RFID already is well adopted and in use. Automated processes with high reading speeds may help to increase the efficiency of the EOL chain. In addition to this option, which is enabled by a RFID instead of a paper manifest, there is another option to increase sustainability through re-usable transponder. Assuming an appropriate life-time, a transponder can help reduce the waste produced by paper that has been used only once.

Like in the supply chain management, the typical format would be an ID with related data stored in a database.

Transponder

There are different options for the transponder. Either passive or active transponders could be used. An active solution would probably support 433 MHz ISO 18000-7 conform transponder, which are already used in some container tracing solutions. The advantage of this type of an active solution is increased read distances and rates. On the other hand, such solutions are generally more expensive. Also, the battery support necessary would mean an increase in the cost of running the transponder and additional hazardous waste.

Passive solutions are also possible in various bands. In case of the attachment of the transponder at container or case level, read rates could be guaranteed easily through an appropriate transponder design. The fixed read conditions help to provide a certain quality of service. So the standard solutions would again be the passive UHF ISO 18000-6 standard and some lower frequency solutions using inductive coupling. The upcoming RuBee P.1902.1 could be quoted as an inductive coupling standard.

In this situation, a combination with a bar code as a back up system may provide some advantages.

For such a closed-loop EOL ID system, tailor-made solutions could be appropriate too. These could be customized towards every eventual need and could go as far as include GPS and other sophisticated technologies. Another possibly interesting solution is just under development in Germany by the Deutsche Post. Deutsche Post, the biggest German courier company, in cooperation with partners like the Fraunhofer Institute for Reliability and Micro-Integration (IZM) and the University of Paderborn, is currently developing a passive RFID transponder under the name D-RFID. D-RFID transponders are designed to replace the paper labels which are currently used to trace mail containers. The project is called Pariflex (Passive RFID with Bi-stable Flexible Display) and supports passive ISO 14443A/B and 15693 conform transponders working at 13.56 MHz. Those transponders have an intermediate read range and will be combined with a bi-stable electronic-ink display. The power supply will be realized through inductive coupling.

ID

The ID has to be uniquely identifiable for a vast number of devices. However, even the amount of necessary ID's may not be too large, since used ID's can be re-assigned. Besides that, it must be possible for the ID to be incorporated into the chosen transponder technology.

Infrastructure

The necessary infrastructure is quite close to the LCID infrastructure, with the exception that it is reduced to the EOL steps. Interrogators have to be in place in all necessary spots and the database has to provide the necessary data access and additional features, like security and differentiated access rights.

4.3 End-of-Life-Tracing (Waste Export)

Another tailor-made EOL application of RFID may lay in the export of WEEE, or respectively, in the traceability of such an export.

In Japan there is a high demand for the improved traceability of WEEE, especially concerning the export of it. The export of WEEE is not legal, in most cases, and should be prevented. On the other hand, export to China, for example, makes sense, because of lower labor costs. Due to lower labor costs, even the recycling facilities located in Japan employ a very high number of foreign workers. In the case of WEEE exports, waste must be treated according to Japanese standards. With a RFID tracing system, it would be possible to follow waste from the point of collection to a certified recycling plant in China, for example.

The main question, concerning the tagging process and the system, is the attachment concept. How should the transponders be attached and should they be attached on every device or just on the containers? This again is a decision between benefit and cost. If the treatment before and after the loading of the transport container can be guaranteed, container level transponders should be sufficient. Container level tagging would reduce the cost and complexity and would also, advantageously, lead to less waste, because of a reduced amount of transponders.

However, the need for traceability may make item level tagging seem more of a necessity. In this case, EOL tracing could employ existing ID's, like the ones mentioned above in the LCID section. This again provides the problem of the long life cycle of electronic products and would prevent a fast implementation. To implement RFID in such a closed-loop application today, WEEE optimized transponders could be used. Closed-loop applications also contain possibilities for the re-use of the transponder. This should reduce the costs and is also preferable for environmental reasons.

Another RFID enabled container level option to verify the proper treatment and safe transport of the export are RFID seals. Tagging the whole container with an RFID mechanism that recognizes the unauthorized opening of the container could be a valuable application.

Transponder

Going to item level tagging the same problems, already described in the LCID section, apply here.

According Japanese law, which up to now only covers home appliances, the target devices can be easily characterized. The home appliances, which provide the most potential for RFID use, are those that are large in size, once contained hazardous substances, and are largely composed of metal.

The size of the devices and the high metal fraction could give inductive coupling solutions an advantage. RuBee or other tailor-made solutions could be possible. For home appliances the usually bigger size of inductive transponders won't play any major role, because of the larger size of the devices.

However, UHF transponders are cheaper in the most cases. A good solution for Japan could be the u-Chip Hibiki. The Hibiki, a five-yen RFID inlet, was developed as an answer to EPCglobal and the ISO 18000-6. The project was only recently completed in 2006, and provides a good cheap chip with reading ranges of up to 3 meters. It is not completely, but almost consistent with ISO 18000-6. The Hibiki would be very interesting for a Japanese EOL tracing system because it was financed by the Japanese government and still needs some major applications. In this context, such a closed-loop application like EOL tracing could provide a good opportunity for the Hibiki and could make it a good choice for a UHF solution.

A second option could be the transponder under development in Germany by the Deutsche Post, which already has been mentioned above. This D-RFID could be combined with the below mentioned RFID seal technology. However, the currently available seal technology is designed for active transponders.

Especially on the container level, the sealing of the container could provide another useful application. Electronic seals (or e-seals) allow controlling authorities to determine, without a physical inspection, whether the seal has been broken and the security of the container is compromised. An ISO standard for e-seals (ISO 18185) has already been proposed and is under revision after some security concerns now.

Active applications could be the solution for providing a high level of security, increased read ranges and incorporating the actual e-seal technology. On the container level, increased read ranges could be a big advantage and because the transponders would be constantly re-used, the cost increase can be amortized in the long run.

Another active solution would also be the already above mentioned ISO 18000-7 standard.

Depending on the requested resolution of the traceability even a GPS system could be combined with the transponder.

Data Concept

The information could again be stored in a database and would be connected to the transponder through a UID. The second possibility would be to store the necessary information directly on the transponder. Also a combination of both, for example, with complementary certificates of authentication, could be a good solution for increasing the security factor.

The ID solution would be a possible choice for item level marking. For item level marking, the transponders have to be as cheap as possible. This goal could be reached through the use of cheap UHF ID transponders, like the Hibiki transponder. A re-writable memory increases the initial cost, but also enables the possible re-use of the transponders and could, thus, decrease the cost long term.

For the container level marking, either passive or active options could be drawn. In the case of more expensive, possibly active, transponders, the increased price for memory does not present as much of a barrier as with the low cost transponders. Here a combined solution could be the right choice, but a database would be necessary to provide both a higher security towards legal transport and treatment, and the possibility of accessing information about a container or device even from distant locations.

Infrastructure

The Infrastructure for a waste export system requires the usual components, like an appropriate database system and interrogator network. Additionally a certification system would be necessary. A recycling plant in China, for example, must be certified. In addition, appropriate treatment at the facility and correct information flow must be guaranteed. All security measures implemented into the transponder and database structure won't have any effect, if the system to entrust the actors is not working well.

4.4 ReUsed Transponder

The re-use of transponders may be a good option for future or even intermediate application. In the near future, many devices, especially ones that are high-tech or apply to the home, may carry RF technology of some kind. Even though these technologies are not designed for use at the EOL, it may be possible to do so. However, the application of such transponders wouldn't enable a full system. Since there is in no big chance of a 100% or almost 100% density of RFID equipped devices, at least in the next 20-30 years, such an application can only act as a possibility to increase recycling processes for some devices.

One positive point regarding the re-use of existing transponders is that there is no additional waste generated for the EOL treatment. Since many devices can be expected to carry RFID in the intermediate future, the possibility of such a system will come into reach sooner or later.

Possible applications highly depend on how the transponders are equipped. Most home applications and stationary devices can be expected to carry an ID. Mobile devices, on the other hand, are not very likely to carry easily accessible ID's due to privacy reasons. Additional data stored in the transponder could be used for any kind of application depending on their type. Another option is the recognition of devices or device classes by their transponder technology and communication protocol structure.

WEEE devices and Technology

A core factor for the feasibility of a re-use system is the RFID technology and stored information the WEEE is carrying and its density. Depending on that technology, information and density of almost any application may be possible.

In many cases, smart home applications can be expected to be active; however, at the EOL, the energy supply may not be in place anymore and, thus, would become passive. They would not be able to provide the information they are carrying anymore, but it could still be possible to detect the existence of the transponder and reach some functionality through this detection of existence. Many other applications; however, would carry passive RFID transponders and could still provide their full functionality at the EOL.

In principle, the more expensive and complex a device is, the more that device is likely to carry some kind of RFID technology. From the point of recycling, this is good news, since large, complex devices usually have high recycling potential.

Interrogators

For such a re-use system, the interrogator technology is a central point. Assuming that there will be all kinds of RFID technologies, they must be capable of all kinds of frequencies and communication protocols. Besides some technical problems, which could at least be solved by multiple interrogators, this mainly provides a cost problem. Multi-frequency and protocol interrogators are much more expensive then single ones. In this context, it would be desirable that not too many different RFID technologies find their way into the devices, but some standardized core technologies will share the market. Developing cheap interrogators that can deal with multiple frequencies may be a core barrier for the feasibility of a re-use system. Ideally, the interrogator should also provide some kind of open platform that could be easily updated. This should enable easy adoption of new technologies, which may enter the market later. If possible, such an update should be realized through firmware updates and possibly guided by a central data network system.

Data Network and Information System

Another necessary infrastructure is a supportive database and information system. This system could act like the database systems mentioned in the other scenarios, but it also should serve as a source of information about available RFID technologies on different products. In the case of certain patterns, which may occur in some devices, this information could be used to speed up the sorting processes or increase recognition rates, for example.

5 RFID ON WEEE OUTLOOK AND PROGRESS ESTIMATIONS

5.1 First Generation

There are various possibilities for RFID on WEEE applications today. The technical feasibility is a given in most cases. However, the economical and environmental feasibility is questionable and has not yet been proven in most cases.

Since currently there is not a considerable amount of WEEE devices equipped with RFID, RFID can only be used on WEEE in closed-loop EOL applications.

A closed-loop EOL application, which seem to be realistic, even concerning economical and environmental parameters, has been introduced above.

5.2 Second Generation

In the intermediate future, some devices can be expected to carry RFID technology. This could enable transitions or extensions of some closed-loop EOL applications through the re-use of existing transponders. Furthermore, a scenario like the above introduced re-use scenario may become more and more feasible.

5.3 Third Generation

Long term, the re-use scenario should provide some serious possibilities for application. At least for complex devices and their recognition, the re-use should become a real option.

In addition to the re-use scenario, the full LCID scenario, drawn above, could become a reality in the long run. The attachment of such an LCID or its incorporation into existing RFID transponders is especially a realistic possibility for expensive and complex devices.

Amazing possibilities also could lay in the LCID-CU concept. The realization of such a concept would enable the complete transparency of a device, the state of the containing parts and components and would provide direct access to this information. Such a system could enable enormous possibilities for the field of recycling and recycling efficiency.

6 CONCLUSION

RFID opens up different perspectives for enhanced treatment of WEEE. Even though complex applications are not possible today, some simpler, EOL, closed-loop applications could be possible. The applications, however, face some economical and environmental challenges. In the long run, even complex life cycle orientated applications will become feasible and will help to reach zero emission targets.

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Early design evaluation of products artifacts': An approach based on dimensional analysis for combined analysis of environmental, technical and cost requirements

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Abstract

The early development process of products imposes to fulfill numerous types of requirements simultaneously. Those requirements are often qualitative and imprecise. The main tasks of a development team consist of grasping and understanding customer needs, refining these needs, synthesizing concepts of solutions, evaluating and selecting appropriate solutions. Evaluating and selecting solutions is a critical stage because various types of metrics are used to measure performances of concepts. This paper presents both theoretical contributions and practical implementations. This article presents a theoretical analysis of resource consumption and environmental impact from the viewpoint of exergy. In addition, this article provides a theoretical answer to the issue of qualitative modeling of early design concepts of solutions. This article opens a fruitful perspective for combining heterogeneous requirements in a coherent and systematic manner by using dimensional analysis calculus.

Keywords:

General Design theory, dimensional analysis theory, environmental metrics, exergy, cost analysis

1 INTRODUCTION

In the development of a new product, the early stage of the design process poses major challenge to the engineering team and to the researchers of the product development community. It is because numerous types of requirements, involving multidisciplinary and multilevel analysis and synthesis, have to be fulfilled simultaneously. These requirements are often qualitative, imprecise and situation-dependent. Nevertheless, the team has to deal with this type of imperfect knowledge. Consequently, the task of a development team, during the early design process can be divided into four main groups (e.g. grasping and understanding customer needs, refining these needs, synthesizing concepts of solutions, evaluating and selecting them). Evaluating, comparing and selecting solutions are critical stages because various types of metrics are used to measure performances of concepts. These metrics are often not compatible and need to be aggregated for simplification and comparability. This represents a real practical problem for the design team. In order to propose scientific consistent answers to design teams, the authors of this article have organized the document as follows:

The second section is focusing on the environmental analysis issues. This section points out shortcomings of traditional LCA approach. This part proposes a modeling approach combining the advantages of both LCA and Functional/systems analysis in order to simultaneously deal with the partial and imperfect knowledge available during the early design phases and to provide flexibility in the definition of the boundaries of the environmental analysis. This section introduces also the concept of exergy as a simplified and broad measure of resource consumption and environmental impact during early design stages. This section ends with a short summary of the method used for the practical computation of the exergy. The third section presents the framework developed in order to model qualitatively requirements and solutions for concepts during early design process. This section starts at first with a short overview of the theoretical foundations of this qualitative modeling approach.

The article ends by a combined discussion and conclusion section which analyses the main contributions of the research work and presents future research work related to this topic. Especially, this section points out that practical case studies have been already conducted but this experimental phase should be pushed further in order to evaluate the entire early design framework. The evaluation and comparison phase, which ends the early design process, should give at some stage an aggregated vision of the different performances of concepts of solution. Consequently, the use of multi-objective optimization methods should end the evaluation process. These two issues are discussed briefly in the final section.

2 ENVIRONMENTAL ANALYSIS DURING EARLY DESIGN PROCESS

2.1 Introduction

Traditionally industrial ecology analysis has been characterized by a fragmented approach encompassing a number of different perspectives and analytical techniques. Practitioners most commonly use two techniques: Life Cycle Assessment and System Analysis. Both Life Cycle Assessment and System analysis embody the notion that environmental problems should be examined from a holistic perspective rather than from a reductionist approach. LCA is used as a descriptive model, while systems analysis is used as a prescriptive model. For this reason, the data requirement in LCA may be more extensive than in systems analysis. LCA is therefore more applicable to problems, with an emphasis on examining specific materials, flows and processes whereas systems analysis is more applicable to problems, which emphasis on examining interrelationships.

The nature of the knowledge available during the early design process requires the use of a prescriptive modeling approach, because interrelationships and details related to specific flow and processes have not been precisely established yet. On the other hand, at this stage of the design process, some alternatives can already be evaluated with precision (e.g. the manufacturing processes). This introduction has presented the dual nature of the environmental requirements needed at the early stage of the design process. It is argued by the authors of the article that two fundamental methodological elements need to be introduced to environmental analysis at the early stage of the design process: a coherent approach combining best characteristics of LCA and system analysis, a simplified resource and environmental impact accounting approach.

2.2 Life Cycle Assessment

LCA is the most commonly used approach by which environmental analysis is carried out during a design process [1]. LCA usually follows a four-step methodology, consisting of: - Scoping: This is the process of identifying the goals that motivate the assessment and determination of the boundaries of a study.

- Inventory analysis: The inventory analysis is a method for accounting the resource requirements of a particular product, process or industry from virgin material extraction to final disposition.

- Impact assessment: The goal of the impact assessment is to relate the inventory data to specific environmental concerns.

- Improvement assessment: This phase identifies those aspects of the materials life cycle that might be most improved, and/or evaluates the potential for new design for environment strategies that offer the main environmental profits.

Nevertheless, LCA approach has been criticized as an unreliable scientific method [2]. Indeed, the limitations include difficulties in identifying the boundaries of the system, a lack of adequate inventory data. Moreover, many data is unverifiable and may well be erroneous. In addition, widely disparate conclusions can be drawn depending on what information is excluded from the study. Finally, the impact assessment is made in terms that are not directly comparable. Nevertheless, the LCA framework guides the investigating process by forcing consideration of factors that may have previously been ignored. Additionally, the life cycle hypothesis underlined in LCA framework offers a holistic view of design problems, which probably leads to better-optimized solutions.

2.3 Systems analysis

System analysis is an analytical approach, which requires a model that characterizes the type of relationships and constraints governing the system and their component Systems analysis typically requires a mathematical model that characterizes the relationships and constraints governing various systems components. The model is usually the result of a careful analysis of the system in question in which quantitative links among components are established.

The boundaries of a study can be defined narrowly (e.g. around the system itself) or more broadly (e.g. to include the system and its environment). System analysis is a design tool, which helps decision-making by focusing on all the elements of a system towards a single objective function. The focus of systems analysis is the objective function, which must be expressed in uniform units of measurement.

Therefore, in order to measure the final objective a uniform metric must be expressed. This aggregated metric should simultaneously embody multiple other metrics. They represent sub-objectives integrated to the overall objective. It is a major challenge to develop such a holistic measure. In the following chapters, the authors present the development of a metric aimed at providing a uniform basis for comparison or expression of disparate material and energy requirements, emissions or environmental impacts.

2.4 Summary comparison of LCA and Systems analysis

The major differences between LCA and Systems analysis are summarized in Table 2. The authors claim that during the early development stage, a suitable approach for environmentally conscious design should combine the suitable characteristics of LCA and systems analysis. A combined model is presented in Figure 2. The framework described in Figure 1 is used as the methodological pattern of the article.

Table 1: LCA and system analysis characteristics

Characteristics	Life Cycle Assessment	Systems analysis
Boundaries	Cradle to grave (e.g. Life time)	Flexible
Data requirements	Broad	Focused
Emphasis	Materials cycling	Uniform metric

This model combines aspects of LCA and systems analysis. In the following chapter, the problem of the environmental metrics is discussed briefly and the concept of exergy as a holistic measure of the resource consumption and environmental impact is proposed.

The goal of the combined approach claimed above in this article is to find a solution, which satisfies the mathematical model for a specific value (e.g. maximum, minimum or nominal target) of the objective function.

2.5 Exergy

Based on what has been stated in the previous section, the selection of a unifying objective metric is an analytical prerequisite in order to combine different types of requirements.

Previous research works have analyzed the different aspects of the environmental impact metrics [3] [4]. These metrics can be classified in six broad families, the financial metrics, thermodynamic metrics, environmental metrics (including health and safety), ecological metrics, socio-political metrics and the aggregated metrics respectively.

It is widely accepted that exergy is a suitable approach for measuring material and energetic resource consumption but it has been claimed by Seager et al. [5] that the concept of exergy can also be used for evaluating the environmental impact. The authors of this article claim that exergy combines aspects of thermodynamic metrics, environmental metrics and aggregated metrics.

Exergy introduced by Rant [6] is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy can theoretically provide a common scientific framework for both LCA and systems analysis, merging the two perspectives into complementary tools

Exergy combines the first and second laws of thermodynamics in a way analogous to Gibbs' free energy. Nevertheless, the advantage of exergy compared to Gibbs' free energy or entropy is the existence of a system of environmental reference states first proposed by Ahrendts [7]. This system identifies the chemical characteristics of three different reference environments for computation of standard exergies: the atmosphere, the ocean, and the earth's crust.

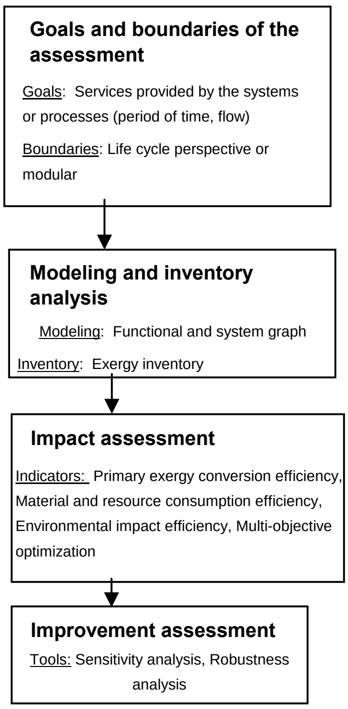

Figure 1: Methodological approach selected

In many cases the most oxidized form of an element provides the appropriate reference state in each environment, nevertheless consideration must also be given to the molar concentration of a compound in the specified environmental sink. Exergy is expressed in Joules (J) unit or ML^2T^{-2} by using the international system of fundamental quantities with *(M) Mass*, *(L) Length* and *(T) Time* respectively.

Exergy has four basic forms, *kinetic, potential, chemical and physical* (e.g. pressure-volume and heat exchange type of work). From an environmental perspective, both the chemical and the physical exergies are the two exergies of interest for evaluating material and exergy consumption.

The following paragraphs give the necessary formulas to compute exergy when the resource consumption is analyzed. T_0 and P_0 are the references used for computing the physical and chemical exergy. The chemical exergy is calculated in the paper by using the method proposed by Szargut et al. [8].

Material and resources consumption

Form of energy such as gravitational, electric and kinetic energy can be completely recovered as mechanical work. Therefore, according to the definition of Szargut, exergy and energy are equal for these types of energies. Consequently, work (e.g. mechanical work) and electrical energy are high quality energies. On the opposite, the variation of exergy associated with a heat transfer between a system and a reference environment is:

$$Ex_Q = (1 - \frac{T_0}{T})Q \qquad (1)$$

With T_0: standard temperature of the reference environment (298.15 K), P_0: standard pressure of the reference environment (1 atm = 101 325 Pa), Ex_Q : transferred exergy associated with the heat transfer (J), Q: transferred heat (J), T: temperature at the place where the heat transfer takes place (K),

The Equation 1 shows that heat is a degraded type of energy because $Ex_Q \leq Q$.

The variation of Exergy linked with a flow of matter can focus on the physical and chemical exergies because they are those of interest from the environmental point of view. The physical exergy is due to the difference of temperature between the flow and the environment.

$$Ex_{Ph} = m[(h - h_O) - T_O(s - s_O)] \qquad (2)$$

With: Ex_{Ph}: Physic exergy (J), m: mass (kg), h: specific enthalpy of the flow (J/kg), h_0: specific enthalpy of the flow at temperature T_0 and pressure P_0 (J/kg), s: Specific entropy of the flow (J/(kg.K), s_0: Specific entropy of the flow at temperature T_0 and pressure P_0 (J/(kg.K). In practice, the entropy is calculated by using the heat capacity as presented in the following formula:

$$\Delta S = \int \frac{C_X}{T} dT \qquad (3)$$

With: Cx is the heat capacity of a fluid at constant pressure (CP) or constant temperature (CT) (J/kgK),

The *standard chemical exergy* of a reference gas, which constitutes the reference atmosphere, is:

$$Ex^0_{Ch_i} = RT_O \ln \frac{P_O}{P_{OO}} \qquad (4)$$

With: $Ex^0_{Ch_i}$: Standard chemical exergy of the perfect gas (kJ/mol), R: perfect gas constant (R=8,314 J/K.mol), P_0: Pressure of the environment (Pa), P_{00}: Partial pressure of the perfect gas at the reference state (Pa).

However, in many cases, the most oxidized form of an element provides the appropriate reference state in each environment, and consideration must be given to the molar concentration of a compound in the specified environmental source. Szargut et al. [8] describes the principles for computation of the *standard chemical exergy* (Ex_{ChP}^{O}) of any compound.

$$Ex_{ChP}^{O} = G^{O} + \sum_{i} (\frac{n_i}{n_P} Ex_{Chi}^{O}) \quad (5)$$

With: Ex_{ChP}^{O} : Standard chemical exergy of a compound (J/mol), G_0: Gibbs free energy of formation of the compound from the elements (J/mol), *ni*: the number of moles, Ex_{Chi}: Standard chemical exergy of the *i*th reactant required to form *n*p moles of the product compound (J/mol),

For evaluating the environmental impact a coherent approach may be to focus on the portion of the chemical exergy, which is resulting from material transfers or changes in composition. This approach called *exergy of mixing* has been proposed by Seager et al. [5]. The exergy of mixing, which is also called composition-dependent component of chemical exergy [8] is computed for the *i*th chemical species of any reaction as:

$$Ex_i^m = n_i R T_0 \ln\left\{\frac{y_i}{y_i^0}\right\} \quad (6)$$

yi is the activity in the thermodynamic system under consideration. For a mixture gas y_i can be evaluated by:

$$y_i = \frac{p_i}{p_0} \quad (7)$$

For a liquid in solution *yi* can be evaluated by:

$$y_i = \frac{C_i}{C_0} \quad (8)$$

For a solid chemical species $y_i = 1$ if the solid is alone in its phase.

y_i^0 is the reference activity in the appropriate environment (sea, earth crust or atmosphere) and can be found for most of the species in the textbook of Szargut et al. [8].

3 QUALITATIVE MODELLING AT EARLY DESIGN STAGE

3.1 Introduction

This section summarizes a part of the approach developed in our research in order to model and compare concepts qualitatively. The goal of the modeling method is twofold. The first aim is to minimize the size of the design problem by transforming the design space in order to obtain a metric space. A metric space is a topological space having a unique metric.

The second objective is to compare concepts of solutions developed for the same type of design problem. This second issue is not analyzed in this paper but is the goal of other actual publications of the authors. This section tries to summarize briefly the way the first objective has been attained [9].

3.2 Metric space

The mathematical definition of Bourbaki of a metric space is given below [10].

There exists a metric on a topological space such that a set S is called a *metric space* if with every pair of points x, y ∈ S, there exists a non-negative real number d(x, y) that satisfies:

- If d(x, y) = 0 then x= y and d(x, x)=0,
- For any pair of points x, y, d(x, y) = d(y, x),
- For any three points x, y and z, d(x, z) ≤ d(x, y) + d(y, z).

The necessary conditions to obtain a metric space during the design process have been extensively described by Coatanéa in his doctoral thesis [9]. It has been demonstrated that a metric space can be built out of an intermediate topological space called classification space [11]. A classification space is a topological structure resulting from a classification. For simplification purpose in this article, we consider that classification space and classification are similar concepts. In the following, the concepts of classification will be exclusively used.

Consequently, in order to obtain metrizability of the design space, the initial necessary condition requires systematizing the use of classifications in the design process. Classification should be used at all the stages of the early design process. The Figure 2 summarizes the levels of classifications introduced in the design framework. The classifications involve both the refinement and synthesis phases of the design process. This is due to the fact that metrizability conditions should be met at the end of the synthesis process.

The comparison and evaluation of solutions are made in a modified design space resulting from the metrization process. The necessary different levels of classifications and the mapping approach are presented in Figure 3.

Four fundamental classifications have been developed or enhanced in this work [9]. At first, the domain classification is categorizing the design activities. An extended vision of the design activity has been developed; because the scope of the design activity has been gradually extended by the introduction of service engineering, environmental constraints, globalization of economy and Internet activities. An extended scope requires working in three different types of design domains, the physical domain (including the life cycle phases and traditional engineering design), the economical domain (dealing with value and cost metrics) and the domain of information exchange (including design of services, modeling of the information exchange, etc…). Second, a reconciled functional classification initially developed by Hirtz et al. [12] has been used (Table 3).

A refinement procedure summarized in Figure 3 (i.e. mapping 1 and mapping 2) has been developed in order to transform an initial natural semantic description into a normalized one. Third, a classified list of basic organs, basic variables, basic laws, substances and fields and their usual names in engineering, economy and information domains have been derived from Bond graph theory [13], Su-fields in TRIZ approach [14]. The mapping between these levels of classification is summarized in Figure 3 (i.e. mappings 3, 4 and 5). When this classification structure has been developed a list of three additional fundamental conditions needs to be met in order to ensure metrizability.

Those conditions are summarized below [9]:

- Having a fundamental system of entourages,

- Having a sufficiently detailed fundamental system of entourage in order to ensure separation,
- Having a countable fundamental system of entourage,

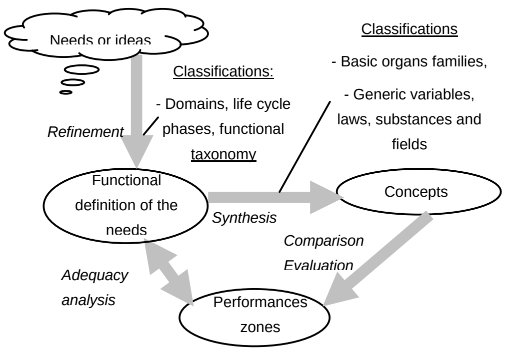

Figure 2: Classifications and design phases

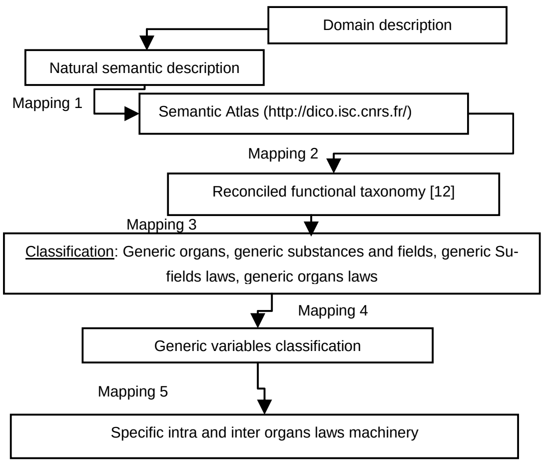

Figure 3: Levels of classification and mapping

In practice, having a system of entourage means that we have a generic set of concepts in order to refine and make synthesis of solutions. The concepts of domain, function, generic organs, substances, fields, generic variables, generic laws (i.e. Su-fields, intra and inter organs laws) and specific names per domain constitute that type of generic set of concepts. The concept of function itself has been extensively analyzed [9] and is seen as an interface between two situations (i.e. an inner situation and an outer situation). This concept is not detailed in this article but it constitutes the central concept used in order to give its coherence to this classification approach. The second condition states that this set of concepts should be sufficiently detailed to ensure separation. Ensuring this property requires at first describing the concepts of solutions by using the initial set of generic concepts and by verifying that at some point the description of different concepts is diverging. If it is not the case then it can mean that the two concepts are similar from the viewpoint of the analyzed performances or that the granularity of the generic set of concepts is not sufficient.

The third condition states that a countable system of entourage exists; this means in practice that every generic variable should be connected with a measurable metric (i.e. a measurable metric can be measured directly like mass or indirectly for example by making a statistical analysis in the case of customers' aesthetic preferences). The measurable metrics themselves should be derived from a limited set of fundamental quantities. An enhanced set of fundamental quantities is proposed in Table 2.

The entire set of conditions constitutes a metamodel structure developed in order to ensure metrizability. It should be noticed by the reader that the concept of exergy developed above fit perfectly within this countable system of entourage because exergy is expressed in Joules or ML^2T^{-2} by using the international system of fundamental quantities presented in Table 2.

Table 2: Fundamental quantities and units

The seven Base SI quantities and units		
Physical quantity (symbol)	Base unit	Unit Symbol
Length (L)	metre	m
Time (T)	second	s
Mass (M)	kilogram	kg
Electric current (A)	ampere	A
Thermodynamic temperature (K)	kelvin	K
Luminous intensity (Cd)	candela	cd
Amount of substance (Mol)	mole	mol
The two non physical quantities and units		
Quantity (symbol)	Base unit	Unit Symbol
Informational (Sh)	shannon	Sh
Economical (C)	cost	€ or $ or others

Table 3: Partial reconciled taxonomy of function

Primary function	Secondary function	Tertiary function	Correspondences
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, isolate, release, sort, split,

It is most probably quite difficult to figure the practical use of the machinery described above for the readers which are not familiar with mathematical design theories and topology. A practical implementation of this theory using practical cases can be found in Coatanéa [9].

4 DISCUSSION AND CONCLUSION

The main contribution of this article shall be considered by the readers from the viewpoint of developing a qualitative design framework aimed at combining coherently heterogeneous design attributes and performances. The final goal of this research work is to be able to aggregate qualitatively elements such as the environmental impact performances, the traditional and fuzzy technical

performances and the economical performances. With this concern in mind, the present article presents necessary initial elements required in order to analyze a system from a qualitative perspective.
The transformation of the design space is done by using two possible methods. The first one relies on the Vashy-Buckingham theorem [15]. The second approach called by the authors as the *bottom-up* approach consists of creating *Π* numbers based on the idea that each basic organ of a complex system is ruled by a law (i.e. a set of law has been classified in the framework). A generic law is defined in our case as:

$$(\sum_{i=1}^{n} Output_i) = (\sum_{j=1}^{m} C_{V_j}.Input_j) \qquad (9)$$

Where C_V are the connecting variables, each side of Equation 9 are dimensionally homogeneous. Consequently, it is possible to build a resulting dimensionless number according to Equation 10.

$$\Pi = \sum_{i=1}^{n} Output_i \,/\, \sum_{j=1}^{m} C_{v_j} Input_j \qquad (10)$$

The approach can be generalized to complex systems or processes according to the Figure 4. A complex system or process can be modelled according to the Equation 11. The bottom-up approach has a major advantage compared to the Vashy-Buckingham approach. Indeed, it provides an automatic clustering of the variables by organs. Later, it is possible using a specific algorithm [9] to associate functions and the dimensionless numbers resulting from the synthesis of solution. This will be the goal of a second article.

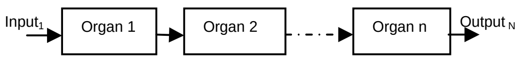

Figure 4: Complex structure model

This lead to the overall expression:

$$\Pi_{Overall} = \frac{Output_N}{Input_1} = \frac{Output_1}{Input_1} . \frac{Output_2}{Output_1} ...... \frac{Output_N}{Ouput_{N-1}} \qquad (11)$$

This article has presented a part of a theoretical framework dedicated to the early design phase. In this paper, we are focusing on the metrization of the design space. This phase logically leads to the analysis of several performance parameters related to dimensionless groups. The general form of a performance function is presented below:

$$Performance_i = (\sum_{j=1}^{m} C_j.\Pi_j) \qquad (12)$$

The evaluation of the performance functions requires that the performances can be measured. This is a resulting consequence when we are using the concept of exergy for evaluating the resources consumption and the environmental impact. Nevertheless, when heterogeneous *Π* numbers and performances are combined, it is necessary to weight *Π* numbers in equations of the type of Equation 12 and to weight performances when aggregated performances parameters are required. This weighting phase remains a central theoretical issue. A valid answer to this issue shall be to use an approach coming from multiple criteria decision aiding (MCDA). Indeed, a class of methods provides recommendations to the decision makers by providing one (or several) binary relation(s) representing the preference among pairs of alternatives [16] rather than on the construction of a synthesizing utility function. These methods are usually referred as outranking methods in the MCDA literature and belong to the so-called European school of MCDA. This kind of approach should provide insight in the comparison of concepts.

5 ACKNOWLEDGMENTS

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Total performance analysis of product life cycle considering the uncertainties in product-use stage

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Abstract

Product life cycle design has gained more interest in recent years due to growing concern about environmental problems. In general, there exist significant uncertainties (e.g., operating condition, user preference, collection rate etc.) in product life cycle and a design method that is robust and tolerant against these uncertainties should be established. To this end, this paper discusses the uncertainties in product life cycle and evaluates their impact on total performance throughout a whole product life cycle. Based on this discussion, a design method for product life cycle that maximizes its total performance handling these uncertainties is proposed.

Keywords:

Total Performance; Product Life Cycle; Uncertainties; Taguchi's Robust Design Method

1 INTRODUCTION

Environmental consciousness has gained more and more interest in recent years, and product life cycle design that aims to maximize total performance while minimizing its environmental load and costs should be implemented. In order to achieve that, practical evaluation of product value, as well as environmental load and cost simultaneously, throughout its whole life cycle is indispensable.

Many studies have focused on evaluation of environmental load and cost throughout whole product life cycle [1-3]. Some of them have calculated environmental performance correlating environmental load with product value associated with its functionality to screen out environmental bottlenecks [1,2], and others calculated economic performance correlating life cycle cost with product value to screen out economical bottlenecks [3]. However, evaluation of rise and fall of product value throughout its whole life cycle has not been studied enough in spite of its significant influence on a total performance. In addition, most of the studies do not evaluate both of environmental and economic performance at the same time. To solve these problems, the authors have proposed a practical evaluation method for the product value along life cycle by correlating it with product functionalities, and design guideline for maximizing product performance through product life cycle with balancing its value, environmental load, and costs [4]. Although it is revealed to be effective for evaluating life cycle performance, prediction of future trend of deterioration of product value is difficult task due to its significant uncertainties in product-use stage. Preference for products and their operational conditions differ from user to user, and this causes significant uncertainties in product conditions, lifetime, and the amount of available resources for component reuse and recycling, which are important factors for a designer to determine adequate life cycle options (e.g., reuse, recycling, maintenance, upgrading, etc.) of products and their components. Therefore, a design method of product life cycle that is robust and tolerant against these uncertainties should be established.

To this end, this paper discusses the uncertainties in product life cycle and evaluates their impact on total performance throughout a whole product life cycle. Based on this discussion, a design method for product life cycle that maximizes its total performance handling these uncertainties is proposed.

2 APPROACH FOR TOTAL PERFORMANCE DESIGN

Our approaches for deriving adequate solution of product specification and its life cycle option are summarized as follows;

- **Total performance index (TPI) as an objective function**

Total performance index (TPI) [4] of a product, which represents efficiency of utility value production from environmental and economic viewpoints at the same time, is used as an objective function in this study.

- **Uncertainties represented as interval values**

There exist significant uncertainties (e.g., lifetime, operating condition etc.) in product life cycle, especially in product use stage, which cause significant variation in TPI throughout whole product life cycle. In order to handle these uncertainties, the authors represent parameters that are used for calculation of TPI as interval values (i.e., from lower bound to upper bound), and calculate TPI of a product as an interval value.

- **Robust design of product life cycle**

The objective of this study is to derive adequate design solution that maximizes the TPI with eliminating the effect of the various uncertainties in product life cycle. To this end, the following approach is employed.

Step 1: Determining optimal specification and lifetime of a product

First, the authors focus on the first life of a product. In this step, adequate specification and lifetime of a product which maximizes the mean of TPI while minimizing the variation of TPI is derived. Since the performance of each functional requirement (FR) is not always proportional to its resulting environmental load and cost and its deterioration due to aging and wear also differs from each other, finding out optimal specification and lifetime of a product is not a simple task. In addition, significant uncertainties in product life cycle cause the significant variation in TPI of a product. To solve these problems, the authors employ Taguchi's robust design method [5]. By employing Taguchi's robust design method, various uncertainties that cause the significant variation in objective function (i.e., TPI in this paper) can be treated as noise factors and near optimum design solution that is robust and tolerant against these factors is determined.

Step 2: Determining optimal life cycle option for components at the end of product use stage

The next step is determining adequate life cycle options (e.g., reuse, repair, upgrading, recycling, and landfill etc.) for each component to improve its TPI after the first product-use stage. This is because some components have residual value at the end of product-use stage and reuse and recycling of components have potential to improve TPI of a product in next generation.

This paper especially focuses on the first step of optimization. The rest of this paper is organized as follows. Section 3 describes how to measure total performance of a product throughout its whole life cycle based on our previous work. Section 4 describes life cycle design method focusing on the specification and lifetime of a product considering the uncertainties in product life cycle. Section 5 illustrates calculation procedure of our method with an example of a laptop computer. Section 6 discusses the result of example. Section 7 concludes the paper.

3 TOTAL PERFORMANCE OF PRODUCT LIFE CYCLE

3.1 Total performance index (TPI)

Since all products are produced to satisfy customer needs, total performance throughout product life cycle is evaluated as balance of customer's utility value (UV) and its resulting environmental load and cost throughout whole life cycle. The authors define TPI as follows;

$$TPI = \frac{UV}{\sqrt{LCE \cdot LCC}} \tag{1}$$

where, *LCE* and *LCC* denote environmental load and cost throughout whole life cycle, respectively.

3.2 Formulation of UV

In general, UV of a product becomes better the higher product's functional performance increases and the longer it is continued to use. Thus UV of a product is defined as time integral of product value, assuming that product value is strongly correlated with its functional performance.

$$UV = \int_{st}^{tt} V(t)dt \tag{2}$$

where, *st*, *tt*, and *V(t)* denote starting and termination time of a product-use stage and product value at time *t*, respectively.

From a viewpoint of Value Engineering (VE) [6], product value at time *t* can be allocated to its dominant FRs from the customers given as follows;

$$V(t) = \sum_i V_i(t) \tag{3}$$

$$V_i(t) = w_i(t) FR_i(t) \tag{4}$$

where, i, $V_i(t)$, $w_i(t)$ and $FR_i(t)$ denote index of FRs, product value allocated to FR_i, weighted factor for FR_i, and functional performance of FR_i at time *t*, respectively.

Weighted factor for each FR represents its importance to the customers. FRs with high importance have great potential to improve product value. In this study, we assume that a product value is measured by its market price. Therefore, importance of each FR can be estimated by conjoint analysis [7] of various products with different specification.

A product value deteriorates by following two causes; namely, (i) physical causes and (ii) value causes [8]. Physical causes include failure and degradation of product due to aging and wear. Value causes include obsolescence of FRs (including aesthetic quality) of a product. The values of products such as computers or mobile phones deteriorate too fast due to their very fast technological innovations. Therefore, both of these causes should be estimated at the same time. Since the value of a product is given as weighed sum of its functional performance, value deterioration along time is given by decreases of functional performance and their importance.

Deterioration due to physical causes

We represent deterioration due to physical causes as a decrease of functional performance $FR_i(t)$. $FR_i(t)$ is estimated by empirical data of deterioration of similar products at their use stage by applying reliability theory. For the sake of simplicity, we express deterioration of $FR_i(t)$ as linear equation as follows;

$$FR_i(t) = c_i(t - st) + d_i \tag{5}$$

where, c_i, and d_i denote deterioration rate and initial performance of FR_i, respectively.

Deterioration due to value causes

Another cause of deterioration of product value is obsolescence of FRs. Assuming that a set of dominant FRs of a product does not change, obsolescence of each FR is expressed by decrease of importance of each FR given as follows;

$$w_i(t) = a_i t + b_i \tag{6}$$

where, a_i and b_i denote the obsolescence rate and initial importance of FR_i, respectively. These values can be estimated by regression analysis on $w_i(t)$ at various time *t.*

3.3 Formulation of LCE and LCC

Focusing on energy using products, the longer a product is continued to use, the higher LCE and LCC of a product become. Thus, the simplest representation of LCE and LCC of a product are given as follows;

$$LCE = \sum_i LCE_i \tag{7}$$

$$LCC = \sum_i LCC_i \tag{8}$$

$$LCE_i = e_i \cdot lt + f_i \quad (9)$$

$$LCC_i = g_i \cdot lt + h_i \quad (10)$$

where, e_i, f_i, g_i, h_i and lt denote partial environmental load and cost allocated to FRi per unit time during product use stage, those throughout all product life cycle except product use stage, and product lifetime, respectively.

f_i and h_i can be decomposed into partial environmental load and cost during each life cycle stage.

$$f_i = f_{i,prod} + f_{i,dist} + f_{i,col} + f_{i,eol} \quad (11)$$

$$h_i = h_{i,prod} + h_{i,dist} + h_{i,col} + h_{i,eol} \quad (12)$$

where $f_{i,prod}$, $h_{i,prod}$, $f_{i,dist}$, $h_{i,dist}$, $f_{i,col}$, $h_{i,col}$, $f_{i,eol}$, and $h_{i,eol}$ denote environmental load and cost of FRi at production, distribution, collection and end of life (EOL) treatment stages, respectively.

LCE and LCC of a product can be calculated by conventional life cycle assessment (LCA) and life cycle costing (LCC) tools, respectively. These values are allocated to each component by referring the material and energy consumption of each component at each life cycle stage at first. Then, LCE and LCC of FRs are calculated from those of components by considering the relation between components and FRs [4].

3.4 Time variation in TPI

Since the product value decreases as given in equations 5 and 6 while LCE and LCC of a product increase as product lifetime increases, there exist optimal lifetime (*olt*) that maximizes total performance of a product as shown in Figure 1. Therefore, from the viewpoint of TPI, a product is ideally utilized when it is continued to use until its optimal lifetime.

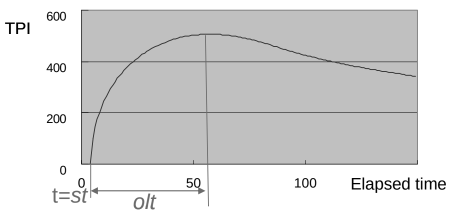

Figure 1: Time variation in TPI

4 TOTAL PEFORMANCE DESIGN CONSIDERING THE UNCERTAINTIES

4.1 Taguchi's robust design method

The objective of optimization is minimizing variation of TPI while maximizing the average of TPI considering the various uncertainties in product life cycle. To this end, the authors employ Taguchi's robust design method [5]. In this method, the search objective is to maximize a design metric over the design space, where each evaluation in the design space incorporates the noise space variation. In order to apply Taguchi's robust design method to optimization of TPI, noise factors, their influence on TPI, and control factors (design parameters) should be identified.

4.2 Noise factors: uncertainties in product life cycle

Product life cycle contains many uncertainties (e.g., operating condition, user preference, product lifetime, amount of available resources for recycling and reuse at the end of product-use stage etc.) and these uncertainties are treated as noise factors in the Taguchi's robust design framework.

Focusing on product-use stage, the difference in operating condition (e.g., operation time, temperature, and frequency of usage etc.) of a product may cause variation in c_i, e_i, and h_i in equations 5, 9, and 10. In addition, user's preference for a product differs from user to user and this also causes the significant variation in a_i and b_i in equation 6.

These variations in product-use stage also influence on lifetime of a product. In this study, the authors assume that a product is disposed of when at least one of its dominant FRs completely loose their allocated values (in case of product sales business strategy, which will be described in Section 4.4). Figure 2 shows an example of value deterioration of FRs of a product. Assuming the lifetime of each FR is the duration until its allocated value decreases to zero, the lifetime of a product is defined as follows;

$$Min(lt_{i,low}) \le lt \le Min(lt_{i,high}) \quad (13)$$

where, $lt_{i,low}$ and $lt_{i,high}$ denote lower and upper limit of lifetime of FRi, respectively. In this figure, FR2 which has the lowest $lt_{i,low}$ and $lt_{i,high}$ determines the lifetime of a product .

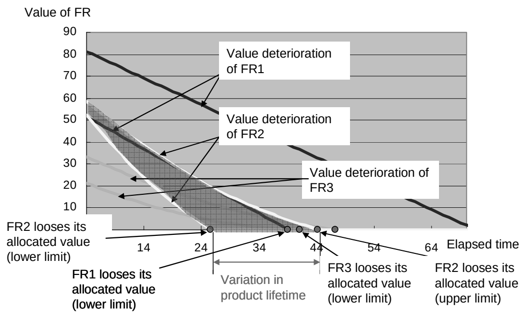

Figure 2: Variation in product lifetime

The life cycle options such as recycling and reuse have great potential to reduce environmental load and cost during production and EOL treatment stages in some cases. However, the potential reduction in LCE and LCC, which is represented as reduction in $f_{i,prod}$, $f_{i,eol}$, $h_{i,prod}$, and $h_{i,eol}$, is influenced by the amount of available resources for recycling and reuse at the end of product-use stage. Amount of these resources also varies as a result of variations of lifetime of a product, collection rate at collection stage, and good item ratio at EOL treatment stage.

Therefore, the parameters a_i, b_i, c_i, e_i, f_i, g_i, h_i and lt should be treated as noise factors, if these values can not be controlled by a designer.

4.3 Variation in TPI

The effect of variation of parameters a_i, b_i, c_i, d_i, e_i, f_i, g_i, h_i and lt on UV, LCE, LCC, and TPI of a product is summarized in Table 1. As b_i and d_i increase, UV increases. As a_i and c_i of which values are negative increase, obsolescence and deterioration of each FR slow down. Thus, a_i, b_i, c_i and d_i have positive effect on UV and TPI. As e_i and f_i (or g_i and h_i) increase, LCC (or LCE) increase. Thus e_i, f_i, g_i and h_i have negative effect on TPI.

Product lifetime also affect on UV, LCE, LCC and TPI. However, its effect on TPI can be both negative and positive. This is because there exist optimal lifetime (*olt*) that maximizes TPI of a product. When actual product lifetime is smaller than its optimal lifetime it has positive effect on TPI, negative effect otherwise.

Conditions 1 and 2, where TPI have the highest and the lowest values under the variations in parameters a_i, b_i, c_i, d_i, e_i, f_i, g_i, and h_i, respectively, can be identified as shown in Table 1. Figure 3 depicts upper and lower bounds of TPI in conditions 1 and 2, respectively. Horizontal axis and vertical axis of this figure represent product lifetime and TPI of a product, respectively. TPI value changes as product lifetime changes, resulting variation in TPI is given as the area coloured in yellow in Figure 3.

Table 1: Positive and negative effect on TPI

	UV				LCE		LCC		Lifetime
	ai	bi	ci	di	ei	fi	gi	hi	lt
UV	P	P	P	P					P/N
LCE					P	P			P/N
LCC							P	P	P/N
TPI	P	P	P	P	N	N	N	N	P/N
Condition 1	Highest	Highest	Highest	Highest	Lowest	Lowest	Lowest	Lowest	
Condition 2	Lowest	Lowest	Lowest	Lowest	Highest	Highest	Highest	Highest	

P: Positive effect
N: Negative effect

Table 2: Control factors in each business strategy

Business strategy	UV				LCE					LCC					Lifetime	Life cycle options
						fi					hi					
	ai	bi	ci	di	ei	fi,prod	fi,dist	fi,col	fi,eol	gi	hi,prod	hi,dist	hi,col	hi,eol	lt	
(1) Product sales				X		X	X				X	X				
(2) Leas and rental				X		X	X				X	X			X	
(3) Closed-loop manufacturing				X		X	X	X	X		X	X	X	X	X	X

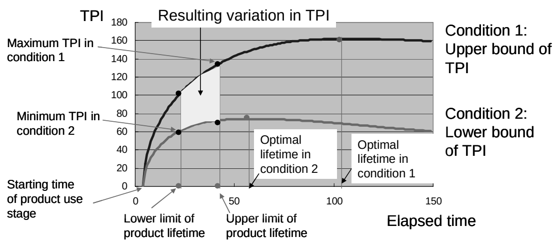

Figure 3: Variation in TPI considering the noise factors

4.4 Business strategy and control factors

In optimization of TPI, the control factors and dominant noise factors change when a designer employs different business strategies. In this study, three types of business strategies are identified as follows;

(i) Product sales strategy

The first type of business strategy is a conventional product sales business strategy, where a manufacture only sells its products and does not care about its products after sales. In this strategy, a manufacturer can only control initial specification and its resulting environmental load and cost at production and distribution stages. Therefore, control factors in this strategy are d_i, and part of f_i and h_i (i.e., $f_{i,prod}$, $h_{i,prod}$, $f_{i,dist}$, and $h_{i,dist}$).

(ii) Lease and rental strategy

The second type of business strategy is lease and rental strategy. In this strategy, a manufacturer lends its products to customers instead of selling them. In this strategy, a manufacture can control lifetime of a product, in addition with control factors in product sales strategy. For maximizing TPI of a product, it is effective to control lifetime of a product close to *olt* described in Section 3.3.

(iii) Closed-loop manufacturing strategy

The third type of business strategy is closed-loop manufacturing strategy, where products are completely collected at the end of product-use stage and sent back to their manufactures so as to promote reuse and recycling of products. Some manufacturers of photocopier and one time use camera employ this strategy to enhance its environmental and economic performance simultaneously. Control parameters in this strategy are f_i, h_i, and life cycle options in addition with those in leas and rental business strategy.

Table 2 summarizes the design parameters in each business strategy.

4.5 Flow of total performance design

Flow of the optimization of TPI of a product is summarized as follows;

Step 0: Product and its initial life cycle definitions

Before the optimization, dominant FRs and initial life cycle of a product should be defined.

Step 1: Selection of business strategy and determining control factors

The first step of the optimization is the selection of business strategy, which determines the possible set of control factors in all parameters associated with calculation of TPI. The levels of control factors are also set in this step. Commonly, two or three levels are selected for each factor.

Step 2: Estimation of UV, LCE and LCC

UV, LCE, and LCC of a product are estimated by using conjoint analysis, LCA, and LCC methods. From these results, original estimate of parameters a_i, b_i, c_i, d_i, e_i, f_i, g_i, and h_i are determined.

Step 3: Identification of noise factors

Considering the uncertainties in product life cycle, the levels of noise factors are determined and incorporated into the original estimate calculated in Step 2.

Step 4: Optimization by control factors

Taguchi's robust design method contains two optimization steps. First one is minimization of variation in output value of a target system. And the second one is maximization of the mean of output value of a target system, when the larger the output value the better. Basically, signal-to-noise (S/N) ratio, which is the ratio of the mean (signal) to the standard deviation (noise), is used as a design metric for the first optimization.

In this study, the output value is TPI of a product. Considering two noise parameter arrangements (i.e., conditions 1 and 2 in Table 1), S/N ratio η in each design parameter setting is given as follows;

$$\eta = 10\log(\frac{\mu}{\sigma})^2 \quad (14)$$

$$\mu = \frac{TPI_{\max,1} + TPI_{\min,2}}{2} \quad (15)$$

$$\sigma^2 = (TPI_{\max,1} - \mu)^2 + (TPI_{\min,2} - \mu)^2 \quad (16)$$

where, μ, σ, $TPI_{max,1}$, and $TPI_{min,2}$ denote the mean and standard deviation of TPI over conditions 1 and 2, maximum TPI over the range of estimated lifetime in condition 1, and minimum TPI over the range of estimated lifetime in condition 2, respectively.

Based on the number of control factors and their alternative levels determined in Step 1, adequate orthogonal array is selected for reducing the number of calculation configuration. Average S/N ratio and the TPI for each level of each control factor are calculated from the result of calculations to separate out its effects on the variation and the mean of TPI. Based on these values, a designer selects adequate levels of control factors that minimize variation of TPI while maximizing the mean of TPI.

5 EXAMPLE

In the following, the calculation procedure for the total performance design is illustrated, using an example of a laptop computer.

5.1 Product definition

Dominant FRs of a laptop computer is summarized in Table. 3. The performance of each FR is measured by functional parameter given in the third column in Table 3. In this example, EOL treatment of a target product assumed to be landfill.

5.2 Selection of business strategy and identification of control parameters

In this example, product sales strategy is selected. Therefore, d_i, which represents the initial specification of each FR, is selected as control factor. For this example, three alternative levels were identified to be studied for the controllable design factors as shown in the 4th, 5th and 6th column in Table 3. Level tow represents the initial setting (reference setting) for the control factors.

5.3 Estimation of UV, LCE, and LCC

To estimate value deterioration due to value causes, the authors executed conjoint analysis of a laptop computer at different two years, 2002 and 2006. Table 4 summarizes the results of this analysis. For example, we can see that weighted factor for “FR1: Computing speed” was 58.65 [kJPY/GHz] at 2002, has decreased to 36.95 [kJPY/GHz] at 2006 due to technological innovation. a_1, which denotes the obsolescence rate of FR1, is calculated as –0.45638, by substituting these two values to equation 6. For the initial importance of each FR, the importance value at 2002 is used. Value deterioration due to physical causes is assumed by referring physical lifetime given in right most column in Table 3.

LCE and LCC of a product were calculated by using conventional LCA and LCC methods, and these values were allocated to each FR by referring its responsibility for a LCE and LCC of a product at each life cycle stage. In general, different performance levels imply different structure of components. Thus, the resulting environmental load and cost throughout whole product life cycle also differ from each other. Assuming that the difference in environmental load and cost during product-use stage is negligible in this example, the parameters f_i and h_i, which represent LCE and LCC over all product life cycle except product-use stage respectively, have three alternative levels corresponding to performance levels of each FR.

The parameters values (not yet incorporated with noise factors) used in this calculation are summarized in Table 5. Due to lack of information, the values of f_i corresponding to performance level one and three are estimated from those at level two, which represents the initial setting for the control factors.

Table 3: FRs of a laptop computer

FRs		Functional parameters	Specification			Physical lifetime
			Level 1	Level 2	Level 3	
FR1	Computing speed	Processor speed	0.49[GHz]	1[GHz]	1.7[GHz]	120 [month]
FR2	Compute large-capacity data	Memory size	0.125[GB]	0.25[GB]	0.5[GB]	120 [month]
FR3	Storage capacity	HDD size	20[GB]	40[GB]	60[GB]	48 [month]
FR4	Portability	Weight	1.3[kg]	2[kg]	3[kg]	120 [month]
FR5	Easily viewable	Display size and luminance	$200[mm] \times 200[cd/m^2]$	$300[mm] \times 200[cd/m^2]$	$381[mm] \times 200[cd/m^2]$	30000 [hour]
FR6	Handle multiple recording media	Number of available recording media and operations	1types	2 types	3 types	48 [month]

Table 4: Importance of each FR in each year

	w1	w2	w3	w4	w5	w6
Unit	*kJPY/GHz*	*kJPY/GB*	*kJPY/GB*	*kJPY/kg*	$\frac{kJPY}{mm \times cd/m^2}$	*kJPY/types*
2002	58.86089	116.7666	1.793528	21.30967	0.001505	29.35913
2006	36.9545	24.64593	0.192244	17.69866	0.001763	9.946558

Table 5: Original estimate of the parameters

FRs	UV [kJPY]						LCE				LCC			
	a_i	b_i	c_i	d_i			e_i [kgCO2/month]	f_i [kgCO2]			g_i [kJPY/month]	h_i [kJPY]		
				level 1	level 2	level 3		level 1	level 2	level 3		level 1	level 2	level 3
FR1	-0.46	58.9	-0.004	0.49	1	1.7	0.407	28.4	57.9	98.4	0.015	35.5	45.47	55.48
FR2	-1.92	117	-0.001	0.13	0.25	0.5	0.151	11.7	23.4	46.7	0.006	11.7	23.42	46.84
FR3	-0.03	1.79	-0.417	20	40	60	0.033	1.71	3.43	5.14	0.001	5.53	10.05	15.05
FR4	-0.08	21.3	-0.011	1.3	2	3	0.177	2.88	4.44	6.66	0.007	20.8	25.8	30.8
FR5	-1E-05	0.002	-200	40000	60000	76200	0.19	2.92	4.39	5.57	0.007	15	22.46	28.53
FR6	-0.4	29.4	-0.021	1	2	3	0.086	5.09	10.2	15.3	0.003	5.04	10.06	17.06

5.4 Determining the noise factors

The result of life cycle costing (LCC) of a laptop computer with initial parameter setting showed that LCC of each FR was dominated by that at production stage, which is controllable in product sales business. The variation in LCC assumed to be small. The result of life cycle assessment (LCA) also showed that LCE of FR1, FR2, FR3, and FR6 were dominated by those at production stage while LCE of FR4 and FR5 were dominated by those at product-use stage, which cannot be controlled and variable in product-sales strategy.

Focusing on UV, the authors assumed that the variation in initial importance of FR1, FR2, FR3, and FR6 is large due to significant variation in user preference for a laptop computer. The authors also assumed that the deterioration rate of FR3, FR5, and FR6, of which performance is influenced by mechanical wear or aging, is large.

Thus, LCE allocated to FR4 and FR5 at product-use stage (i.e., e_4 and e_5), initial importance of FR1, FR2, FR3, and FR6 (i.e., b_1, b_2, b_3, and b_6), and deterioration rate of FR3, FR5, and FR6 (i.e., c_3, c_5, and c_6) were identified as major noise factors in this example. It was assumed that major noise factors and other noise factors could be 20% and 5% higher or lower than the original estimate shown in Table 5, respectively.

5.5 Optimization by control factors

There exist six control parameters, each of which corresponds to initial performance of each FR, with three alternative levels. L18 orthogonal array (OA) is used to study the design space (viz., three alternative values of d_1, d_2, d_3, d_4, d_5, and d_6 given in Table 5 are assigned to the columns two to seven in L18 OA). Since the influence of the noise factors is identified as described in section 4.2, each calculation is conducted on two noise parameter arrangements: conditions 1 and 2 in Table 1 considering the variation in product lifetime, which can not be controlled in product sales business strategy. TPI of a product is calculated over the range of estimated product lifetime as given in equation 13 to calculate $TPI_{max,1}$, and $TPI_{min,2}$ in equations 15 and 16.

S/N ratio and average TPI of a product at each level in each control factor are calculated as shown in Figures 4 and 5. Control factors d_1, d_2, d_3 and d_5 have the highest S/N ratio at level one, one, one and three, respectively. Control factors d_1, d_3, d_4, d_5, and d_6 have the highest average TPI at level three. For minimizing variation in TPI, level one, one, one and three are selected for d_1, d_2, d_3 and d_5, respectively. For maximizing average of TPI, level three are selected for d_4 and d_6.

Figure 6 shows the result of optimal design solution and that of initial parameter setting where all control factors set level tow. The vertical and horizontal axis of this figure represents TPI and lifetime of a product, respectively. This figure shows that variation of TPI in optimized setting is smaller than that in initial setting and the average of TPI is also larger than that of initial setting.

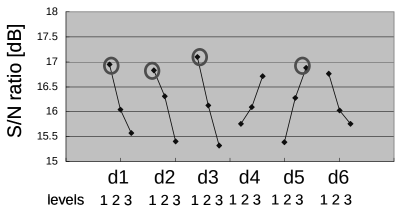

Figure 4: The average S/N ratio of each control factor at each level

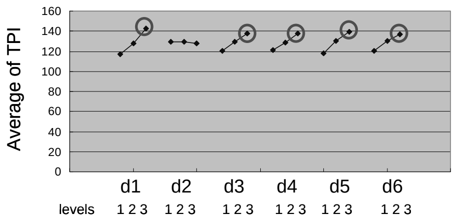

Figure 5: The average TPI of each control facto at each level

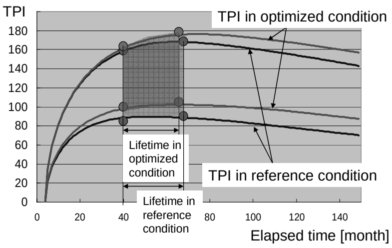

Figure 6: Variations of TPI in optimized and initial setting of design parameters

6 DISCUSSION

In this design example, the variation in TPI is reduced approximately 3.0% and the reduction is very limited. One reason for that is TPI of a product changes as its lifetime changes. If a lease and rental strategy where a designer can control product lifetime in addition with its initial specification is employed, variation in TPI can be reduced more significantly. For example, if the lifetime of a product is controlled between 63 months and 65 months, variation in TPI is reduced about 7.4%. Lease and rental strategy is more suitable for a laptop computer than product sales strategy, in this example.

Another reason is that the control parameters which are selected to maximize the average of TPI have side effect on minimization of variation in TPI. In case of best setting for minimization of variation in TPI, variation in TPI is reduced approximately 23%, although it deteriorated the average value of TPI. Finding out the control factors that can control the variation and the mean of TPI independently is important for deriving successful design solution.

7 CONCLUSION

This paper considered various uncertainties in product life cycle, discussed their influence on TPI of a product, and proposed a design method that can maximize the average of TPI while minimizing the variation in TPI resulting from these uncertainties. The optimization procedure of TPI was also illustrated with an example of a laptop computer. Future work includes following topics;

- Evaluation of the effect of life cycle options considering the uncertainties in product life cycle such as collection rate and good item ratio of EOL products
- Application of total performance design method to practical examples including various kinds of products.

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Effects on Life Cycle Assessment – Scale Up of Processes

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Abstract

Taking processes under development into consideration, Life Cycle Assessment (LCA) analysis result of pilot plants, mini plants or laboratory experiments do not necessarily represent the environmental burdens which would be caused by a large scale plant (mass production). Especially for comparative LCA studies there is a necessity to analyse, whether there are influences on environmental burdens due to scale up.

There are effects which should be taken into consideration for such scale-up prognosis in LCA. This paper reports on an innovative systematic procedure, which enables the industry to make prognosis for production scale plant based on LCA of pilot processes.

Keywords:

Life Cycle Assessment; Process Development; Scale Up

1 INTRODUCTION

In recent years, society as well as politic emphasize more and more the “sustainability” of products and technologies. Accordingly, industry and society give more than ever priority to environmental issues, which establish together with economic and societal aspects the fundament of sustainability [1].

Life Cycle Assessment (LCA) is a method which is widely implemented in industry, research and development in order to analyze the environmental performance of systems i.e. of products, materials and technologies [2]. With this method the entire life cycle of a system can be taken into consideration for an environmental evaluation – production, utilization and end of life.

An LCA analysis can be carried out at different stage of development – either at laboratory level, pilot plant, small scale plant or large scale plant [3].

The LCA results do not necessarily represent the environmental burdens which would be caused after scaling up to a typical mass production - although the quality of the LCA analysis is assured due to direct and accurate processes data. Especially in comparative studies, in which the environmental burdens of processes under development are compared to processes already running in large scale, there is the necessity to make assumptions for a large scale plant.

In this report, the first approach of a prognosis method is presented.

2 PROGNOSIS METHOD

2.1 Assumption and conditions

A LCA analysis of a pilot plant must be available in a modular form, i.e. for each technical process there must be a module. The planning for the large scale plant must be available. Furthermore, there is no change either in the quality or in the quantity of the product – the “functional unit” remains the same. A further condition is, that there is no change in the physical basis of the processes within the development in the considered processing line.

Within this report, key terms are defined as following: „Unit processes” are the smallest and basic process steps in chemical engineering. “Processes” are naturally occurring or designed sequence of changes of properties/attributes of a system/object – a complex process can consist of couple of unit processes. An „apparatus” is a facility in order to realize one or more unit operations. In an apparatus material or product can be converted, treated, transported, stored etc. A „plant” covers all processes, each realized as apparatus, which are necessary for the implementation of the overall function of the processing. A “pilot plant” is a small chemical processing system which is used in a development stage of a product or process in order to generate information about the behavior of the system for use in design of larger facilities (=industrial plant). Furthermore “apparatus” brought up in this report refers to those, which is to be scaled up, i.e. those processing capacities are to be scaled up from a small size to large size apparatus.

2.2 Relevance Analysis

As described in [4], due to error margin of LCA and prognosis in general, it is not meaningful to track each small change in an apparatus or plant complex, which has negligible contribution in total life cycle at the stage of the first LCA analysis.

The described prognosis method concentrates therefore on relevant aspects. Hence, the first step is a relevance analysis of the considered scale up apparatus on basis of the LCA analysis of pilot plant. As it is assumed, that at the stage of the first LCA analysis the apparatus are known, which will be scaled up, a targeted-oriented relevance analysis can be carried out. A relevance analysis should not only identify the relevance of considered apparatus but also of their in and outputs in the LCA results (material and energy). Fig.1 shows an exemplary relevance analysis for a particular environmental impact category.

The relevance analysis comprehends a life cycle “phase” – production, utilization or “End of Life” (EoL). Assuming that the product stays exactly the same, usually in the utilization phase apparatus are not used. The scale up of apparatus under consideration are usually part of production / End of Life phase. The environmental impact of a particular life cycle phase is usually not affected by a process belonging to another life cycle phase, assuming there is no change in the product. Therefore only the relevant life cycle should be taken into consideration in a relevance analysis.

A question is to be posed, how the processes and the input / outputs (material and energy) are to be classified, in order to make a meaningful relevance analysis possible.

Since a scale up or any kind of technical changes is implemented each for technical processes, the processes must be considered each separately. Hereby the upstream and downstream processes must refer to each appropriate process. Each process and their belonging inputs and outputs are summed up in Figure 1 as a “module”.

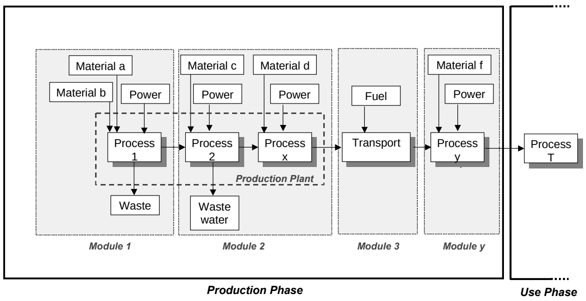

Figure 1: System boundaries and “module”.

Processes are to be taken into consideration according to their contribution in the considered life cycle phase. Those processes which cover a certain percentage of total impacts should be considered in the scale up analysis. This threshold X must be determined by the LCA expert for each analysis individually in dependency on the overall picture. However 80 % is an often used number, which is proposed in this paper. For other processes, not covered by this 80% contribution, the scale up should be neglected.

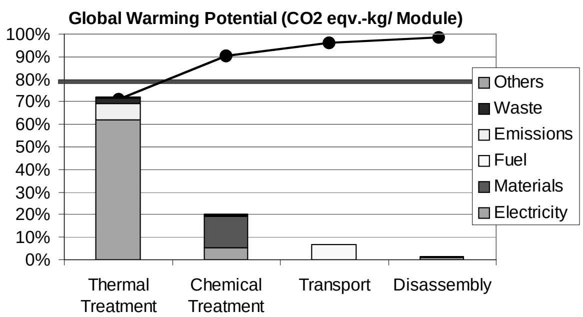

Figure 2: Example for relevance analysis.

In the example in Figure 2 the processes “thermal treatment” and “chemical treatment” cover more than 80 % of the environmental impacts in one life cycle phase. Transport and Disassembly can be neglected.

Depending on the impact category the contribution of each module differs. The relevance analysis should be therefore carried out for all categories, which were regarded for the LCA analysis of pilot plant [1].

After this relevance analysis, all processes must be focused, which showed up to be relevant in at least one of the impact categories.

2.3 Process as System

In the context of this method, “scale up” stands for the increase of physical size of an apparatus, which leads to an extension of processing capacity.

Under consideration of apparatus as a system, a scale up of the apparatus can lead to changes in material or energy efficiency. These changes, which reflect in change of in- and outputs (material and energy), affect the LCA analysis. If a LCA analysis is carried out at a late stage of the process development, a relatively optimized efficiency can be assumed for the pilot plant and its apparatus. In this case, the effect on LCA due to scale up is assumed to be negligible – an improvement or change of material or energy efficiencies is expected to be limited.

2.4 Plant as System

In the context of this paper, the system “Plant Complex” includes the plant (processes / apparatus and equipment) Not only the changes in energy and material efficiency of the certain process can have influence on the LCA results as described above, also changes within a plant configuration (e.g. apparatus arrangement) can have effect on the result.

Improvement of plant efficiency and economic efficiency are the main drivers for the change in plant configuration.

Optimization potentials can be found in the use of “synergy effects” among the process parts. An example for such synergy effect is the use of waste heat from one process part in another process part within the same production plant (see Figure 3).

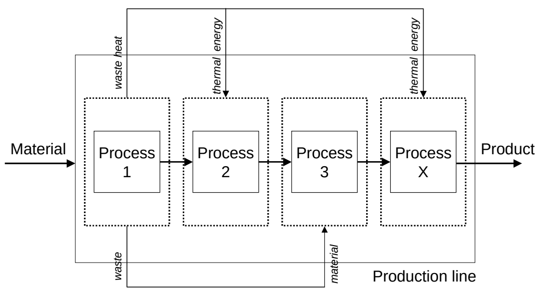

Figure 3: Example synergy effect between processes.

Waste from one apparatus can be recycled as input material for another apparatus. The same counts for waste water. One question at this point is how to deal methodologically with the reused or recycled materials or heat, which cannot be used in the same plant and therefore leaving the system boundaries. Either allocation or system expansion can be applied [5]. A further effect to be considered for the LCA prognosis of a large scale plant is the effective implementation of technical aspects, which are not directly bound with the technique of the apparatus or plants. Examples are the target oriented use of technical building equipments (air conditioner, heating systems, lightening etc.) and clean room systems.

Energy Optimization

Due to increasing energy prices reduction in energy use leads to reduction of the investment payback time. Private and governmental organizations world-wide make suggestions for the optimization of the energy efficiency of industries [6].

In most cases the "energy use" has high environmental contribution in producing industries. For instance, in the chemical industries, 65 % of the Global Warming Potential is caused by thermal energy (e.g. by steam) [7]. Accordingly the contribution of energy use in environmental impacts in chemical production is relatively high. Therefore, the optimization in energy use affects the LCA results significantly. Both thermal energy use and electric energy use are relevant for the environmental performance of a product. Electric driven machineries e.g. pumps, generation of compressed air, ventilator, etc. cause about 70 % of total industrial energy use [8]. Optimizations for electric and thermal energy use can be achieved for instance by:

- Thermal insulation of plants
- Introduction of co-generation
- Reduction of compressed air leak
- Heat Recovery, etc.

Thermal plants

Generally heat recovery in industrial apparatus can be carried out by introducing a heat transfer system or a heat pump. As a result a part of the actual heat loss can be used to heat another apparatus or plant within the system. The reduction of heat loss and hence the reduction of energy use in the plant depends on the system and is to be determined individually. In an advanced stage of a process design the heat value is already pre calculated and can be used for a prognosis of LCA as well. However if this is not the case, factors can be used for a prognosis, which will be developed within this work, based on statistic data and experiences.

Electric driven machineries

In case of electric energy, there is almost no energy "output" which can be reused for another apparatus as it is in thermal energy. But depending on the apparatus and its efficiency a reduction of energy use up to 50 % can be reached.

$$X_j^{Large}[MJ] = r_j \cdot X_j^{Pilot}[MJ] \qquad (1)$$

r_j = reduction factor

j = process type

For example, for a pump a theoretical maximal reduction of primary energy use by 50 % can be achieved.

$$X_{Pump}^{Large}[MJ] = 0{,}5 \cdot X_{Pump}^{Pilot}[MJ] \qquad (2)$$

In the following, reduction factors for further electric driven machineries are summed up [8]:

- Reduction of compressed air leak 20 %
- Adjustment of running time of Ventilator on time of operation 50 %
- Pumps with rotational speed control 50 %
- General introduction of high efficiency motors 8 %

With these reduction respectively optimizing factors, electric energy use for the optimized case can be assumed and the LCA prognosis can be carried out.

In a development phase of a product or process, often the energy requirement of an approached large plant is pre-calculated in advance, since the energy use goes directly in the production cost of a product/material. Therefore the factor **rj** can be assumed as to be available. If this is not the case, e.g. the LCA analysis is carried out in an early development stage, an assumption for the factor **rj** can be used, which will be investigated within this work further on.

In the past, conducted projects aiming at energy optimization have shown significant reduction potential in primary energy use. Either by consequently use of synergy effects or by other strategies (e.g. better thermal isolation).

Plant Utilization

A processing plant usually consists of several apparatus and equipment, which usually differ in their processing capacities. Compared to a pilot plant a commercial processing plant is organized as to use the processing capacity of each apparatus/plants most efficiently.

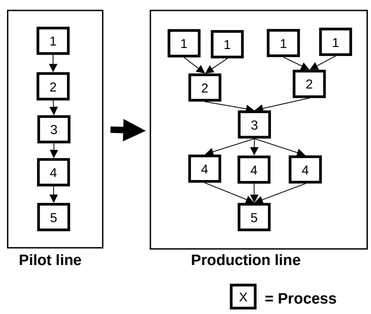

Figure 4: Graphic example for the change of capacity utilization.

In a pilot plant, the processing capacity is not necessarily fully used. The capacity utilization, which is the ration of actual output to the potential output is less than 100 %.

This can have a significant effect on the energy use for apparatus/plants which have high energy requirements in stand-by modus, by starting up, shutting down or in idling. Depending on the targeted total processing capacity, the amount of required apparatus/plants or machines in a production line can differ. The number of each apparatus/plants bases on the total production amount and the processing capacity of each process.

If set up and shut down of an apparatus might be neglected, as soon as there is an idling time between the processing of two products, the energy use due to idling is to be distributed to the products.

Assuming $\mathbf{t_o}$ is the starting time of the processing including idling and $\mathbf{t_y}$ is the end of processing, idling time in the Figure 5 are:

$\Delta t_1 = t_1 - t_0$ (3)

$\Delta t_3 = t_3 - t_2$ (4)

$\Delta t_x = t_x - t_{x-1}$ (5)

Processing time for one product in the Figure 5 is

$\Delta t_{process} = t_2 - t_1$ respectively t_y-t_x (6)

Energy use for one product is to be defined as:

$E_p = W_i \times \{(t_x - t_{x-1}) + (t_y - t_x)\}$ (7)

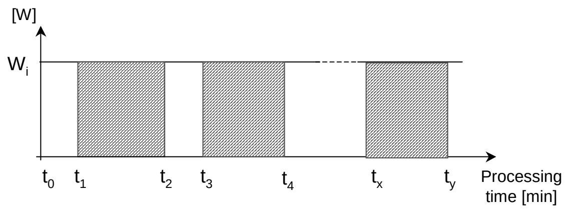

Figure 5: simplified diagram for a energy progression for an example process.

Due to optimization of capacity utilization, the idling time $\mathbf{\Delta t_x}$ can be reduced. The higher the power performance or the apparatus during idling ($\mathbf{W_i}$), the higher is the effect on energy use due to improvement in capacity utilization. This is the case for instance for heating systems – such as furnace or oven. For those processes, the start up and shut down of the process require relatively long time. During the start up or shut down the apparatus cannot be used for actual processing. Therefore industries sometimes prefer running the process in idling.

2.5 Plant Complex as System

In the system "Process Complex" the upstream and downstream processes are brought into focus. The so called "up-stream" and "down-stream" processes stand for material and energy provisions respectively waste, waste water treatment or co-product processing, which are within the boundary of LCA analysis (see Figure 6). With this consideration, the LCA experts extent their observation from the technical scale up of "process" to the LCA point of view.

Even though a process is not to be scaled up, changes in terms of environmental burdens can still happen. Changes can be caused by the changes of technology for up- or downstream processes.

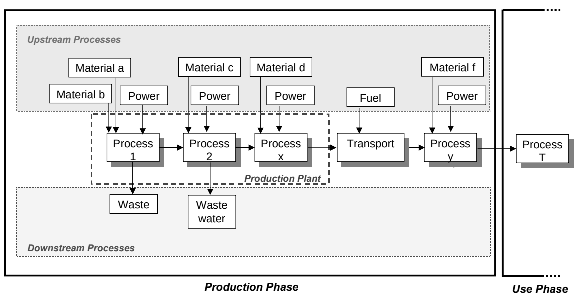

Figure 6: Example for upstream and downstream processes.

With the upstream processes, all processes are mentioned, which are necessary for provision of material or energy required in the main line of production phase. The main line is drawn by the production or processing way of the main product. For instance in Figure 6, the main product starts by process 1, going through process 2, x and transport, ending at process y. The material and energy provision required for these mentioned processes are the "upstream processes".

Comparable counts for "downstream" processes. In a LCA analysis, all waste or co-products, which comes out from any of the main processing line, must be followed. The processes, which treat waste or co-products are the so called "downstream processes".

For instance electricity for a heating system can be substituted by thermal energy provided by natural gas. There is no change in the required quantity of energy, but the environmental burdens caused by this upstream (here: energy provision) changes.

Another example is the substitution of non renewable energy by renewable energy. This can affect and improve the environmental performance of the product significantly. For heating processes the electricity can as well be substituted by primary energy carrier.

Depending on the legal situation which differs from country to country, the way of waste treatments are regulated. In addition, at the stage of a pilot plant, waste is often deposited or incinerated due to small amount and its economic unimportance. In a large scale plant, due to large amount of the waste, the materials can be reasonable to be recycled from the economic point of view.

With "Plant Complex", the technical and LCA aspects are brought together. Hence, changes in these upstream and downstream processes have influence on the LCA analysis.

3 CONCLUSION

There are demands and necessities for a systematic prognosis for a scale up of apparatus and plants using the actual LCA analysis based on pilot plants.

An essential condition of a prognosis method is the availability of modular LCA analyses for the pilot plant and essential information of planned large plant design.

Considering the unavoidable margin error in LCA, a relevance analysis is the first step of a systematic prognosis, in order to make an assumption for a large scale plant considering relevant aspects. The proposed method bases firstly on consideration of scale up apparatus. Secondly the environmental effects due to plant optimization as well as optimization of utilization should be considered in the prognosis.

At the end the optimization factors in plant complexes must be considered. In this part of the prognosis, the upstream and downstream processes (energy and material provision as well as waste treatment etc.) are considered.

Using this systematic procedure LCA experts will be supported in making assumption for scale up cases, by using the LCA results of pilot processes and by collecting only relevant information from the plant developer.

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Development of a Management Tool for Assessing Environmental Performance in SMEs' Design and Production

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Abstract
Small and medium sized manufacturers offer opportunities in reducing life cycle impacts, as green demand cascades through supply chains, and challenges due to their lack of environmental management and life cycle engineering skills. This research explored existing management tools to meet manufacturing SMEs reported need for self assessment. Drawing on the principles of environmental performance evaluation, this paper presents the development and application of a spreadsheet tool for diagnosing environmental performance in SMEs' product design and production and relates it to the tools used recently in the UK by Perform and Benchmark Index and the ecoBiz assessment used in Australia.

Keywords:
Manufacturing; SME; Environmental Performance; Management Tool

1 INTRODUCTION

The macro indicators in the UK show a progressive reduction in conventional manufacturing activity, due in part to rising environmental costs and the unsustainable use of materials and energy. Spreading cleaner, environmentally sustainable manufacturing through supply chains can potentially enhance the competitiveness of smaller companies, promoting the life cycle engineering of products, through:

- Ecodesign – limiting non-renewable resource depletion through material choices, reducing pollution and increasing resource-efficiency in production and product use.
- Cleaner production - moving end-of-pipe solutions to those preventing pollution; minimising energy, consumables, waste.
- Waste cycling, using by-products/wastes as raw materials.

Uptake depends on the drivers and barriers and the manufacturer recognising their status, potentially through using environmental indicators; evaluating the contribution of improved practices to business performance.

At a micro level, practical performance measurement tools are necessary to track status and improve decision making within companies. Through performance analysis individual producers can align with customer preferences and/or internal ambitions to reduce environmental impacts, also the requirements of environmental legislation. This appears to present a greater challenge among small and medium sized enterprises (SMEs) who collectively typically contribute 60% of commercial waste and 80% of pollution incidents [1]. SMEs' management of environmental performance is typically poor with only 27% of UK medium sized businesses (50-250 employees) having an Environmental Management System in 2005 [1].

Managers need to operationalize their environmental goals and evaluate progress [2]. This paper shows how recognisable principles can be applied to enable manufacturing SMEs to evaluate their own environmental performance cost-effectively, to identify progress in improving product development and production towards clean practices.

2 RESEARCH CONTEXT

In 2003 a project started at Warwick Manufacturing Group (WMG) to investigate how small and medium-sized manufacturers in the West Midlands region of the UK could be effectively supported in adopting eco-product innovation and clean manufacturing technologies.

The project's aim was to understand how environmentally conscious product design and cleaner production practices can be introduced effectively to stimulate step changes in SMEs' environmental performance.

Following research on drivers, barrier and enablers, were reviewed. A diagnosis tool for environmental performance in design & production was developed.

Feedback on which enablers to implementation of cleaner practices achieve the best results in manufacturing SMEs is informing the design of support to address a perceived gap in existing provision. Practical self-diagnosis of environmental performance improvements will reinforce change during and following any external intervention.

3 DRIVERS, BARRIERS & ENABLERS FOR ECO-PRODUCT INNOVATION AND CLEANER MANUFACTURING TECHNOLOGIES

Recent UK surveys [1, 3] - suggest most smaller UK manufacturers already recognise emerging environmental issues alongside increasing customer demands, competition and more demanding legislation. The strongest pressures steering business leaders towards environmental sustainability, are confirmed in a more focused WMG survey [4] as;

- compliance with environmental regulations,
- anticipated cost savings from efficiency or reduced taxes,
- enhancing customer relations, and,
- internal concern for social & environmental responsibility.

Many manufacturers have already identified significant environmental aspects and typically seek to reduce waste, energy & water use and to recycle more; also to integrate environmental management into procedures.

Barriers to achieving progress are:

- Financial; high cost / extended payback or lack of capital.
- Current lack of customer demand.
- Technical; cleaner technologies "not yet proven", poorly available, or perceived as conflicting.
- Knowledge based; lack of in-house expertise, uncertainty about environmental regulations, poor external advice.

Where external assistance is limited, preferred enablers include:

- Training (self-study); both in general environmental awareness and cleaner design/production.
- Guides, to cleaner design/production, preferably online.
- Performance measurement tools, enabling self-diagnosis.

41% in the WMG survey suggested a spreadsheet for self analysis would be a suitable basis for measuring environmental performance and identifying priorities.

4 ENVIRONMENTAL PERFORMANCE EVALUATION IN DESIGN AND PRODUCTION

ISO 14031 defines Environmental Performance Evaluation (EPE) as a process to facilitate management decisions regarding an organization's environmental performance by selecting indicators, collecting and analysing data, assessing information against environmental performance criteria, reporting and communicating, and periodically reviewing and improving this process. In manufacturing SMEs' operations, this requires methods to represent complex issues by simple metrics, enabling benefits to be attributed, costs to be justified and experiential learning in life cycle engineering.

A simplified measurement of business environmental performance can draw on a diverse range of indicators; reflecting different decision types, contexts and stakeholders. In each case indicators should be objective, understandable, significant (covering relevant aspects), consistent with the objectives and allow for meaningful comparisons at a reasonable cost i.e. workable from available data [5]. Olsthorn *et al.* [5] offer a review of classifications of environmental indicators and initiatives, notably including the Global Reporting Initiative and ISO 14031, the latter aimed at formalising the approach to internal performance measurement rather than a set of standard indicators. Environmental indicators are typically physical aspect indicators, complemented by management indicators, the latter both quantitative and qualitative, assisting in evaluating the efforts of managers in undertaking actions to improve environmental performance. Wells et al. [6] for example report this combination in customer satisfaction measures, process measures and results measures; results normalized to product or bottom line impacts.

Where feasible and desirable, proxy indicators can aggregate environmental indicators into a single value approximating a combined measure of the environmental impact of a product or a material. 'Eco-indicator '99' is one of the most widely used proxy indicators, especially in product design, good at modelling damage occurring from emissions [7].

Until the standardisation of proxy indicators or at least productive efficiency indicators (relating physical & economic inputs and outputs) and management indicators, the objective here is the application of a process to select those which can be applied in manufacturing SMEs, and application examples.

4.1 Applying Environmental Performance Evaluation in Management

A means for applying environmental performance evaluation (EPE) in manufacturing SMEs is needed, integrating established management practice with a method for evaluating performance suited to each company's operations.

Between the generic environmental management process of ISO 14001 and the rigorous process of LCA, guidance is available in ISO 14031 [8].

ISO 14031

The EPE process may be used with or without an environmental management system in four stages; Figure 1.

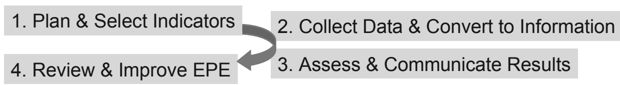

Figure 1: The four stages of EPE, after ISO 14031.

In stage 1, selecting indicators for EPE, the following questions may be used. Are indicators…

…related to meaningful environmental conditions e.g. air/water quality?

…sensitive to causal aspects and their changing (frequency)?

…flexible or robust to changes in organisation to reveal trends independent of levels of business activity?

…relevant and understandable by interested parties?

…obtainable in a cost-effective, consistent & timely manner?

Examples of simplified aspect indicators are; energy use; water use and emissions; solid, liquid, gaseous especially eco/human toxic substances.

Benefits

Improvements arising from EPE mirror those from proactive environmental management; actions which reduce total costs, reduce liabilities and improve product quality, while responding to the other cleaner manufacturing drivers for SMEs such as those outlined in section 3.

ISO 14032 gives examples from companies applying EPE. Appreciating self-assessment methods which suit wide industrial application comes also from the following examples.

4.2 Example Applications of Environmental Performance Measurement

GEMI

In the 1990s, the Global Environmental Management Initiative (GEMI) developed one of the first self-assessment techniques; the Green Management Assessment Tool (GMAT) based on the ICC's 16 Principles for Environmental Management. Over 1400 mainly US companies marked 61 elements of performance on an 8 point scale, taking 1-1.5 hours to complete an assessment. Eagan and Joares [2] reported that managers using GMAT heightened their awareness of environmental issues and many then helped to move their companies in a greener direction. Their study focused on large manufacturing sites and suggested further testing was needed on SMEs.

Perform - Sustainability Performance Benchmarking

The UK Science Policy Research Unit compiled 79 indicators from sustainability reporting guidelines, existing reporting obligations, legislation and measures developed by sector organisations. Measures were standardised and normalised e.g. tonnes of CO_2 per tonne output. 30-50 minutes were required to complete the assessment through a web or printed form and a free benchmarking report was offered to the 133 firms providing data between 2001 and 2004.

The main aim was research, for example seeking (but finding very few) correlations between environmental performance and profitability. Large variability was seen between different producers even in same sector – environmental performance per unit output varying by factors up to 100. [9]

Benchmark Index

Benchmark Index in the UK is the widest used source of financial, manufacturing and social responsibility performance benchmarking modules, although the latter module is optional and less established. The 47 core and 16 manufacturing indicators include energy and water costs, the optional 24 social responsibility indicators adding the cost of (hazardous) waste. The 3 modules take approximately 30+10+15 minutes to complete on a printed form, once required data is available.

The extensive benchmarking database shows profit correlates with capital, marketing & training expenditure, lower debt, greater value-add, prompt deliveries, high stock turns and smaller size [10]. No conclusions are currently reported from environmental metrics, although Benchmark Index seeks to collect further data to test the contribution of environmental improvement to financial success.

EcoBiz

EcoBiz is a Queensland Environmental Protection Agency programme with over 150 companies following launch in 2004. Six steps include a baseline assessment and a reassessment of EPIs and production (eco-)efficiency alongside a breakdown of resource costs per production unit.

The self-assessment spreadsheet compiles materials, waste, energy and water quantities & costs, normalised by production units, summarizing overall measures for comparison with results before an action plan or with a previous period. Company cases show cost and resource savings from pursuing eco-efficiencies. Uptake among SMEs is good, time commitment being the main internal limit [11].

Hence, EPE can assist in integrating environmental conditions or concerns into operational measures to determine actions and demonstrate improvement. However, in the UK, with the Perform Benchmarking process having closed and the Benchmark Index process yet to have developed coverage of environmental performance, the support for self-assessment of environmental performance in SME's design and production is limited.

5 WMG PROJECT TOOL FOR ENVIRONMENTAL PERFORMANCE ASSESSMENT

A diagnostic set of quantitative and qualitative measures is therefore being developed as part of the WMG project. These are applied in a cleaner manufacturing diagnostic spreadsheet tool, in development through trials in collaboration with a selection of manufacturing SMEs.

5.1 Design of the Diagnostic Tool

Design factors which contribute to the success of environmental performance measurement are discussed below. Building on ISO 14031, indicators need to;

- relate to meaningful environmental conditions eg. air quality
- be sensitive to causal aspects and their changing, adequately reflecting all foreseeable levels of performance
- be accurate and reproducible sufficient to detect changes over time; not overly reliant on knowledge which is not shared
- be flexible or robust to changes in organisation to reveal trends independent of levels of business activity
- be 'user-friendly'; relevant and understandable by interested parties, also non-threatening to those with less knowledge
- be obtainable in a cost-effective, consistent, reliable and timely manner
- enable the degree of performance gaps to be identified to help respondents to pursue desirable changes.

The diagnostic spreadsheet tool is designed for self-analysis either onscreen or printed and divided into seven sections:

1. Company Profile incl. Environmental Issues
2. General Cleaner Manufacturing & Environmental Management Action
3. Cleaner Manufacturing Action - Production
4. Cleaner Manufacturing Action - Design
5. Environmental Costs/Savings
6. Resource Metrics : Energy, Water, Material Input/Output
7. Environmental Business Support Options

75 quantitative and qualitative measures are prompted and counts of undesirable, intermediate or desirable results are summarised automatically by the spreadsheet to provide an overview. Measures should cover significant aspects to complement any EMS - few SMEs manage such measures.

Quantitative Measures

To track changes in environmental efficiency, quantitative indicators of resources and costs such as those below need to be normalised using a unit of production output for the same scope of operation. Entries for the following are prompted in the spreadsheet which calculates a percentage change from a previous or baseline period.

- Quantity and cost of electricity/gas/oil/other fuel used
- Percentage of energy supplied from renewable sources
- Water consumption and cost
- Quantity and cost of effluent (incl. wastewater) discharged
- Weight of (non-)hazardous raw materials consumed
- Weight of (non-)hazardous auxiliary materials consumed
- Percentage of recyclates / renewable material used by cost
- Weight of (non-)hazardous waste disposed
- Percentage of auxiliary materials reused or recycled by cost
- Cost of (hazardous)/(auxiliary) raw materials purchased
- Net waste disposal+removal costs after amounts awarded for waste (eg recycling) are deducted per year
- Cost of disposal/removal of hazardous waste produced per year as part of production of goods/service
- Revenue attributable to improvement e.g. by-products sold.

CLEANER MANUFACTURING	PERFORMANCE MEASUREMENT	Company Confidential Date updated:	Company Name		
3. Cleaner Manufacturing Action - Production			2006		
Has the company investigated and/or introduced new/replacement production processes/technology specifically to reduce energy use?	Introduced…	Investigated - may introduce…	Investigated, but not likely to introduce…	Not investigated…	Not aware
	Enter "Yes" ↓ *or*	enter "Yes" ↓ *or*	enter "Yes" ↓ *or*	enter "Not" ↓ *or*	"Not aware" ↓
	… the following ;	…depending on ;	…because ;	…because ;	
Has the company investigated and/or introduced new/replacement production processes/technology specifically to reduce waste?	Introduced…	Investigated - may introduce…	Investigated, but not likely to introduce…	Not investigated…	Not aware
	Enter "Yes" ↓ *or*	enter "Yes" ↓ *or*	enter "Yes" ↓ *or*	enter "Not" ↓ *or*	"Not aware" ↓
	… the following ;	…depending on ;	…because ;	…because ;	
Has the company investigated and/or introduced new/replacement production processes/technology specifically to reduce/substitute polluting substances?	Introduced…	Investigated - may introduce…	Investigated, but not likely to introduce…	Not investigated…	Not aware
	Enter "Yes" ↓ *or*	enter "Yes" ↓ *or*	enter "Yes" ↓ *or*	enter "Not" ↓ *or*	"Not aware" ↓
	… the following ;	…depending on ;	…because ;	…because ;	
Approximately what percentage of products… %	…**could be remanufactured** at the end of service life if feasible changes were made, collection arranged?	…**are remanufactured** at the end of service?	…**could be recycled** at the end of service life if feasible changes were made & collection arranged?	…**are recycled** at the end of service?	…**are suitable for energy recovery** e.g. through incineration in a waste to energy plant?
	Enter approx %↓	Enter approx %↓	Enter approx %↓	Enter approx %↓	Enter approx %↓
Are production wastes (by-products) of value to other companies?	None, apart from general external recycling of common wastes e.g. metal waste	Yes…			Approx percentage of waste + by-products recycled, or reused, by weight
	Enter "None"↓ *or*	enter "Yes" ↓ and	…the following are supplied for external use	…the following could be supplied to suitable recipient	Enter approx %↓

Figure 2: Cleaner manufacturing action - production sheet (part) in the diagnostic spreadsheet tool.

CLEANER MANUFACTURING	PERFORMANCE MEASUREMENT	Company Confidential Date updated:			
4. Cleaner Manufacturing Action - Design*			2006		
	****Please go to the next section if product/sub-assembly design is not carried out in the compa***				
Which environmental impacts…	Handle hazardous or potentially polluting materials e.g. chemicals, fuels, oils	Emit to air particulates or potential pollutants e.g. smoke, VOCs, gases	Use non-renewable resources, incl. fossil fuels	Use water for more than sanitary facilities	Supply non-recyclable products
	Enter "Yes" ↓	Enter "Yes" ↓	Enter "Yes" ↓	Enter "Yes" ↓	Enter "Yes" ↓
…have already [illegible] addre[illegible]ed [illegible]hr[illegible]h [illegible]lea[illegible]er de[illegible]					
[illegible]ld [illegible]e addre[illegible]ed [illegible]hr[illegible]h [illegible]lea[illegible]er de[illegible]re[illegible]					
Could introducing designs with better eco performance enable your business unit to make progress towards any ambitions for environmental improvement?	Yes, current design options, such as…	Yes, *potential* design options, such as…	Maybe - design options may be found	No environmentally beneficial design options are unlikely	Not aware
	Please specify ↓ *or*	please specify ↓ *or*	enter "Maybe" ↓ *or*	enter "No" ↓ *or*	"Not aware" ↓
Which cleaner design approaches with environmental benefits…	Design to significantly reduce material in the product	Design to greatly extend life e.g. by durability, modularity or maintenance/ repair	Design for disassembly at end-of-life	Selection of materials to enable recycling or recovery at end of life	Design to otherwise avoid waste at end-of life e.g. enabling remanufacturing, recycling, recovery
	Enter "Yes" ↓	Enter "Yes" ↓	Enter "Yes" ↓	Enter "Yes" ↓	Please specify ↓
…have already been applied to product designs?					
…could be applied to product designs in future?					
Which additional cleaner design approaches…	Selection of materials with lower environmental impact through to supply	Design to reduce environmental impact during use e.g. lower energy or consumables	Design to avoid pollution at end-of life	Design for cleaner manufacture; enabling production impacts to be reduced	OTHER
	Enter "Yes" ↓	Enter "Yes" ↓	Enter "Yes" ↓	Enter "Yes" ↓	Please specify ↓
…have already been applied to product designs?					
…could be applied to product designs in future?					
Approx percentage of products…	…in current range that have been re-designed or replaced to make them cleaner	…expected to have been re-designed or replaced to make them cleaner, in 3 years time	…have a form of environmental product declaration explaining likely environmental impacts in use	…have instructions for minimising environmental impact during use	…have instructions for environmentally safe disposal
	Enter approx %↓	Enter approx %↓	Enter approx %↓	Enter approx %↓	Enter approx %↓
Average product (first) life in use		Years			
Approximate percentage of products' content (by weight) in the current range designed…	…with recycled content	…for remanufacture at end-of-life	…for recycling at end-of-life	…for energy recovery (typically incineration) at end-of-life	
	Enter approx %↓	Enter approx %↓	Enter approx %↓	Enter approx %↓	

Figure 3: Cleaner manufacturing action - design sheet in the diagnostic spreadsheet tool.

Further quantitative management indicators show, for example, the proportion of production representing cleaner technology, or that incorporating ecodesign for remanufacturing, recycling, recovery and recycled content. Prompts for such ecodesign indicators are shown in Figure 3.

Qualitative Measures

Qualitative measures of environmental performance broaden the evaluation where judgements are needed; such as the degree to which products are designed to be cleaner. A Likert scale can be used, although this does not bring objectivity, standardisation or a relationship to quantified indicators.

Variability in such subjective judgements can be reduced by the use of criterion based reference statements for each level of potential response. In the case of the introduction of production technology to minimise waste, the diagnostic tool differentiates levels using simple reference statements; “introduced; investigated - may introduce; investigated, but not likely to introduce”; and, “not investigated” – see Figure 2.

Responses are colour coded in the spreadsheet using the convention of red, amber, green to indicate least desirable, intermediate and most desirable levels of performance. Responses could equally be rated and then weighted, if suitable weighting factors were appropriate, to enable prioritisation between aspects. The aim is to enable an ‘at a glance’ identification of priorities for improvement or reward.

5.2 Development with Trial SMEs

Three companies were selected to trial the diagnostic tool from those expressing an interest in the project following the survey of drivers & barriers in West Midland SMEs; section 3.

Company A is a small CNC machining SME, making progress addressing significant environmental aspects in production, although yet to establish an EMS. Company B is a small remanufacturer of forging dies seeking to address rising energy costs, alongside some green demands and waste issues. Company C is a medium sized tanker vehicle manufacturer seeking an improved environmental profile with customers through design as well as production techniques.

Feedback showed the tool spreadsheet was easy to use and, while extensive, could be completed at an acceptable pace.

The following suggestions for diagnostic tool development are related to an understanding of the key issues from the initial environmental performance evaluation – Table 1.

Co.	Key Issues from EPE	Suggestions for Tool Development
A	1. Generally intermediate awareness & action at management and technical levels - typical aspects; handling pollutants, emissions, water, energy & waste. Sensitivity to barriers limiting progress, but insufficient internal resource to unblock.	Identifying proportion of environmental performance which can be allocated to internal functions or suppliers. Relating training/support needs to barriers faced by company functions would ideally fit with a top level training needs analysis.
	2. Water use reduced progressively mainly through investment in metalworking fluid recycling.	Adding checklists of (further) improvement opportunities linked to cleaner processes queries.
	3. Further energy auditing is needed to attribute fuel costs to processes. No added value in normalising energy use to sales.	Building a picture of energy flows from ratings (*cf.* EcoBiz) or metering is of key interest, if feasible.
	4. Investigation of machined part cleaning processes seen as important next step - reducing solvent emissions, although limited implementation until viability proven. As a low tier supplier, end of life issues appear external.	The diagnostic records ambitions for changes, but would need to add a standardised eco-efficiency calculation based on robust proxy indicators and investment appraisal to enable ‘what-if’ proposals to be ranked.
B	1. Limited awareness & action at management & technical levels; drivers are mainly internal ambition & energy costs. Limited internal capability, although opportunity to introduce changes alongside a lean initiative. End of life issues are appreciated – since the co. is a re-manufacturer.	Energy issues could be broken down further, using a specific energy diagnostic as an add-on where of interest. Design and a number of other aspects are unfamiliar and though elements of the diagnostic can be passed over, pre-selecting categorised parts could aid focus.
	2. Resource use, particularly electricity & gas has followed production output with only minor savings made through changing production equipment such as air compressors.	Normalisation to production output may be distorted when the production unit or the way it is used changes, so guidance is needed to ensure a convenient choice is also robust.
	3. Waste quantities and (hidden) costs need to be tracked and compiled to supplement energy, water and material cost data.	Some of the hidden costs of waste could be added to the diagnostic, such as consumables used in reprocessing.
	4. Investigation of gas vs electric furnace HT is seen as a next step. Support is needed to integrate environmental criteria to prioritise non-costed impact reduction.	(As above) A standardised eco-efficiency calculation based on robust proxy indicators and investment appraisal would enable proposals to be ranked.
C	1. Good top management ambition has enabled cleaner production opportunities to be taken beyond compliance and cost saving, although at technical levels there is less discretionary action.	Top management expect to see an overview e.g. summary of periodic changes in aggregated performance indicators. Technical operators still value indicators of their individual functional performance.
	2. Solvent use has reduced through paint booth replacement. Basic energy saving has somewhat mitigated price rises. Materials and waste reduction have yet to be tackled.	In judging the extent cleaner production practice has been adopted, subsidiarity suggests greater freedom to examine specific areas, rather than aggregating to an overall %.
	3. A focus on bespoke engineering of small batches has limited the development of processes and compromises the normalisation of resource metrics. It also limits end of life thinking to the salvage of fittings or recycling materials rather than remanufacturing.	With a variety of major and minor design projects being processed each year, some ability to respond at the level of a product group where groups do not fit a consistent product range could help avoid an amalgam response.
	4. Investigation of water based paint processes and applying ecodesign are important next steps, although the yield from ecodesign is seen (understandably) as speculative. Integrating an ecodesign capability requires external advice to meet the internal demand.	(As above) A standardised eco-efficiency calculation based on robust proxy indicators and life cycle costing would enable proposals to be ranked – particularly important at the design stage when there is most freedom to change costs.

Table 1: Company suggestions for tool development.

6 CONCLUSION

A proportion of small and medium sized manufacturers are prepared, and able, to adopt ecodesign and cleaner production to address drivers for reducing environmental impacts from their products and production processes. There remains a need coupled with a desire expressed by SMEs themselves, to bring indicators of environmental performance within the realm of busy managers, and to adapt their use to ensure they are practical for self-assessment.

Reviewing GMAT, Perform, Benchmark Index and EcoBiz indicators among GRI and similar sets shows some commonality, although limited tools, pre-formatted for design & production aspects, appear suited to SMEs in the UK.

Within an ISO 14031 process of environmental performance evaluation, a set of simplified measurements of business environmental performance can be created. This should draw on a variety of objective, understandable & significant indicators, consistent with the objectives of cleaner manufacturing to enable meaningful comparisons, at least internally, at a reasonable cost i.e. where data is available. Until greater standardisation, common aspect indicators such as energy metrics may be supplemented by management indicators selected against the criteria in section 5.1.

A spreadsheet appears to be a suitable format for prompting, compiling and relating indicator results, also to highlight qualitative judgements. Criterion based reference statements reduce variability when users try to distinguish indicator levels

An environmental performance diagnostic spreadsheet tool is being developed through trials with three SMEs. It prompts the user to input up to 75 indicators combining quantified and qualitative information to give a profile of the cleaner manufacturing status and action particularly in production and design. It also shows changes in cost & resource indicators and provides a management overview of status on one page, updated from the detailed indicators automatically.

The relative importance between indicators is ascribed by the user – a significant limitation, accepting the full consequences of performance, such as remote environmental impacts, are not easily accessible using proxy indicators.

With manufacturing SMEs in the West Midlands region of the UK potentially typical of those SMEs responding to the challenges, suggestions for developing the tool have come from identifying key issues in three companies addressing typical aspects of environmental performance. These include;

- attributing performance to functions or product groups, not just the company as a whole, given the need to target action;
- providing (ideally context sensitive) checklists to identify potential improvement opportunities, *cf.* those from EcoBiz;
- adding a what-if 'standard' eco-efficiency calculation for production (investment) and design scenarios, although further work is needed to apply proxy indicators;
- catering for a specific interest in energy flow diagnosis, perhaps attributing energy use to equipment ratings/metering.

In the context of the WMG project to investigate how SMEs can be supported in integrating aspects of cleaner manufacturing, this paper has offered a working form of environmental performance diagnostic tool. Ongoing development will enable further companies to benefit, fostering a relationship to target environmental business support and also assess its effectiveness through the project. Longer term evaluation of results should attribute performance trends to particular interventions. Any wider implementation across similar operations, could enable some benchmarking comparison of environmental performance with factors explaining high performance considered for transfer.

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An Approach to the LCA for Venezuelan Electrical Generation Using European Data

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Abstract

Data bases for LCI calculation are not available in many countries or regions, but many evidences exist from which the environmental impacts of materials, manufacturing processes, energy generation, product end life and others are also different among them. Consequently, it's necessary to make efforts in order to develop data for LCA applications, or, in absence of other options, to use existing data for LCA approach in developing countries or regions. In this paper, results from the use of European data (specifically Spanish data) for eight electrical generation technologies are applied over the energetic generation mix of Venezuela, obtaining interesting results that can be used to explore the possibility of making LCA in the power sector of Venezuela.

Keywords:

Europe/Spain/Venezuela LCA, Electrical Power Generation LCI, LCE

1 INTRODUCTION

There are many evidences about the necessity of consider regional differences for LCA applications around the world [1]. It includes variability of quantitative methods and data, regional variability of life cycle inventory and site-dependence of products and processes LCA. One product or process may have "one or more ecodesigns", depending on the regional considerations and regional impacts of different product life cycle analysis. More specifically, product manufacturers for export may consider these regional aspects of LCA-based ecodesign in order to develop more efficient environmental marketing strategies.

LCI data is not reliable and/or is not available for electrical power generation in Venezuela. Energetic-mix for electrical power generation varies from one country to others. European data is available for LCA calculation in many fields, including energetic purposes. For example, AUMA [2] provides information about electrical power generation data for LCA in Spain that can be used like reference for other regional applications.

The objective of this work is to propose and develop an approach to Venezuelan electrical power generation data for LCA, using data for the same purposes obtained for Spain. It is assumed that Spanish values are good references for calculations and approximations. These values and approaches are enumerated in each one of the stages of the LCA to be able to make a later comparison. In this study, eight different technologies from electrical generation were evaluated in relation to twelve different categories from impact.

The reached results were quantified in environmental terms referred to a new unit of measurement denominated "ecopoint of impact". More "ecopoints" implies more environmental impact.

2 AVAILABLE DATA AND ASSUMPTIONS

In Table 1 are included the primary power plants types that were taken into account for this study. In Table 2 are the 12 categories of impact that were evaluated during the process of accomplishment of this LCA. The preceding study includes "from the pick up or extraction of the primary energy, to the generation of the kWh (Kilowatts per hour) spilled to the electrical net for its later use." [1]. All the data is calculated on TeraJoule (TJ), equivalent to 277,778 kWh.

PRIMARY ENERGY
Nonrenewable
natural Gas
Soft coal/ Anthracite
Lignite
Petroleum
Nuclear
Renewables
Aeolic
Hydroelectric
Solar photovoltaic

Table 1: Primary power plants types.

With respect to the hypotheses adopted in the geographic and temporary scope, the reference study clarifies that the geographic scope is confined to the Spanish State, although for the accomplishment of inventories of the nuclear technology the used data are of European origin. In the Aeolian and photovoltaic case, they come respectively, of the plants of Grechenberg (Germany) and Plalk (Swiss).

For the case of the remainders, and due to the nonexistence of registries or historical series, it has been necessary to use estimations in reduced geographic areas, like those of those regions where it has been possible to collect data, series or estimations, from which have been able to be made extrapolations to a general scope. [2]

In each one of the systems were considered factors like:

1. Fuel Obtaining and pick up of the primary energy
2. Treatment of the fuel
3. Transport of the fuel
4. Construction of the power station (works and equipment)
5. Operation and maintenance of the power station.

CATEGORIES OF IMPACT
Carcinogen substances
Heavy metals
Fog of winter
Photochemical fog
Ionizing radiations
Industrial remainders
Radioactive remainders
Exhaustion of power resources
Global warming
Reduction of the ozone layer
Acidification
Land degradation

Table 2: Categories of impact that were taken into account for the accomplishment of this study..

Factors like these were not considered:

1. Obtaining of the raw materials for the manufacture of the power station.
2. Land Occupation.
3. Dismantling.
4. Residual Heat.
5. Protection of the biodiversity

2 PROCESSING DATA

2.1 Inventory of impacts:

The inventory data have their source of origin mainly in studies made by the ETH (Federal Swiss Institute of Technology, Laboratorium Für Energiesysteme, Zurich), e.g. [3] and [4]

2.2 Impact Evaluation:

Clasification

The classification assigned by the AUMA was respected, which classifies each one of the exits and entrances of the systems of processes in 12 categories of impact. These categories of impact are the presented ones in Table 2 during the definition of objectives.

Characterization

The factors of characterization corresponding to the enunciated categories of impact present certain differences with accepted by other international organizations like the I.P.C.C and United Nations. For the purposes of this first study the factors of characterization will be taken and accepted corresponding to the tabs by the AUMA. [2]

Normalization:

For the comparison of the different environmental impacts that they were taken into account, the AUMA generated a series of factors of normalization based on the generated levels of contamination at European level against the population of that continent. These factors of normalization cannot be generated of precise way for each category of impact in Venezuela by the lack of data in many of them. For that reason the proposed factors of normalization were taken.

Evaluation:

The used factors of evaluation for this section respond to the allocation corresponding to the approach to the damage, e.g., an approximated consideration of the damage caused by each impact in specific. In this case, the factors that were considered to approximate the damage generated by the impact factors were [2]:

- Extra death by million inhabitants.
- Consequent diseases to periods of fog.
- Deterioration of the ecosystem in a 5%.
- Diminution of the reserves.

This approach is favored with respect the approach that contemplates the distance to target because the subjective components of the problem (social, political and geographic), diminishes.

Interpretation of the results:

Each country has a combination of primary sources that generate the total of electricity that consumes its population (If it is assumed that its electrical generation does not depend on the imports). That mix power one is unique for each country and it was calculated from the data and preceding methodology. The results of these calculations are in Table 3.

The interpretation of the results of this analysis responds to the multiplication of each one of the factors generated in the stages of inventory and the evaluation. This result should be calculated for each category of impact and each evaluated product-system (technology of electrical generation). The table thus briefed is independent of energetic mix of each considered country. These results are showed in Table 4.

The corresponding result for each category of impact is expressed in ecopoints by TJ (TeraJoule). These ecopoints can be multiplied by the fraction of participation of this system product within mix the power one of each country, which would give like result the total of ecopoints of this country for each category of impact.

These totals can be added between them, to obtain therefore the amount of ecopoints of each country by TeraJoule of generated Energy. If the values are taken from Venezuela, for example, it is possible to appreciate that energetic mix is integrated by 15.5% from natural gas power plants, 72% by hydraulic power stations, and 12.5% are generated in thermo electrical power stations that use distilled liquid of petroleum. If these fractions are multiplied by the total ecopoints of each category of impact, it obtains Table 5. This same procedure is followed for the Spanish energetic mix.

	Spanish energetic mix (%)	Venezuelan energetic mix (%)
Lignite	7,3	0,0
Soft coal/ Anthracite	31,3	0,0
petroleum	5,5	12,5
Natural Gas	1,5	15,5
Nuclear	36,3	0,0
Hydraulic	18,0	72,0
Eolic	1,0	0,0
Solar	0,0	0,0

Table 3: Energetic mixes for Spain and Venezuela (1999)

3 DISCUSSIONS

The values by category of impact can be added each country and to obtain the total of ecopoints associated to the generation of electricity in that country by each TeraJoule. In table 5 it is possible to be observed the total of ecopoints associated each category of impact and the extreme total of ecopoints for each country. Column 3 represents the relation between the total of Spain and the one of Venezuela for each category of impact, that is to say, how much contaminates Spain with respect to Venezuela for each category of impact, and, by TeraJoule of energy altogether generated.

It is important to note that the results of this first study were calculated with the values of inventory corresponding to the AUMA study, therefore, the Venezuelan values calculated here would correspond to the environmental impact of the Venezuelan power stations if they had made in Europe.

This is important by the cumulative effect of energetic-mix. If something makes in another country, the electrical energy that is used will be the available one in the network of that country. Therefore, this study estimates that the Venezuelan electrical power stations were constructed with European energetic-mix.

Another consequence to take the values from AUMA is that the values of evaluation also are European. This causes that the Venezuelan power stations are considered as if they operated in Europe, since the values of evaluation include factors like the importance of the environmental impact within their social surroundings, political, economic and geographic, as well as the population affected by the process, the amount of total polluting agents of a region, etc.

In fact, for illustration purposes, it could affirm that the treatment that has been granted to this information in this first analysis, could correspond to "a fictitious" country called "Eurovene", which has all the characteristics of generation of energy of Venezuela, but it is located in the middle of the European Community. This hypothetical country is governed by the political-geographic directives of all the other members of the European Economic Community. Being "Eurovene" part of an established economic community, the processes that entail the contamination generation affect all the community, reason why the indicators that are used when weighing the generated damages are such that it uses any other member.

Obviously, this model presents "a small problem" to the hypothetical board for the development of the LCA in Europe, because they "forgot" to take into account the electricity generated by the hypothetical "Eurovene", reason why to the LCA for "Eurovene" does not affect the total European energetic-mix, but it is affected by this one.

In ideal conditions, energetic-mix for Venezuelan is over-rated based on his environmental impact. Theoretically, the hydroelectric power stations count as of the cleaner power plants (does not assert that is the cleanest since the studies at world-wide level include the hydroelectric minipower stations solely, which is not, obvious, the case of Venezuela. Given the ample participation which this type of power stations has in energetic-mix of Venezuela, it is possible to be affirmed that the Venezuela electrical generation is, in principle, cleaner than the European.

This does that the assumed values of LCI in this study give an environmental load to the Venezuelan power stations that would have to be smaller. The lack of certainty in this last one must to that, by the existing differences in the political, socioeconomics and legal realities between Latin America and Europe, the generation of polluting agents on the part of Venezuela could not fulfill the pattern previously predicted and to be greater to the awaited one.

Figure 1 represents the percentage participation (within the total of ecopoints of each country Spain/Venezuela) for each category of impact. A noticeable tendency can be observed, not only in the total but in most of the categories of impacts, that Spain has a greater amount of ecopoints than Venezuela. Nevertheless, in some categories this characteristic is reverted.

When identifying which categories of impact are those that present the difference, can be observed that they are Ozone depletion, Carcinogenic substances and photochemical fog.

When reviewing what power sources have the greater penalty for these categories of impact, it is observed that, unfailingly, the use of derivatives of petroleum is penalized hard in each one of them (see Table 4).

That entails to the necessity of verification, which is the participation of petroleum in energetic-mix of each country? For Venezuela, petroleum has a rate of participation of 12.5% within the power market, whereas for Spain is single of 5.5%.

Thus, it is possible to be asserted that, if is desired to diminish the environmental impact of Venezuela in these environmental lines; the quota of participation of petroleum within the Venezuelan power market is due to diminish. A possible solution is the substitution to natural gas for the use in thermoelectrically power stations, that does not present noticeable penalties in any category of impact, if is compared it with other power plants.

	Lignite	Coal	Petroleum	Natural Gas	Nuclear	Hydraulic	Eolic	Solar
Global warming	135,00	109,00	97,00	95,80	2,05	0,41	2,85	15,40
Ozone depletion	0,32	1,95	53,10	0,86	4,12	0,05	1,61	3,66
Acidification	920,00	265,00	261,00	30,50	3,33	0,46	3,49	97,00
Land degeneration	9,83	11,60	9,76	6,97	0,28	0,06	0,27	1,97
Heavy metals	62,90	728,00	244,00	46,60	25,00	2,58	40,70	167,00
Carcinogen substances	25,70	84,30	540,00	22,10	2,05	0,76	9,99	75,70
Fog of winter	519,00	124,00	135,00	3,08	1,50	0,15	1,48	53,30
Photochemical fog	0,49	3,05	36,90	3,47	0,32	0,06	1,25	3,03
Remainders	50,90	12,90	0,62	0,58	0,28	0,52	0,29	1,84
Ionizing radiations	0,02	0,05	0,02	0,00	2,19	0,00	0,01	0,12
Radioactive remainders	5,28	10,60	7,11	1,34	565,00	0,32	1,83	34,90
Exhaustion of the power resources	5,71	5,47	13,60	57,80	65,70	0,07	0,91	7,06

Table 4: Total of ecopoints per TJ of electricity for each category of impact associated to the different primary sources from energy. This table is the turn out to multiply the different inventories associated from each technology by the factors generated in the stage of evaluation of the inventory. .

Category of impact	**Total Spain (ecopoints/TJ)**	**Total Venezuela (ecopoints/TJ)**	**Relation Spain/Venezuela**
Global warming	51,59	26,31	2,0
Ozone depletion	5,09	6,54	0,8
Acidification	166,24	36,23	4,6
Land degeneration	5,10	2,26	2,3
Heavy Metals	256,52	38,13	6,7
Carcinogen substances	59,27	68,66	0,9
Fog of winter	84,76	16,77	5,1
Photochemical fog	3,21	4,99	0,6
Remainders	7,99	0,54	14,9
Ionizing radiations	0,81	0,00	338,9
Radioactive remainders	209,29	1,28	162,9
Exhaustion of the power resources	27,61	10,35	2,7
Total ecopoints	877,50	212,06	4,1

Table 5: Totals of ecopoints/TJ by country and category of impact. The last row corresponds to the sum of the ecopoints, whereas the third column corresponds to the quotient between the total of Spain and the one of Venezuela for each line.

On the other hand, it is possible to be asserted that "Eurovene" contaminates less than Spain by each consumed kWh, which seems logical if the energetic-mix are compared. The relation between ecopoints is from 4 to 1.

This relation becomes greater or smaller depending on the category of impact, being, for example, of 2 for Greenhouse gases.

The relation in radioactive remainders and ionizing radiations is of 162.9 and 338.9, respectively, which must to that in Venezuela there is not generation of electricity by nuclear energy. The great participation of this power source within energetic-mix of Spanish (36.3%) is a decisive factor so that those total values of contamination are generated in that country.

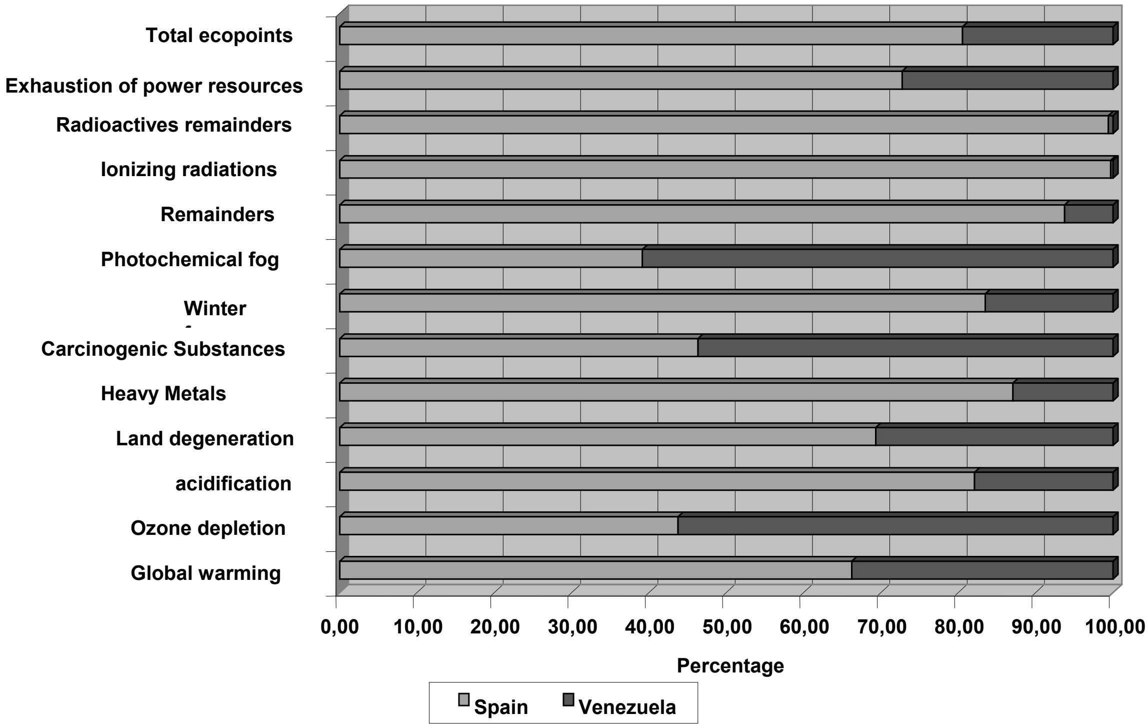

Figure 1: Percentage Participation of each country (Spain/Venezuela) within the total for each category of impact. The line of 50% represents the points where both countries would have the same total of ecopoints

4 CONCLUSIONS

Still does not exist the sufficient information in Venezuela on the categories of environmental impact in the power sector like carrying out comparable to European LCA's European on products and processes. Nevertheless, the European data allows an approach to the analysis of the sector of electrical generation in Venezuela and to establish preliminary comparative tendencies

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In Search of Customer Needs for Home Energy Management System in Japan

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Abstract
Energy cost reduction and consequently contribution for global environment is often said to constitute main advantage of Home Energy Management System (HEMS). However, this strategy would be able to attract merely LOHAS (Lifestyle of Health and Sustainability) market. We investigate cunsumer attitudes toward HEMS based on Focused Group Interview (FGI) method targeted for planning or actually having ones own house. Our results suggest that target marketing for those who intend to have own house is quite effective, though rennovation market seems to be less attractive for HEMS. Our analysis also implies that ideal marketer for the target may be existing home security service provider and alike because HEMS by itself does not induce cusomers to make additional expenditure and should be marketed as one of supplemental function for other home related services at this time.

Keywords:
Home Energy Management System; Focused Group Interview method; Marketing for integrated system

1 INTRODUCTION

Establishing the scheme of strategy for reduction of energy consumption seems to be emergent agenda all over the world. While energy consumption in industrial sector in Japan has increased slightly from 1970 to date, that of household sector has doubled partly due to the upgrading of home appliances as well as the explosive prevalence of internet [1]. This fact suggests controlling of energy in household sector should be main concern for the parties who are responsible for energy consumption problems.

Typically, energy savings in household sector has been realized by the improvements in energy efficiency of home appliances by itself. However, diminishing improvements based on energy saving technology of this kind can be apparently observed. Therefore, for realizing more energy saving in household sector, it seems necessary to put more focus on total energy management rather than energy efficiency of each appliance and then establish integrated household energy management system. In fact, some public agencies as well as electronics companies researched technological feasibility of integrated energy management service for household sector, such as Home Electronics Management System (HEMS) of which New Energy and Industrial Technology Development Organization (NEDO) originally initiated to achieve the targeted 6% reduction of greenhouse gas contained in Kyoto Protocol [2]. With utilizing subsidiaries from NEDO, several field tests as to HEMS had been done and, on average, the test results assured energy conservation effect of HEMS [3].

As such, it can be safely to say that integrated management system for appliances based on IT is technologically feasible enough to commercialize at the present moment. Neverthless, the companies struggle to introduce such services/products and the problem may seem to partly lie in marketing strategy for HEMS itself and related products. Given the original objective of HEMS, energy cost reduction and consequently contribution for global environment inarguably constitute main advantages of HEMS. However the objective is noble, it becomes meaningless if cunsumers would not have the willingness to buy. Marketer should realize and evaluate whether marketing strategy based on the objectives would attract potential customers of HEMS. If this would not be work for wide range of cunsomers, then the strategy would attract merely customers classified to emerging Lifestyle of Health and Sustainability (LOHAS) market so that the spillover effect may be quite limited considering the characteristics of current LOHAS market. Although there is no clear-cut definition of LOHAS, it is sometimes thought that they are the consumers who take environmental and social issues into account at buying decision [4]. Ueno et al. [5] shows the the degree of energy saving resulted from HEMS usage has positive relationship with energy conservation consciousness of household [5]. This implicitly suggests that HEMS of this moment may have potential merely in LOHAS market.

For stable and wide prevalence of HEMS, it should be needed to reconsider potential appealing point of HEMS in marketing concept and then design marketing strategy suitable for wider (general consumer) market. Needless to say, each electronics firm and possibly other firm which is interested in HEMS and alike may undertake some marketing research and determine its marketability and consequently establish marketing strategy aiming to wide market. However, in general, the methodology for and the results of marketing research are not publicly available so that we cannot evaluate the appropriateness of the strategy.

2 INTELLIGENT HOUSE AND HEMS

2.1 Intelligent House

In the late of 1980s', a plan for integrated home energy management system which was called "Intelligent House" initiative was conceptualized and discussed over its feasibility by Ministry of Posts and Telecommunications [3]. It was intended to promote laboursaving in housework, home security, health care, amusement communication function based on home computerization with the initiative.

To investigate the feasibility of commercializing the concept, consumer group interview and diffusion model formulation based on customer wants had been conducted. Although the research suggested attractive market opportunity, it ended up with unfortunate result partly due to the lack of technological infrastructure necessary for realizing the concept at that time. Eventually, we can discuss about the feasibility seriously the commercializing such kind of system with the dissemination of mobile phone and internet now.

2.2 HEMS and information technology

HEMS can be said as current version of intelligent house [2]. It is purported to realize optimal energy consumption within household through comprehensive control over electric and/or air-conditioning facilities. It is known that "ECONET (Energy Conservation and Homecare Network)" is one representative of technological infrastructure for HEMS. ECONET is architecture for realizing energy saving and at-home care by connecting home appliances via information network and controlling these equipments systematically.

For that purpose, information technologies such as electrical line carrier and specific power-saving radio transmission are employed and consequently no additional wiring is needed within household. As such, required technology for HEMS already exist or will come into exist in near future and cooprative activities based on common architecture among related firms steadily go on.

The apparent mission of HEMS concept suppoted by archtecture such as ECONET lies in effective energy consumption and many efforts has been devoted for technology development for it. Contrary, there are too few researches on marketing aspect of HEMS to estimate its marketability, while it was done during intelligent house research. There is no guarantee that the conclusion obtained from intelligent house research for marketability holds. For instance, cost competitiveness or usability of the system itself and linkage with the rise of consumer awaness for ecology or sustainability may affect marketability of HEMS as of this moment.

3 SURVEY OF GENERAL PUBLIC ATTITUDE

3.1 Research objective

We intend to get a key to promote market opportunity for energy conservation system. For that purpose, following four elements are necessary to be considered:

- Target
- Appeal points
- Function
- Price

Due to budgetary restriction on the research, we preliminarily assume target customers and then consider the potentially promising approach concerning other three elements toward targeted market. We particularly focus on emotional value of HEMS because we believe that attracting customers based on potential value in addition to apparent functional advantages including such as centralized control would give a clue for faster and wider to market. Figure 1 exhibits our basic ideas.

3.2 Methodology

It is common to apply questionnaire survey to investigate general public attitude. Imanishi [6] analyses general attitude toward HEMS in terms of offering price and system specification based on questionnaire method and reports partly similar results concerning pricing to ours mentioned later. Although the methodology is suitable for gathering mass data and quantifying the survey result, questions have no validity if it would not fit to mind set of respondents and may sometimes lead to ill judgement. Given the fact that HEMS market is at its introduction phase of product life cycle, investigating unexpressed thought or feeling behind the obtained response is crucial for establishing appropriate marketing strategy. Therefore, we employ focused group interview (FGI)

3.3 Respondents to the survey

We assume that individuals who have the will and/or actually plan to purchase single family home or renovate their own home formulate potential market for HEMS. We exclude the individuals who plan to purchase or actually live in

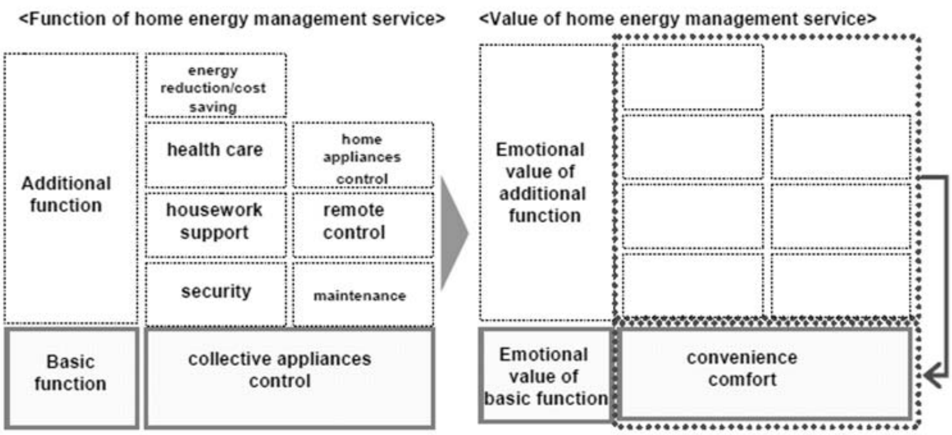


Figure 1 Transformation of HEMS function into value

since they cannot decide to introduce HEMS on their own will. More specifically, potential respondents should satisfy following conditions:

- people of 30' or 40's satisfying:
  - not owning their home regardless of the type of home
  - planning to purchase single family home
- people of 50' or 60's satisfying:
  - owing their own family home
  - planning to renovate home

We picked out potential interviewees who satisfied the above conditions from the survey panel consisting of 1,500 individuals living in Tokyo and then confirmed actual respondents depending on their appointments.

3.4 Outline of FGI

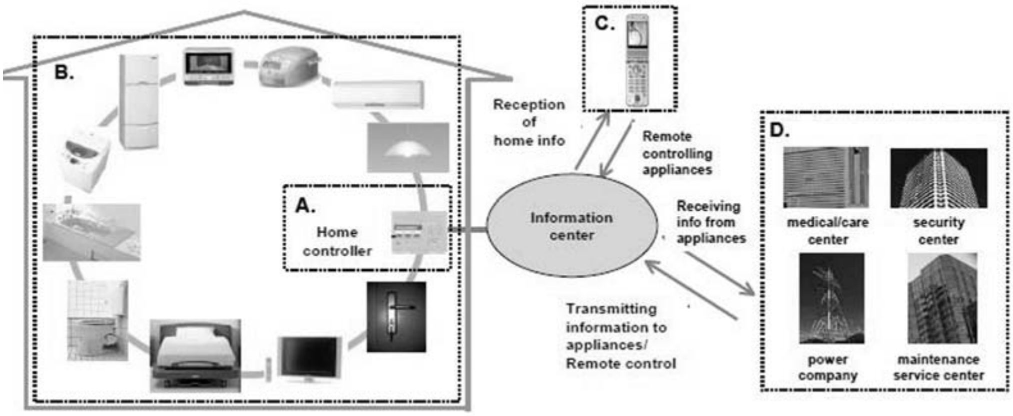
We held FGI on May 28 and 29, 2006 at WELLCO interview room (Shibuya, Tokyo). Figure 2 shows the overview of the facilities and table 1 describes the composition of interviewees. A disciplined interviewer led 2 hours discussion within each group described in table 1 based on laddering method with which interviewer directly and repeatedly asks 'why' for ascertaining structure of consciousness of participants [7].

(a) interview room (b) monitor room

Figure 2 Interview facilities (WELLCO interview room)

attribute	#
Group1: 30's, 40's-male	6
Group2: 50's, 60's-male	6
Group3: 30's,40's-female	6
Group4: 50's,60's-female	6

Table 1 Composition of interviewees



	place	notation in the figure	function	detail
Networking all home appliances	house	A	central control of appliances	•conserving power •controllable at one place
		B	appliances interaction	•collective control •interactive functioning
	outside	C	linkage with mobile terminal	•information receipt •remote control
		D	Linkage with outside institution	•Information sending/receiving •remote control

Figure 3 Images of integrated energy management service

At the beginning of the interview, the interviewer handed out figure 3 and supplementary detail interpretation (not presented in this paper) to the interviewees for promoting their understanding of HEMS. Besides, the material included additional services which can be available by networking home appliances for interpreting priority of energy management service among related ones from customer perspective. We then go ahead to interviewing research along with the interview flow depicted in figure 4. At first, the interviewer explained the intent and precaution and asked participants to make self-introduction for relaxing them. Second, the interviewees were asked about their sense of “convenience” and “comfort” in living and potential achievements from such way of living. Third, the session went into the main theme and they told and discussed about attractive function of HEMS and the reason for it, possible changes in living with it, affordable price and other marketing factors. Forth, the discussion moved on to the consciousness toward energy reduction for ascertaining appeal power of such value to them. Finally, interviewees told freely around the theme and overall impression.

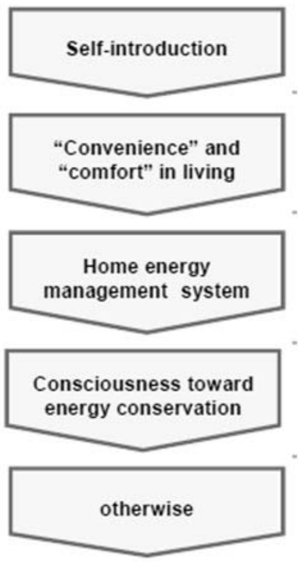


Figure 4 Interview flow chart

4 FGI RESULTS

4.1 Target

Given the validity of our assumption that individuals who have the will and/or actually plan to purchase single family home or renovate their own home constitute potential market for HEMS, FGI results suggest that intensive marketing to 30’s as well as 40’s may be promising because they evaluate technological progress positively so that they don’t hesitate to take innovation into their home as long as brand-new technology contributes to raise up their living in any sense. Contrary, the results suggest that 50’s and 60’s expressed negative evaluation and were in general reluctant to introduce HEMS. In short, the reason for their hesitation lies in their image of aging. At a glance, health care, more specifically care support function may bring some value and increased sense of relief to older segment. However, they would keenly aware aging a facing technological innovation so that HEMS never lead to comfort living as far as they don’t consider the necessity of care support as real concern. This result has implications for high-tech product marketing in general that the strategy should not make them image aging.

4.2 Appeal points

We extracted appeal points of HEMS from participants’ opinions based on the information presented in figure 3 with evaluation grid methodology and found that “time saving,“ ”distance shortening” and “security ensuring” consisted of large part of functional value. We can infer from the finding that HEMS may bring emotional value such as “fulfilment,” “liberation,” “peacefulness,” “relaxing” and “relief.”

From the result, we can specifically recommend to focus on three appeal points at marketing HEMS. First, one can stimulate those who feel busy and search better way to effective time usage by emphasizing time saving aspect. Second, one can produce care-free feeling by concentrating on distance shortening. Third, it can be appropriate to promote sense of safe by stressing security ensuring. Since consumers usually consider many factors affecting their satisfaction at actual purchase decision making, well-constructed strategy for attracting their emotion should be established

4.3 Function

We asked the interviewees to rank possible functions provided by HEMS described in figure 1. If each participant ranked certain function within top 3, we gave one point to the function (i.e. equally weighted). Table 2 shows the summary data of the aggregated score and number of participants who ranked each function within top 3. For instance, energy reduction/cost saving function was ranked top by three participants, second by three and third by five and consequently amounted to 11 points. As the table shows, we can conclude that average participant signify, in order of priority, security, remote control and energy/cost saving function.

Generally, there can be observed some kind of functional fixation in consumer behaviour. If one would go through contracting security service, she will naturally call on an established security firm given the existence of searching cost. Even though HEMS can provide comprehensive or integrated home related service, consumers who want to contract security function will visit any consumer electronics retailer with little chance because it is hard to think security in combination with electronics. Therefore, at least during market penetration phase, ideal marketer for HEMS may not be electronics manufacturer or retailer.

Rather, security firms or power companies can easily access to consumers who potentially contract one of function HEMS can provide so that electronics companies should be better to support these firms during the phase. For instance, networking device which is necessary for realizing HEMS may be well marketed by security firms as the requisite for providing service than marketed as pre-installed appliance (say internet appliances). It should be more extensively investigated to recommend desirable market structure for HEMS.

Function	Total score	top	second	third
Energy reduction/cost saving	11pts	3	3	5
Home appliances control	7pts	0	2	5
Remote control	12pts	1	5	6
Housework support	5pts	2	2	1
maintenance	4pts	2	1	1
Health care	10pts	1	5	4
security	20pts	14	5	1

Table 2 Consumer priority on each function

4.4 Pricing

It is apparent that at least some of the listed functions have been, to some degree or another, already provided either independently or in combination. Therefore, potential size or growth speed of HEMS market may heavily depend on offering price. We presented average monthly charge of internet provider, fire insurance premium, utility per household and contract fees of security firms to the participants and asked acceptable monthly charge of HEMS. We obtained the conclusion following:

Front fee: no more than 50,000 JPY

Monthly charge: no more than 20,000 JPY

It is noteworthy that many participants insisted flexible assortment of functions fitting to their lifestyle will be desirable. Imanishi [6] reports identical result as to pricing and the need of flexibility based on questionnaire so that both qualitative and quantitative research suggest same pricing policy. In other words, if governmental bodies require fast penetration of HEMS for meeting the target designated in Kyoto Protocol and estimate market price for it would be higher than the above, then subsidiary for lowering substantial contract price will be effective. At the same time, marketer should provide fine-tuned pricing plan reflecting customer needs.

4.5 Consciousness toward energy conservation

We additionally included the question concerning consciousness toward energy conservation to examine potential effectiveness as an appeal point. It is interesting that group 3 of our sample (30’s and 40’s female) thought of energy reduction in connection with monthly power charge, while male interviewees on average grasped it at some abstraction level such as geoenvironmental issue. The sharp contrast between the consciousnesses of each segment may ascribe to some socio-political or sexual elements. This suggests that careful conception of the term “energy conservation” should be needed when firms use it as an appeal point.

5 CONCLUDING REMARKS

In this paper, we investigate consumer consciousness as well as needs concerning HEMS based on qualitative methods. To the extent we know, there are no academic papers based on professional or commercial marketing research to date concerning HEMS. Hopefully, our results will be apparent benchmark for both practitioners and academicians being interested in promoting HEMS.

Given the FGI result presented here, we recommend that effective marketing of HEMS may target on 30’s and 40’s who plan to have single family home with emphasizing on emotional value such as “fulfilment,” “liberation,” “peacefulness,” “relaxing,” and “relief.” Moreover, energy management control system alone will not attract consumers enough to make contract so that it should be marketed as a part of integrated but flexible IT based management service. This fact also implies potential marketer of HEMS may be security firms or power companies because of consumer priority on related services. Finally, price range acceptable for integrated service should be no more than 50,000 JPY for front fee and 20,000 JPY for monthly charge, respectively. It should be realized that consumers are not willing to pay the full amount for HEMS and possibly merely small amount.

From global perspective, it is unarguably emerging and important issue to reduce CO2 emission for realizing sustainable society and HEMS can to some extent contribute the objective. Although continuous education or enlightenment activities to raise general consciousness toward energy conservation should be important, we should seek any approach to attract consumers who are not keen to the problem other than subsidiary by appealing to their other emotional values. Well-established marketing strategy for the product/services relating to the objective such as HEMS should increase social welfare.

ACKNOWLEDGMENTS

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The Influence of Durable Goods on Japanese Consumers' Behaviours

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Abstract
The rapid progress in diffusion of durable products plays an important role to change people's lifestyle in Japan. The wide spread of home electric appliances which play an auxiliary role of housework like refrigerators has reduced time spent on housework and raised the value of an hour of our lives. Regarding refrigerators, consumers who possess a refrigerator without freezer storage are able to purchase and preserve perishable foods. When consumers possess a refrigerator with freezing compartments, they can additionally purchase and preserve frozen products. The more sophisticated equipment households possess, the greater variety of goods and services they can reach. In short, the technological development changes people's lifestyle and consumers' needs. In this paper, a theoretical framework of consumer behaviours will be illustrated based on the microeconomic theory. The model describes the effects of durable products on a diversity of consumption. The diversification of consumption may affect to the change in the industrial structures and the dynamic changes in production activities due to the changes in consumers' needs may affect the environment.

Keywords:
Consumer Behaviour Model; Lifestyle; Durable Products

1 INTRODUCTION

People's life style has changed over time. In Japan, the national economy has grown rapidly after the World War II, and their life styles have drastically changed while the living standard has sharply improved [1]. When the consumers' life styles have changed, the goods and services the consumers want will also change. Therefore, the changes in life styles have created the new types of consumer needs, and the new demand may have a power to stimulate the national economy. In addition the changes of the consumers' demand have impacts to change the industrial structures.

In Japan, various consumer durable products have spread after the war, and the disposable products of daily necessities have also spread. Those products eased the burden of housework and child-care [1]. The main three durable products which rapidly spread in 1960s in Japan (electric washing machines, electric refrigerators and electric vacuum cleaners) and the new three durable products called 3C in Japan (colour televisions, air conditioners and automobiles) which modestly spread after 1970s are the products which everyone has the strong desires to possess. The consumers' life styles must have changed by holding those newly introduced durable products. The possession of the new durable products also creates the new consumers' needs for its usages; for example, the increased demand for microwavable dishes to use microwaves. In addition, the newly introduced durable products bring additional changes in consumers' life styles. Because many durable products such as electric washing machines and electric refrigerators play an auxiliary role of housework and reduce time pent on housework, consumers who possess and take advantages of those durable products can spend more time for their own self. The changes in their allocation of time may also have the additional impacts to change their life styles. As the additional changes in consumers' life styles also create the afresh new demand, the cycle of these changes in consumers' wants affects to change the industrial structures. Because the environmental impacts of production activities vary among industries, the continuous changes of consumers' life styles can have the great impacts on environment through the industrial structure changes. It is important to understand the possibility that a durable product can be the cause to change the relative size of environmental impacts. In this paper, a new consumer behaviour model will be introduced, and the model describes the situation that a durable product has impacts to change consumers' shopping patterns and their life styles. As it will be shown, the durable product plays the major role to change consumer behaviours.

2 THE IMPACTS OF DURABLE GOODS

2.1 The spread of durable products

A variety of durable goods had spread rapidly after the 1960s in Japan. Electric washing machines, electric refrigerators and vacuum cleaners remarkably spread in 1960s [2]. In 1970s automobiles, room air-conditioners and microwaves have modestly spread. Such wide and rapid spreads of home electric appliances which play an auxiliary role of housework has reduced time spent on housework and raised the value of an hour of our lives. Moreover the founding and creation of new goods have created the previously unimaginable lifestyle and enabled a wide variety of human wants easier to satisfy. Thereafter households' consumption behaviours must be affected more or less by the introduction of a durable product.

It is important to notice that electric appliances have impacts not only to reduce time spent on housework but also to change consumers' lifestyles through the changes in styles of shopping. In addition, the choices of the consumable goods and services for a consumer will be broaden when the consumer has a new electric appliance. In short, a range of the consumable goods and services can be technically determined by which durable product the consumer has. Regarding refrigerators, consumers who do not possess a refrigerator must do grocery shopping everyday. When the consumers possess a refrigerator which does not equip a freezing storage, they can purchase and preserve perishable foods more than they can consume in a day. When consumers have a refrigerator with a freezing compartment, they can additionally purchase and preserve ice creams and any frozen foods. The more sophisticated equipment the consumer possesses, the greater variety of consumption goods and services the consumer can reach.

2.2 Effects of the spread of electric appliances

The influences of electric appliances on the consumers' life styles can also be known from the economic growth Japan has experienced. The technological innovation and the consumer revolution are said to be the key for the economic growth [3] [4]. The newly introduced technologies have enabled firms to manufacture new products such as electric refrigerators, electric washing machines and vacuum cleaners. In fact such new products have stimulated the consumer demand and supported the economic growth against the economic depression Japan had faced in 1957. Also [4] has pointed out that the clear economic target of households, companies and even the government have shared was 'improvement of the living standard', and everyone could image the desirable future lifestyle clearly as a life with electric washing machines, radios, televisions and refrigerators in our house, and an active life with automobiles. The modern economic growth which aimed at the improvement of the living standard had meant that consumers could have the higher quality of goods and services and take advantage of the greater variety of consumable goods and services. As the diffusion rate of electric appliances has increased, the consumers' wants have changed and the changes must have affected the industrial structure of Japan. In other words, the spread of durable products plays an important role in the development of the industries and in the economic growth. Unfortunately, even though the importance of impacts of durable products has been argued, the argument is still a matter for speculation and any theoretical arguments and frameworks are not developed yet [3] [4]. Some consumer behaviour models have considered the impacts of durable products such that electric appliances have affected consumer behaviours through the changes in the allocation of time and in the amount of the electric power usages [5] [6] [7]. However the models are not formed to describe the situation that the durable products may promote the diversification of lifestyles and the consumers' needs as it is explained in the previous section. In the next section, the historical data will be summarized to support that the electric appliances have actually affected the consumer behaviours in Japan.

3 THE CHANGES IN CONSUMER BEHAVIORS

The historical data of refrigerators will be reviewed because the refrigerator is one of the products which have extensive impacts on the consumer behaviours.

3.1 The power usage

The wide spread of electric appliances raised the electric power consumption. In fact the expenditure for energy usage in Japan has increased while refrigerators spread rapidly. The amount of the electricity used per household was 4,139 (10^6J) in 1965, 12,048 (10^6J) in 1980 and 19,787 (10^6J) in 2004 [8]. The power usage has increased about 5 times in last 40 years. The increase in the operating cost of electric appliances must influence consumer behaviours through the changes in the budget allocation. The consumption function introduced in [7] is formed that the possession of electric appliances affects the demand for electricity.

3.2 Changes in grocery shopping

Refrigerators may reduce time spent for grocery shopping. A consumer who does not have a refrigerator may go grocery shopping everyday. When a consumer has a refrigerator, he/she needs to do grocery shopping less frequently since some foods can be preserved in a refrigerator. Consumers who have a larger refrigerator in size need to do their grocery shopping further less. The ratio of households which actually answered to do grocery shopping at least every other day was 80% in 1974 [9]. The ratio lowers over time as it is shown in Figure 1. In 2003, about 60% of households do grocery shopping at most twice a week. The frequency of grocery shopping has decreased as the capacity of released refrigerator has increased. As it is shown in Figure 2 only refrigerators in the small size were available until late 1970s. Refrigerators in the larger size were newly introduced and spread modestly from the late 1970s. Once consumers have the bigger size of refrigerators, they preserve the greater volume of foods and the frequency of grocery shopping decreases. The reduced time spent for the housework may be reallocated for the other consumer activities, and the consumers' behaviours change [5] [10].

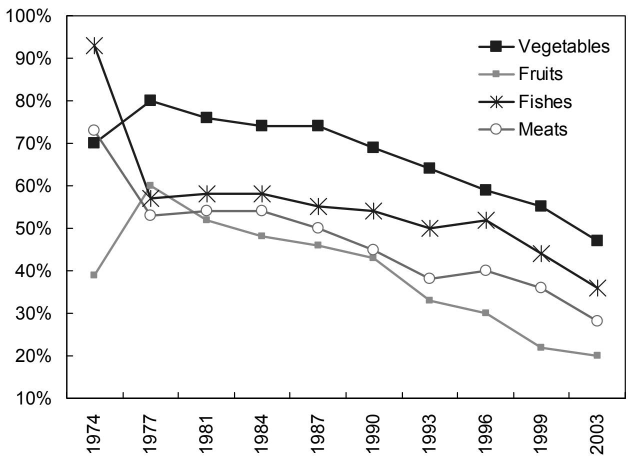

Figure 1: The ratio of households going for a grocery shopping at least every other day. [9]

3.3 The changes in food consumption

Refrigerators enable not only to reduce time spent for housework but to broaden our consumption choices. Figure 3 shows that refrigerators enable consumers to purchase new types of products such as frozen foods and ice creams. Frozen foods were available at a department store in Tokyo in 1952, but there were poor demand for frozen foods at that time. In 1957 most department stores in Tokyo have a frozen foods corner while the demand for frozen foods was still little.

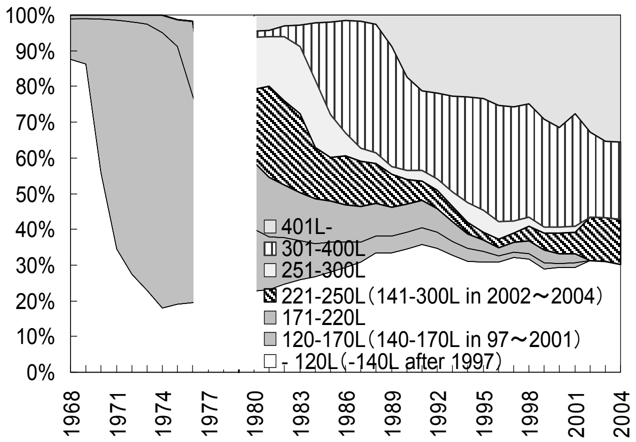

Figure 2: The refrigerator shipments by its capacity. [11]

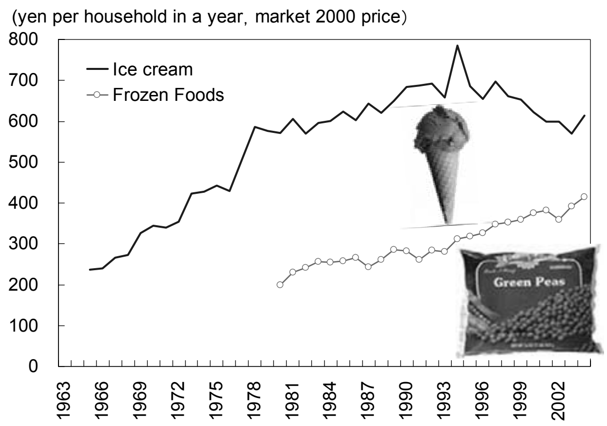

Figure 3: The expenditures on frozen products. [12]

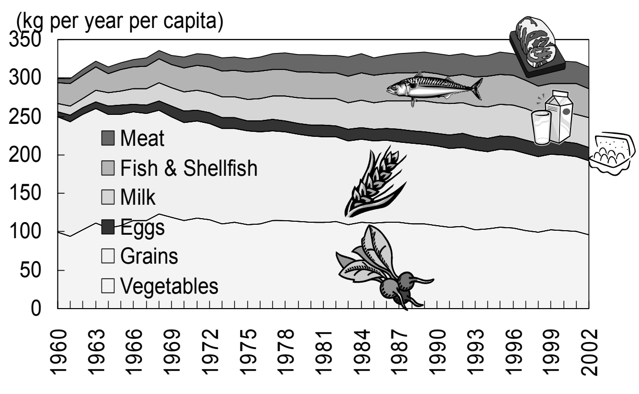

Figure 4: The change of dietary content. [13]

In 1963 supermarkets opened the frozen foods corner and the demand has increased gradually as refrigerators with freezing compartments have spread after 1970s.

The spread of refrigerators has affected the consumers' demand for traditional diets. Figure 4 shows changes in diet content in Japan. Protein-rich foods like Meat, Fish, Milk and Eggs have raised its share and carbohydrate ingestion from Grains has decreased.

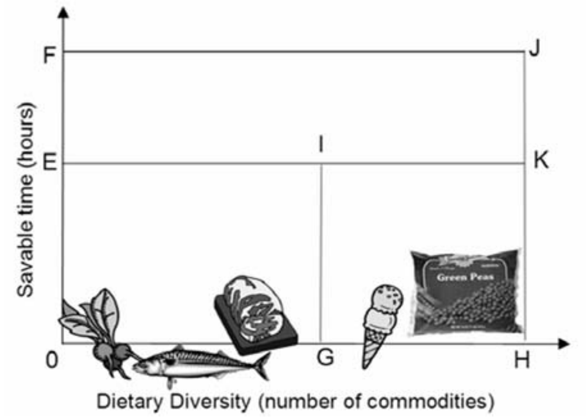

Figure 5: Effects of refrigerators.

Altogether refrigerators enable not only to save our time but also to broaden our consumption choices. The overall effects of refrigerators are visually described in Figure 5. The origin described in Figure 5 is the state where a consumer has no durable product, and the area in the X-Y coordinate represents the additional consumption benefits consumers can earn by holding a durable product. The X-axis in Figure 5 represents a degree of dietary diversity (the number of commodities consumers can newly purchase). The Y-axis represents reduced time spent on housework due to the usage of the durable product. When a consumer has a refrigerator, the consumer can lower the frequency of grocery shopping due to the storage capability of refrigerators, and save time by E. Also he/she can broaden his/her consumption choices by G because refrigerators enable consumer to purchase and preserve several types of perishable foods. With refrigerators, consumers can make the additional consumption benefits by the area 0EIG. When a capacity of refrigerators is the same, consumers who have a refrigerator with a freezing storage can save the same amount of time by E but broaden consumption choices further by H because they can now purchase and preserve frozen products. The total consumption benefits increase by GIKH. When the storage capacity of a refrigerator increases, consumers can preserve greater volume of foods and do grocery shopping further less. Therefore they can save more time by F. Refrigerators in larger size expand the consumption benefits by EFJK. The more advanced and larger refrigerator consumers possess, the greater benefit they can make.

The effects of consumer behaviours through the changes in allocation of time (the effects on the Y-axis) have gained attention in earlier researches (for example in [5]), but the effects on the diversity of consumable goods and services (the effects on the X-axis) have not paid attention. There is not any established microeconomic model describing the effects on the X-axis yet. In the next section, a new consumer behaviour model which considers the effects on the X-axis will be introduced.

4 A NEW MICROECONOMIC MODEL

The consumer behaviours may change depending on the specification of the durable products consumers possess. In this section the consumer behaviour model based on microeconomic theories will be introduced. Although it is possible to form the model that households maximize utility with the combination of market goods and time as it is introduced in [5], the attention will be focused specifically on the effects of durable products on the diversity of consumable goods and services to simplify the model.

For simplification, let us assume the world of two consumption goods (q_1, q_2) available, and households are assumed to have certain durable product (K), and suppose that there are two types of the durable product (K_A and K_B) and a household only possesses either one. The durable product of type A (K_A) enables households to consume only q_1, but the durable product of type B (K_B) enables to consume both q_1 and q_2. This condition can be explained with refrigerators. K_A can be a refrigerator without a freezing storage, and K_B can be a refrigerator with a freezing compartment. Also, q_1 is any perishable foods and q_2 is frozen foods.

As in standard theory, let us suppose that a consumer i maximizes a utility function

$$U_i = u(q_1, q_2 K_B, Z_i) \quad (1)$$

subject to $$y = p_1 q_1 + p_2 q_2 + p_A K_A + p_B K_B \quad (2)$$

$$K_A + K_B = 1 \quad (3)$$

$$K_A K_B = 0 \quad (4)$$

$$q_1, q_2 \geq 0 \quad (5)$$

where $u(\ )$ is an utility function, y is an income, Z is demographic factors of the consumer i and p_1 and p_2 are prices for q_1 and q_2 respectively. Also, p_A and p_B are the user costs of the durable goods K_A and K_B respectively. The methodology to estimate user cost for durable goods is not the point of argument in this paper. Therefore, the user-cost is assumed to be properly estimable and given.

The equation (3) and (4) together express that a consumer has either type of the durable product because K_A and K_B inevitably take the value of 1 or 0. The value will be 1 when a consumer possesses the corresponding type of the durable good and 0 when does not. Consumer utility U is a function of Z_i, q_1 and the product of q_2 and K_B. Therefore the amount of q_2 does not affect the utility for those who have the type A durable product (K_A=1, K_B=0). Regarding refrigerators, consumers whose refrigerator has no freezing storage may not increase their utility by purchasing a product (q_2) which they can not preserve but rather spoil. Therefore, the utility is determined by the amount of q_1 when K_A=1 and the utility becomes a vertical line as it is shown in Figure 6. The utility maximizing point is where the budget line (CD) and horizontal axis cross (D) when K_A=1.

Whether a consumer possesses either K_A or K_B itself does not affect the utility level, and the utility level to consume q_1 by the limit of income y must be the same regardless of the durables. Therefore utility to consume q_1 by D when K_A=1 and utility to consume q_1 by the same amount when K_B=1 must be the same. The utility is convex when K_B=1 since $u(\ )$ is an increasing function as shown in Figure 6. Although the utility curve u in Figure 6 may be discontinuous at point D, let us assume continuity for simplification.

When the user costs for durables p_A and p_B differ, the budget line for each durable products varies. For instance when user cost of type B durables is comparatively higher than that of type A durables, the budget line for consumers who possess type B durables shifts downward as it is shown in Figure 7. In Figure 7, consumers are indifferent to have type A durables with consumption of q_1 by D and to have type B durables with consumption of q_1 and q_2 by E. If the user costs of type B durables is higher than that is shown in Figure 7, consumers can maximize their utility to have type A durables.

Regarding refrigerators in 1970s, when a user cost (p_B) of newly introduced product such as refrigerators with freezing compartments (K_B) becomes affordable, the refrigerators K_B have rapidly spread to maximize their utility and consumers could consume the new types of products (q_2) such as frozen foods. The demand of q_2 is highly dependent on the spread of durable products K_B.

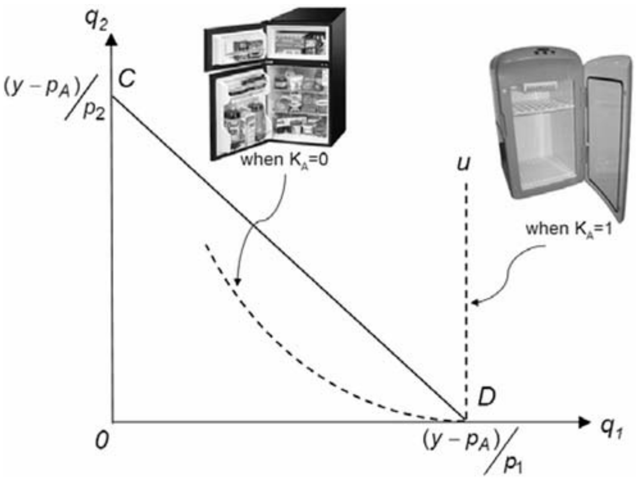

Figure 6: New consumer behaviour model (1).

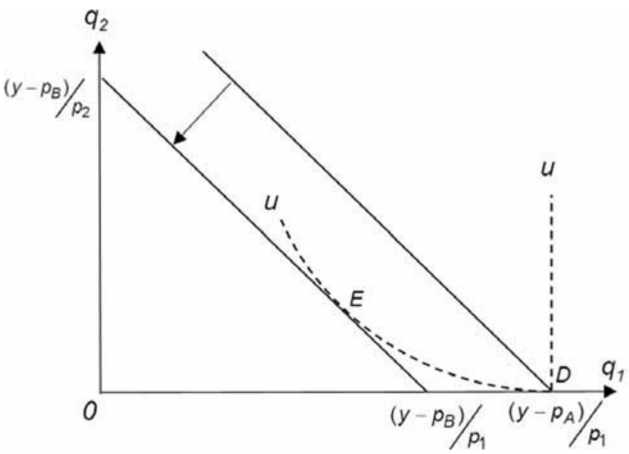

Figure 7: consumer behaviour model (2).

5 SUMMARY

In this paper, the statistical and the theoretical surveys have supported the situation that consumers may not only save the time spent for housework but also broaden their ranges of consumable goods and services when consumers possess a durable product. The changes of life styles also bring influential changes to the industrial structures. In addition to the changes in well-selling products in Japan, the industry trends within the Japanese retail industry have drastically changed due to the life styles' changes. Because the newly increased demand for foods like frozen foods is mainly sold at super markets. As the consumers' demand for frozen foods has increased due to the rapid spread of refrigerators with freezing compartments, the number of supermarkets has increased and the number of local specialty stores like butchers and fish stores has decreased [14]. The changes of distribution routes have a great impact on the degrees of environmental impacts. Therefore, to evaluate the overall environmental impact of a durable product, it seems to be the one approach to include the environmental effects of the lifestyle changes to the use stages of a durable product in the life cycle assessment researches. The empirical works which take into consideration the changes in consumers' life styles are one of the remaining works for future.

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An Experimental Analysis of Environmentally Conscious Decision-making for Sustainable Consumption

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Abstract
This study examines problems of environmentally conscious decision-making in resource consumption using experiments with human subjects. Environmentally conscious behavior is an important issue related to environmental problems such as natural resource exhaustion. However, environmentally conscious behavior must confront the dilemma posed by self-interest and public interest. This study constructs a decision-making model of this situation based on a game-theoretical approach. Experiments with human subjects reveal that a sense of crisis of resource exhaustion can influence decision-making. Vast resources are often consumed and resources decrease furiously when adequate resources remain. Environmentally conscious behavior emerges as resources approach exhaustion.

Keywords:
Environmentally conscious decision-making; Sustainable consumption; Game theory; Experimental economics

1 INTRODUCTION

This study examines problems of environmentally conscious decision-making in resource consumption.

Environmentally conscious behavior is a necessity to realize sustainable consumption. However, environmentally conscious behavior has characteristics of the dilemma posed by self-interest and public interest: environmentally conscious behavior is necessary to realize sustainable consumption, but it is frequently unprofitable; self-interested behavior that ignores environmental issues usually brings high profit or other benefits. Accordingly, free-rider problems arise, rendering the realization of sustainable consumption difficult. For example, although each oil producer might wish to exploit oil as much as possible to increase its own profits, overexploitation might exhaust oil resources. The extracting companies can make no profits if all the resources are exhausted. In other words, the producers must cooperate to achieve sustainable use of oil resources.

Manufacturers confront a similar dilemma in production activities. Manufacturers generally incur large costs to produce eco-friendly products. However, they can produce ordinary products at lower cost than eco-friendly products. If no one manufactures eco-friendly products, the environmental burden would be increased.

Moreover, this dilemmatic situation is applicable to our consumption in daily life. We can choose an environmentally friendly product or other products when we make a purchase. At present, we often think that a recycled product is inferior to brand new products with respect to product quality or design. However, such products are not good for environmental resource conservation, and consumers might ultimately be affected by a damaged environment. Similarly to these environmental problems, innumerable social dilemmas confront humans in the real world.

This paper models this situation simply based on a game theoretical approach. In our model, decision-makers such as manufacturers make decisions based on the amount of consumption of natural resources. Their profits will increase and the environment will worsen if natural resources are overly consumed. In contrast, if natural resources are less consumed, the environment can be conserved but their profits decrease.

This study conducts economic experiments with human subjects to analyze the associated decision-making. Economic experimentation is a new tool for social science study [1]. Economic studies that adopt this method are established as experimental economics. Just as engineers and scientists do in other fields, an economist can design an economic experiment or game to examine a particular theory or policy. The experimenter recruits participants for the experiments, promises that they will receive a monetary reward according to their performance in the experiments, and observes their actions in the experiment to verify whether those actions reflect the theory or policy as it was hypothesized.

The purpose of our study is to determine how environmentally conscious behavior arises under circumstances in which a dilemma exists between self-interest and the public interest.

This paper is organized as follows. Section 2 presents related literature. Section 3 explains our model and theoretical predictions. In section 4, we describe experiments with human subjects and present the results. Section 5 discusses how the environmentally conscious behavior emerges using experimental results. Finally, section 5 concludes our analyses with a few remarks.

2 RELATED LITERATURE

In this section, we explain the literature related to our study. The field of sustainable consumption is closely related to the present study in terms of its objectives. However, we approach those objectives using game theory and experimental economics.

Sustainable consumption

Numerous studies of sustainable consumption have been made [2]. For example, households' sustainable consumption patterns are analyzed using the waste input-output model [3]. Lenzen [4] and Wier et al. [5] studied household energy consumption and CO_2 emissions. Most of those studies of household environmental impact specifically examine energy consumption. Duchin [6,7] proposed the use of a social account matrix to construct scenarios about consumption. Hubacek and Sun [8] developed I-O based scenarios for land use and water consumption. The concept of a rebound effect is important for sustainable consumption. Greening et al. [9] present a survey of studies that were undertaken in the U.S.,; the survey results indicate that the rebound effect is between about 0% and 50%. None of those studies treats problems of sustainable consumption as decision-making problems. Our study specifically addresses decision-making related to consumption, which confronts the dilemma between self-interest and public interest.

Game theory

Environmental problems are exacerbated by the dilemma posed by self-interest and group-interest. A famous explanation by Hardin [10] characterized these problems as "the tragedy of commons". These problems, which are called "social dilemmas", have spurred numerous theoretical studies, such as those that describe provision and use of public goods [11–14] and common-pool resources [15,16]. However, such studies mostly subsume that decision-making is accomplished independently in each period. For example, in a typical public good game, a player selects an amount of investment and obtains a payoff in each period. However, in this study, we model a game in which the value of resources is sustained over many periods. That is, players obtain a payoff from environmental resources and they can observe the decreasing resources because environmental resources are not reset at initial values in each period. In this situation, we examine whether players cease self-interested behavior before exhausting the environmental resources.

Experimental economics

In general, many studies have addressed public goods and common-pool resource games in the field of experimental economics. In those studies, similar games exist with sustained resources over a period, such as those investigated by Herr et al. [17], Walker et al. [18], and Bru et al. [19]. From the foundation of these games, we extend them to represent environmental problems: natural resources continue to be consumed and depleted endlessly. The present study particularly examines the transition of environmental resources. We examine whether subjects' behaviors can be altered by the effects of that resource transition or not.

3 MODEL

3.1 Decision-making model based on game theory

Based on game theory, we model a general decision-making system. The players are decision-makers with respect to consumption of natural resources. Using this game, we analyze how environmentally conscious behavior can emerge.

Let us consider an *n*-person game. Each player chooses action EC or EH. Action EC represents environmentally conscious behavior and action EH represents environmentally hostile behavior. Let R_t be the amount of natural resources in period t, which all players own jointly.

In each period, a player must decide to take action EC or action EH. If a player chooses action EC in period t, the player consumes a small share of natural resources, which we call share S. The amount of use is so small that the natural resources can recover all the consumption within the period. Namely, no destruction of natural resources occurs: R_t is renewed and the stock does not decrease. On the other hand, if a player chooses action EH in period t, the player consumes a large share of natural resources, which we call share L. In this case, the natural resources can recover only a part of that consumption. We define r as the amount of recovery, where $r < L$. Accordingly, the destruction of natural resources occurs and R_t decreases. In period t, the aggregate reduction of natural resources is represented as $n_{EH}(L-r)$, where n_{EH} denotes the number of players who choose EH in period t. It is noteworthy that R_t is not reset in each period and is carried over from the previous period: $R_{t+1} = R_t - n_{EH}(L-r)$. Figure 1 depicts this decision-making model by using a game-theoretical framework.

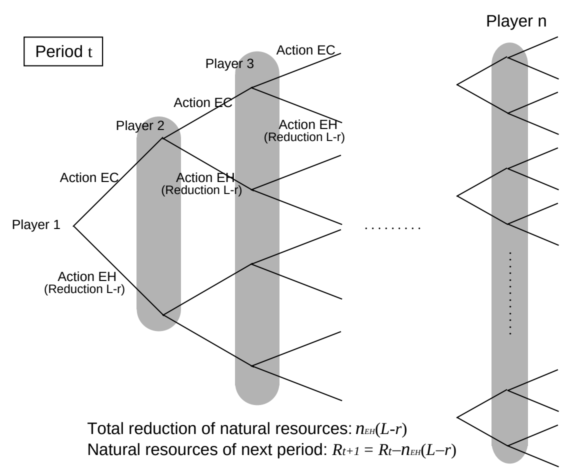

Figure 1: Model explanation by extensive form of game theory

Two types of payoff are defined: a consumption payoff and a natural resources payoff. The consumption payoff in period t for any player is $u_1(a_t) = a_t$, where $a_t \in \{S, L\}$. The natural resources payoff for any player is $u_2(R_T) = R_T / n$, where T is the final period of this game and players do not know T. The satisfaction derived from consumption of natural resources in each period is u_1; u_2 denotes the benefit from the ultimately remaining natural resources. A player can know the value of R_t in period t, but cannot know the final exact amount of the natural resources payoff until the game is finished. The overall payoff that a player can obtain is the sum of u_1 and u_2 . Figure 2 shows an illustration of this game.

In this game, we prepare two types of game endings. The game can finish at period T . Alternatively, the game is finished when natural resources are exhausted ($R_t = 0$). Because R_t might be negative in the former game, a player might receive a negative payoff from natural resources. Therefore, it can be regarded as a game that represents problems of degradation of natural resources such as atmospheric pollution and greenhouse gases. On the other hand, the latter game can be regarded as involving environmental problems that represent limited natural resources such as petroleum, natural gas, bauxite, and so on. We respectively call these two games the degraded resources game and the limited resources game. Next, we consider theoretical predictions related to the games.

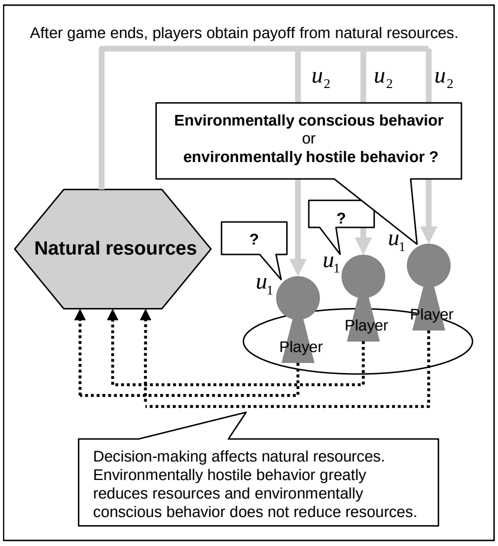

Figure 2: Illustration of the model

3.2 Theoretical prediction

Degraded resources game

In this game, we can consider two types of theoretical equilibrium. First, an equilibrium exists in which all players always choose EH, which we regard as an infinitely repeated game because players do not know the final period of the game. If a player has a discount factor δ ($0 < \delta < 1$), the natural resources payoff u_2 becomes zero as t approaches infinity: $\lim_{t\to\infty} \delta^t u_2 = 0$. Therefore, a player ignores u_2 and always chooses EH. Second, we can consider another equilibrium when we presume that the natural resources payoff u_2 is calculated, then divided into each period. In this case, the equilibrium depends on the value of natural resources reduction in each period $L - r$; the size of R_T , which might retain its value after T repetitions, does not matter. This game is equivalent to the *n*-person prisoner's dilemma if the following inequality holds [20]:

$$\frac{L-r}{n} < L - S < L - r \qquad (1)$$

The total payoff with all EC is greater than that with all EH if this constraint holds.

Limited resources game

In this game, a Nash equilibrium is the strategy by which a player continues without R_t decreasing below zero. This continuing strategy is the best response for each player if the other players select this strategy. In other words, this strategy is that a player can select action EH as long as R_t is positive; otherwise, a player always selects action EC. If a player selects action EH, which makes R_t negative, then the game is finished and a player cannot obtain any payoff from this game. For this reason, the continuing strategy is a Nash equilibrium. Innumerable combinations of this strategy exist.

4 EXPERIMENTS WITH HUMAN SUBJECTS

4.1 Experimental design

In our experiments, we conducted four treatments. Treatments 1, 2 and 3, the degraded resources games, are conducted with different initial resources R_0 =0, 1000 and 5000, respectively. In treatment 4, the limited resources game is conducted. The setting of each treatment is shown in Table 1.

Table 2 shows other parameters used for the experiments. These parameters are determined to be satisfied with inequality (1) and are common to all games. Table 3 presents the game in another way: the consumption payoff and resource reduction by action of a player. As we define n=3, three players make decisions in a group. Accordingly, the total amount of natural resource reduction is 90 if three players participate in the game and if all players choose action EH.

Table 1: Four treatments

	Game type	Initial resources
Treatment 1	Degraded resources game	$R_0 = 1000$
Treatment 2	Degraded resources game	$R_0 = 0$
Treatment 3	Degraded resources game	$R_0 = 5000$
Treatment 4	Limited resources game	$R_0 = 1000$

Table 2: Parameters for experiments

Number of subjects in a group	$n = 3$
Small share of natural resources	$S = 30$
Large share of natural resources	$L = 46$
Amount of recovery in action EH	$r = 16$

Table 3: Consumption payoff and natural resources reduction change by action of a player

	Consumption payoff in each period	Amount of natural resource reduction
Action EC	30	0
Action EH	46	30

4.2 Human subjects

Subjects were recruited from among undergraduate students and graduate students at the University of Tokyo and Kyoto Sangyo University. The number of subjects in each game is shown in Table 1. Then, based on methodology of experimental economics, subjects are rewarded according to the total payoff, calculated as one yen per point in games.

Table 1: Number of subjects in each treatment

	Number of subjects
Treatment 1	45
Treatment 2	45
Treatment 3	24
Treatment 4	42

4.3 Results of the degraded resources game

In this game, decisions are repeated until period T. Subjects do not know when the game finishes. To conceal period T from subjects, we use a number between 50 and 70, which is determined randomly. After T repetitions, each player obtains a natural resource payoff R_T/n, where R_T denotes the remaining natural resources after finishing the game. Each player obtains a negative payoff from natural resources if R_T is negative. In these parameters, the total payoff (consumption payoff plus natural resources payoff) cannot be negative because all players always choose EH and get 16 in every period if we consider converting the natural resources payoff into each period.

Figure 3 shows the transition of average natural resources R_t. The figure shows that natural resources were constantly diminished in all treatments: some subjects continued to choose action EH and neglected the payoff from natural resources. These treatments imply that the change of initial natural resources R_0 does not affect a decreasing tendency.

Figure 4 shows the transition of the average ratio of action EC. That figure shows that 60–80% of subjects select action EC. In treatment 1, the ratio of EC is low until the 10th period; the ratio increases after the 25th period. On the other hand, fluctuations are few through the periods in treatment 3, indicating that those subjects did not change their behavior to a great degree.

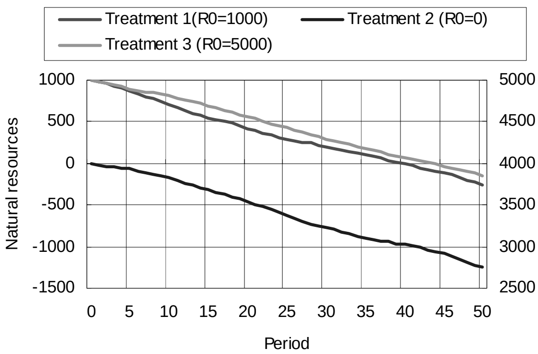

Figure 3: Transition of natural resources

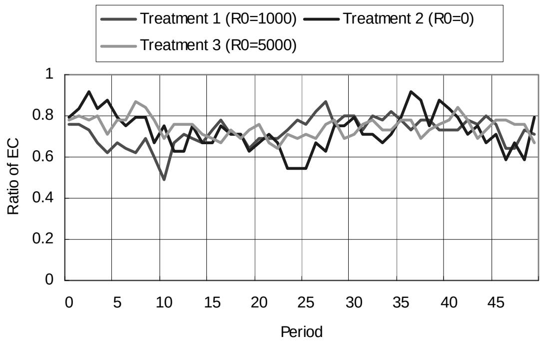

Figure 4: Ratio of environmentally conscious behavior EC

4.4 Results of the limited resources game

In this game, decisions are repeated until $R_t = 0$. However, we must define the maximum period $T_{\max}$ to avoid the case in which all players choose EC and the game continues indefinitely. The maximum period is determined as around 50–70. Players do not know the maximum number of periods. A message that the game is over is shown suddenly on the display in front of subjects when the period reaches $T_{\max}$.

Figure 5 shows the transition of average natural resources R_t. Comparison with Fig. 3 shows that although natural resources decrease until the 30th period, the decrease of natural resources can stop after that. Therefore, subjects prefer to continue the game by preserving natural resources, rather than seeking the myopic consumption payoff. As a result, most subjects choose action EC. In most subject groups, depletion of natural resources does not occur and the resources can be preserved indefinitely. In treatment 4, only two groups out of all 14 groups finished before reaching $T_{\max}$.

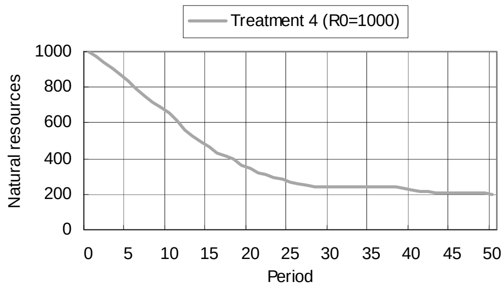

Figure 5: Transition of natural resources

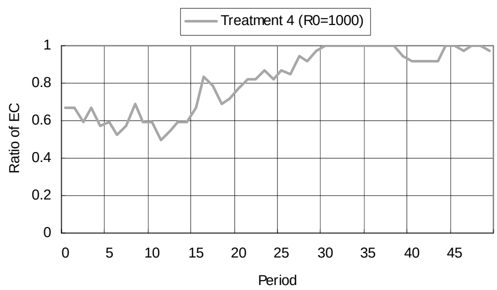

Figure 6: Ratio of environmentally conscious behavior EC

Figure 6 shows the transition of the average ratio of action EC. Compared with Fig. 4, although the ratio of EC is low in the early period, the ratio increases drastically in the latter half. Environmentally conscious behavior is fostered by a sense of crisis of resource exhaustion.

4.5 Comparison of the degraded resources game and limited resources game

A comparison of all four treatments is instructive. Figure 7 shows the transition of natural resources in all treatments. For easy comparison, we arrange the initial natural resources to be equivalent and plot the amount of reduction in Fig. 7. That figure shows that reduction in the first 20 periods is similar for treatments 1 and 4. On the other hand, treatments 2 and 3 show a similar appearance of reduction through all periods.

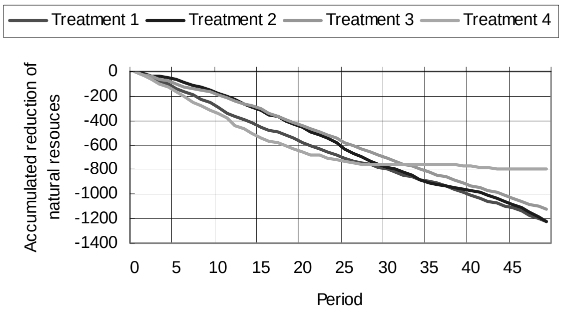

Figure 7: Transition of natural resources in all treatments

Next, we examine the relation between the change of behavior and the amount of remaining natural resources. Figures 8–11 show the frequency of behavior change in several amounts of resources. The vertical axis stands for the frequency of behavior change and the horizontal axis stands for remaining natural resources. In these figures, treatments 1 and 4 present a common remarkable feature. The line graph of "EH to EC" shows a peak around 10 in Figures 8 and 11. This means that before natural resources become zero, many subjects change their behavior from environmentally conscious behavior (EC) to environmentally hostile behavior (EH). Interestingly, many subjects change EC to EH, even though the game does not finish in treatment 1 when the natural resources become zero.

Treatments 2 and 3 mutually show a similar tendency. From Figures 9 and 10, it is found that subjects who change their behavior are few. Accordingly, in those treatments, there is no trigger to induce subjects to change behavior from environmentally hostile behavior to environmentally conscious behavior.

From these results, we can infer that a sense of crisis of exhaustion is important. However, it does not matter whether the exhaustion is true or not. A sense of crisis can trigger environmentally conscious behavior.

5 DISCUSSION

These experimental results indicate that environmentally hostile behavior cannot be halted in the degraded resources game (treatments 1, 2 and 3) even if the natural resources are decreasing, but the environmentally hostile behavior can

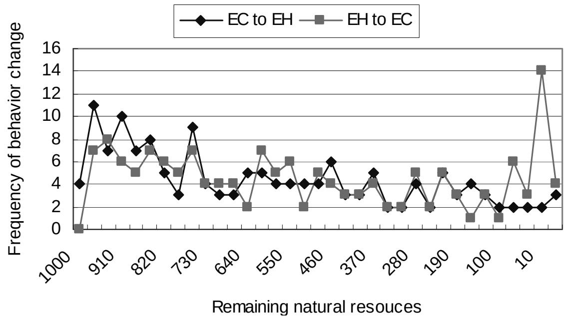

Figure 8: Relation between behavior change and remaining natural resources in treatment 1

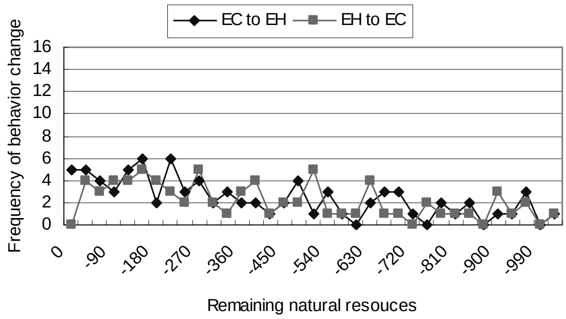

Figure 9: Relation between behavior change and remaining natural resources in treatment 2

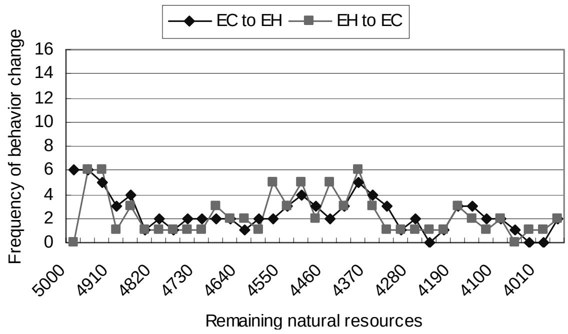

Figure 10: Relation between behavior change and remaining natural resources in treatment 3

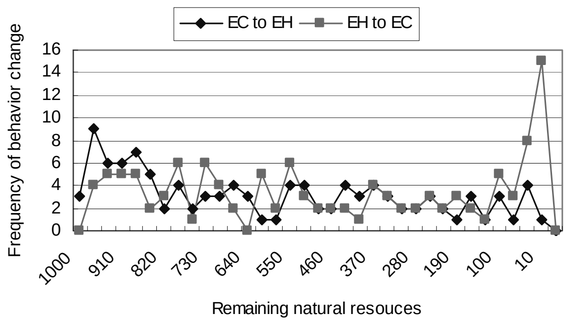

Figure 11: Relation between behavior change and remaining natural resources in treatment 4

decrease and disappear before exhausting natural resources in the limited resources game (treatment 4). The degraded resources game can be regarded as a representation of environmental problems for which exploitation of natural resources might engender negative effects in the distant future such as increasing greenhouse gases, atmospheric pollution, and deforestation. In this situation, environmentally conscious behavior to conserve natural resources is difficult. However, if people feel a sense of crisis, cooperative behavior might be elicited from environmentally hostile people because experimental results show that natural resources' depletion to zero elicits environmentally conscious behavior in treatment 1.

On the other hand, the limited resources game can be regarded as an environmental problem such that people cannot obtain benefit from natural resources if they are exhausted. This situation corresponds to problems such as overexploitation of mineral resources, oil, and other fossil fuels. People cannot receive benefits from these natural resources if they are exhausted through overexploitation: for example, people cannot perpetually use aluminum products if bauxite deposits become unavailable. In the limited resources game, a player can obtain no payoff if natural resources become fully depleted because the game is finished. Accordingly, it is implied that people who face the use of limited natural resources have a strong incentive to adopt environmentally conscious behavior.

Results of both the degraded resources game and the limited resources game imply that awareness of natural resource limitations might be powerful to compel people to halt environmentally hostile behavior.

6 CONCLUDING REMARKS

This study examined problems of environmentally conscious decision-making in resource consumption using experiments with human subjects. A decision-making model of a dilemma situation was constructed based on game theory. In the model, two types of game were prepared: a degraded resources game and a limited resources game. These experimental results suggest that environmentally conscious behavior depends on the properties of environmental problems. Especially, self-interested behavior might cease when humans become aware of a scarcity of natural resources.

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An Integrated Model for Evaluating Environmental Impact of Consumer's Behavior: Consumption 'Technologies' and the Waste Input-Output Model

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Abstract
This paper is concerned with a new integrated analytical model for evaluating environmental loads induced by consumer behavior. The model consists of two components: One is the waste input-output (WIO) model that is a consistent framework for the hybrid life-cycle assessment and life-cycle costing. The other is an economics model of consumer behavior within the constraints of limited income and time based on the concept of consumption 'technologies.' Because consumers are regarded as industrial sectors in the newly developed model, not only time and income rebound effects but also a part of the so-called economy-wide rebound effects is accounted for.

Keywords:
Sustainable consumption; Rebound effect; Waste input-output; Consumption technology

1 INTRODUCTION

The growing attention to issues of sustainable consumption has been accelerated by the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns (The Marrakech Process) by UNEP/UNDESA. In order to promote sustainable consumption, suitable methods for quantifying the environmental impact of consumer behavior are necessary. The life-cycle approach is one of the most important and well-developed concepts on which such methods can be based [1]. The purpose of this paper is to propose an analytical model for evaluating environmental impacts of consumer behavior based on the life-cycle approach.

The so-called rebound effect is well recognized in the literature of energy economics and industrial ecology that should be properly taken into account in analyzing consumer behavior [2] [3]. Takase and colleagues [4] have extended the waste input-output (WIO) model [5] to take account of the income rebound effect, that is, the rebound effect due to spending money left over by consumer's 'green' activities. Jalas [6] [7] has discussed a time use perspective on the consumer behavior and taken account of the time rebound effect, that is, the rebound effect due to making use of the time left over. Takase and colleagues [8] have introduced the concept of consumption 'technology' and developed an integrated analytical model which considers both the income and time rebound effects.

The integrated model that is newly developed and proposed in this paper consists of two components. One is the WIO model that is a consistent framework for the hybrid life-cycle assessment (LCA) and life-cycle costing (LCC) [5] [9]. The environmental loads induced by purchasing products can be evaluated by the WIO quantity model [5] in a manner similar to the conventional input-output model in LCA. The environmental loads are related to the upstream of the three stages of consumption (purchase, use, and disposal) [4]. In addition, the prices of goods and services including waste treatment are calculated, given industrial technology and consumers' life style, by the WIO price model [9] [10].

The other component of the newly developed model is an economics model of consumer behavior within the constraints of limited income and time based on the concept of consumption 'technologies' a notable feature of which is similar to the idea proposed by G. S. Becker [11] in 1960s. In the consumer model, given prices, income, and time, the consumers are assumed to choose their activity levels of various consumption 'technologies' which maximize their utility. A consumption 'technology' in the model is expressed as a set of products and time necessary to achieve some purpose, such as eating and transportation.

The newly developed model is an extension of the model developed by Takase and colleagues [8], as explained below. We have the WIO price model as a component of our model while Takase and colleagues do not. The consumer in our model is regarded as an industrial sector while the consumer in Takase and colleagues' model is regarded as a final demand sector. A part of the so-called economy-wide rebound effects is thus taken into account in our model [1].

2 THE MODELS TO BE INTEGRATED

2.1 The waste input-output quantity model

Let there be n^{I} goods-producing sectors, n^{II} waste treatment sectors, n^{W} types of waste and n^{E} types of environmental loads. The basic equation of the WIO quantity model [5] is given by

$$\begin{bmatrix} \mathbf{x}_{\mathrm{I}} \\ \mathbf{x}_{\mathrm{II}} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{\mathrm{I}} & \mathbf{A}_{\mathrm{II}} \\ \mathbf{SG}_{\mathrm{I}} & \mathbf{SG}_{\mathrm{II}} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{\mathrm{I}} \\ \mathbf{x}_{\mathrm{II}} \end{bmatrix} + \begin{bmatrix} \mathbf{X}_{\mathrm{IF}} \\ \mathbf{SW}_{\mathrm{F}} \end{bmatrix}, \tag{1}$$

where subscript I refers to goods-producing sectors, subscript II to waste treatment sectors, $\mathbf{x}_{\mathrm{I}}$ to the vector of outputs of goods-producing sectors, $\mathbf{x}_{\mathrm{II}}$ to the vector of activity levels of waste treatment sectors, $\mathbf{A}_{\mathrm{I}}$ and $\mathbf{A}_{\mathrm{II}}$ respectively refer to the conventional input coefficient matrix of goods-producing sectors and waste treatment sectors, $\mathbf{G}_{\mathrm{I}}^{+}$ and $\mathbf{G}_{\mathrm{II}}^{+}$ respectively refer to the gross waste generation coefficient matrices of goods-producing sectors and waste treatment sectors, $\mathbf{G}_{\mathrm{I}}^{-}$ and $\mathbf{G}_{\mathrm{II}}^{-}$ respectively refer to the gross waste input coefficient matrices of goods-producing sectors and waste treatment sectors, $\mathbf{G}_{\mathrm{I}}$ and $\mathbf{G}_{\mathrm{II}}$ respectively refer to the net waste generation coefficient matrices defined as $\mathbf{G}_{\mathrm{I}} = \mathbf{G}_{\mathrm{I}}^{+} - \mathbf{G}_{\mathrm{I}}^{-}$ and $\mathbf{G}_{\mathrm{II}} = \mathbf{G}_{\mathrm{II}}^{+} - \mathbf{G}_{\mathrm{II}}^{-}$, $\mathbf{X}_{\mathrm{IF}}$ refers to the vector of final demand for goods, $\mathbf{W}_{\mathrm{F}}$ to the vector of waste generation by the final demand sector, and $\mathbf{S}$ to the allocation matrix, the (i,k) component of which refers to the share of waste k that is not recycled but treated by treatment sector j. Let $\mathbf{R}_{\mathrm{I}}$ and $\mathbf{R}_{\mathrm{II}}$ respectively denote the direct emission coefficient matrices of goods-producing sectors and waste treatment sectors. Gevin industrial technologies ($\mathbf{A}_{\mathrm{I}}$, $\mathbf{A}_{\mathrm{II}}$, $\mathbf{G}_{\mathrm{I}}$, $\mathbf{G}_{\mathrm{II}}$, $\mathbf{R}_{\mathrm{I}}$, $\mathbf{R}_{\mathrm{II}}$), consumers' lifestyle ($\mathbf{X}_{\mathrm{IF}}$, $\mathbf{W}_{\mathrm{F}}$), and waste management policy ($\mathbf{S}$), the industrial output $\mathbf{x}$ and environmental load $\mathbf{e}$ are obtained as

$$\begin{bmatrix}\mathbf{x}_{\mathrm{I}}\\ \mathbf{x}_{\mathrm{II}}\end{bmatrix} = \left(\mathbf{I} - \begin{bmatrix}\mathbf{A}_{\mathrm{I}} & \mathbf{A}_{\mathrm{II}}\\ \mathbf{S}\mathbf{G}_{\mathrm{I}} & \mathbf{S}\mathbf{G}_{\mathrm{II}}\end{bmatrix}\right)^{-1}\begin{bmatrix}\mathbf{X}_{\mathrm{IF}}\\ \mathbf{S}\mathbf{W}_{\mathrm{F}}\end{bmatrix}, \tag{2}$$

$$\begin{aligned}\mathbf{e} &= \begin{bmatrix}\mathbf{R}_{\mathrm{I}} & \mathbf{R}_{\mathrm{II}}\end{bmatrix}\begin{bmatrix}\mathbf{x}_{\mathrm{I}}\\ \mathbf{x}_{\mathrm{II}}\end{bmatrix} + \mathbf{E}_{\mathrm{F}}\\ &= \begin{bmatrix}\mathbf{R}_{\mathrm{I}} & \mathbf{R}_{\mathrm{II}}\end{bmatrix}\left(\mathbf{I} - \begin{bmatrix}\mathbf{A}_{\mathrm{I}} & \mathbf{A}_{\mathrm{II}}\\ \mathbf{S}\mathbf{G}_{\mathrm{I}} & \mathbf{S}\mathbf{G}_{\mathrm{II}}\end{bmatrix}\right)^{-1}\begin{bmatrix}\mathbf{X}_{\mathrm{IF}}\\ \mathbf{S}\mathbf{W}_{\mathrm{F}}\end{bmatrix} + \mathbf{E}_{\mathrm{F}},\end{aligned} \tag{3}$$

where the inverse matrix is assumed to exsit and $\mathbf{I}$ refers to the identity matrix of suitable order and $\mathbf{E}_{\mathrm{F}}$ to the direct emission by the final demand sector.

2.2 The waste input-output price model

The basic equation of the WIO price model [9] [10] is given by

$$\begin{aligned}\begin{bmatrix}\mathbf{p}_{\mathrm{I}} & \mathbf{p}_{\mathrm{II}}\end{bmatrix} &= \begin{bmatrix}\mathbf{p}_{\mathrm{I}} & \mathbf{p}_{\mathrm{II}}\end{bmatrix}\begin{bmatrix}\mathbf{A}_{\mathrm{I}} & \mathbf{A}_{\mathrm{II}}\\ \mathbf{S}(\mathbf{I}-\mathbf{D})\mathbf{G}_{\mathrm{I}}^{+} & \mathbf{S}(\mathbf{I}-\mathbf{D})\mathbf{G}_{\mathrm{II}}^{+}\end{bmatrix}\\ &+\mathbf{p}_{\mathrm{W}}\begin{bmatrix}\mathbf{G}_{\mathrm{I}}^{-} - \mathbf{D}\mathbf{G}_{\mathrm{I}}^{+} & \mathbf{G}_{\mathrm{II}}^{-} - \mathbf{D}\mathbf{G}_{\mathrm{II}}^{+}\end{bmatrix} + \begin{bmatrix}\mathbf{v}_{\mathrm{I}} & \mathbf{v}_{\mathrm{II}}\end{bmatrix},\end{aligned} \tag{4}$$

where $\mathbf{p}$ refers to the vector of prices, $\mathbf{v}$ to the vector of primary input per unit of output, subscript W to waste, and $\mathbf{D}$ to a diagonal matrix with the rate of recycling in its diagonal and the rate of recycling follows from (2). Gevin industrial technologies ($\mathbf{A}_{\mathrm{I}}$, $\mathbf{A}_{\mathrm{II}}$, $\mathbf{G}_{\mathrm{I}}$, $\mathbf{G}_{\mathrm{II}}$, $\mathbf{v}_{\mathrm{I}}$, $\mathbf{v}_{\mathrm{II}}$), consumers' lifestyle ($\mathbf{X}_{\mathrm{IF}}$, $\mathbf{W}_{\mathrm{F}}$), market price of waste materials ($\mathbf{p}_{\mathrm{W}}$), and waste management policy ($\mathbf{S}$), the price of good is obtained as

$$\begin{bmatrix}\mathbf{p}_{\mathrm{I}} & \mathbf{p}_{\mathrm{II}}\end{bmatrix} = \bar{\mathbf{v}}\left(\mathbf{I} - \begin{bmatrix}\mathbf{A}_{\mathrm{I}} & \mathbf{A}_{\mathrm{II}}\\ \mathbf{S}(\mathbf{I}-\mathbf{D})\mathbf{G}_{\mathrm{I}}^{+} & \mathbf{S}(\mathbf{I}-\mathbf{D})\mathbf{G}_{\mathrm{II}}^{+}\end{bmatrix}\right)^{-1} \tag{4}$$

where

$$\bar{\mathbf{v}} = \mathbf{p}_{\mathrm{W}}\begin{bmatrix}\mathbf{G}_{\mathrm{I}}^{-} - \mathbf{D}\mathbf{G}_{\mathrm{I}}^{+} & \mathbf{G}_{\mathrm{II}}^{-} - \mathbf{D}\mathbf{G}_{\mathrm{II}}^{+}\end{bmatrix} + \begin{bmatrix}\mathbf{v}_{\mathrm{I}} & \mathbf{v}_{\mathrm{II}}\end{bmatrix}. \tag{5}$$

Note that the price of goods depends upon the consumers' lifestyle through the rate of recycling $\mathbf{D}$ although the vectors ($\mathbf{X}_{\mathrm{IF}}$, $\mathbf{W}_{\mathrm{F}}$) representing consumers' lifestyle do not appear in (4) and (5).

2.3 The consumer model

A typical model for describing consumer behavior in the literature of economics is of the form:

$$\begin{aligned}&\text{maximize} \quad u(\mathbf{q}) = u(q_1, \ldots, q_n)\\ &\text{subject to} \quad \mathbf{pq} = Y\end{aligned} \tag{6}$$

where u refers to a utility function which represents the degree of consumer's satisfaction obtained by consuming goods $\mathbf{q}$, and Y .refers to consumer's income. The above utility maximization problem (6) is quite general and abstract. One might think that it is unrealistic to assume that a consumer maximizes her or his utility. However, we employ the assumption because there is not any much better tractable methods for describing consumer behavior to consume all the types of goods to our knowledge and it is expected that at least an average tendency is figured out by the utility maximization problem.

In the above utility maximization problem (6), only the income budget constraint $\mathbf{pq} = Y$ is taken into account. Because no time restriction is taken into account, an optimal solution to the utility maximization problem (6) might be infeasible in the reality. In other words, the consumer can purchase a bundle of goods $\mathbf{q}$ which is an optimal solution to (6) but might not be able to consume it due to the possible shortage of time. To incorporate the time restriction into the model, the concept of consumption 'technologies' is useful, which is similar to the idea proposed by G. S. Becker [11] in 1960s. It is assumed that consumers choose not the amount of goods directly but the activity levels of various consumption 'technologies' to maximize their utility. Let there be m consumption technologies. Let $\mathbf{B}_q$ denote the matrix of goods input coefficients, $\mathbf{b}_t$ the vector of time input coefficients and $\mathbf{z}$ the vector of activity levels of consumption technologies. Suppose, for instance, that the first consumption technology is 'eating breakfast at home'. Then, the components of the first column of $\mathbf{B}_q$ refer to the amount of food (e.g., water, bread, egg, sausage, milk, salt, pepper, and edible oil) and the amount of energy (electricity and gas), and the first component of $\mathbf{b}_t$ refers to the length of time for cooking one serving of breakfast and washing dishes. Therefore, the consumer's utility maximization problem in which the time restriction is taken into account can be written as

$$\begin{aligned}&\text{maximize} \quad u(\mathbf{q}) = u(\mathbf{B}_q\mathbf{z})\\ &\text{subject to} \quad \mathbf{pq} = \mathbf{pB}_q\mathbf{z} = Y, \quad \mathbf{b}_t\mathbf{z} = T\end{aligned} \tag{7}$$

where T refers to the amount of available time.

3 THE INTEGRATED MODEL

We integrate the three models explained in the previous section as in Figure 1. First, consumption levels and patterns affect the amount of industrial outputs, waste generation, and the rate of recycling through the WIO quantity model. Second, the rate of recycling affects the prices of goods through the WIO price model. Third, the prices affect consumption levels and patterns through the consumer model. Namely, a part of the economy-wide rebound effect is accounted for through changes in prices.

In order to integrate the WIO quantity model and the consumer model, we divide the final demand sector into two parts as

$$\mathbf{X}_{\mathrm{IF}} = \mathbf{X}_{\mathrm{IH}} + \mathbf{X}_{\mathrm{IO}}, \quad \mathbf{W}_{\mathrm{F}} = \mathbf{W}_{\mathrm{H}} + \mathbf{W}_{\mathrm{O}}, \tag{8}$$

where subscript H refers to consumer (or household) and subscript H to the other final demand sectors. Note that $\mathbf{X}_{\mathrm{IH}}$ corresponds to the quantity $\mathbf{q}$ of goods consumed in the consumer model described in the previous section. Because the generation of waste by consumers, $\mathbf{W}_{\mathrm{H}}$, is inevitably caused by goods purchased, $\mathbf{X}_{\mathrm{IH}}$, the equality $\mathbf{W}_{\mathrm{H}} = \mathbf{K}_{\mathrm{H}}\mathbf{X}_{\mathrm{IH}}$ holds with a coefficient matrix $\mathbf{K}_{\mathrm{H}}$ of the consumer.

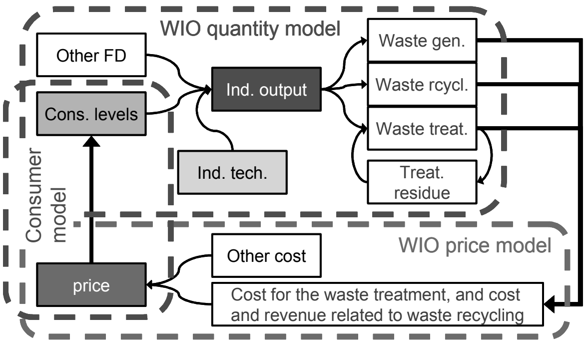
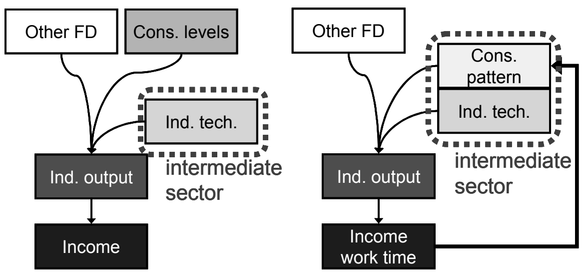


Figure 1: Integration of the three models.

In addition, we endogenize the consumer, that is, we regard the consumer as an industrial sector in our model [13], as in Figure 2(b). Because the activity level of the endogenized consumer 'sector' is measured in hours of labor, the consumer chooses her or his consumption pattern in our model, considering a trade-off between more income and less time for consumption. Of course, the consumer as an employee cannot work longer than offered by her or his employer. Namely, another part of the economy-wide rebound effect is accounted for through the labor market.



(a) Final demand sector (b) Intermediate sector

Figure 2: Endogenization of consumer.

4 APPLICATION OF THE INTEGRATED MODEL TO THE JAPANESE ECONOMY

4.1 Data and settings

We apply the integrated model to the Japanese data: the WIO table of 2000 [12] which has 396 industrial sectors, 13 treatment sectors, 49 types of municipal solid waste, and 29 types of industrial waste, and the governmental surveys on household expenditure and time-use in Japan. We consider 15 types of consumption technologies (Table 1). The operation levels of transportation are measured in person-km based on the average speed and governmental statistics of passenger transportation. The operation levels of eating activities are measured in food intake per day per capita. The others are measured in time.

Table 1: Consumption technologies.

Consumption technologies	Operation level in 2000
1 Travel by car	18.598 [person-km]
2 Travel by train	6.744
3 Travel by bus	1.879
4 Cooking and eating at home	0.786 [foods intake/day]
5 Eating precooked food at home	0.039
6 Eating out	0.175
7 Sleep, nap and rest	8.255 [hours]
8 Housework	2.463
9 Work	3.662
10 Schoolwork	0.849
11 Reading and recreation	1.298 [hours]
12 TV, radio, music and videos	2.397
13 Sport	0.283
14 Light meals	0.266
15 Others	0.799

We choose the following functional form of the utility function:

$$u(\mathbf{q}) = \sum_{i=1}^{15} \beta_i (q_i - \alpha_i) \tag{8}$$

However, non-zero values of α_i are employed only in sensitivity analyses later, and they are set equal to zero in the main part of secenario analyses.

4.2 Numerical example

We impose additional constraints such that the total amount of food intake is equal to or greater than the 95% of the initial level, the total amount of transportation is equal to or greater than the 90% of the initial level, the operation level of sleep, nap and rest is equal to the initial level. As for an environmentally 'friendly' scenario, the consumer is imposed additional constraints such that 'travel by car' is reduced by 50% and 'cooking and eating at home' is reduced by 66.7%, although this might be an unrealistically drastic change.

The results of scenario analysis can be summarized as follows. As for transportation (Figure 3), 'travel by bus' has increased more compared to 'travel by train', that is, 17%/7% is greater than 45%/25%, because 'travel by bus' is more time-consuming than 'travel by train' and there is a surplus of time. As for eating (Figure 4), 'eating out' has increased more compared to 'eating precooked food at home' because 'eating out' is more time-consuming than 'eating precooked food at home' and there is a surplus of time. Although 'eating out' is more expensive than 'eating precooked food at home', the change is feasible due to the increase of income by 1.4%.

As for other activities, 'TV, radio, music and videos' has increased much (by 41.5%) due to a surplus of time. As for environmental impacts, CO2 emission has decreased by 2.21% and the consumption of landfill site has decreased by 3.58%.

A sensitivity analysis is carried out for checking whether or not the results of scenario analysis mentioned above is robust to the specification of the utility function. In the literature of economics, it is known that α_i is regarded as the minimum requirement level of consumption activities. Setting the value of α_i equal to 0.2 or 0.5 for luxuries and 0.5 or 0.6 for necessities, we have performed the same calculations. As a results, the qualitative aspects of the results have not changed.

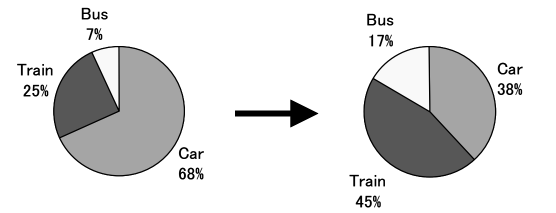


Figure 3: Change in transportation

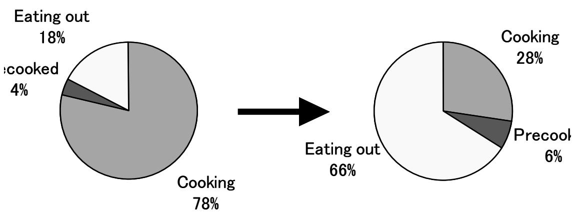


Figure 4: Change in eating

5 CONCLUDING REMARKS

This paper has proposed an analytical model for evaluating the environmental impact of consumer behavior by introducing the concept of consumption 'technologies' and by integrating the waste input-output quantity and price models and one of the economics model describing consumer behavior. A notable feature of the newly developed model is its ability to account for a part of the economy-wide rebound effect as well as the income and time rebound effects. As a numerical example, it has been shown that 'cooking and eating at home' and 'travel by car' are less environment-friendly. Conducting more realistic case studies based on survey data is an important remaining future task.

In the developed model, the change of consumer's behaviour has been caused by merely imposing an upper bound to the activity level of a consumption technology which is thought not to be environmentally friendly. The model can be straightforwardly applied to the case where a green tax is introduced to change consumer behaviour.

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Proposal of a Measuring Method of Customer's Attention and Satisfaction on Services

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Abstract

Now a day, with the emerging growth of the service industry, manufacturing companies are convinced that their products must be strengthened with service. Thus, we have developed a new discipline called Service Engineering that aims to produce a novel method to design service from an engineering viewpoint. In this paper, the authors propose an evaluation model that enables service designers to measure receivers' satisfaction. The authors proposed the "Satisfaction – Attribute Value Function" as an evaluation model that suits man's behavior. Applying to an example, the result of our method had richer information than the result of conjoint analysis.

Keywords:

Customer Satisfaction, Value Engineering, Service Evaluation, Service Engineering

1 INTRODUCTION

The life cycle periods of products are shortened in recent years, and service is paid attention as a way to achieve high additional value. Design process of services needs to include an evaluation that allows the designer to know how the service is rated by customers. In conventional engineering, manufacturing products are evaluated by functions they have. As services are artifacts as same as products, the same method as for manufacturing products is considered applicable to service design. From the same point of view, we assume that the customer evaluates properties of its functions and feels satisfied. However, service is likely to be evaluated more subjectively. Therefore, we need a new model that represents man's subjective behavior. This paper aims at proposing an evaluation method for service designers that makes this degree of satisfaction to be measured as quantitative value. This quantitative value of customer satisfaction enables the designer to know, for example, how much the price can be increased after modified the service, or clear up which functions are needed for each marketing segment.

In second chapter of this paper, models and concepts proposed in Service Engineering [1] that our proposal is based on are introduced. In third section, we introduce two current evaluation frameworks: Kano Model from Engineering and Prospect Theory from Behavioral Economics. In forth and fifth chapter, we propose a new evaluation method combining these methods. In sixth chapter, an application of the method is shown, and we make a comparison with conjoint analysis. Conclusions are argued in seventh chapter.

2 SERVICE ENGINEERING

2.1 Definition of service

Service is generally perceived as an activity that changes the state of a service receiver [1]. Figure 1 defines service; a service receiver receives service contents from a service provider through a service channel in order to change own states by the contents. This state of a service receiver is called RSP (Receiver State Parameter).In this definition, a service receiver is satisfied by only means of how much the receiver's states are changed preferably.

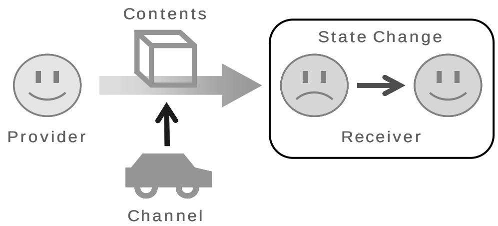

Figure 1. Definition of Service

2.2 View model

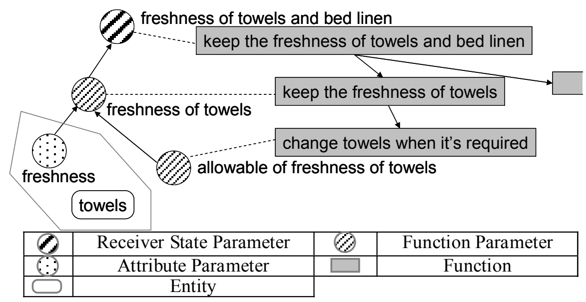

Figure 2. View Model

As Figure 2 shows, a model written in the form of network diagrams is called View Model [1]. The top node, a hatched circle, indicates RSP. A square represents a function that influences a parameter connected with a dotted line. Each node represents either function or attributes of a service. The nodes surrounded by the solid line at the left bottom illustrate the realization structure.

A Function Parameter (FP), influencing directly to the RSP, is called Contents Parameter (CoP) and FP influencing indirectly through CoP is called Channel Parameter (ChP). Each substantial artifact, constructing a service, is defined as entity, of which attributes are defined as attribute parameters (APs).

2.3 Existing Evaluation Method

To design service effectively and more value-added, designers needs a method to compare multiple services. We proposed Analytic Hierarchy Process (AHP) [2] based importance analysis method of RSPs, a QFD [3] (Quality Function Deployment) based importance analysis method of CoPs, and an influence analysis between a RSP and FPs using Dematel [4] method [5]. These methods enabled service designers to know which part of service should be paid attention and made them easier to improve services. However, these methods cannot make the designer know how much upgraded service is improved. For this purpose, we need a method that evaluates services totally using the viewpoint of service receivers.

3 SATISFACTION MODELS IN OTHER FIELDS

Some studies have dealt with customer satisfactions. Karl Albrecht categorized relationships between customer's expectation and provided products into four levels [6]. Bernd H. Schmitt advocated the concept of experimental marketing and categorized customer experiences into SENSE, FEEL, THINK, ACT, and RELATE [7]. In this chapter, two models on customer satisfaction used in our model is introduced.

3.1 Kano Model

A customer satisfaction model was proposed for quality management by Kano [8]. This model categorizes quality attributes into five kinds of elements according to customer satisfaction: attractive quality element, one-dimensional one, must-be one, indifferent one, and reverse one. Figure 3 illustrates the first three quality elements out of the five. Horizontal axis indicates the state of physical fulfillment on a parameter. Attractive quality elements influence little to customer satisfaction, even if they are not fulfilled physically. This is because the elements are strongly expected. On the other hand, must-be quality elements are recognized as matters of course, and thus makes great dissatisfaction once they are little fulfilled.

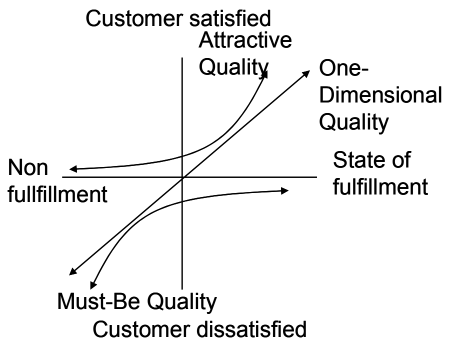

Figure 3. Customer Satisfaction Model by Kano

3.2 Prospect Theory

Prospect theory was developed by Kahneman and Tversky [9], which was originally proposed as a criticism of expected utility model in economics. It describes how individuals evaluate losses and gains based on empirical evidence. It consists of two theories: value function and weighting function. The former describes the relationship of value to gains and losses as illustrated in Figure 4. Its horizontal axis shows gains and losses in the form of absolute values such as an interest of investment or a reward of lottery. The origin indicates the prospect of the individual, which is called a reference point. Its asymmetry implies that losses give a stronger impact than gains. This feature is called loss aversion. Note that the curve in Figure 4 turns saturated when the losses or the gains become farther from the reference point.

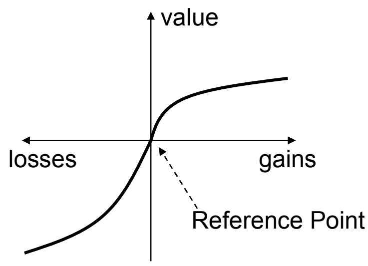

Figure 4. Value Function of Prospect Theory

The weighting function represents that individuals behave according to a psychologically biased probability rather than its theoretical probability. Individuals often misunderstand the occurrence probabilities of phenomena, i.e., an individual expects the preferable phenomenon in higher probability than in its actual one when the probability is very low.

4 CUSTOMER SATISFACTION EVALUATION

In this chapter, we propose a new evaluation method for customer's satisfaction. First, we define function called Satisfaction-Attribute Value function. This enables the designer to calculate satisfaction of the receiver. Second, we propose an evaluation flow that uses the S-AV function.

4.1 Satisfaction - Attribute Value Functions

We propose the "Satisfaction - Attribute Value (S-AV) function" in this section. The definition of the S-AV function (S_r) is a bunch of mappings between satisfaction (S_{FP}) of a receiver for an RSP and FP values of a service (Equation 1). Here, satisfaction is expressed as a real number from -1 to 1. The designer can estimate satisfaction of the receiver for an RSP by using the S-AV function according to the value of FP.

$$S_{FP} = S_r(FPValue) \quad (1)$$

We defined the word satisfaction as change of an RSP according to the definition of service. The designer hardly knows the change of the RSP, which is an internal state of a receiver. However, the designer can estimate the change of the RSP from changes of FPs, because the RSP is influenced by FPs. The value of FP is expressed in the form of attribute value that is quantitative and visible by the designer. That is, the designer can estimate how the satisfaction changes by changes of FPs by using the S-AV function. A set of questionnaires to the receivers is used to decide the S-AV function. Details are described in Chapter 5.

4.2 Experimental Appraisal Importance and Attention Importance

The satisfaction for the service is given by the weighted sum of satisfaction for each RSP. We assume that the weight is determined by two classes of importance, "experimental appraisal importance" and "attention importance". The former is accumulated through repeat receptions of a service and inversely proportional to the satisfaction. The latter is used when the receiver evaluates after receiving the service. This importance is proportional to the level of satisfaction (or dissatisfaction). We introduce attention importance to decide weight of a FP for following evaluation steps.

4.3 Evaluation Steps

[Step 1] Describe Service in View Model

In first step, the designer has to describe supposed service in view model. Above all, the designer should decide a persona of the receiver. Persona is a virtual character of the receiver. Therefore, to decide the persona is just as same as to decide target customer in marketing process. Describing the service in the view model, the designer can decide RSPs that the receiver has and relationships between FPs and affected RSPs.

[Step 2] Decide Weight for each FP

Although a view model has a network structure of FPs, each FP does not influence equally on the RSP. Therefore, to decide which FPs are more influential, the designer allocates weights to each FP. This step is done by the existing evaluation method using QFD and Dematel.

[Step 3] Find S-AV Function for each FP

In third step, setting S-AV functions on each FP, the designer can define relationships between satisfaction about the RSP and each FP value. Namely, each FP has just one S-AV function. S-AV functions should be set on FPs placed at the end of the network structure. Instead of setting S-AV functions on these FPs, the designer can set on FPs that is affected by a few of these FPs. In this case, the designer needless to set S-AV functions on FPs that are affected only by those already have S-AV functions.

[Step 4] Set Attribute Parameter Values

In this step, the designer configures supposed attribute value on FPs have S-AV functions. By setting attribute values, he/she becomes to be able to know supposed degree of satisfaction given by each FP.

[Step 5] Calculate Receiver Satisfaction

Finally, the designer can calculate receiver's satisfaction for the whole service. Satisfactions about each RSP are given by following Equation 2. This equation means satisfaction about RSP is given by weighted sum of S-AV functions. Here, w_{FP} is weight value obtained in Step 2.

$$S_{RSP} = \sum w_{FP} S_{FP} \tag{2}$$

Satisfaction for the whole service is also calculated by the weighted sum of satisfactions for RSPs, given by Equation 3. w_{RSP} is the weight value given by the existing evaluation method for allocating weight of each RSP using AHP.

$$S = \sum w_{RSP} S_{RSP} \tag{3}$$

This satisfaction about the whole service is given as a real number from -1 to 1 as same as return value of S-AV function.

5 FINDING S-AV FUNCTION

In this chapter, we argue a concrete method to find S-AV function defined and used in the previous chapter.

5.1 Characteristics of the S-AV function

S-AV function is one of so-called perceptions-minus-expectations models [11]. The basic ideas of these models are that the receiver evaluates difference between the service expected and the service actually received. SERVQUAL [10], which is one of the famous evaluation methods for service, is perception-minus-expectations model, too. Moreover, our S-AV function has following characteristics from the prospect theory.

Reference Point

Satisfaction is decided by difference between a service that the receiver expected and an actual service. Moreover, the expectation strongly depends on receiver's knowledge, experience and other personal factors. Therefore, we match the reference point to the personal differences in S-AV function. Using the concept of the reference point, S-AV functions are represented by a combination of two functions connecting at an attribute value that the receiver expects. They are called gain side function and loss side function respectively. Generally, the receiver's expectation has two levels: desired and adequate [11]. The reference point indicates an adequate level rather than a desired level. The range from the adequate level to the desired level is called zone of tolerance. This means attribute values, which are inferior to the adequate level, lead the receiver to dissatisfaction. On the other hand, attribute values exceed the adequate level satisfies the receiver.

Loss Aversion

According to an experiment of the prospect theory, the receiver would judge it as "loss" and behave to averse loss, if an quality element of the service was worse than expected. Therefore, the loss aversion feature in the prospect theory is applicable to S-AV function. However, this hypothesis involves a contradiction with the kano model, because loss at attractive quality does not cause dissatisfaction according to the kano model. This contradiction is caused by difference of viewpoint. The value function in the prospect theory discusses the whole value of a service. On the other hand, the kano model argues a part of a service. Accordingly, some parts of the service could be ignored, even if actual qualities were worse than expected. S-AV function has the same viewpoint as the kano model. Hence, we introduce loss aversion feature only if the FP is categorized as One-Dimensional function. This means S-AV function has a constraint expressed as Equation 4.

$$|S_r(a+b)| < |S_r(-a+b)| \tag{4}$$

(a is margin from the reference point,
b is attribute value on the reference point)

Decrease of Response

Satisfaction for a service generally converges if a functional performance was improved to some extent. This trait is caused by the same psychological reason as the decrease of response to value by increasing gains or losses. Therefore, the decrease of response feature also can be applied. That is, the shape of S-AV function has a constraint expressed as Equation 5 and 6.

If AV is better than the reference point, then

$$\frac{d^2 S_r}{d(AV)^2} < 0 \tag{5}$$

If AV is worse than the reference point, then

$$\frac{d^2 S_r}{d(AV)^2} > 0 \tag{6}$$

5.2 Classification of the S-AV function

Applying Prospect Theory, S-AV function obtained three constraints for its shape. Moreover, classifications of quality elements proposed by Kano model suggest further constraint to decide the shape of the S-AV functio. Hence, we introduce Kano's three quality elements to classifications of FPs as the following.

Attractive Function

If the FP is an attractive function, a decline in the functional performance will not be effect on the satisfaction of the whole service. Therefore, S-AV function on the FP has a constraint expressed as Equation 7.

If AV is worse than the reference point, then

$$S_r(AV) = 0 \tag{7}$$

One-Dimensional Function

The FP categorized as an one-dimensional function has no additional constraint except Loss Aversion mentioned before.

Must-Be Function

Likely as attractive function, if the FP is a must-be function, a functional performance exceeding receiver's expectation will not contribute to the satisfaction for the whole service. Therefore, the S-AV function on the FP has a constraint expressed as Equation 8.

If AV is better than the reference point, then

$$S_r(AV) = 0 \tag{8}$$

Consider these constraints enumerated thus far, the shape of S-AV functions are to be constructed as Figure 5.

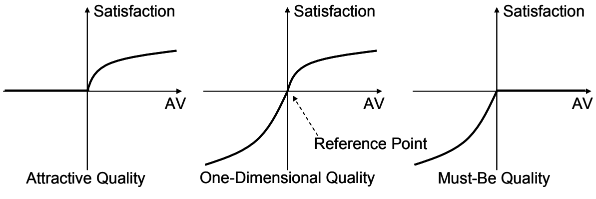

Figure 5. Shapes of S–AV Functions

5.3 Deciding the S-AV function

To calculate numerical satisfaction, a concrete numerical equation needs to be decided. However, how precise the numerical parameters of the equation are less important, because the shape of function has larger decisive magnitude for satisfaction value itself. Accordingly, the shape of the function has to be decided carefully through the result of market survey and user test on target segment.

In this section, we propose a simple method to decide approximate S-AV function in the form of numerical equation needed to calculate a numerical satisfaction value. Here, we represent each side of the S-AV function using an exponential function expressed by Equation 9.

$$S_r = a\left(1 - e^{-\frac{b}{a}(v-c)}\right) \tag{9}$$

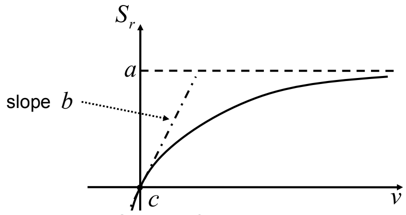

Figure 6. Shape of Approximate Function

In the equation, parameter ***a*** means the converged maximum satisfaction, parameter ***b*** means the slope at the reference point, and parameter ***c*** means the attribute value at the reference point. Variable ***v*** is an input value of this function that means attribute values. Figure 6 shows the shape of this function.

We selected this approximate function in the point of easiness to set the parameter values and capability in satisfying the constraints by the shape. An S-AV function is constructed with two exponential functions that have different parameter values. If the FP is categorized as an attractive or a must-be function, it should be set under the rule of Equation 7 or 8 respectively.

In the following part of this chapter, let us discuss the simplified method to decide an S-AV function using these exponential functions individually by categories of FP.

Attractive Quality Function

The designer has to determine two sides of functions. A function for attribute values exceeding the reference point is called gain side. Another function, which is inferior to the reference point, is called loss side. If the FP is categorized as an attractive function, only the gain side function needs to be decided, because the satisfaction value of the loss side function is always zero (Equation 7).

To keep consistency with one-dimensional quality element argued below, assume that an attractive function can provide 0.5 as the satisfaction value at the maximum. Generally, an attractive function is the receiver's need that is not yet generally recognized, so that we decided maximum satisfaction provided by the best attribute value available in the market as 0.4, leaving buffer to further satisfaction. Thus, the designer can decide parameters of Equation 9 by setting parameter ***c*** to receiver expected attribute value, parameter ***a*** to 0.5 and parameter *b* to satisfy maximum attribute value in the market.

One-Dimensional Function

If the FP is categorized as one-dimensional function, the designer start with the side that has the range of attribute value available in the market is wider. The function of this side is decided as the same method as attractive quality. Except the point if this side is the loss side, the minimum satisfaction value at the worst attribute value is decided as -0.8. According to the loss aversion feature in the prospect theory, the absolute satisfaction value in the loss side is twice as large as one in the gain side. It is empirically known that the magnitude of dissatisfaction by losses is 2 to 2.5 as much as it of satisfaction by gains [9].

Secondary, the designer work on with the other side. As same as the first side, the designer set a pair of an attribute value and a satisfaction value. In this side, we use the attribute value that its distance from the reference point is as much as the maximum / minimum attribute value in the market used in previous step. The satisfaction value at this attribute value is decided under the same rule as previous step, would be 0.4 or -0.8.Thus, the combination of these two functions constructs the S-AV function.

Must-Be Function

Strategy to decide S-AV function for a FP of must-be function is the same as above two kinds. Namely, decide satisfaction value at the minimum attribute value in the market to -0.8. The gain side function is expressed as Equation 8.

By using above methods, the designer becomes to be able to decide S-AV function as the concrete numerical equation.

6 APPLICATION TO AN EXAMPLE

6.1 Door-to-door parcel delivery service

To verify the proposed method, we performed an experiment settled on door-to-door parcel delivery services. We conducted a survey and described the service on the view models. We focused on redelivery part of the service and listed four RSPs: "flexibility of redelivery", "in advance notification of parcel arrival", "deliver parcel in safety" and "accept changes of address or time for delivery flexibly." Related FPs for each RSP are listed as shown in Table 1.

Table 1. List of RSPs and FPs (partial)

RSP	FP
Flexibility of redelivery	(a) earliest redelivery hour
	(b) latest redelivery hour
	(c) Max. days to keep parcel (in the center)
	(d) Fastest redelivery time from order

6.2 Method

We decided the S-AV function by using a questionnaire about one of the RSPs "flexibility of redelivery." Respondents are person living alone or whose family going out on daytime (n=8). We prepared questions for each FP as shown in Table 2 based on a method that Ernzer had improved [12] the original Kano method [8]. Additionally, we conducted conjoint analysis to the respondents in order to make a comparison with our method. For conjoint analysis, we prepared four services that have different attributes, is shown in Table 3. The respondents were asked to order the Service A-D. Also, AHP [2] analysis was conducted to find out importance of FPs.

Table 2. Questions about (A) expectation and (B) kano class

1. earliest redelivery hour	
(A) Which do you think is the nearest quality you expect?	1. before 6 AM 2. 6 AM 3. 7 AM 4. 8 AM 5. 9 AM 6. 10 AM 7. after 10 AM
(B) What do you feel if actual quality would be different from your expectation?	1. An earlier option must be available 2. An earlier option is preferable 3. It's all well and good 4. I wouldn't mind

Table 3. Profiles for conjoint analysis

Attribute \ Service	A	B	C	D
(a) Earliest redelivery hour	6 AM	6 AM	9 AM	9 AM
(b) Latest redelivery hour	7 PM	11PM	7 PM	1 AM
(c) Max. days to keep parcel	5 days	9 days	11 days	5 days
(d) Fastest redelivery time from order	30 m	6 h	6 h	2 h

6.3 Result

Table 4 shows the questionnaire result. Each data in the table is the mode value of effective answers.

Table 4. Classifications of FPs and Expectations for FPs

Result \ FP	Earliest redelivery hour	Latest redelivery hour	Max. days to keep parcel	Fastest redelivery time from order
Class	A[1]	O[2]	O	O
Expectation	8 AM	10 PM	11 days+[3]	1h 10m
Conjoint imp.	24.12%	20.15%	14.10%	41.63%
AHP imp.	0.096	0.26	0.23	0.41

1. Attractive function 2. One-Dimensional function
3. Longer than 11 days

Table 5. Result of S-AV function evaluation

	Service A	Service B	Service C	Service D
S_r (a)	0.40	0.40	0	0
S_r (b)	-0.99	0.45	-0.99	0.50
S_r (c)	-0.058	-1.00	-1.00	-0.058
S_r (d)	0.30	-0.26	-0.67	-0.68
Satisfaction for RSP[1]	-0.19	-0.18	-0.58	0.016
S-AV rank[2]	3	2	4	1
Conjoint rank	3	2	4	1

1. Weighted sum of S_r using AHP importance in table 4
2. Sorted by satisfaction for RSP

Moreover, S-AV functions were described based on expectation in Table 4 (Figure 7). Horizontal axises show attribute value, and vertical axises show satisfaction. Each shape of S-AV functions was decided by question B in table 2. The range of attribute value was decided by an actual service. Although the earliest redelivery hour of the actual service was 8 AM, we used 6 AM as the best realistic attribute value. Latest redelivery hour of an actual service is 9 PM. Therefore, the range was assumed 9 AM – 11 AM. Maximum days to keep parcel of the actual service are 90 days.

Table 5 shows the result of evaluation using S-AV functions in Figure 7. In this evaluation process, we used AHP method to decide importance of FP to preserve independence from conjoint analysis.

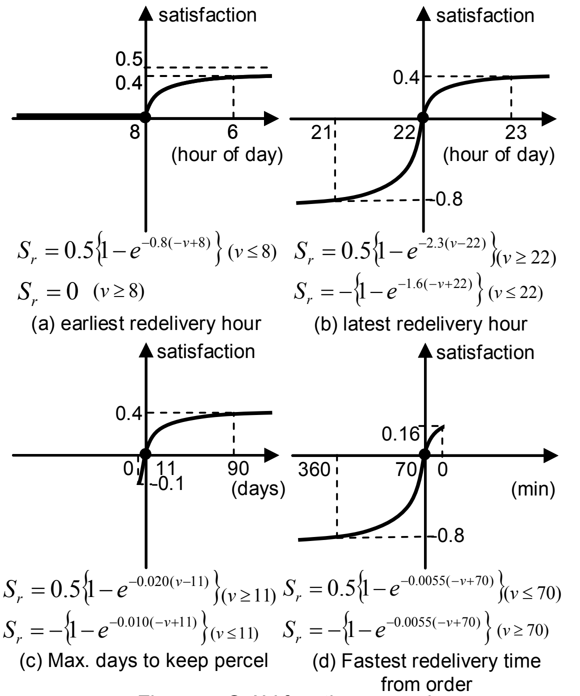

Figure 7. S-AV function examples

6.4 Discussions

Comparison with the conjoint analysis

The S-AV rank in table 5 was equal to the result of the conjoint analysis. Moreover, our method is superior to the conjoint analysis in three points:

- Free from limitations of the conjoint analysis: number of profile and number of attribute.
- Shows not only rank but also degree of satisfaction
- Less dependent on questionnaires, because S-AV functions can be reused.

Individual differences in questionnaire result

In this example, we used the mode value to extract the represented value. However, the variance of each question was different: the variance of expectation of (c), (d) was larger than (a), (b). This information could be used to categorize respondents and make another persona. If another persona was made, the S-AV function in Figure 7 would be changed and the evaluation would result differently.

7 CONCLUSION

This paper proposed a model for service designers to calculate satisfaction of the service receiver. The designer assumes the receiver's satisfaction by his expectation for each function. Using the model, the designer calculates satisfaction from the concrete attribute values that represent properties of each function in actual service. By applying the method to an example, it was proved effective and possible to predict the changes of satisfaction quantitatively when the designer changes attribute values on some FPs. Moreover, the method enables the designer to know differences of each receiver clearer than conjoint analysis. This allows the designer to propose more efficient and value-added improvement policies. Future works include clarifying how the receiver changes importance for each RSP by receiving service repeatedly. Besides, we will introduce a concept of cost to the method and getting up to real service receiver.

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A Life-cycle Comparison of Clothes Washing Alternatives

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Abstract
Several clothes washing alternatives are investigated with a specific emphasis on characterizing the benefit, if any, associated with servicizing a washing machine product. The pay for use alternative will consider a laundromat, in which people wash their clothes and pay a fee for that service. Another alternative is selling washing machines for home use. The alternatives are evaluated in terms of their economic costs and environmental impacts to provide a quantitative comparison of the alternatives. The environmental evaluation is obtained using SimaPro 7.0. Specific measures of performance that are considered include costs, energy, and water usage.

Keywords:
Sustainable; Servicizing; Utilization

1 INTRODUCTION

The world is faced with a number of sustainability-related challenges. In the developing world, these include poverty, rapid population increases, lack of safe drinking water and food, and poor sanitation and education systems. In the industrialized world, over-exploitation of material resources, excessive wastes, and extravagant energy consumption are the dominant concerns. These challenges were addressed in the so-called Brundtland Report, *Our Common Future* [1], which recognized the need to establish long-term environmental strategies to achieve sustainable development. The report defines sustainability as meeting "the needs of the present generation without compromising the ability of future generations to meet their own needs," which embraces a global scope in terms of environmental, economic and social systems. The Brundtland Report was followed with the high-profile Rio Summit in 1992 and the Johannesburg Summit in 2002 that established goals and principles for sustainable development [2,3].

The need to become more sustainable is especially acute in the United States. According to the U.S. EPA (Environmental Protection Agency) [4], 245 MTons of solid waste was generated in 2005. Of this waste, 34.2% was from paper, 13.1% from yard trimmings, 11.9% from food scraps, 11.8% from plastics, 7.6% from metals, 7.2% from rubber, leather, and textiles, 5.2% from glass, 5.7% from wood, and 3.4% other. In terms of household water consumption, Americans use an average of 60 gallons/day of which 30.9% is associated with toilets, 25.1% clothes washing, 11.6% showering, and 10.9% faucet [5]. Domestic energy usage in the U.S. is dominated by space heating (31.5%), water heating (12.6%), lighting (12.0%), and space cooling (11.1%) [6]. To achieve greater sustainability, innovative strategies must be pursued in the U.S. to avoid the generation of wastes, over-consumption of water resources, and excessive energy utilization.

One strategy that has been suggested to promote sustainability is dematerialization. In essence, dematerialization seeks to reduce the total amount of material that is used to satisfy the needs of customers. Reducing the dependence of the economy on materials would produce a number of benefits, including a decrease in the amount of solid waste and limiting human exposures to hazardous materials. Dematerialization can be achieved by reducing the weight of products, which generally requires a change in product geometry and/or material. Another dematerialization approach is to increase product life; this serves to slow the movement of materials through the economy. A third method to encourage dematerialization is offering a service as opposed to a physical product to meet the needs of a customer. Selling a function/service to consumers as opposed to selling a physical product may require dramatic changes in the corporate mindset, since the corresponding business models may differ substantially [7].

The transition from selling physical products to selling a function has been called "servicizing" or "functionalizing." During this transition, it is likely that some physical product will remain as an integral element of the delivered service, essentially forming an integrated product/service system. For such product-based services, the distinction between manufacturing and traditional service sector activities becomes somewhat blurred [8]. The servicizing transition offers business entities many opportunities for upgrading, refurbishment, and recycling, each of which offers additional sustainability benefits. Garcilaso et al. [7] provide a number of examples where products are being transformed into services, including rental cars, laundromats, and web-based music. These examples include business models that utilize "pay for use" and leasing that result in reduced material flows, conservation of resources, and extended producer responsibility, all of which are consistent with sustainable practices.

While service-based products are often touted as being superior to physical products in terms of dematerialization/ sustainability, few efforts have actually investigated their environmental benefits – if any. For example, consider a clothes washing machine such as is commonly used in homes across the U.S. Many material resources are used to manufacture such a product, and wastes are produced in the process. During the use of a "washer," water, energy, and other resources are consumed. An alternative to a home-based washing machine is the service provided by a laundromat (or launderette), a facility that has equipment for both washing and drying clothes. The machines in a laundromat are often coin operated, and vending machines are available to purchase detergent, bleach, fabric softener, and so forth.

The goal of this paper is to investigate clothes washing with both a home-based machine and a laundromat, and characterize the benefit, if any, associated with a washing machine service (a laundromat). The alternatives will be assessed using Life Cycle Assessment (LCA) in order to determine both economic costs and environmental impacts. The results of this analysis will be reported for each of the alternatives; with the environmental dimension of the life cycle evaluated using SimaPro 7.0. Specific measures of performance to be considered include costs, material resource consumption, energy, and water usage. The life cycle performance of each alternative will be compared and, ultimately a recommendation will be made regarding clothes washing in terms of economical and environmental benefit.

2 CLOTHES WASHING ALTERNATIVES: SCOPE AND SYSTEM BOUNDARIES

In 2001, 84 million households in the United States had clothes washing machines [9]. Use of these machines accounted for 10 billion kWh or 0.9% of the total national energy consumption. It may be noted that this energy amount does not include the energy used to heat water entering the washer. As noted in the Introduction, clothes washers also use a significant amount of water and consume considerable material resources. Owing to the magnitude of the energy, water, and materials attributable to clothes washing, enhancing the sustainability of this activity will bring about a significant benefit. It has been suggested that a clothes washing service, such as is provided by a laundromat, can improve the sustainability performance. With this in mind, four clothes washing alternatives are considered:

1. Home washer-hot cycle
2. Home washer-cold cycle
3. Laundromat-hot cycle
4. Laundromat-cold cycle

Each alternative was assessed in terms of how much energy, water, etc. is used.

Several assumptions were made in order to compare the alternatives referenced above. According to U.S. Census Bureau the average household size is 2.64 persons [10]. Therefore, an average household size of 3 persons was assumed. Generally, a laundromat has machines for both washing and drying clothing; however, only clothes washing is considered in this analysis. As one might expect, homeowners may select from a wide array of washing machines: differing size capacities, loading types (front vs. top), and efficiencies. To simplify the analysis, it was assumed that both homeowners and the laundromat facility would utilize the same 2005 U.S. industry-average washing machine type [11].

The life-cycle of a washing machine is displayed in Figure 1, and as is evident, the distribution and end-of-life stages will not be considered within the system boundaries of this assessment. The use stage and the cradle-to-gate manufacturing stage of the washing machine are included in the assessment. Thus, the assessment includes material resource, energy, and water consumption as well as customer transportation to/from the laundromat.

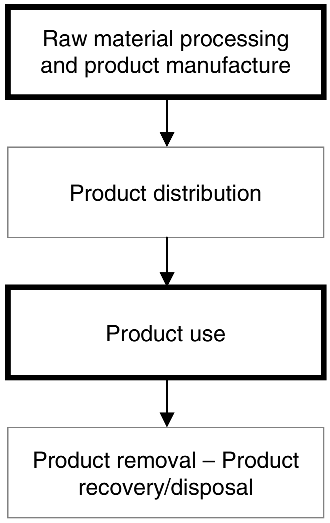

Figure 1: Washing Machine Life-cycle and Stages Investigated (bold boxes).

The functional unit selected for study in this investigation was the number of wash cycles for six families over one year. For the case of the laundromat, this amounts to six families essentially sharing the use of a single machine. For the home-based alternatives, six washing machines are needed to replace the single machine at the laundromat. It may be noted that this usage-related information depends on a number of variables, including: region/country, consumer behavior, and technological capability of the washing machine [12].

3 INVENTORY ANALYSES

In assessing the clothes washing alternatives it was necessary to obtain information concerning the materials, cost, energy consumption, and water usage associated with a washing machine. Several materials are used to manufacture a washing machine. Table 1 shows the material composition data for a 2005 U.S.-based industry-average washing machine [11].

From a direct cost standpoint, the initial purchase of the machine, maintenance cost, detergent cost, vehicle fuel cost, and vending cost per use (for utilization of a machine in a laundromat) were considered. In the case of home washing, the cost for energy consumption and water usage was considered as well. First, let us consider purchasing a washer for home use. An average household in the U.S. runs a clothes washer 392 cycles per year [13]. A top loading washing machine such as that considered herein, costs $525 on the average [13] and has a lifetime of 5,000 cycles [14] (approximately 13 years). Over the lifetime of the machine the cost for maintenance is about $300 [11]. A user consumes about 0.09 liters of detergent per cycle at a cost of about $0.16 per cycle.

Material	Mass (kg)
Steel	42.96
Iron (gray cast)	0.41
Aluminum	2.68
Copper	1.18
Rubber	1.09
Polypropylene	9.07
ABS	0.05
PVC	0.54

Table 1: Material Composition Data for 2005 Industry-Average Washer.

In order to account for the cost of energy and water for the home washer alternative it is necessary to determine the energy consumption and water usage per cycle. When considering the hot cycle, energy is required in order to run the machine and heat the water. For the cold cycle, only the electrical energy required to run the machine is considered. The energy consumed in heating water can come from a variety of sources, e.g., electricity, natural gas, and oil. According to the Rocky Mountain Institute, the total electricity consumed by a clothes washing machine in hot and cold cycles is 870 kWh per year and 100 kWh per year, respectively [15]. Nationwide, the source for electricity varies considerably across the U.S., with the percent generated by each source summarized in Table 2. According to the study conducted at Lawrence Berkeley National Laboratory [16], 30 gallons per day of water (113.6 liters per day) per household is consumed solely for washing clothes. This amounts to 41,464 liters of water per year, or 106 liters of water per cycle. Thus, using a density of 1kg/L for water, a total of 41,464 kg of water is consumed per year. For the home case, the user pays for electricity and water. In Houghton, MI, U.S.A. the cost for energy is $0.05130/kWh [17] and water costs $0.00111/L – of course, these cost rates vary substantially across the U.S.

Source	
Coal	51.50%
Natural Gas	16.5%
Oil	3%
Nuclear	20%
Hydroelectric	7%
Other renewables	2%

Table 2: Electricity source breakdown [18].

When a user patronizes a laundromat they do not directly pay for the energy and water needed for the washing machine, or the machine purchase and maintenance costs. However, the user will have to spend money for fuel to travel to the laundromat. Travel considerations were incorporated by assuming a travel distance of 5.94 km one-way, or 11.88 km round trip, from the user's home to the laundromat, driving a 2000 Honda Civic with 8.4 L/100 km fuel economy (28 miles per gallon) and an average fuel price of $0.61/L [19, 20]. Approximately 51.89 liters of fuel are consumed per year due to traveling roundtrip to the laundromat once per week.

Table 3 shows a synopsis of the total energy and water usage for each option. Table 4 shows a cost summary for each alternative from the user's perspective. Details are reported in units per year.

	Alternative 1: Purchase Washer	Alternative 2: Laundromat
Energy Consumption (Hot Cycle)	870 kWh	870 kWh
Energy Consumption (Cold Cycle)	100 kWh	100 kWh
Water Consumption	41,464 kg	41,464 kg
Detergent Consumption	35.28 L	35.28 L
Fuel Consumption	N/A	51.89 L

Table 3: Energy and Water Usage Summary (per family, per year).

	Alternative 1: Home Washer	Alternative 2: Laundromat
Initial Machine Purchase ($525 – 13 year life)	$40.38	$0.00
Maintenance ($300 – 13 year life)	$23.08	$0.00
Detergent	$62.72	$62.72
Fuel Costs	$0.00	$31.65
Cost per Cycle (assumes a $0.75 vending charge per cycle)	$0.00	$294.00
Water Costs	$46.03	$0.00
Energy Costs (Hot Cycle)	$44.63	$0.00
Energy Costs (Cold Cycle)	$5.13	$0.00

Table 4: Direct Costs (per family, per year).

4 ASSESSMENT AND COMPARISON OF ALTERNATIVES

Using SimaPro 7.0 and the inventory analysis on the material composition of a clothes washer, energy consumed in hot and cold cycles, and water usage for the production and use stage of clothes washing, the environmental impact assessment for each of the four alternatives was determined.

The method used for environmental impact assessment was Eco-Indicator 99. This method refers to the weighting set belonging to the individualist perspective. With this method, particular attention is paid to factors that damage the human health, ecosystem quality, and energy resources. The aim of this assessment was to compare the different alternatives in terms of total environmental impact. The results of this impact assessment are presented here (in eco-indicator point units, Pt). The reader is cautioned that the absolute point values for each alternative depend on a number of factors such as the geographical region and usage pattern. Changing a factor will produce similar changes in the results of all the alternatives, thus increasing or decreasing the absolute point value.

The reader is also reminded at this juncture that the functional unit assumed for this study is the number of wash cycles for six families over one year. While this assumption is not necessary in comparing the wash cycles for the laundromat and home-based washing machine in terms of cost and environmental impact, it is critical in assessing the manufacturing impacts associated with producing one machine that serves 6 households (laundromat) and 6 home-based machines.

Figure 2 shows a comparison for the home washer, with the left bar showing the hot cycle and right bar showing the cold cycle. From this figure, it is clear that the impact is considerably higher when the hot cycle is used. In particular, the hot cycle has a much larger effect on human health, attributable to the heating of water, which leads to higher impact. It can also be seen from the figure that the impact in terms of resources and ecosystem quality is virtually the same for both the hot and cold cycles.

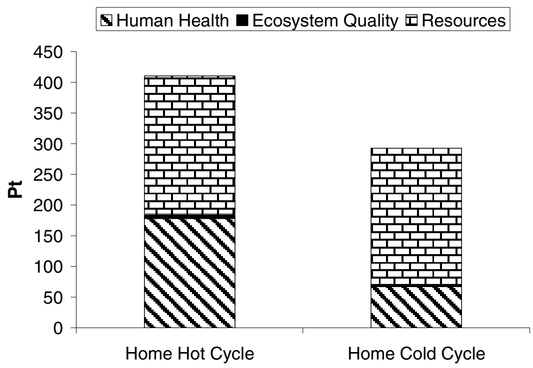

Figure 2: Home Washer – Hot vs. Cold Cycle.

Figure 3 shows the comparison of the hot and cold cycles for the laundromat. Similar to Figure 2, it can be seen that at the laundromat the cold cycle is a better alternative. Again, a smaller effect on human health is associated with the cold cycle, which leads to the cold cycle being superior to the hot cycle.

Figure 4 compares the impact of using a hot cycle at the laundromat and at home. In this comparison, it was found that the effect on human health does not depend on where the clothes are washed. However, the impact on resources was found to be lower when the laundromat is used to wash the clothes. Seemingly, the human health differences evidenced in Figures 2 and 3 are attributable to the extra energy, and concomitant emissions, associated with heating the water for the hot cycle. The laundromat vs. home comparison of Figure 4 suggests that resource differences are due to the manufacturing impacts of creating one washer (laundromat) as opposed to 6 washers (home). Fuel usage for travel to/from the laundromat does not appear to have a significant impact. Similar results were found to be true when the cold cycles are compared at the laundromat and at home (Figure 5).

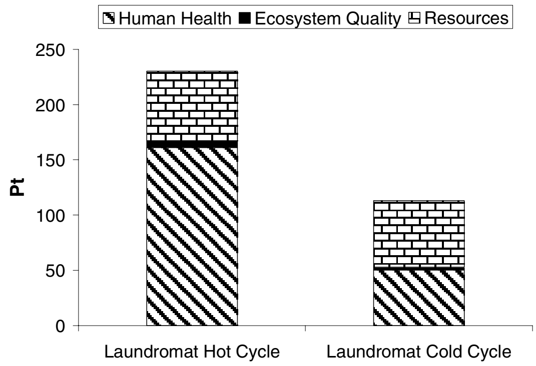

Figure 3: Laundromat – Hot vs. Cold Cycle.

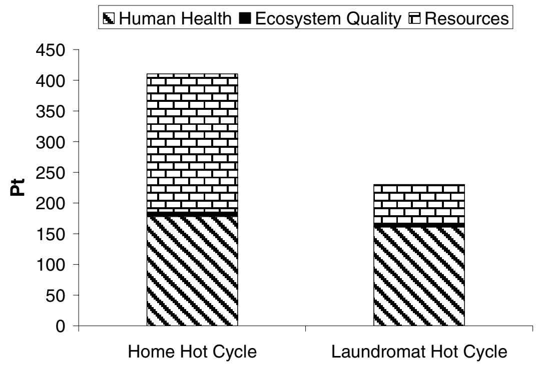

Figure 4: Hot Cycle – Laundromat vs. Home Washer.

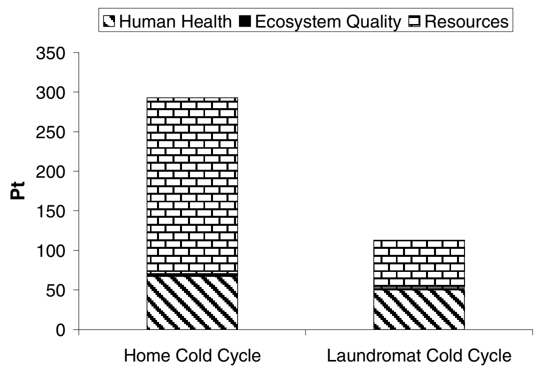

Figure 5: Cold Cycle – Laundromat vs. Home Washer.

Figure 6 shows the comparison of total impact points for both hot and cold cycles at the laundromat and at home. The cost incurred per family for each alternative is also shown in this figure. As can be seen from the figure the environmental impact of clothes washing is lower when the laundromat is used, however, the cost to the user is more than the home alternative.

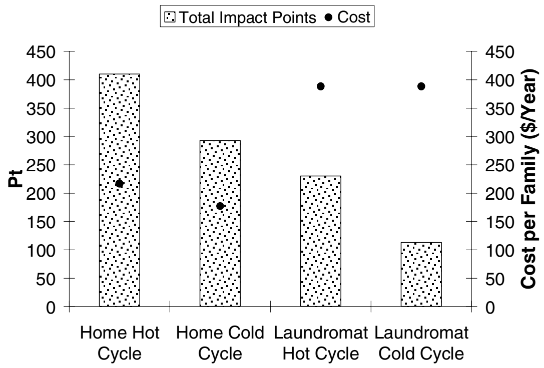

Figure 6: Comparison of Four Clothes Washing Alternatives in Terms of Eco-Indicator Points and Costs.

In order to understand the individual impact of materials, cost, energy consumption, and water usage associated with a washing machine on each of the three factors used for environmental impact assessment, the breakdown of environmental impact for hot cycle for home washer was investigated (Figure 7). As can be seen from the figure, the energy consumed by the washing machine in heating the water is the major contributor to the human health impact factor. For the resources impact factor, the material composition of the machine has the most significant contribution.

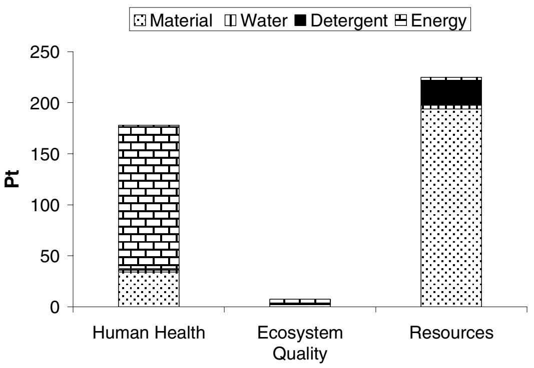

Figure 7: Breakdown of Environmental Impact for Home Hot Cycle Alternative

5 SUMMARY AND CONCLUSIONS

Four clothes washing alternatives have been assessed in terms of environmental impact and economic costs. The four alternatives that were considered in the assessment were hot and cold cycles performed at home and in a laundromat. The functional unit was the number of cycles performed by 6 families over the course of one year. Essentially, this suggests that the 6 families will share a washing machine located in the laundromat facility versus each family owning their own machine at home. Many other assumptions relating to costs and energy/water utilization have been made throughout the paper. The environmental impacts have been estimated using SimaPro 7. The assessment was performed using cost information associated with Houghton, MI, U.S.A.

Based on the environmental assessment and economic cost analysis, the following conclusions can be drawn from the study:

- From a financial perspective, a home-based washer is approximately half as expensive as using the laundromat. This difference in costs is largely attributable to the vending charges associated with laundromat machine utilization – assuming that a laundromat user will have the same number of loads/year as home machine user.
- The washers at the laundromat have a much better utilization than home-based washers. In particular, each laundromat machine has 6-times higher utilization than a home-based machine.
- The hot cycle has a much higher environmental impact than the cold cycle for both the laundromat and home-based machines. This difference is attributable to the extra energy that is required to heat the water for the hot cycle. The cold cycle is also slightly less expensive than the hot cycle for home usage.
- The laundromat has a much smaller environmental footprint than do the home-based washers. This difference is associated with the fact that the laundromat-based alternatives have one-sixth of the washing machines and therefore consume one-sixth of the material resources as compared to the home-based alternatives.

In summary, using a clothes-washing example, the alternatives examined in this paper have demonstrated that service-based approaches offer significant environmental benefits when contrasted against pure product-based approaches. Dematerialization is achieved in this case via a laundromat in which multiple users share the same machine – thus avoiding the environmental impacts of manufacturing associated with fabricating a physical product for each household.

As a final comment, apart from simple inconvenience, the principal shortcoming associated with the laundromat alternatives are the higher costs. The analysis presented herein has assumed that a user will have 392 loads per year – for both the laundromat and the home-based alternatives. However, it is likely, for the laundromat alternatives, that a user will have larger loads (higher clothes mass/load), and will thus be able to process their dirty laundry using far less than 392 loads per year.

6 ACKNOWLEDGEMENTS

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Methodology and Application of Parts Qualification for Compliance to Environmental Rules

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Abstract

The worldwide spread of environmental rules concerning electrical and electronic equipment has increased the need for improved efficiency of Design for Environment (DfE). At present, assembly manufacturers request parts suppliers to submit parts data to confirm compliance with environmental rules. Especially, assembly manufacturers are strongly interested in the chemical content of parts. When confirming the accuracy of the data, an analytical instrument is often utilized by both assembly manufacturers and parts suppliers. However, it takes a huge number of man-hours. To solve the problem, we have proposed the methodology and application to confirm the accuracy without using an analytical instrument. Firstly, we have developed logic to extract benchmark data from the existing parts database by applying statistical processes. "Benchmark data" are used for comparison to confirm environmental data for parts. We also developed a tool that produces a benchmark map, which is a matrix of benchmark data. Then we proposed the evaluation method using benchmark data in quality assurance workflow to enable to confirm the credibility of the data. The use of benchmark data will reduce the risk of non-conformity or the number of man-hours needed for parts selection and parts qualification.

Keywords:

Assembly Manufacturer; Material Declaration; Accuracy; Benchmark Data; Quality Assurance

1 INTRODUCTION

In response to the Restriction of Hazardous Substances (RoHS) Directive, which took on 1July 2006, the European Union (EU) has strengthened the requirements for hardware manufacturers in the EuP Directive that entered into force on August 2006 and the Registration, Evaluation and Authorization of Chemicals (REACH) Regulation, which will be effective sooner than initially expected. To comply with these regulations, assembly manufacturers (AMs) have requested that parts suppliers (PSs) provide parts data with environmental specifications, e.g. materials declarations. Based on the data submitted by parts suppliers, AMs confirm compliance with these rules [1].

However, due to a long manufacturing supply chain, assembly manufacturers as well as parts suppliers are facing difficulties with identifying the chemical content of their own products. As part of this process, AM employees in charge of parts qualification must confirm the accuracy of submitted parts data before authorization of the parts. Measurement of all aspects of the part using an analytical instrument is recommended to avoid the risk of non-conformity. However, this requires a huge amount of man-hours. Therefore, a RoHS Directive guidance document published by the UK government recommends checking only the materials that are likely to contain regulated chemicals [2]. The guidance recommends specifying the materials to be analyzed.

In the present research, we have developed a method to narrow the number of parts to be checked using an analytical instrument by calculating the risk of containing substances regulated by the RoHS directive, and evaluated the method by applying real parts data. We confirmed that the method successfully narrows down the parts to be checked.

2 PRESENT METHOD AND OUR APPROACH

Figure 1 shows the typical qualification workflow of AMs. After AMs receive part data and the drawing of the part, an AM employee in charge of quality assurance (QA) confirms the accuracy of the part data (accuracy check), and then checks if the part conforms to qualification requirements (compliance judge). The QA employee utilizes the part drawing of the part when he/she specifies the possible location of regulated substances. An analytical instrument is utilized as an accuracy check.

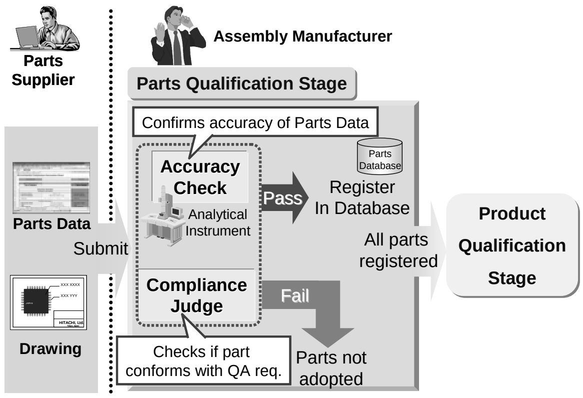

Figure 1 Qualification workflow

At AMs where analytical instruments are not introduced, QA confirms the parts data with the drawings. The ability of QA to judge the accuracy correctly depends on the amount of experience. The problem is that the decision may differ between individual QA employees and in some case misjudgement occurs without enough technical knowledge. Therefore, more AMs have begun using an analytical instrument to resolve this problem, although a huge amount of man-hours is required.

To reduce the necessary man-hours, a few methods have been suggested that do not require analytical instruments. For example, a 'Content Possibility Map' has been suggested and utilized [3]. The map shows the relationship between likely contained regulated chemicals and the materials in each part (benchmark data). The Content Possibility Map is based on the experiment data of materials and literature research.

However, the benchmark data utilized by the Content Possibility Map does not distinguish the material by usage. For example, copper used in electronic parts is not distinguished from copper used in mechanical parts.

According to the parts data submitted by PSs, the composition of chemical substances depends on function, sites of material usage as well as the materials themselves. More precise benchmark data could be produced if the function were considered. However, this too requires a huge number of man-hours to acquire the needed benchmark data for each function.

Moreover, the benchmark data change over time due to new discoveries and the application of new materials or new environmental regulations, and the data must be updated regularly. In addition, the renewal of the map needs additional man-hours for further analytical investigation or literature research.

To address these problems, we focused on the existing parts database that AMs commonly manage for green procurement. Taking the number of registered parts data in the database into consideration, we assume that benchmark data can be extracted from the existing parts database, without consuming additional time for analytical investigation.

3 METHOD OF BENCHMARK DATA EXTRACTION

Japan Electronics and Information Technology Industries Association (JEITA) and Electronic Industries Alliance (EIA), which are the representative organization of electric and electronics industries of both Japan and US, have agreed to standardize the structure of parts data [4]. This framework, which is called Joint Industry Guideline (JIG), has spread worldwide thanks to supply chain network among all over the world. The major structure of parts data is shown in Figure 2.

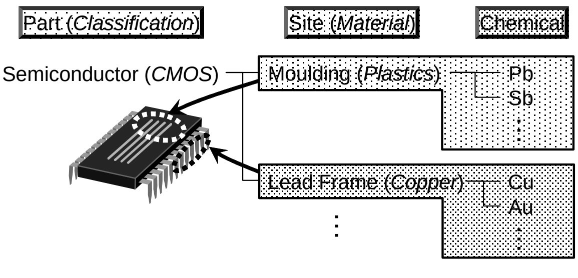

Figure 2: Parts data structure

Part data include not only the names of chemical substances but also the content by weight or concentration. In addition, part data specify the site where a chemical substance is utilized. Normally, the dominant material is also specified for each site.

In addition, each part is assigned a single part classification. The part classification can be utilized to divide the parts into smaller groups with regard to the function of parts. Several standardized parts classifications have been suggested (e.g. ECALS code) [5].

Taking advantage of the data structure, we suggest 2 steps to get high quality benchmark data. (1) data refinement, and (2) outlier removal (Figure 3). Additionally, we also suggest the (3) detection of chemical trends to identify newer chemical information.

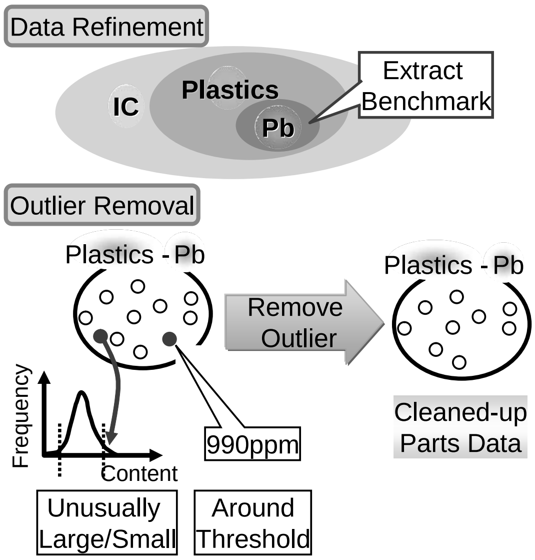

Figure 3: Extraction of Benchmark Data

3.1 Data Refinement

In the present research, parts classification is utilized to refine the parts data. This method is based on the assumption that similar parts data refined by parts classification would have the same chemical composition and a benchmark data refined by parts classification would become more precise than that without refinement.

3.2 Outlier Removal

The existence of the low quality parts data must be considered when developing benchmark data from the database.. This occurs because different employees of different PSs register in each database of each AM. Not all PSs register in the same way. The quality of the data extracted from the database needs to be improved. The unusual values of low quality data can be considered as 'outliers'. To improve the uniformity of the refined parts data, the outliers are removed.

The outliers have been found to have particular patterns based on the reason for abnormality. Currently, we have identified 2 types of outlier patterns. These data are removed from refined parts data.

1. Around-Threshold Registration

Some PSs register a lower content of regulated chemicals by RoHS Directive, such as 990ppm, intending to show RoHS compliance. In this case, a supplier does not register the part based on chemical content.

2. Unusually Large/Small Chemical Content

The part data with unusually large or small chemical content have been shown to be likely incorrect [6]. This type of error occurs due to incorrect registration or an inappropriate analytical check. These are also removed to avoid the risk of contamination of the benchmark.

3.3 Detection of Chemical Trend

The trends of chemical use in products are identified using the following process. A common parts database manages the registration date of parts data, which are utilized to identify trends.

We have investigated the chemical content trends of parts using the classification for electronic parts (Figure 4). The vertical axis 'Ratio (%)' is the ratio of parts that contain a chemical substance (lead (Pb) or brominated flame retardants (Br) or Antimony (Sb)). As the figure shows, the amount of Sb is decreasing each year, while the amount of Br is increasing. Based on the results, we assumed that chemical content trends appear for other parts classifications.

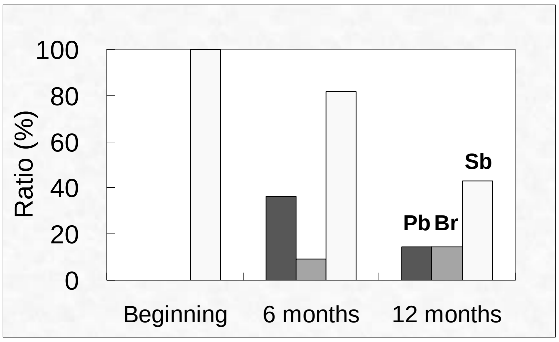

Figure 4: Detection of Chemical Trend

In this way, we derive parts classification specific benchmark data with the chemical trend.

4 EVALUATION METHOD BY BENCHMARK DATA

4.1 Parts Classification Specific Benchmark Map

This method explained above enables to derive parts classification specific benchmark map. Currently we have developed a tool that can immediately produce a benchmark map by receiving the input of a part classification.

A 'Benchmark Map' is a set of benchmark data generated in matrix form. An output image of a benchmark map is shown on Figure 5. This image is a map of one part classification. The map shows the relationship between sites (or materials, vertical axis) and substance (horizontal axis). One box consists of benchmark data for a single substance. The map can be read, for example, 75-100% of Site B, which is used in this part classification, contains antimony, for an amount of 0.10 to 0.50 wt%. The use of antimony is declining, a trend indicated in the map.

A benchmark map will be useful when detecting an incomplete registration (e.g. a certain site is not reported and the site may contain a restricted substance), or outlier value (e.g. chemical content is unusually large/small). Chemical content trends can be applied in the following way. When checking part data, parts that do not contain a chemical that is more popular each year, the chemical data may be considered incorrect. In this way, the trend information will be utilized to prioritize the order in which the analytical check of parts is completed.

Part Classification: xxx   Unit: wt%

	Pb	Sb	Bi	…
Site A (Material X)	0.0050 - 0.30 →	N	N	
Site B (Material Y)	N	0.10 - 0.50 ↘	0.10 - 5.0 ↗	
Site C (Material Z)	0.0010 - 0.20 →	0 - 2.0 ↘	N	
⋮				

Background Color: 0-25% 25-50% 50-75% 75-100%

Figure 5: Output Image (Benchmark Map)

4.2 Application Image

The output map shown in Figure 5 will be utilized in the parts qualification stage exercised by QA at AMs. Figure 6 shows a workflow example of the parts qualification.

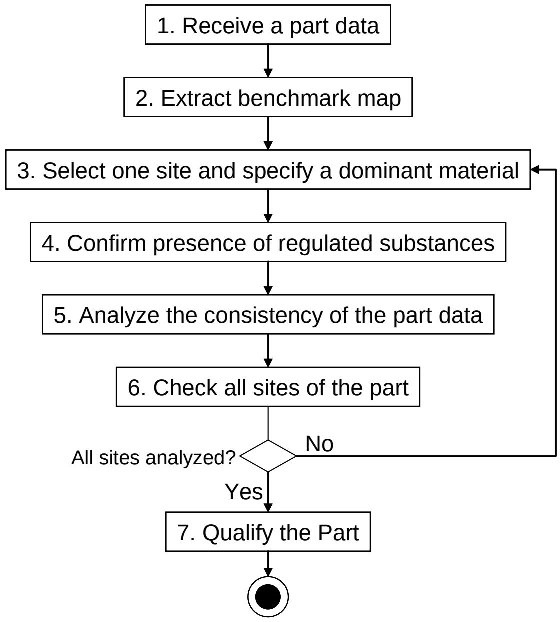

Figure 6: Workflow of Parts Qualification

1. Receive a part data

First, an AM receives part data from a PS. The part data will be directed to a person in charge of QA.

2. Extract benchmark map

Receiving a part data, QA identifies a part classification that the part belongs to. A benchmark map can be extracted by specifying the part classification.

3. Select one site and specify a dominant material

Part data consist of several sites. Here QA selects one. In most cases a site has the dominant material. It is able to confirm the material by checking a drawing of the part or reported chemical composition.

4. Confirm presence of regulated substances

By checking the map, QA confirms the site has the risk of substance existence, and, if contains, confirms the amounts or concentration that are regulated by RoHS directive.

5. Analyze the consistency of the part data

Focusing on the substances regulated by RoHS directive, the part data are compared with the benchmark map. When the data are not consistent, the part is checked further using an analytical instrument. If consistent, the part data is likely a correct data.

When the number of sites to be checked is too large to check all of them, chemical trend might be helpful to give priority of analytical inspection.

6. Check all sites of the part

7. Qualify the part

When all sites are analyzed according to the benchmark map, the evaluation of the part data is complete.

5 RESULTS AND DISCUSSION

We considered 4 parts classifications as examples to discuss the results. Two are from electronic parts (one from a semiconductor, the other from a connecting device), and the others are from mechanical parts (one from a power transmission device, the other from a power control device). We assume that QA presently utilizes a 'Content Possibility Map' (see [3]). The characteristic of the new method with benchmark maps is that the map is unique to each part classification. Then we derived the number of sites where analytical checks are recommended based on the present method and the method that utilizes the benchmark map.

Parts Classification		Present	Benchmark Map	Difference (%)
Electric	Semiconductor	4.2	1.7	60.3
	Connection	4.7	1.7	63.1
Mechanical	Power Transmission	0.1	0.2	-73.3
	Power Control	1.9	1.0	49.4

Table 1: The number of sites where analytical checks are recommended

As the results clearly indicate, there is a decrease in the number of sites. For example, while the present method recommends that nearly 5 different sites be checked for a connection part, the benchmark map gives 2 sites to check. This is because 'parts classification specific' benchmark maps are produced, which the present method is not able to create.

The number of sites to be checked has increased in some parts classification using the benchmark map (power transmission) because a few sites are evaluated as subjects to be checked according to benchmark maps, while those are not subjects to be checked in the present method.

However in total, the use of the benchmark map would narrow down the number of sites that need to be checked by an analytical instrument. This will bring the following benefits.

1. The benchmark map will reduce the risk of non-conformity.

Based on the present method, the number of the sites to be checked might exceed the capacity of an analytical instrument. Therefore some sites might not be investigated although there is a certain risk of inconformity. Using the benchmark map, the sites that have a larger risk will be specified more narrowly, and will reduce the risk of non-conformity more effectively.

2. The benchmark map will reduce the man-hours needed.

By checking the sites that are specified by the benchmark map, the number of sites to be checked will decrease for most parts classifications.

However, some points still require more analysis. We have not yet evaluated the amount of risk that remains presently and how much can be avoided using the benchmark map. To calculate the impact of the risk, we need to confirm that the suggested method can extract the violated material, which does not contain the regulated substance according to submitted data, while it does contain the substance when measuring with an analytical instrument. However, it is difficult to find this kind of material and we have not acquired a suitable evaluation result so far.

We need more parts data to evaluate this, which will be a topic for our research in the future.

6 CONCLUSION

1. We have developed a method to extract benchmark data from an existing parts database by taking the following steps.

   a) Data Refinement

   b) Outlier Data Removal

   c) Detection of Chemical Content Trend

2. We have proposed an evaluation method utilizing benchmark data. We have developed the tool to extract benchmark data and a benchmark map (a matrix of benchmark data). The map also includes the ratio of parts that contain each chemical, the range of chemical content and chemical use trends.

3. The benchmark map is effective when QA prefer to narrow down the number of parts to be checked. By utilizing the benchmark map, the risk of non-conformity and the expected man-hours for the tasks should be reduced.

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An Overview of Academic Developments in Green Value Chain Management

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Abstract

Currently, whenever Sustainable Product Design is the topic of discussion among industry partners, such as in the electronics industry, the focus is strongly determined by regulatory issues, in particular related to end-of-life management of products. Generally spoken, academic institutes do not have a very active role (anymore) in these discussions. As the role of academic institutes is to foresee (social, economical, environmental) developments and their future impacts to society, including industry, it is understandable that a time lag can be observed between academic institutes signalling and studying such developments, and industrial adoption of (some of) these ideas, often more effectively once the future has become reality. In this light, this presentation discusses, from an 'academic ivory tower' perspective but based on factual and anecdotal evidence from industry, future developments related to Sustainable Product Design that might become more real to industry in years to come. These include green marketing, communication, change management issues, and green value chain management.

Keywords:

Green Value Chain Management, Sustainable Product Design, Academic Research

1 BACKGROUND

Since the early 1990s research into green value chain management has received attention from an increasing number of scholars. Whereas in most cases, academic scholars have been the first to pick up on new developments, in industry, activities were rapidly picked up as well and evolved there from a manual approach (development of tools and manuals, sometimes in cooperation with research institutions), via project approaches (pilot projects, co-operations) to an integrative approach, when environmental considerations with regards to products were included in corporate strategies.

In the past few years, it seems however that industry and academia have gone their separate ways. Traditional ecodesign approaches in industry go, in many cases, as far as showcases, corporate sustainability reports and official corporate policies. However, and in particular in the electronics industry, in practice the inclusion of environmental considerations refers to defensive, reactive strategies to environmental legislation. Since the mid-nineties, legislative developments in the European Union and Japan in particular have forced industry to take action on phasing out substances (RoHS, lead) and end-of-life requirements (for example WEEE in Europe). Nowadays, these subjects maintain to be highest on the agenda of industry, and this is where most resources are spent.

These observations can be traced back in the way the current status of academic research into green value chain management is described; in summary: this is as 'lacking momentum' (Tukker et al. [1], Baumann et al. [2], McAloone et al. [3]). Whereas at the end of the 1990s, it was still common to express optimism about opportunities for competitive advantage from ecodesign activities, researchers and practitioners have increasingly expressed dissatisfaction about the frequency, quality and speed of the process of implementation of DFE practices. It is not the point of this paper to discuss this issue in depth, this has been done in Boks [4]. An important conclusion is that industry nowadays is spending almost all available efforts in dealing with legislative developments, with little room for proactive, alternative thinking. Stevels [5] states that ecodesign is in a proactive kind of crisis, bringing forward three reasons:

- low hanging fruits have been picked, and based on traditional functionalities further improvement potential is limited,
- lack of market demand because environmental criteria are subordinate to traditional purchase criteria,
- and conflicts of interest in the value chain.

In the meantime, part of academic scholarship persists in an exhibition of 'fundamental' ecodesign beliefs, looking for ways to persuade industry to use ecodesign tools for finding options for sustainable alternative design strategies. Fortunately, in academia also a number of research topics are currently researched that aim to understand and facilitate better the incorporation of environmental issue in corporate decision-making – within in the framework of industrial thinking. It is reasonable to assume that some of these research efforts will find their way in future business, just as 10 to 15 years ago academic research has taken the initiative for researching and understanding many of industry's activities today.

Some of these new research activities are directly related to end-of-life topics. In 2003, Pascual et al. [6] describe the current situation of green value chain management research using a number of propositions, and using data from about 850 conference papers that addressed ecodesign issues for the electronics industry in the 1998-2002 period. One conclusion was that most of the developments in ecodesign appear to be based on paradigms that already exist for many years – and are end-of-life focused. Issues that have a high legislative and/or emotional priority (i.e., end-of-life issues) appear to dominate the choice of research topics - something which cannot always be justified from a scientific point of view (i.e. end-of-life vs. energy consumption).

But, in understanding why companies do or do not take up ecodesign activities, increasingly a broader perspective is taken. New areas of scholarship aim to adopt adjacent disciplines in search of explanation of why integration, implementation and operationalisation of ecodesign activities is or is not successful. In the current context, these new areas of scholarship include for example general design methodology, management sciences, financial accounting, change management, or organisational and occupational psychology.

The remainder of this paper will therefore focus on briefly introducing and discussing a number of these relatively new topics related to environmental value chain management. These topics can be seen as the current 'working set' of variables that are seen by the authors as either currently being explored by academia and/or relevant for further exploration, to explain the impasse ecodesign is in today, and to further the cause of integrating sustainability thinking in industry.

2 RECENT DEVELOPMENTS IN ACADEMIA

2.1 Customisation of ecodesign strategies

No matter whether the focus of research attention was on end-of-life issues, broader ecodesign methodology, or other green value chain topics, there is and always has been little research attention for customisation of ecodesign or green management strategies. Obviously, a lot of research has been done in the context of the electronics industry, or the furniture or food packaging industries for that matter. Also, distinctions have been made between strategies for multinationals and small and medium-sized companies. At Delft University of Technology, in recent years ecodesign strategies for emerging economies have been researched [7]. In the forthcoming UNEP ecodesign manual, the target audience is clearly addressed, and elements of ecodesign methodology have been adapted to various audiences in various industrial settings in the world. At Delft University of Technology, these experiences have contributed to the close-to-realisation of a chair in Sustainable Design for the Base of the Pyramid, building on the ideas of Prahalad and Hart [8] (see also section 2.5).

But these signs of customisation of ecodesign knowledge are still on a general, industry-wide or geographically dependent, level. Attempts to research customisation of ecodesign knowledge within an industry branch are virtually non-existent. Nevertheless, it is very likely that company-specific factors determine to a large extent the appropriateness and acceptance of ecodesign strategies. For example: in the electronics industry, established multinationals like Sony or Matsushita attribute a different weight to communication of environmental performance than, say, local Asian manufacturers. In the same way, given the legal system, North American companies deal differently with claims about environmental performance than the electronics industry in the European Union. Present research at Delft University of Technology focuses on the identification of clusters of companies in order to characterize the electronics industry, representing similar backgrounds and attitudes towards environmental issues. Such clusters will include 'value' companies, who are interested in superior environmental performance though as part of many aspects in which they want to be superior. It could be that their strategy is one of risk management, avoiding bad press, while at the same time trying to maintain a high level of environmental performance. One of their characteristics is the pro-active behaviour towards environmental legislation, teaming up in branch organisations and active lobbying. A second cluster could include companies with similar objectives but with rather defensive strategies, companies with aggressive marketing and pricing strategies, less fundamental research, that are less proactive towards cooperation, sign agreements late, etc. There are also niche players, that operate in limited segments of the market, for example selling only high-end products, that may not even reach end-of-life, or at least have a very long lifespan and get handed over to 2nd, 3rd users, collectors etc. These have a very strong value proposition to customers, and their strategy is likely to avoid interference between environmental issues and their main value propositions. A fourth cluster could be local Asian manufacturers with little visibility in the international press, that will address environmental issues in terms of regulatory requirements only; price fighting rather than superior quality is the business they are in (which is in some aspects a sensible ecodesign strategy), and they will therefore benefit from customised ecodesign strategies. A fifth cluster could address so-called 'low visibility giants'; companies that extensively manufacture (and design) electronics products, in particular the inside, but mainly as outsourced manufacturing for value companies in particular. Their role is very interesting because it is potentially very powerful. A variation of this cluster includes companies that manufacturing subassemblies and components for application in products for brands worldwide.

2.2 Focus on the role of the individual designer

The importance of the role of the individual designer is frequently debated in ecodesign literature. Loriot [9] argues that the personal role of designers in ecodesign practice is still under debate, by quoting various scholars; Margolin [10] considers the first major obstacle to environmental implementation within design is the will and self-motivation amongst designers, to believe in their role in ecodesign and in a less harmful practice. Conversely, Van Hemel affirms that designer's personal commitment and values are not significant factors of sustainability. Rather, customers' demands and governmental policies are far more important drivers [11]. But then again, Charter argues that individual motivation of employees seems to be very influential for ecodesign to expand within enterprises [12].

Lindahl [13],[14],[15], Ritzén [16] and others state that if the ambition is to integrate Design for Environment into ordinary product development, then there is an essential need to involve and consider one of the main presumptive users of DfE methods and tools: the designer. The main line of reasoning here is that the user (i.e. the designer) is the one interpreting tool results, and that therefore the success of a tool is very dependent on the user, and that stress should be put on research to understand and improve the way designers use tools. Their research puts the designer in the centre of attention, stressing the consideration of designer's needs where tool use is concerned.

2.3 Focus on the soft side of ecodesign

Boks [4] and Verhulst et al. [17] suggests studying the role of socio-psychological factors as a factor of influence for adoption, and focuses research attention on a more departmental level, looking at various aspects of ecodesign implementation having different levels of manageability. This is in particular the case early in the design process where dissemination of information, creativity, and awareness creation play an important role. The most important obstacles that are found are gaps between proponents and executors, organisational complexities (unclear responsibilities, cultural differences between departments), and lack of cooperation. Recent research shows that such internal value chain factors are experienced by companies themselves as relatively more important than external value chain issues, in particular in earlier stages of the product development process. A clear distinction is made between the types of internal value chain issues, as, with regards to success factors, conventional internal value chain issues appear to play a dominant role, whereas in terms of obstacles, more socio-psychological factors are mentioned. Assuming that the introduction of sustainability criteria can be regarded as a change process for involved industries, theory from change management may be able to explain (better) occurrences of individual and organisational resistance to such change processes, which may in many cases be the cause of lack of momentum in operationalisation of ecodesign strategies [17].

It is suggested that, as these sociological, psychological, emotional and intangible factors that can 'make or break' implementation processes, the involvement of (business) psychologists and business organisation specialists could turn out to be crucial here; at least much more crucial than the role of conventional (academic) ecodesign research as supposedly, there is already enough information about how to do ecodesign, it is just pertinent to make it readily available to the right people, and to make sure they know how to use it. Unsurprisingly, originating from less scientific contexts (though with academic support), the inclusion of internal value chain considerations has materialised in ISO 14062, a non-prescriptive technical ISO document addressing both the internal and external value chain of companies. This document proposes the use of practical methods such as (environmental) benchmarking [18] for embedding environmental considerations into regular business processes [19].

2.4 Expansion towards sustainability

Whereas until recently, environmental issues were studied separately, in the late 1990s integration with economic and business principles has been increasingly the focus of research. Only recently, sustainability as an overarching concept is studied, including not only environmental and economic, but also social issues. This development is most clearly seen in yearly reporting of the industry; until few years ago, companies published 'environmental reports', whereas today, they publish 'sustainability reports', 'green management reports', 'corporate social responsibility reports' and 'corporate citizenship reports'. The lack of 'consensus' on terminology used here shows in itself the level of immaturity of sustainability reporting. At least two important reasons exist for the problematic integration of all aspects of sustainability into reporting: problems with performance measurement (see section 2.4.1), and related to that, problems with environmental accounting (see section 2.4.2).

2.4.1 Performance measurement

Performance measurement in the context of ecodesign has in the past almost exclusively limited itself to performance measurement of products. Companies have used, sometimes but usually not with the assistance of tools of academic origin, a wide range of concepts and tools to perform such measurements [20]. However, for these purposes, system boundaries were usually chosen conveniently narrow around the product, and environmental performance measurement of 'ecodesign activities' has consequently been neglected. Clearly, the costs and benefits of ecodesign in the bigger picture of a company are difficult to determine – although some scholars successfully explored the use of for example Activity Based Costing techniques for mapping and evaluating ecodesign input activities [21],[22]. A recent survey of electronics companies revealed that, although institutional initiatives such as the development of guidelines help companies to calculate effects of their environmental related investments and expenses, the economic effects (in monetary units) of 'environmental' investments are in an immature stage. Also Labuschagne and Brent [23] conclude that there is currently no consensus on the exact procedure to assess the environmental performances of operational activities, which is even more complicated when social dimensions are considered as well. Whereas environmental effects (in physical units) of such investments are easily calculated by companies, the integration of environmental activities in regular financial accounting practices needs much further research, as companies find great difficulties in making explicit the time and efforts invested in ecodesign processes, and in keeping track of benefits resulting from ecodesign activities, irrespective of any conceivable output form, such as through improved sales figures, avoided liability costs, improved lobby position, or image improvement [24]. Stevels proposes a new way of performance measurement all together, to be used not only internally, but also in communication with third parties; here it is proposed that an eco-value concept be further developed by using a ratio calculated in terms of consumer expenditure for a product divided by the environmental load of that product over the life cycle. According to Stevels [25], this would result in a number of paradigm shifts in the way companies and governments deal with environmental issues, and subsequently bring momentum back to ecodesign activities. Labuschagne and Brent state however that procedures to develop indicators for potential sustainability performances would, most probably, be company-specific – reflecting again the importance of customisation discussed in section 2.1.

2.4.2 Environmental accounting

Much of the environmental management and ecodesign literature (e.g. [26][27], describes various benefits from such practices, claiming win-win strategies where both the environment and the bottom-line get positive results. From a business perspective, these claims have not been clearly demonstrated yet. A methodological approach would help to clarify implications – positive or negative – of ecodesign activities at the bottom-line. The practice of identification, measurement, accumulation, analysis, preparation, interpretation, and communication of financial and non-financial information used by management to plan, evaluate, and control the environmental aspects of an organization is known as environmental accounting.

Generally spoken, companies are hardly aware of basic figures such as their annual environmental costs [28]. Therefore, the effects of green investments on a company's bottom-line are difficult to predict, and knowledge how to do this is very immature. Nevertheless, first attempts to establish methodological approaches to track environmentally related financial issues can be found in some Asian countries. Since the Japanese Ministry of Environment (MOE) released voluntary Environmental Accountability Guidelines in May 2000, the Japanese industry is active in this field. The guidelines are based on three concepts:

- Environmental conservation costs: investment and expenses related to the prevention, reduction, and/or avoidance of environmental impact, removal of such impact, restoration following the occurrence of a disaster, and other activities are measured in monetary value.
- Environmental conservation benefits: benefits obtained from the prevention, reduction, and/or avoidance of environmental impact, removal of such impact, restoration following the occurrence of a disaster, and other activities are measured in physical units.
- Economic benefit associated with environmental conservation activities: benefits to a company's profit as result of carrying forward with environmental conservation activities are measured in monetary value.

A recent study from Delft University of Technology, based on interviews with several Asian companies, revealed that the current level of implementation of environmental accounting in the electronics industry is still very limited [24]. For example, respondents in this study criticized the ambiguity and lack of concreteness when defining how to convert physical units into monetary units. This ambiguity leads to different interpretations of the guidelines that make it difficult to compare results between different companies. It was also mentioned that the guidelines are a good initiative for disclosing information, but too problematic to be used with internal purposes.

A lack of connection of environmental activities with business considerations is considered an obstacle for successful ecodesign/environmental management implementation. The guidelines have a great integration potential due to the promotion of equal terminology among environmental practitioners and managers. In practice, full cross-functionality is not ensured; environmental accountability is performed and disclosed separately from financial accountability practices. Also disclosure of data is done separately from financial reporting.

2.5 Other developments

In addition to the above, several other relatively new research areas can be identified. These include for example research into Product Service Systems (PSS), which has received an increasing amount of attention in recent years. To improve the success rate of the sustainable product services systems, the available knowledge from more traditional new product development and new service development is integrated with PSS theory.

Green marketing and communication is another research topic which is still in its infancy. Pioneering work has been done by for example Ottman [29], but again, customisation for (clusters within) the electronics industry is yet to be studied in more depth. A third topic worth mentioning is research into product innovation for the base of the pyramid. As mentioned in section 2.1, this research is based on the work of Prahalad, and focuses on new paradigms in product development for designing products for communities in emerging economies, based on local circumstances and infrastructures. In Western Europe, (also) the electronics industry has shown great interest in these initiatives, for example in the medical industry.

3 CONCLUSIONS

In this paper, a number of academic research initiatives in the field of green value chain management have been identified that focus on the current lack of speed of implementation in industry. Although mostly descriptive in nature, several of these research initiatives appear to have potential for adoption by industry in future years, just like -- what now can be regarded as elementary – approaches developed in academia in the mid-1990s have been adopted by industry already. To what extent this will result in established components of future business remains, as with all academic research, to be seen, but interest from industry indicates that great potential is ahead..

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Life Cycle Innovations in Extended Supply Chain Networks

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Abstract

In today's business environment enterprises are challenged to rapidly develop successful innovations that have to consider various requirements. Many failures of innovations in different phases of their life cycle can not comprehensively explained by previous theoretical approaches. Against this background, the Life Cycle Innovation framework is proposed in this paper. The integration of the Life Cycle Innovation model within the concept of extended supply chain networks leads to a model that represents the whole life cycle of a product. The approach allows to classify and to describe prior failures and serves as the framework for a simulation approaches.

Keywords:
Life Cycle Innovation; Extended Supply Chain; Simulation

1 INTRODUCTION

As studies show, innovation is the cornerstone of competitive advantage and one of the top priorities for long-term growth and success for companies in nearly all industry sectors. By 2007, the sales of new products introduced in the three preceding years are expected to generate 35 percent of total revenue, a huge increase from 21 percent in 1998. Companies across industries are shortening the time to market for new products from an average of more than 18 month in 2001 to less than 13 month in 2007. In consequence, by 2010, products representing more than 70 percent of today's sale will have reached the end of their life cycle on average [1]. Decreasing time to market and shorter product life cycles, as well as rising product variant diversity through integration of specific customer demand, increasing production volume fluctuations, and rapidly changing technologies are major factors that strongly intensify the dynamics of innovation processes. Additionally, an increasing number of interrelated and interdependent business processes in extended supply chain networks which explicitly include end-of-life aspects, the ongoing internationalization and the quickly increasing amount of product- and process-related innovation information that must be exchanged result in a significant increase in complexity [2].

While innovations can be seen as a key factor for a company's survival and success on the market, managing the innovation process within the complex and dynamic environment remains a very difficult task. Paradoxically, however, building or restructuring their innovation operations along their extended supply chain networks to profitably bring new products and services to market is near the bottom of most manufacturers' priorities [3].

2 THEORETICAL BACKGROUND

The basic requirement for an innovation is that the product or process "must be new (or significantly improved)" [4] compared to the former state. Depending on the various possible fields of application the term innovation can be defined and specified in different ways [4] [5]. Important and common distinctions in this context are made between incremental and fundamental innovations, product- (good or service) and process-innovations or technological and organizational innovations.

Innovation literature differs three different levels regarding innovation processes which will be presented in the following: a national level in the sense of national systems of innovation (NSI), the company-level view and cooperations respectively (regional) networks.

2.1 Innovations in a national context

From today's perspective, innovations are not the result of efforts from single firms, but of interactions between different players in a national or even international. To explain these various complex interdependencies of several actors, the concept of "National Systems of Innovation" (NSI) was introduced at the beginning of the 1990s. According to that concept, a country's innovation system is based on a complex network with actors that offer (develop) technology (e.g. universities, research institutes) and others which demand and use it (e.g. companies). These actors are imbedded within the influencing framework, which includes aspects like the basic educational system, political decisions regarding R&D and innovations, legislative settings (e.g. patent law, taxation), financial and communicational infrastructures, industry structures (e.g. competition, market accessibility), international relations or the general social and economic situation of a country [6] [7] [8]. Studies also focus the variables that actually determine the innovation climate (restraining and supporting factors) in countries and the innovation behavior of companies within an economy. Due to the importance for innovative behavior on a national level, environmental protection and political decisions are specifically addressed by several authors [9] [10].

2.2 Innovations from a company level perspective

As stated above, national policy and regulations are major triggers for the creation of innovations within companies which notably is true for ecological driven projects. In addition, research identified other variables like market and society expectations, technology advancement in general, the company's own vision and values, or other internal characteristics which can strongly influence sustainability oriented innovative behavior [2].

The innovation process itself involves several departments within a company and is often described as linear process with successive phases called the "innovation pipeline" [11] [12]. However, traditional linear phase models of the innovation process are often idealized and theoretical approaches; they do not consider a realistic framework (phases are not necessarily successive), interactions of different phases (e.g. feedback loops) or interactions with other actors. Over the years, in an evolutionary process the innovation process models more and more developed to rather interactive approaches, which shall integrate these realistic settings [13]. The so called "fireworks"-model can be seen as the latest stage of this evolution process and is based on long-term empirical studies [14]. Although there is no basic, generally accepted process model one generic approach can be derived which is applicable for all products (goods and services) and business organizations: it always begins with the creation of ideas, their evaluation and finally the realization and use of accepted concepts [15]. Independent from the underlying process, in the end just a few of the original amount of ideas are actually realized due to permanent evaluation with technical and economical criteria, even less are successful on the market. This process is described by the so called funnel model [16]. Besides the innovation process itself, another focus in literature lies on the management of innovations within a company based on some major determinants. They can be divided in hard or structural factors like the innovation strategy (e.g. product versus process innovation, innovator versus adopter) or organizational structures and processes which build the framework of the innovation management [11] [17]. Soft factors like leadership, corporate culture, human resources in general, experiences with prior innovations, or informal communication are less directly controllable but have important influence on idea generation and knowledge transfers within a company [4] [18]. Research considers innovation promoters as individuals who support and potentially enforce innovations within an organization as one of the most important factors for success in the management of innovations [19] [11].

2.3 Innovations in cooperations and networks

To improve the innovation process and share costs and risks, cooperation on different levels is a common way for companies to meet the strong need for innovations in the marketplace [20]. Studies underline that collaboration is stronger in dynamic environments and also worth the effort because it has positive effects on innovational success [4]. Concerted research and development can basically take place between all actors of the NSI. In this case cooperations between businesses within with similar needs and problems in different or even the same branches (which could also include direct competitors) or within a supply chain [21] are considered. Whereas temporary bilateral activities are common for several years, multilateral network structures become more and more relevant nowadays [4]. Examples for that are concepts which are based on geographical closeness of the actors like regional technological cluster of companies (e.g. Silicon Valley). "Innovation networks" allow the optimization of the acquisition and realization of innovations by the sharing of information and knowledge [21]. By using innovation networks, companies virtually in-crease their R&D capabilities and derive benefit from faster identification and evaluation of ideas and prototypes as well as from increasing probabilities of innovation success.

Key factors that strongly influence the success of all network based concepts. Examples are the complementarily and compatibility of partners (regarding their visions, goals, expectations, innovations or cooperation cultures), the capability of communication and transfer structures, and the efficiency of the network management [22] [20] [23]. As stated above, individuals namely so called promoters are key players to enforce innovations on the company level. This is also true for the network level: recent research enhanced the approach with the introduction of the "extended promoter model" which includes interactions of promoters from different actors (e.g. companies) within so called "innovation communities" [22] [11] [19].

3 INNOVATION AND SUSTAINABILITY

3.1 Innovations and Life Cycle Orientation

Ongoing industrialization and increasing world population more and more results in negative ecological effects. The increasing amount of greenhouse gases, pollution with waste and hazardous substances and the shortage of natural resources are just a few examples that are challenging problems for the future. To stop or slow down these tendencies, further technological developments have to address basic principals of sustainability like efficiency, sufficiency, allocation, consistence, prevention, and risk avoidance [2] Technological advancement naturally strongly depends on innovations which could improve or replace current technologies. As a result innovations can be seen as a necessary but not sufficient condition for more sustainable products and processes. Ecological innovations can only take effect if there is a link with an exnovation – the replacement of an older process or product with the improved alternative. Due to various interdependencies and lacking transparency of the innovation processes the actual success of such innovations is hardly predictable. To assess the ecological improvement, possible rebound-effects or other risks have also to be considered [2].

To enforce the consideration of sustainability when developing new products and processes, several legal requirements came into force in recent years. Environmental driven regulations like WEEE (Waste Electrical and Electronic Equipment), RoHS (Restriction of the use of certain hazardous substances in electrical and electronic equipment), or ELV (end-of-life vehicle) forced companies to evolve new production techniques and explicitly incorporate end-of-life-aspects. In the sense of an integrated product policy (IPP), companies have to cope with extended product responsibilities throughout the whole life cycle of their goods. Re-x options like re-use or remanufacturing also offer economic advantages and opportunities to save costs or achieve additional revenues. Furthermore, the restricted availability of natural resources also leads to higher market prices for these materials. As a result of these developments and its actual legal and economical consequences, the sustainability of an innovation is not longer just a desirable side-effect but a central objective of companies' innovational activities.

3.2 Sustainability through Life Cycle Management

Within a life cycle management framework, innovation processes naturally stand for the very beginning of a product's life cycle and can be classified as part of the product management [24]. With respect to superior values like sustainable development on a normative level, innovations idealistically emerge through the conscious search within chosen fields which are defined through the life cycle strategy process. Life cycle design as the rather operational level stands for the further development of filtered innovative ideas including the conduction of design-for-x options [25].

Life cycle oriented product planning includes the conscious consideration of impacts in all life cycle phases. An integrated approach with an optimization over all stages which explicitly includes reverse logistics and material flows automatically leads to closed-loop supply chain approaches and is an essential precondition for sustainable innovations [26]. In the following the term Life Cycle Innovation is used for this kind of innovations with an integrated perspective and a strong emphasis of sustainable development.

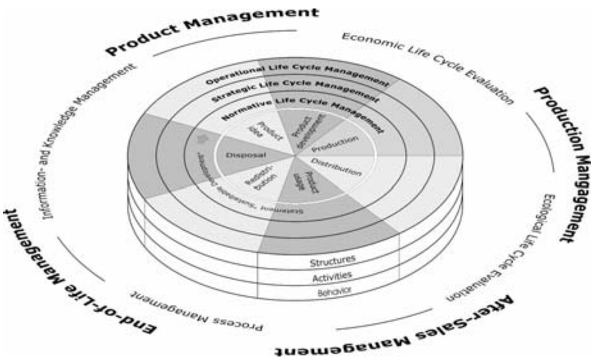

Figure 1: Braunschweig model of Life Cycle Management.

3.3 Ecological innovations within the business environment

Looking at environmentally oriented innovations of the last couple of years it is obvious that there are many approaches offensively trying to cope with new legal regulations and open new sources for revenues. However, despite of good underlying ideas the full ecological and economical potential could mostly not fully tapped for various reasons as these following examples underline:

- Failure of fuel economy rule in 1975 (USA): The rule did not reflect market demand and car sellers preferred to pay fines for further selling high fuel consumption cars.
- Volkswagen Lupo 3L: The first series-production vehicle with a fuel consumption of three liters per 100 km (realized by lightweight construction and new materials) was not accepted by customers due to it's high price.
- Remanufacturing: Whereas Asian and US firms predominantly chose to actively develop remanufacturing concepts for exploiting potentials besides fulfilling legal regulations, European companies act rather passive and just try to reduce costs.
- Volkswagen SiCon process: The recycling process was developed to achieve future recycling and recovery quotas. It has been implemented in different European countries but not in Germany, as the legal requirements (Deponieverordnung) were changed unexpectedly and disturbed the supply with secondary raw materials.
- The German Refund system for empties, the Green Dot (DSD – Duales System Deutschland), Cherry's 'Green Line' keyboard: All these concepts suffered severe problems with redistribution processes after usage.

These examples show that the success of ecological innovations depends on multiple interdependent variables. External factors like legal requirements, market prices for resources, the political and cultural background of the country or competition as well as all phases respectively actors within the extended supply chain system can obviously strongly influence the success of ecologically driven innovations. These interdependencies are highly complex, dynamic and very specific regarding the different innovations. Causal coherences are not necessarily transparent and comprehensible. An integrated framework to classify life cycle oriented innovations, all involved actors and existing interdependencies would help to gain system comprehension and could be the base for detailed simulation based analysis and optimization.

4 DEVELOPMENT OF A DESCRIPTION APPROACH

4.1 Problem Definition

Literature review shows various approaches trying to explain the emergence and management of innovations on different levels. However, looking at the listed examples of ecologically motivated innovations above, it is obvious that these cases can not really be classified and described with any existing description framework. Reasons for that are:

- Relatively isolated consideration of the national and the company perspective whereas this strict distinction is not necessarily given in reality.
- Lacking consideration of multilateral networks. This is notably true for vertical concerted activities which are crucial for the success of an innovation.
- The extended supply chain has to be taken into account to include end-of-life aspects like redistribution, disposal or recycling and respect relevant aspects for innovations like new ecologically driven directives (e.g. WEEE, ELV, RoHS). Current innovation research is restricted to traditional supply chain structures and, as a result, a holistic approach with respect to the whole life-cycle is missing.
- Linear phase models of the innovation process are still common, although only interactive approaches reflect realistic circumstances.
- Since models are not necessarily consistent among each other and compatible to different types of innovations or branches there is no generally accepted model.
- Prior models are mostly qualitative descriptions that do often not really help to understand the actual working innovation system.

Increasing complexity requires a turning away from innovation models that focus only on individual actors and single life-cycle phases. In fact, an integrated life-cycle oriented model of the extended supply chain network and its innovation processes working in and covering all product life phases and actors of an innovation seems to be a promising approach.

4.2 Framework for Life Cycle Innovations in the extended supply chain

To gain deep-insight into complex innovation processes and to foster Life Cycle Innovations, it is necessary to take a systemic view of innovation processes inside the extended supply chain network system. Therefore a Life Cycle Innovation Framework is proposed which integrates prior theoretical work and into an integrated description model (figure 2). It bases on both literature review and finding from various case studies. As defined above, the framework relates to product management where the evaluation and implementation of innovations actually take place. In this sense figure 2 does not show the physical level of an extended supply chain network system. It rather depicts the structure and system borders of the Life Cycle Innovation Framework with its integrated consideration of all actors' innovation processes through information flow under the influence of various external factors.

As stated above, innovations emerge within companies through various reasons. External factors are influencing the system. Every actor in the network has its own "innovation funnel" which can be described through a very generic three-step innovation process consisting of the creation, evaluation, and implementation of ideas. However, the positive evaluation within a single company is just a necessary but not a sufficient condition: to be able to successfully implement and enforce the innovation within the complex business environment of an extended supply chain network, all other affected actors must be integrated, too. As a result of external influences as well as internal parameters, each actor has specific requirements regarding every innovation within the system. To enable the implementation and to tap the full potential of innovative products and processes within the network, all these requirements need to be considered holistically and matched through all phases of the life cycle. The introducing examples show that this does not necessarily happen in reality.

4.3 Ecological Potentials within the Life Cycle Innovation Framework

Little mistakes, missteps, and delays in the innovation processes often cause negative effects that get each other going due to the creation of reinforcing feedback-loops. If a company forgets to notify one ore more actors of the extended supply chain network about a change in an innovation project, or inadequately communicates the information along the supply chain, it will slow down the innovation processes along the supply chain and thereby diminish the revenue and profits of the whole supply chain. In extreme cases, inadequate communication and synchronization of requirements between partners of the extended supply chain network can lead to economical or ecological failures, as the overall success of an innovation can not be measured before the innovative product leaves to its end-of-life stage.

Since insufficiently synchronized requirements and processes cause wasted time and development efforts, optimizations in innovation processes of extended supply chain networks lead to more efficiency in terms of time and resource input. Additionally, the probability of successful innovations increases. Through integration and conscious information exchange of all relevant actors the emergence of more and better ideas is also probable. All of these aspects lead to

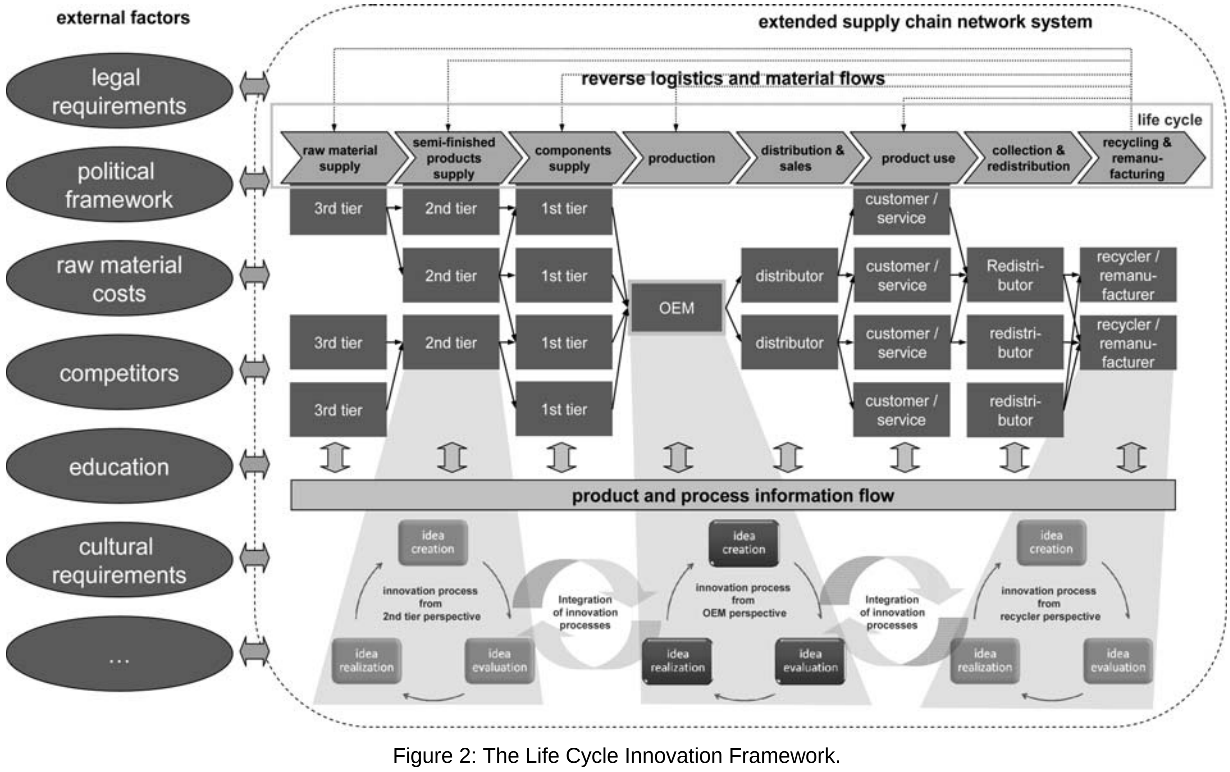

Figure 2: The Life Cycle Innovation Framework.

positive effects in economical as well as ecological dimensions. Less input in terms of ecological relevant resources is seized per innovation. Furthermore, there could be more, better, and more matured innovations in the system which increases the total ecological improvement in the end.

The shape of the generic innovation funnel of each company depicts the positive influence by extending the number of innovation input actors and the faster synchronization and matching of requirements along the extended supply chain network (Figure 3). With an increase of innovation ideas, the innovation funnel will get wider (a). With shortening the synchronization and matching time, filtering and management of innovations on the network level is faster – the funnel will get tighter in an earlier phase (b). Idealistically, there will be a combination of both effects resulting in more and better innovations with higher success probability (c).

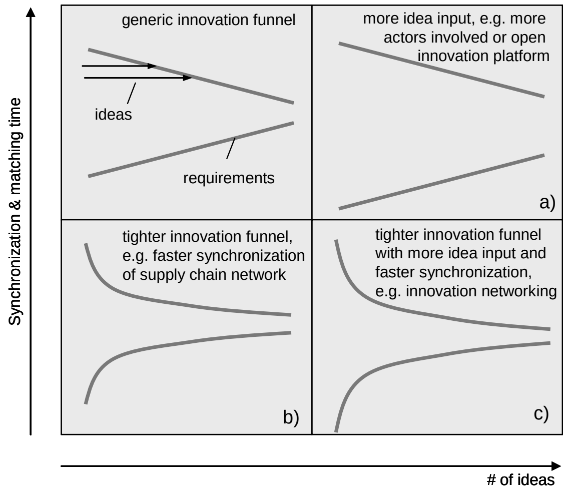

Figure 3: Effects on the innovation funnel.

5 SIMULATION BASED ANALYSIS

5.1 Motivation and Goals

Qualitative descriptions of systems can certainly help to gain general system understanding about influencing factors and dependencies. However, due to the complexity and dynamic interdependencies within an extended supply chain network, clear predictions about the actual behavior of the system are hardly possible. Against that, a simulation approach enables to reveal potential and trade-off effects within the Life Cycle Innovation model. Through variation and optimization of parameters, simulation experiments allow deriving optimal strategies and could serve as decision support.

Just as the relevance of the topic, the amount of simulation approaches considering innovations increased during the last couple of years. These models generally base on continuous simulation with System Dynamics and focus relatively specific problems strongly referring to the NSI-concept or innovation on the company level. An integrated approach trying to describe behavior within an extended supply chain network system is missing.

Therefore, the proposed description model of the Life Cycle Innovation Framework was implemented using simulation model. Against prior simulation approaches based on System Dynamics, discrete simulation was used and implemented with Anylogic 5.5™ in this case. The model bases on the theoretical concepts of the description approach (promoters, generic innovation process, etc.) which were realized with the combination of standard elements of the simulation software.

The core element of the simulation is a generic company module which can be adapted to specific company characteristics by parameters. These parameterized modules can be combined to network structures representing the extended supply chain. Within the company modules, innovations emerge as a discrete flow of innovation entities which have randomly assigned characteristics like a certain attractiveness, coordination requirements regarding different other actors (companies) of the network, or a defined ecological potential. Each innovation firstly has to pass the internal innovation funnel before getting considered on the network level. On this level the coordination of all innovations and actors takes place. This means that specific innovations' requirements are reduced due to a matching procedure with the other companies in a successive multi-phase coordination process. The actual realized ecological improvement of each innovation in the end depends on its specific underlying ecological potential and the degree of matching the coordination requirements through the whole innovation process. To enable the internal and network coordination process, each company has to provide resources which could be interpreted as promoters. Since resources are working on different levels and coordination phases, their availability is restricted which naturally can lead to resource bottlenecks.

Major influencing factors that were integrated into the model and serve as individual parameters for companies and coordination phases are the idea inflow rate (the time between occurring ideas within a company or from external sources), resources (quantity, qualification, priorities) as well as specific coordination capabilities and thresholds for innovation evaluation.

5.2 Analyzing model behavior

In a first model approach a simplified structure is used to test model behavior and gain understanding for basic interdependencies. It consists of an extended supply chain system with only four actors (tier, production, use and end of life). Figure 4 shows exemplarily result diagrams from a basic run with different variables measured over time. Considered target variables which can be used to evaluate system behavior are the ratio of successful to total innovations within the whole system (box a), the throughput time of an innovation from the idea until leaving the innovation system border (influenced by factors like the complexity and coordination requirements of each innovation or the utilization of the system, box b), the costs per innovation (caused by seizing resources, box c), and the total ecological improvement that was gained by innovative products and processes (sum of all individual improvements, box d). Through varying specific parameters and detailed analysis of the results from first basic runs, some basic hypotheses regarding innovation management within an extended supply chain network found support:

- Ecological improvement, costs, throughput time and success ratio are not necessarily complementary but rather competing goals.
- Concerted activities of all involved actors are crucial for an innovation's success.

- Under given innovation input quantity, there is a specific critical amount of resources that leads to the most efficient results.
- When resource availability is restricted, the perfect synchronization of all requirements is not the ideal strategy when aiming at maximizing total environmental improvement.
- In order to maximize environmental effects, priorities of companies' innovation resources should be set on the network layer.

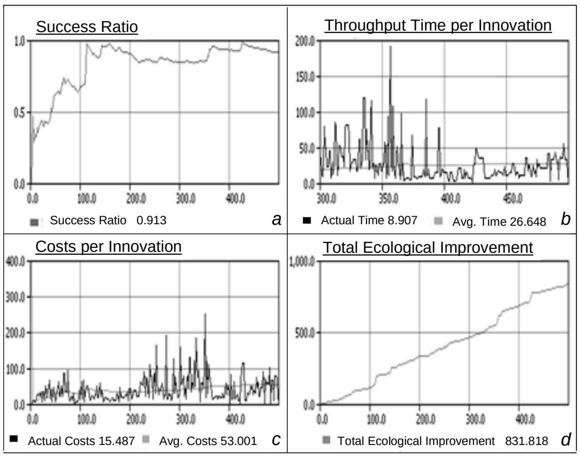

Figure 4: Diagrams from basic model run.

6 SUMMARY AND OUTLOOK

In this paper a Life Cycle Innovation model was proposed as a description framework which is explicitly applicable for environmental driven innovations. The approach was also transferred in a first basic simulation model allowing to analyze actual behavior of the complex and dynamic system. This leads to deeper understanding of the interdependencies and potentially enables to derive optimal strategies for the management of innovations within extended supply chain networks. However, the simulation approach is a conceptual model and further studies are needed to validate model structures. Additionally, the previous simulation model has to be enhanced with more involved players and factors including further integration of external variables.

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Evaluating eco-efficiency of appliances by integrated use of hybrid LCA and LCC tools

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ABSTRACT
Airconditioners are the appliance with the largest share of electricity consumption in Japanese households. In our preceding study, it was found that the high-end model (with the highest environmental performance with regard to Global Warming Potential and landfill consumption) turns out to be the one with the lowest life cycle cost, and the low-end model (with the lowest environmental performance) the one with the highest life cycle cost. This paper is concerned with investigating if the above finding still holds for more recent data, say for 2005, and also in analyzing possible changes that have occurred since 2002 from the perspective of eco-efficiency. Compared with the previous results, we notice a significant reduction in the cost at the use phase due to the convergence in efficiency at the use phase, and the resulting reduction in life-cycle costs among alternative models. There was thus a significant increase in eco-efficiency between 2002 and 2005 in terms of both CO_2 and landfill consumption.

Keywords:
LCA, LCC, Waste input-output analysis, airconditioner, eco-efficiency locus

1 Introduction

Airconditioners are the appliance with the largest share of electricity consumption in Japanese households (Figure 1). Furthermore, the share is still increasing. Airconditioners are thus of significant environmental importance in Japan, and have been the subject of several LCA studies [2] [3]. With regard to the end-of-life (EoL) phase of airconditioners, it is important to note that since 2001 its collection and recycling (material recovery and treatment of coolant) has become mandatory in Japan [4]. While [2] is concerned with the implication of replacement of appliances with different energy efficiency over time for the case of no mandatory recycling, [3] is concerned with the comparison of appliances with different energy efficiency for the case of mandatory recycling. From the methodological point of view, [3] is characterized by an integrated application of LCA and LCC (life-cycle costing) that was made possible by the use of a common hybrid approach based on waste input-output (WIO) [5]) [6]. For the purpose of evaluating environmental and economic sustainability of a product, an LCA of the product needs to be accompanied by a complementary evaluation of its cost aspect, that is, LCC [7]: however excellent a product may be environmentally, it would not come into wide use unless it is also economically affordable.

In preceding study [3], we investigated airconditioners of 2.5kW models that were available in the Japanese domestic market in 2002, and found that in the absence of discounting (or discounting at a rate well below 5%) the high-end model (with the highest environmental performance with regard to Global Warming Potential and landfill consumption) turns out to be the one with the lowest life cy-

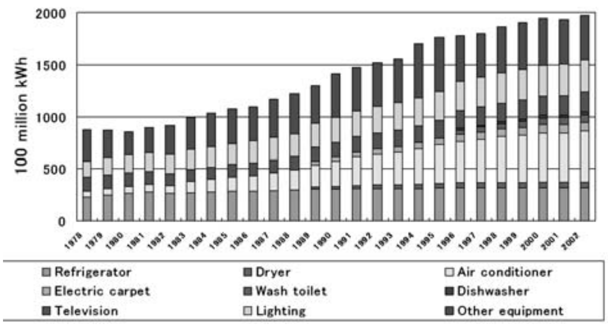

Figure 1 Electricity consumption by applainces: Japanese household. Source [1]

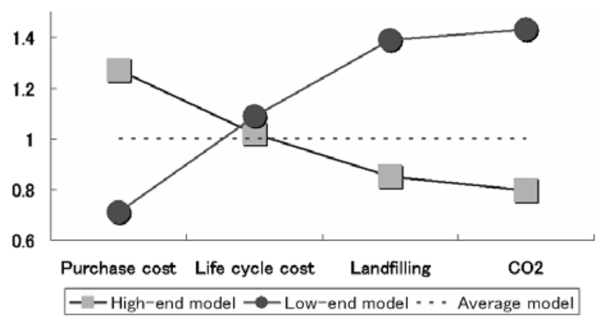

Figure 2 Cost and environmental load of different air conditioners types: relative values with the levels of cost, landfilling, and CO2 set unity for the average model (discount rate=0) 2002 models. Source [3]

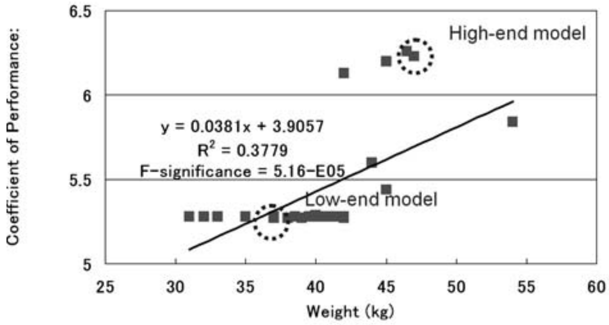

Figure 3 Weight and efficiency of airconditioners, 2.5kW models, 2005

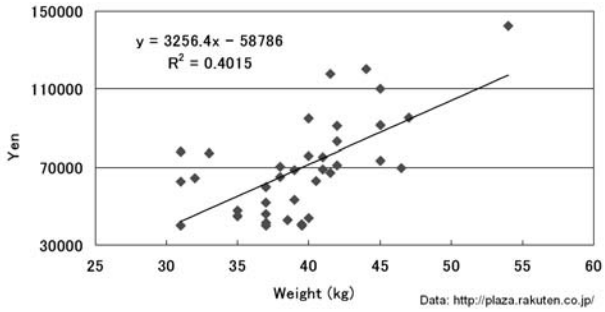

Figure 4 Weight and price of airconditioners, 2.5kW models, 2005

cle cost, and the low-end model (with the lowest environmental performance) the one with the highest life cycle cost (Figure 2). The market of airconditioners in Japan is highly competitive, with a large number of new models introduced every summer and winter. In this paper, we are interested in seeing if the above finding still holds for more recent data, say for 2005, and also in analyzing possible changes that have occurred since 2002 from the perspective of eco-efficiency. While the term eco-efficiency is in wide use, up to now, no standardization is available [8]. Still, it can generally be accepted that product A is more eco-efficient than product B with equal environmental performance when its life-cycle cost is lower. As a means for graphical representation of eco-efficiency, the concept of ”eco-efficiency locus” is introduced that resembles ”eco-efficiency portfolio” [9].

2 Methods

We use the integrated LCA-LCC methodology [3]. The major body of data are Japanese WIO table for the year 2000 with 408 industry sectors, and 78 waste types [11]. The functional unit under consideration is a unit of airconditioners (2.5kW) that is used for 10 years, and then is subjected to recycling in line with the Japanese law on recycling of electrical appliances [3]. The data on energy efficiency (electricity consumption), price (purchase cost), and weight were taken from web catalogues of the year 2005 [10]. The weight of an airconditioners tends to increase with an increase in its energy efficiency (Figure 3). In fact, about 40% of the difference in price can be accounted for by the difference in weight, that is, by the amount of material input (Figure 4). The increase in weight can mostly be attributed to the use of a larger heat exchanger as can be seen by an increase in the material composition of copper and aluminum alloys (the main components of a heat-exchanger) in Table 1.

Table 1 Material composition of airconditioners

Year of manufacturing	1996	2002
Steel	0.46	0.46
Plastics	0.17	0.18
Copper alloys	0.15	0.17
Aluminum alloys	0.09	0.10
Other alloys	0.02	0.01
Gasses	0.03	0.02
PCBs	0.03	0.02
Others	0.06	0.03

Source. Association for Electric Home Appliances

Table 2 Aiconditioner types to be analyzed

Type	Price 10^3yen	COP	Weight kg	Manufacturer
High-end	95	6.23	47	M electric Co.
Low-end	40	5.27	37	M electric Co.
Average	67.5	5.75	42	Hypothetical

COP: coefficient of performance (the ratio of the cooling/heating effect produced in kW divided by the energy input expressed in kW).

In line with [3], three representative models (high-end (**H**), low-end (**L**), and average (**A**)) for the 2005 data were chosen, the specifications of which are given in Table 2. While the high-end and low-end models correspond to real products ((Figure 3)), the average model is a hypothetical one that is obtained by taking the mean value of **H** and **L**.

A challenging task in implementation is how to incorporate the difference in weight, energy efficiency, and price into the computational framework. The difference in weight implies that more resources are used in the production and EoL process of **H** than **L**, whereas the difference in electricity efficiency implies that the opposite is the case for electricity consumption in the use phase. The input coefficients of airconditioners in the Japanese input-output table for the year 2000 [12] were taken as those referring to the production technology of **A**. In order to obtain the input coefficients of **H** and **L**, the coefficients of **A** that refer to inputs with mass were adjusted in proportion to

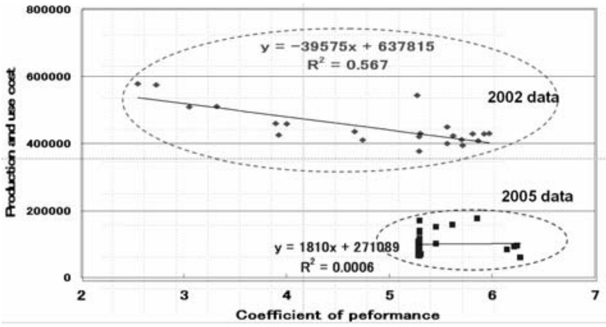

Figure 5 Cost (production and phase) and efficiency: 2002 and 2005 models

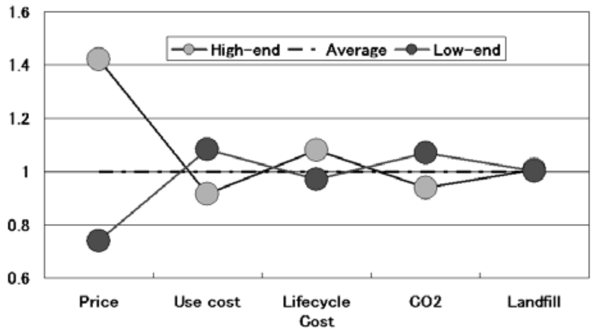

Figure 7 Cost and environmental load of different air conditioners types: relative values with the levels of cost, landfilling, and CO2 set unity for the average model (discount rate=0) 2005 models.

the difference in weight. For the sake of simplicity, we assume that the product price represents the unit cost, which can be justified because consumers are the focus of this study. The unit cost is obtained by multiplication of input coefficients with the corresponding price of input. While the above adjustments of input coefficients in proportion to weight results in a higher unit cost for **H** than the other models, the difference is small compared to the difference in price in Table 2. In line with [3], the remaining difference in product price was accounted for by adjusting non-physical inputs such as R&D and services. The input coefficients for electricity were also adjusted to account for the difference in electricity consumption in the use phase. No discounting was done in the computation of LCC.

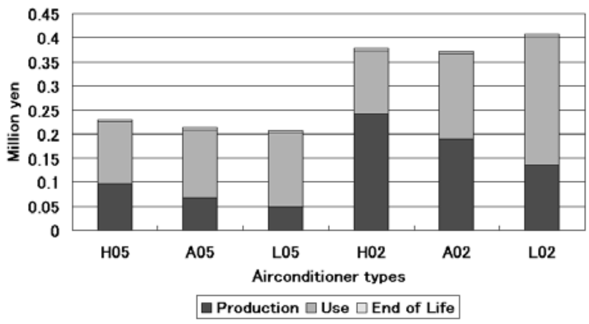

Figure 6 Life-cycle cost of airconditioners: 2002 and 2005 models

H05(02), A05(02), and L05(02) refer to the high-end model, the average model, and the low-end model for 2005 (2002).

3 Results and discussion

Before turning to the results of WIO analysis, we show in Figure 5 the association between the performance and the cost at the production and use phase for both 2002 and 2005. We notice a significant reduction in the cost at the production and use, and the convergence in efficiency (coefficient of performance) at the use phase. The difference in performance between models decreased remarkably. In particular, for the 2005 data, the negative correlation between the performance and the purchase and use cost (LCC except for the EoL cost) that existed for the 2002 data is no longer present. The overall reduction in the product price resulted in a decreasing share of cost at the production phase in life-cycle cost, while the convergence in performance resulted in smaller differences in the cost at the use phase (Figure 6).

Figure 7 summarizes the results of WIO-LCC-LCA that were obtained for the 2005 data. Compared with the results for 2002 data in Figure 2, we notice a significant reduction in the cost at the use phase due to the convergence in efficiency at the use phase, and the resulting reduction in life-cycle costs among the three models. In particular, the cost advantage of **H** over **L** that existed for the 2002 data is no longer observable. With regard to environmental burdens, **H** performs slightly better than **L** in terms of CO2. In terms of landfill, however, no difference is observed between **H** and **L**.

Figure 8 and 9 give a visual representation of the above results in the form of "eco-efficiency locus", which resembles the concept of eco-efficiency portfolio [9]. The reduction in production cost and the convergence in performance resulted in a shift of the locus toward the origin. A shift of the locus toward the origin represents an increase in eco-efficiency. There was thus a significant increase in eco-efficiency between 2002 and 2005 in terms of both CO_2 and landfill.

The above results indicate that competition in performance among manufacturers has resulted in the convergence of performance and of life-cycle cost among alternative models of airconditioners. It remains to be seen if she same conclusion can be drawn for other durable products such as refrigerators, washing machines, and automobiles.

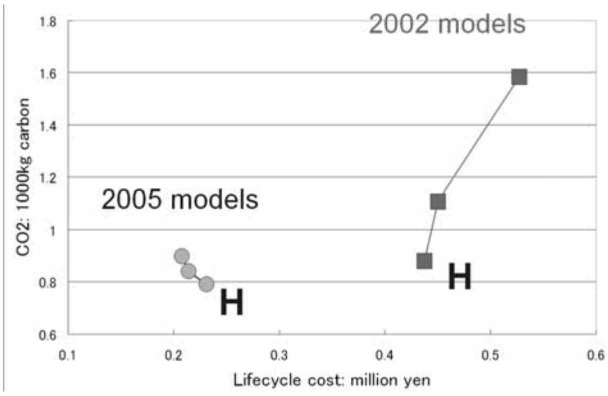

Figure 8 Efficiency locus of airconditioners in terms of CO_2 emission and LCC: 2002 and 2005 models

H refers to high-end model.

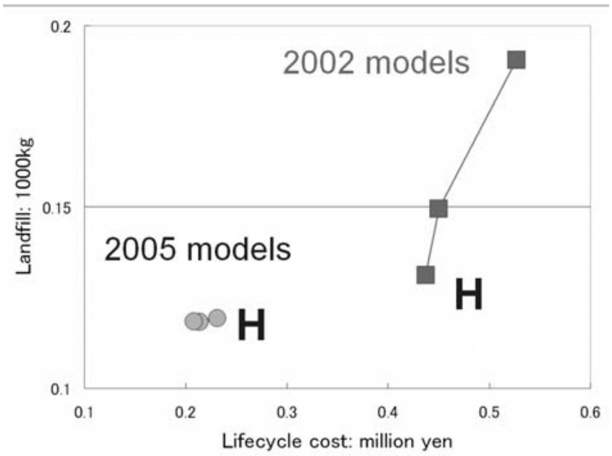

Figure 9 Efficiency locus of airconditioners in terms of landfill requirement and LCC: 2002 and 2005 models

H refers to high-end model.

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Machine Life Cycle Cost Estimation via Monte-Carlo Simulation

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Abstract
Recently an increasing number of customers demands more extensive warranties from the machine building industry. In order to control and maintain the arising costs from the seller's point of view, the paper in hand presents a generic and comprehensive approach to estimate the distribution function of machine warranty cost. Based on the estimation of the failure rate distribution certain life cycle cost elements are quantified either deterministically or stochastically depending on their characteristic. The Monte-Carlo simulation is used for the flexible consideration of the entire system and the estimation of risk figures such as the Value-at-Risk.

Keywords:
Production Management, Life Cycle Cost, Monte-Carlo Method

1 MOTIVATION

During the last several years more and more companies, especially in the automobile industry, detected the high relevance of the life cycle cost of their production equipment. Although life cycle costs are normally referred to as all of the costs generated during the life cycle of an item [1], the article in hand focuses on the maintenance costs because of two reasons. On the one hand the maintenance costs are mostly driven through the failure rate of an item which is normally modeled through the Weibull probability function [2, 3]. Ergo it is more complex to consider them than deterministic costs that can easily be added and varied. On the other hand analyses show that the maintenance costs are a key differentiator between offers of different suppliers. Initiated through this perception an increasing number of companies demand a warranty for the maintenance costs today [4]. These costs annually reach up to 10% of the machine acquision costs, in some cases even higher as shown in figure 1 [5].

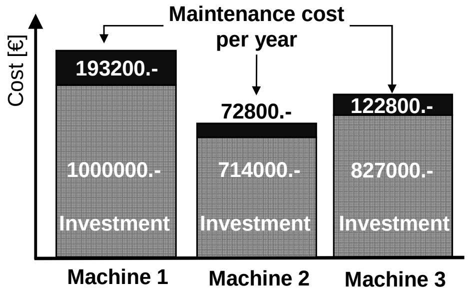

Figure 1: Comparison of the annual maintenance cost and investment [6].

For the machine manufacturer the following risks arise from this framework which is in the following referred to as life cycle cost contracts. First the machine reliability calculation can result in inaccurate values. State of the art are methods like the experience based Failure Modes Effects and Criticality Analysis (FMECA) [7] and the data based Weibull analysis [3]. The calculation error generally depends on the existing experience, the available data and its quality. Thus precision depends on the efforts done regarding data quality. Apart from forecast accuracy, the second risk arises from the statistical variance of the failure rate. Assumed constant, the reciprocal value of the failure rate is the mathematical expectation of the time between failures; the Mean Time Between Failures (MTBF) [1]. A field data analysis of 10 identical turning machines in similar operations over a period of 12372 operating hours conducted by the Institute of Production Science shows a standard deviation of the MTBF of 580.1h at an average of 1030h (figure 2).

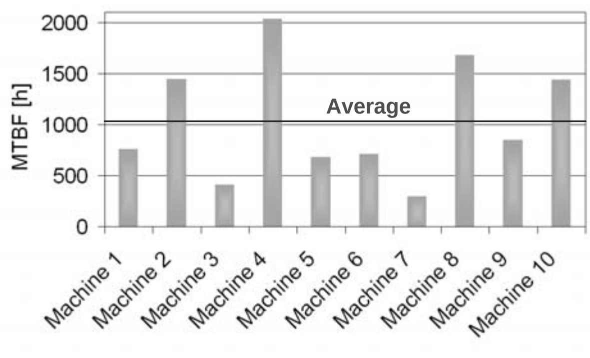

Figure 2: MTBF values of identical machines in similar operations.

Obviously the maintenance costs of the machines also vary in a wide range. Thus the risk to the machine manufacturer in case of a life cycle cost contract is immense without precise life cycle cost estimation. The height of the penalties can even reach up to 30% of the machine price in current contracts [4]. Different scientific methods are known to calculate the mathematical expectation of the failure rate for technical systems such as the Bool model, the Markov model, the Fault Tree Analysis and the Monte-Carlo method [8]. Because of its flexibility the Monte-Carlo method is most promising in this context. It is defined as a methodology for obtaining estimates of the solution of mathematical problems by the means of random numbers [9]. In literature it was first mentioned in 1949 in context with the Manhattan project [10]. The Monte-Carlo method uses statistical distribution functions on component level as input parameters but results in average values [9, 11, 12]. Against, methods to combine deterministic and stochastic life cycle costs are a deficit in research today. Furthermore no approach exists to calculate the life cycle cost distribution function of technical systems.

2 AIMS

This article provides a general approach for the estimation of statistical life cycle cost distributions for machines and components to provide the basis for the risk calculation of life cycle cost contracts. In most cases only some data from different sources are available for the calculation. The proposed method is required to handle these circumstances. Beside the prognosis of stochastic cost elements, the calculation of deterministic cost elements is subject matter. The core aim is the combination of stochastic and deterministic cost elements to identify the statistical life cycle cost distribution. The result of the method enables the machine manufacturer to calculate the Value-at-risk of a certain offer.

3 PROCEDURE

The presented life cycle cost estimation procedure consists of three stages. The first step is the calculation of the failure rate distributions on component level to consider the stochastic cost influences. In the second step, the deterministic life cycle cost elements need to be calculated while existing life cycle cost standards must be considered. The third step consists of the Monte-Carlo simulation to combine the stochastic and deterministic life cycle cost elements. Flexibility regarding both, time intervals to cover different contractual periods and the machines part list to take different assemblies into account, is necessary.

3.1 Estimation of failure rate distributions

The two main methods to estimate the failure rate distribution of components, used in the proposed procedure, have been mentioned already. On the one hand there is the Weibull analysis which is based on data from machine service, spare parts, maintenance and fatigue tests [3]. A condition for the use of the Weibull analyses is the assignability of the failure times to root cause components. On the other hand there is the experience based FMECA which supports the user through a detailed structure but still feature uncertainties because extensive experience is required [7]. Especially in the offer preparation stage machine manufacturers face the following problems:

- Field data comes from several sources with variable quality levels. Particularly service and spare part data quality is arguable.
- Not all possible types of data are available in any case. Especially data from customers and suppliers is often unavailable.
- Field data refers to different machine types which only share some identical parts and assemblies.
- Fatigue tests are limited by shrinking product development times and expenses.

Nevertheless, in order to calculate failure rate distributions with sufficient precision for life cycle cost contracts, the calculation procedure needs to be planned in detail. Machines normally consist of a huge number of components, but the statistic broadness of the field data for a precise analysis is only given for some components. So it is important to break down the machines bill of material to a manageable detail scale by defining life cycle relevant machine components. For the appraisal of the relevant machine components, the analysis of the required spare parts during the two year free replacement warranty period is used. Although long term effects of changing failure rates during the life cycle are underestimated, this procedure provides a reasonable approximation.

After the identification of the relevant parts of the machine, the available data sources must be assigned to every machine component. The most precise field data for reliability examinations is normally gained from the production data acquisition and the maintenance department of the machine operating company (see customer data in figure 4). Maintenance data consist of a manual description of maintenance actions divided into preventive and reactive maintenance. This information is mostly linked to the required spare parts which are ordered from the machine manufacturer or a third party. The advantage of spare part data is the possibility to link it directly to the bill of material through the identification number. Field data from production data acquisition also include short term breakdowns that are mostly not caused by the production equipment. The differentiation of equipment breakdowns, the assignment of the root causes for breakdowns and the identification of broken machine components is normally not possible in retrospect. In most cases machine manufacturers have only limited access to in-service field data. Then only data from spare part business and warranty services is available.

Because Weibull analyzed field data provides most valid results, this method is preferred dependent on data quality. In order to minimize statistical variance influenced by different stress requirements, the machine pool needs to be divided into stress classes according to the in-service utilization at the customers. By an increasing number of stress classes the prediction quality gains accuracy. Against the data availability limits the number of stress classes to a maximum of three. The Weibull analyses then needs to be conducted for every stress class. If no data is available at all, statements about the MTBF need to be requested from the machine manufacturer suppliers. If even from the supplier no statement is available, knowledge based approaches offer the possibility to come to average values for the MTBF and the Mean Time To Repair (MTTR). Due to requirements from most automotive customers, the FMEA is commonly used in the machine development process [13]. In order to implement it systematically for reliability forecasts, the standard FMEA sheet needs to be adapted by a quantification of the failure rate, the MTTR and the spare part cost according to figure 3. Not needed for calculation is the criticality assessment as it is for example required in a FMECA procedure. Once the mean values of the repair time and the time between failures in the adapted FMECA have been estimated or were given from the supplier, the mathematical distribution must be assigned assuming an exponential distribution. In this case the reciprocal value of the MTBF is equal to the failure rate which is constant and fully describes the exponential distribution.

Failure	Occurrence probability		Severity					Detection		RPN
	Rating	Av. of failure rate class	Effect	Conse-quence in service		Cost [€]	MTTR	Rating	Effectiv. of prevention measure	
Voltage regulat. untight	**3**	$5*10^{-5}$	Mach-ine break-down	Service order	**6**	590	3.5 h	**9**	No prevention measure in place	**180**

Figure 3: Adapted FMECA sheet.

Once analyzed, the different results of the calculation must be assessed considering the given constraints. In the first instance the number of input failures is a knock out criteria. Although the Weibull analyses using linear regression works already with more than one failure record, a reasonable calculation of the Weibull distribution parameters starts with about 10 failure records [3]. The matching of the distribution function and the input data is described by the correlation coefficient which is used to prioritize the results from the different data sources. Comprehensive examinations show that data from the described source normally fit with a correlation coefficient of 0.9<σ<1 to Weibull distributions. An overview of the whole procedure is given below in figure 4.

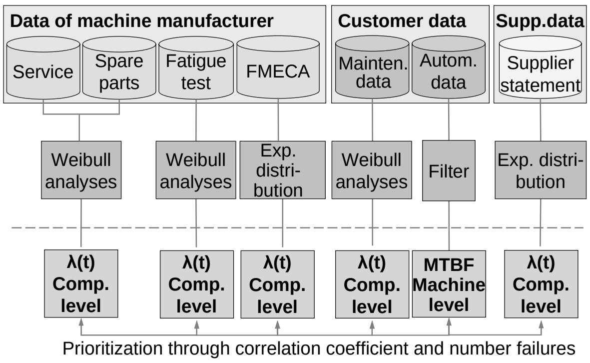

Figure 4: Calculation of the failure rate distribution.

3.2 Components life cycle cost estimation

As discussed before, only those life cycle cost elements are assumed stochastic that are linked to machine failures. All other cost elements are set deterministic which means that the behavior is known for the complete life cycle whether it is periodically increasing like the capital costs for example or steady. The aim of this step is to quantify exactly these costs. Because the complexity of life cycle cost examinations depends on the number of life cycle cost elements that are considered in the analysis, a selection is suggestive. Existing standards propose numerous life cycle cost elements that build the basis for the selection and also provide calculation formulas [14, 15, 16]. For the offer preparation purpose the relevant life cycle cost elements must be at least chosen according to the contractually defined requirements. The methodology works with any kind of deterministic cost schedules. Examples are cost elements like power supply cost, investment cost or tool cost. Because most of them can only be modeled with discontinuous functions or number sequences, the addition to one overall number sequence reduces complexity. This task is graphically shown in figure 5. The overall cost number sequence is needed in the following to implement the deterministic cost elements into the machine cost calculation. The stochastic cost elements are not finally calculated until the third step – the Monte-Carlo-Simulation – starts.

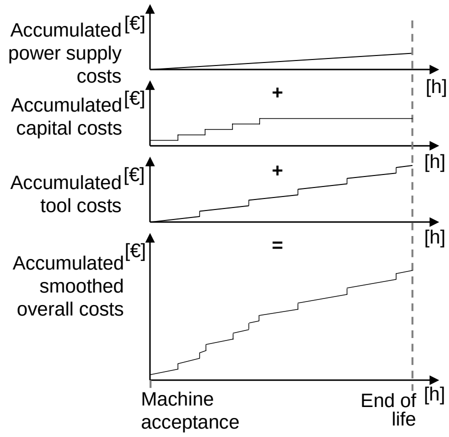

Figure 5: Deterministic cost element addition.

3.3 Monte-Carlo simulation

The Monte-Carlo method was already proposed by several authors for the calculation of the mean values of reliability key figures of systems [8, 11, 12, 17]. Against, the described approach augments these research works by the integration of the life cycle cost and their statistical distribution into the Monte-Carlo simulation. Therefore the previously defined machine components, to which the failure rate distributions and the MTTR are assigned, need to be aggregated to machine level or the required component level (see figure 6).

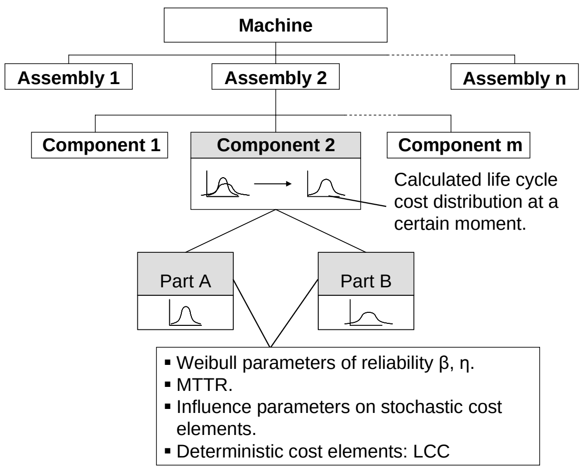

Figure 6: Aggregation of life cycle cost distribution.

From step one the failure rates and the MTTR's are known, step two delivers the deterministic cost elements and the influence parameters on the stochastic cost elements such as hourly rates and spare part cost. Therewith all necessary input parameters are defined and can be processed according to figure 7.

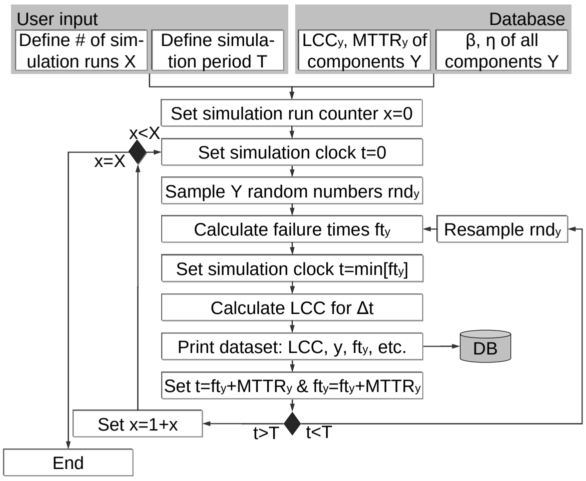

Figure 7: Monte-Carlo algorithm for life cycle cost estimation.

The algorithm starts with the definition of the overall number of simulation runs X. An increasing number of simulation runs maximizes accuracy while the calculation time grows as well [11]. The second parameter to define previously is the simulation period T which represents the time period of consideration. Further on the deterministic cost elements LCC and the MTTR are provided on machine component level from a database. These figures have been determined in section 3.1 and 3.2. In order to initialize the algorithm the simulation counter x as well as the simulation clock t is set to null. Then for all components y a random number is sampled.

$$0 \leq rnd_y \leq 1 \tag{1}$$

By using these random numbers the times to failure (ft_y) for all components are calculated using the Weibull distribution function solved to ft_y [3].

$$ft_y = \eta \cdot \left[\ln\left(\frac{1}{1 - rnd_y} \right) \right]^{\frac{1}{\beta}} \tag{2}$$

The simulation clock is set to the smallest ft_y, which represents the earliest component failure in the period of consideration T. For this point in time the failure cost are calculated using $MTTR_y$ and the previously defined cost influencing factors. Besides all deterministic cost elements LCC are computed for the considered time period ft_y. All costs, the failure time and the component are printed to a database table which finally builds the overall simulation result. In order to regard the downtimes all ft_y and the simulation clock are put forward with MTTR. While the simulation time is smaller than the overall simulation period the presented procedure repeats by resampling the rnd_y of the failed component according to figure 7. If the t exceeds T the simulation counter x is increased by one. As long as x is smaller than the overall number of simulation runs the procedure repeats to start with setting the simulation clock to null. When x reaches X, the algorithm ends.

The result is documented in the annexed data base table. It includes all failure events, the downtime, all failure cost and deterministic cost elements for hundreds of virtual machine life's. Therewith several analyses are possible:

- System reliability by using the Weibull analysis on the simulation result.
- Availability of the system and any subsystem.
- Expectation of the systems life cycle cost.
- Stochastic fife cycle cost distribution of the machine or any subsystem (see figure 8).

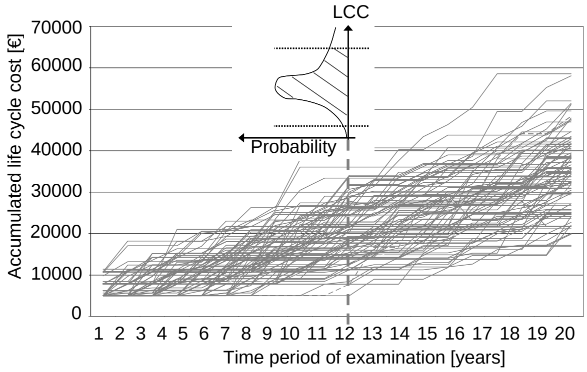

Figure 8: Exemplary accumulated life cycle cost.

As a result of the simulation figure 8 shows the accumulated life cycle cost of a whole machine including deterministic and stochastic cost elements. Every single line in the diagram (100) represents the cost emergence of one virtual machine over a time period of overall 20 years. This already gives good impression about the variance of the expected machine life cycle cost in every point of time. The further analysis over all simulation runs at a certain point in time additionally results in the machines life cycle cost probability distribution. A Gaussian distribution normally is a good approximation.

In order to increase the methodologies accuracy, the simulated distribution can be approached by using load classified input data. The whole calculation would then of course have to consider these load classes. The combination with the Weibayes approach is conceivable [18]. In general the advantages of the use of the Monte Carlo simulation in this context compared to statistical convolution is that the time scale can be brought in, modeling is most flexible and above all the combination of stochastic and deterministic cost elements is possible. Although the convergence characteristics of the Monte-Carlo simulation are not too good, the calculation error converges towards zero for an infinite number of simulation cycles.

4 SUMMARY

The proposed life cycle cost estimation procedure builds the basis for the minimization of risks that are arising from life cycle cost concepts recently implemented by the automotive industry. Especially the statistical variance of the life cycle cost has a broad impact on the risks for the machine manufacturer in the offer preparation stage. The proposed methodology considers all necessary steps starting from data acquisition and ending with Monte Carlo simulation for life cycle cost distribution calculation. The life cycle cost elements linked to the machine reliability are stochastically modeled while the rest of the elements are assumed deterministic. From there the calculation of the failure rate distribution as the statistical impact factor on the stochastic life cycle cost is focused in step one. The available data sources are examined and described. For the analysis of the data the Weibull method is proposed. If no data is available, an adapted FMECA can be applied alternatively. The second step covers the comparatively simple calculation of the deterministic life cycle cost elements. The combination of stochastic and deterministic cost elements and the aggregation to the required level in the bill of material is subject matter of step three. Suggested is the application of a Monte-Carlo simulation algorithm, because the estimation of the life cycle cost distribution is of special interest in order to correlate the expected costs for the machine manufacturer to the according probabilities.

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Life Cycle Cost Estimation Tool for Decision-Making in the Early Phases of the Design Process

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Abstract

Design is a process that involves information processing and decision-making. As cost is an important factor that must be considered in the decision-making at this phase, proper information about costs is extremely important for designers. The authors present a cost model and tool developed to help designers estimate the life cycle cost of their products and to permit them to make more cost-effective design decisions. The tool can be used in a concurrent engineering environment to provide cost estimates for different design alternatives. What-if analyses can be performed to compare costs when using different components, materials or manufacturing processes.

Keywords:

Life cycle cost estimation; cost model; DFE (Design for Environment) tool

1 INTRODUCTION

Typically, product designers make their design decisions based on a product's technical and functional features. From the designer's point of view the most important criteria for products are quality, durability, performance and conformance with the customer's specifications [1].

Recently, additional criteria have become important in the decision-making process at the design stage; for example the life cycle impact on the environment is now very important because of standards [2, 3] and legislative requirements [4].

An approach to integrated design of products and related processes is concurrent engineering (or integrated product development) [5], which makes designers consider in the design process all elements of the product life cycle from raw materials extraction through manufacturing to end of life.

The primary goal of concurrent engineering is the minimisation of product costs while maximising its quality and performance [6]. This simultaneous approach to product development – concurrent engineering – can offer opportunities to embed cost performance in the design process.

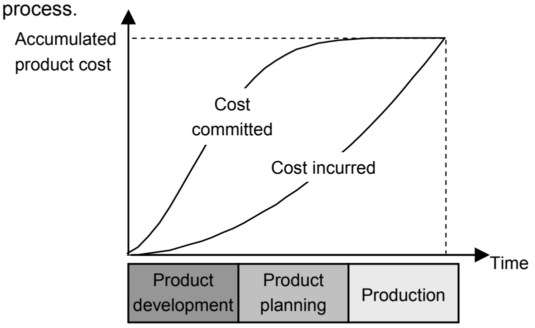

Figure 1: Product development and costs [9].

It is well-known that 70-80% of the production cost is committed at the early design phase [7, 8] (see Figure 1). Efficient cost management recommends that costs be controlled when committed, or else they cannot be minimised afterwards [9]. Therefore, unnecessary product costs must be eliminated in the commitment stage [10].

In addition to the production costs, a large proportion of the costs of the use and end of life phases are also committed during product development. The estimation of these costs early in the design stage is important because they represent a competitive factor, a differentiation in selecting a product.

In order to be able to use cost as a decision criterion in the design phase, one must be able to measure the costs of product's life cycle stages. As costs are not known in advance, a cost estimation system is necessary to generate the required information [11].

This paper presents a cost estimation model based on the Activity-Based Costing (ABC) methodology and other costing techniques for use in life cycle design. The model combines both product and process aspects which are necessary for the calculations (sections 2 and 3 discuss the product and the process models). The cost model is presented in detail in section 4. Section 5 shows how the cost model is integrated as a module within the DFE (Design for Environment) Workbench software tool.

The purpose of the tool is to enable different design configurations (different materials, different components, different processes) to be compared not only from an environmental compliance view but also from a cost perspective. The tool offers support in the decision-making process at the early phases of the design process. The inclusion of cost permits more informed business decisions and considerations to be undertaken by the designer.

2 THE PRODUCT MODEL

The product model follows the STEP standard (Standard for the Exchange of Product Model Data) [12]. It supports an object-oriented representation easy to integrate with a PDM and various CAD systems (e.g. Catia, Pro-Engineer). The product model provides information necessary for cost estimations and for calculating the impact on the environment over its life cycle. The information contained in the product model, briefly presented in Figure 2, is:

- Hierarchical product structure (sub-assemblies, components, parts).
- Identification data for product, sub-systems, purchased items, suppliers, materials.
- Materials information, properties associated with materials.
- Geometric data, dimensions, weight.
- Information relating the part to the adjoining components in an assembly (fasteners).
- Package data.
- Manufacturing information (process data).
- Financial data.
- Data pertaining to any life cycle phase of the product/sub-system.

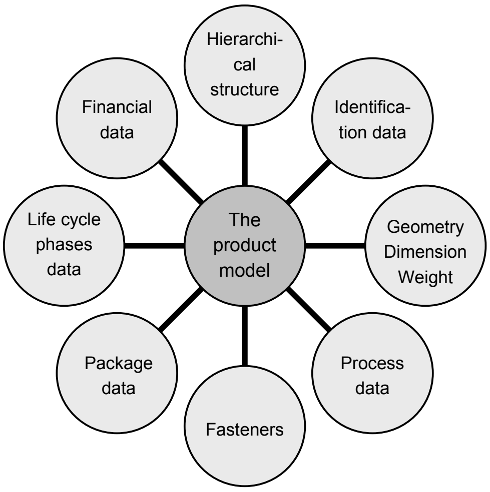

Figure 2. Content of the product model.

The STEP model was chosen because it supports integration with CAD and it permits integration of data as a total product model supporting many different users.

3 THE PROCESS MODEL

A process model was developed to support the cost calculation for the manufacturing phase of the product's life cycle.

The process model is driven by two groups of data. The first group, *process input data*, consists of data related to external inputs to the process (e.g. components, materials), and the second group, *specific process data*, contains internal data that characterise the process (e.g. lot size). A structured IDEF0 [13] graphical representation of the model is presented in Figure 3.

The data related to external inputs to the process include:

- Components, sub-assemblies with all the information associated to them as described in the product model (see Section 2).
- Direct materials.
- Consumables.
- Direct labour.

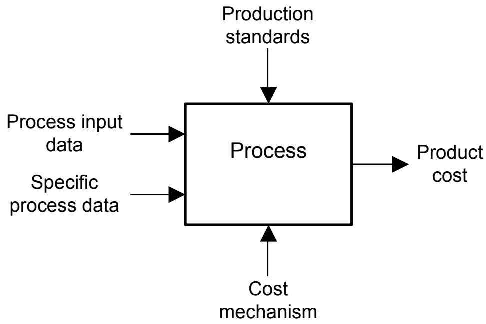

Figure 3. The process model.

Internal data specific to the process are also necessary for the cost calculation, such as:

- Process (activity) driver.
- Batch information (e.g. lot size).
- Scrap and rework.
- Waste.

The development of the process model as presented in Figure 3 was intended to support the use of ABC for calculating the manufacturing cost of a product.

4 THE COST MODEL

The cost estimation tool is intended to support designers in the decision-making process by giving indications of the individual life cycle stages costs (e.g. manufacturing) and the overall life cycle cost of the product so that comparisons of design alternatives at the early stages of the design process can be made.

4.1 The cost structure

In order to permit comparisons on an individual life cycle stage cost basis as well as on a total life cycle cost basis, various costs associated with the product life cycle (see Figure 4) are defined:

- *Manufacturing cost* – is the most important for the manufacturer. It comprises costs such as the raw materials cost and the actual production cost.
- *Environmental cost* – is the indirect cost of the manufacturing company which is related to the environment. It is important to see how changes in design can affect different elements of the environmental cost (such as package cost, waste disposal cost or licences and fees).
- *Use/operation cost* – costs like the repair/maintenance cost or the energy or fuel cost (depending on the type of product) are included in this category.
- *Retirement and disposal cost* – this component of the life cycle cost becomes important for the designer especially in the context of recent legislation (e.g. ELV Directive, WEEE Directive, Integrated Product Policy (IPP) [4]).

The cost model considers the classification of costs into *direct costs* and *indirect costs*. Direct costs can be allocated directly to the cost object (the product). Indirect costs cannot be allocated directly to a cost object; they are collected in cost centres and subsequently allocated to cost objects.

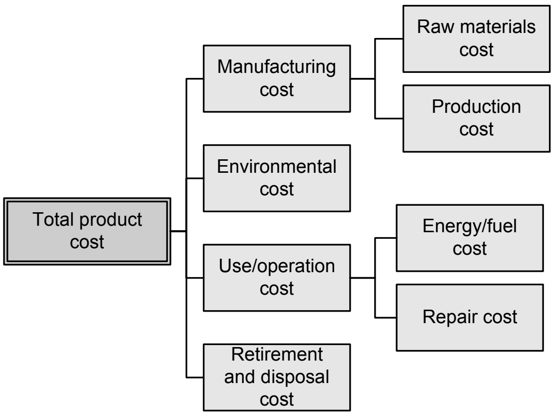

Figure 4. The cost breakdown structure.

4.2 The cost calculation

To effectively compare alternatives, the designer must be able to accurately estimate costs for the complete system so that 'what if' scenarios can be built. The costing information is derived from the description of the product and its components (see Section 2), and from the description of the processes the product/components are subjected to (see Section 3).

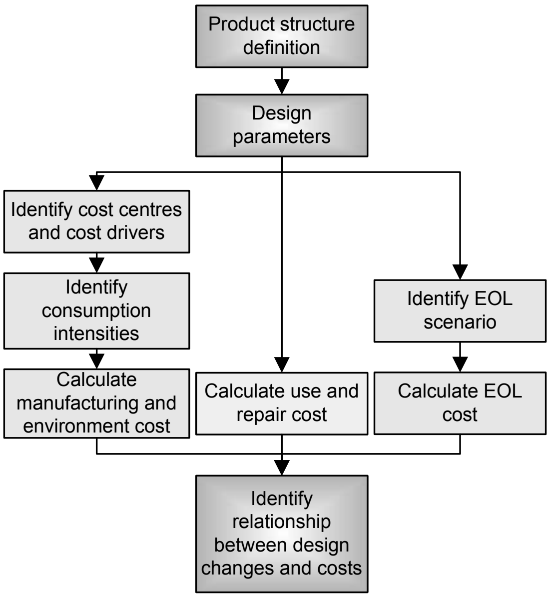

Figure 5. The cost model.

The cost model is a combination of life cycle costing (LCC) [10], feature-based costing and activity-based costing (ABC) [10]. As the majority of the costs considered in the model are future costs, their present value is calculated using an appropriate discount rate. The cost model aims to give the designer a complete picture of the product cost and to show the influence of different changes in the design on the total cost of the product as well as on different elements of the cost. The cost calculation follows the steps presented in Figure 5.

The manufacturing cost

The manufacturing cost model uses the product decomposition as described by the product model. For bought-in components only attributes which describe the product are considered (i.e. mass, dimensions). Meanwhile, for manufactured components the variables which describe the product *and* those which describe the processes through which they go are considered. Thus, the cost model is based on the link between the design parameters (product's elements' attributes) and the manufacturing processes.

The raw materials cost included in the manufacturing cost is shown separately. Raw materials cost is direct cost and can be traced directly to the product. The direct costs category also includes consumables cost and direct labour cost.

The overhead is traced to the final product using the ABC method [8, 10] which follows the following steps:

1. Identify the indirect costs (resources).
2. Choose each resource driver.
3. Calculate the annual resource rate.
4. Break up the processes into activities and build the activities hierarchy.
5. Identify the amount of resource drivers consumed by each activity.
6. Calculate the total activity cost.
7. Choose each activity driver.
8. Calculate the consumption intensity (the unit price of a driver unit).
9. Calculate the overhead cost per product.

The R&D cost is considered part of manufacturer's cost; therefore the model includes this cost in the overhead.

The methodology is extended by using feature-based cost estimation in coordination with ABC (consumption of cost centres depends on the design parameters). This allows the designer to evaluate the product cost based on physical properties very early during the product design stage.

The environmental cost

The environmental cost is actually an overhead. It is treated separately, although it follows the same ABC methodology, because it is important to be traced to the product separately in order to see the influence of design changes on this cost category.

The model takes into consideration only the internal environmental costs related to the product, which represent environmental costs that have a direct financial impact on the company (such as waste treatment cost, labelling cost, licence and permit fees, prevention and environmental management cost, fines and penalties).

The use/operation cost

The costs categories considered in the cost model for the use/operation phase are repair/maintenance cost and energy/fuel cost. Design parameters such as Mean Time to Failure (MTTF) for unrepairable components and Mean Time Between Failures (MTBF) for repairable components are considered in the repair cost model. Depending on the type of product (energy consuming or fuel consuming), energy cost or fuel cost is modelled for the entire product lifetime.

The retirement and disposal cost

An end of life (EOL) option is defined for each component of the product and costs associated to that particular option are modelled.

4.3 The outputs of the model

The outputs of the model are:

- A summary of the costs necessary to produce, use and dispose the product. This information is shown per product and per component and is broken down into: total life cycle cost, manufacturing cost, labour cost, materials cost, component cost, consumables cost, recycling cost, disposal cost.
- A graphical representation of the product cost of each life cycle stage that permits the designer to see at which stage improvements should be made.
- A graphical representation of the components' costs. This will show a hierarchy of costs and the designer will be able to see which component is the most cost-effective and which needs re-design.

5 THE SOFTWARE – INTEGRATION OF THE COST MODEL INTO THE DFE WORKBENCH

The cost model presented in the previous section was integrated as a cost module into the existing DFE Workbench which will be briefly presented below.

5.1 The DFE workbench

The DFE Workbench [14, 15] is a design for environment software tool integrated into a CAD environment (Pro Engineer 2001, Solid Works 2000, Catia V5 R16). It has been developed to assist and advise the designer in the development of environmental superior and compliant products in order to meet the requirements of the latest legislation related to environment and customers' needs.

The DFE Workbench consists of the following modules (see Figure 6) [14, 15]:

- The Impact Assessment System (IAS).
- The Structure Assessment Method (SAM).
- The Advisor Agent.
- The Knowledge Agent.
- The Report Generator.

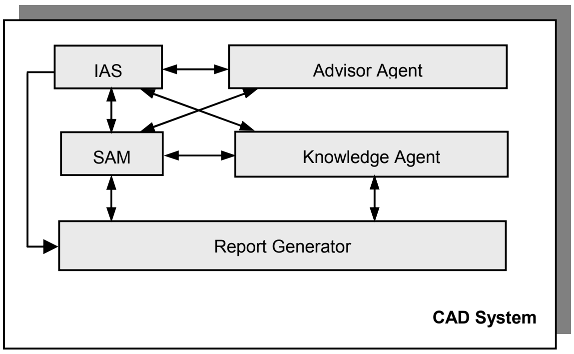

Figure 6. The DFE Workbench structure [14, 15].

The *Impact Assessment System (IAS)* is an abridged quantitative approach to LCA, performing synthesis, evaluation, prioritisation and improvement of environmental data. Environmental impact can be calculated for the entire product or for each of its components.

The *Structure Assessment Method (SAM)* is a complex methodology, which quantitatively measures and records data such as material compatibility/substitution (taking into account fasteners), components' serviceability, number and types of fasteners, number and types of tools required for disassembly and total standard disassembly times and component removal times.

The *Advisor Agent* has two functions: firstly to prioritise variables generated by the IAS and SAM tools; secondly to give advice to the designer on alternative structural characteristics in order to enhance either the environmental impact or structural characteristics of the emergent design.

The *Knowledge Agent* provides advice to the designer in a consultative mode. For example, the designer can use the Knowledge Agent to find a material with specific mechanical and environmental properties and then use the selected material in the design process.

The *Report Generator* automatically generates reports on the product designed by the user.

5.2 The integrated software tool

The cost estimation model was integrated within the DFE Workbench (see Figure 7), thus permitting a comprehensive overview of the environmental impact and associated cost of a product over its entire life cycle and offering a real support to decision-making at the early design phase.

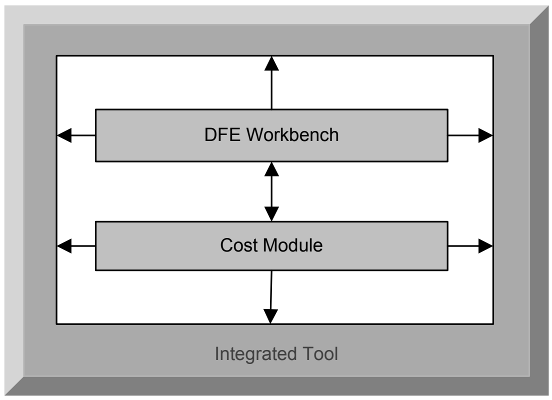

Figure 7. The integrated tool.

The integrated tool system provides a database and management software that permits the collection and analysis of information related to product, processes, end of life, suppliers and cost records. Figure 8 shows the data flow from different company's departments which are potential providers of data (e.g. designers, accountants, environmental manager, manufacturing engineers) into the database (solid arrows).

This information is processed to calculate the product costs and the environmental impact, which are of great potential value for designers, as well as for the environmental manager or the accounting department. In Figure 8 dashed arrows show the flow of information from database to the potential users (designers, environmental manager and accountancy).

'What if' scenarios can be built by considering various design configurations and, based on the information offered by the tool, decisions can be made. The tool is not meant to replace the decision-making process itself, but to offer support to decision-makers.

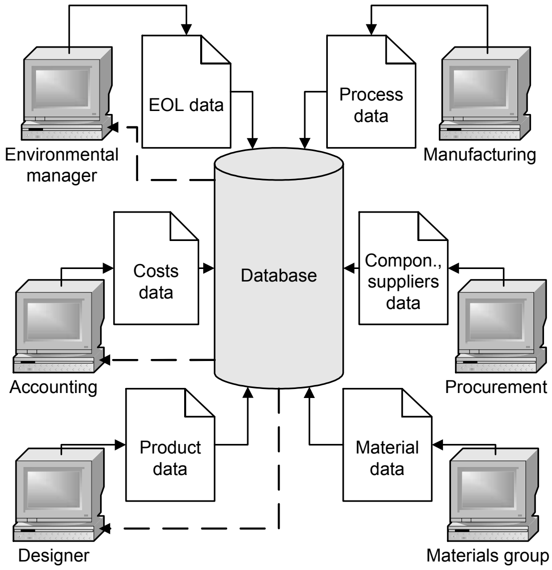

Figure 8. The integrated system structure.

6 CONCLUSIONS

The life cycle cost estimation tool integrated with the DFE Workbench offers a powerful decision-support tool to designers in the early phases of product development.

The system provides results like costs and environmental impact at product level or component level in the context of the full life cycle of the product, thus offering a solid base for decision-making to the product designer when it comes to producing environmentally-compliant products in a cost-effective manner.

It should be noted that the tool is currently under further development. In the future a case study will be carried out for test and validation of the model, and for collection of data necessary to populate the database.

7 ACKNOWLEDGMENTS

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Design to Life Cycle by Value-Oriented Life Cycle Costing

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Abstract

Industrial products basically have to satisfy the customers' wants and needs as a basic input as well as technical and ecological requirements while providing maximum economic benefit throughout the life cycle. In the early stages of design and development all these requirements have to be considered in terms of their long-term impacts on the entire product life cycle. The approach discussed in this paper combines quality and value-driven tools with the methodology of life cycle costing including the assessment of environmental aspects. While traditional cost optimising was successful by streamlining operations and returning to core competencies, this approach allows for sustainable cost optimisation in the early stages of product development and correlates with quality planning as well as ecologic product assessment. Based on the Value-Oriented Life Cycle Costing method, product components are evaluated over their life cycle to identify those components incurring high life cycle costs compared to their functional value. In order to achieve an efficient and effective design to life cycle the methods of Quality Function Deployment and Value Analysis are aligned with the methods of Life Cycle Costing and Life Cycle Assessment to be integrated into a comprehensive approach. This paper describes the theoretical background and explains the practical implementation based on a case study. The results of the practical analysis conducted illustrate the optimisation potential to be realised when implementing the approach in comparison to traditional design solutions.

Keywords:

Life Cycle Costing; Design to Life Cycle

1 INTRODUCTION

The ability of a company to compete effectively on the increasingly competitive global market is influenced to a large extent by the cost as well as the quality of its products. Industrial products for example basically have to satisfy the customers' wants and needs as a basic input as well as technical and ecological requirements while providing maximum economic benefit throughout the life cycle. In the early stages of design and development all these requirements have to be considered in terms of their long-term impacts on the entire product life cycle. An engineering design should not only transform a need into a description of a product but should ensure the design's compatibility with related physical and functional requirements. Therefore, it should take into account the life of the product as measured by its performance, effectiveness, producibility, reliability, maintainability, supportability, quality, recyclability, and cost [1]. Designers are in a position to substantially reduce the life cycle cost of the product they design by giving due consideration to life cycle cost implications of the design decision they make. In an attempt to improve the design of products, reduce design changes and the incurred life cycle cost, the approach of design to life cycle by value-oriented life cycle costing as discussed in this paper combines quality and value-driven tools with the methodology of life cycle costing including the cost assessment of design related environmental aspects. The approach has been developed considering the perspective of a designer who wants to improve product performance over the whole life-cycle while simultaneously optimising costs. The procedure also helps product sales and distribution to convince customers about the profitability of the product by delivering a plausible and transparent explanation of costs incurring during the utilization and disposal phase.

2 CONCEPT OF VALUE-ORIENTED LIFE CYCLE COSTING

2.1 The basic concept of Value-Oriented Life Cycle Costing

The developed concept of Value-Oriented Life Cycle Costing is intended as an instrument for employing cost as an evaluation criterion in design. It enables both, to obtain a design satisfying customers' needs and wants expressed as functional requirements as well as cost optimisation by identifying cost drivers during the life cycle. Moreover it makes proposes for use of engineering process technology to reduce life cycle cost.

The approach of Value-Oriented Life Cycle Costing enhances the traditional concept of cost analysis over the life cycle of a product and helps to combine life cycle costs with functions and value aspects of the product. The Value-Oriented Life Cycle Costing method includes elements of process-oriented Life Cycle Costing and of the Value Analysis and Quality Function Deployment approaches.

In order to give the designer quick and accurate estimates of the financial consequences of design decisions and procedures to determine the optimal design the approach of Value-Oriented Life Cycle Costing includes three modules, as illustrated in Figure 1.

The first module comprises the prioritization of customer demands and customer needs as well as their translation into product related technical functions based on the approach of Quality Function Deployment. The second module is based on the procedure of value analysis and focuses on the optimization of product functions. The used approach enhances the traditional modus operandi by considering life cycle costs instead of manufacturing costs. Moreover the second module of the Value-Oriented Life Cycle Costing approach does not only optimize already realised product functions but also looks at new product functions, which have to be implemented in order to fulfil additional customer requirements (see Figure2).

The third module includes the elements of life cycle costing. The cost evaluation considers the life cycle cost of already implemented functions as well as cost estimation of new functions and is conducted on level of functional units. While the traditional life cycle costing approach allocates costs to cost objects using arbitrary allocation bases, the Value-Oriented Life Cycle Costing procedure is process-based and traces costs using cause-and-effect relationships (drivers) between costs and cost objects (Figure 3). This difference is important mainly in relation to management of overhead costs.

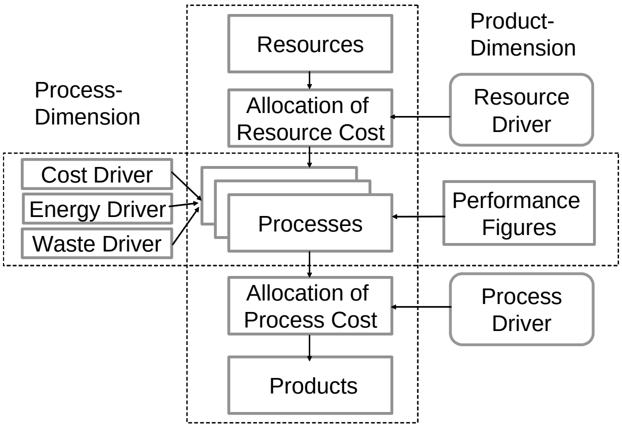

Figure 3: Value-Oriented Life Cycle Costing is process based

Value-Oriented Life Cycle Costing assesses the function costs for both the whole product as well as for its functional units. It provides an insight in the nature of realized costs, whether or not they are caused by a value driver or by an important functional unit. If a cost driver without important value is identified, then it should be optimised by re-design. The method of Value-Oriented Life Cycle Costing considers the whole life cycle of a product, and illustrates the trade-offs between the different life cycle phases. A functional unit for example may be realised at very low manufacturing costs but causes high costs in the utilisation phase by an intensive need for support and maintenance activities. The designer has two optimization options: to optimize the used functional unit by improving its performance or optimise the function independent from the already existing realisation and replace or abandon the used functional unit.

2.2 Cost issues in the design to life cycle concept

The life cycle cost of a product is made up of the costs of the manufacturer, user and society. The total cost of any product from its earliest concept through its retirement is borne by the user and has a direct bearing on the marketability of that product [2]. As purchasers, we pay for the resources required to bring forth and market the product and as owners of the product, we pay for the resources required to deploy, operate and dispose of the product. While the life cycle cost is the aggregate of all the costs incurred in the product's life, it must be pointed out that the developed approach focuses on the cost that can be influenced by designer. Some of the costs incurred in the life of the product are not a result of the design. These costs are related to the "way we do things" [3].

Classifying life cycle cost into management related costs and design related costs we are focusing on the latter component. One cost category for example, that may not be of interest to the designer is the research and development cost. This cost is not related to the actual design of the product but rather to the kind of product being developed, the resources committed to the process and the manner in which these resources are used to arrive at a design solution. The approach of design to life cycle looks at the cost issues in the production and construction, usage and disposal phases of products.

The production and construction cost consists of manufacturing cost (fabrication, assembly, test), facility construction, process development, production operations, quality control, and initial logistic support requirements (e.g. initial consumer support, the manufacture of spare parts, the production of test and support equipment, etc.). [1,4,5,6,7,8]

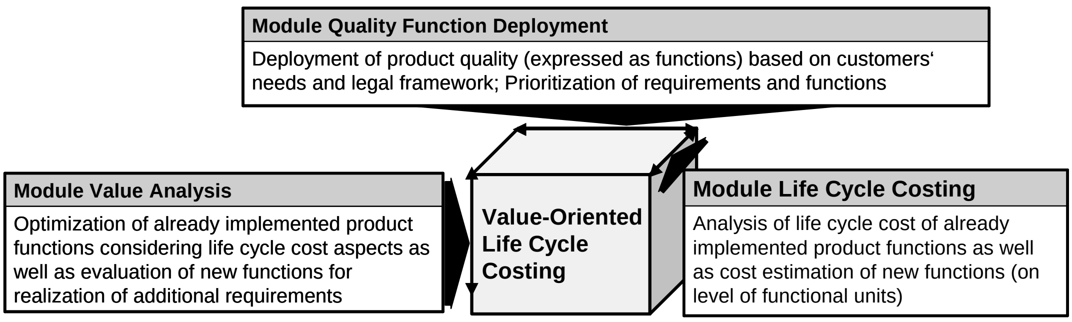

Figure 1: Modules of the Value-Oriented Life Cycle Costing approach

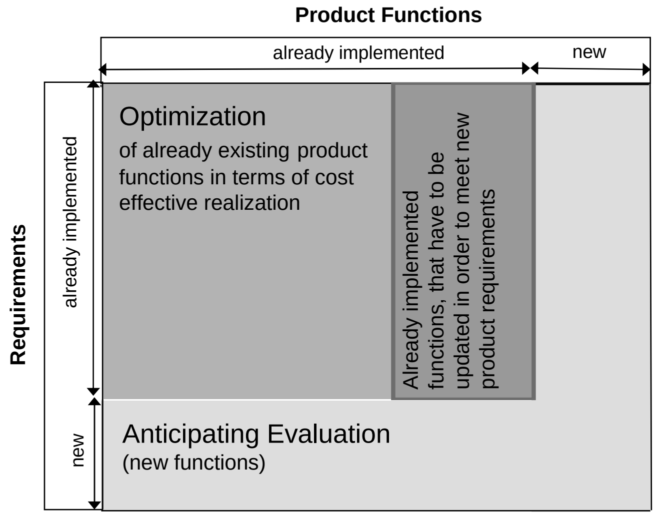

Figure 2: The optimization approach includes already existing as well as new functions

The primary focus in this phase is on determining the optimal design of the product and sequences of processes to produce and assemble the constituent parts into a complete product. Increasingly, this component is becoming a large proportion of the total production and construction costs. Another concern in this phase is the effect of the activities on the environment. [3]

The operation and support cost comprises consumer or user operations of the product in the field, product distribution (marketing and sales, transportation and traffic management), and sustaining maintenance and logistic support throughout the system or product life cycle (e.g. customer service, maintenance activities, supply support, test and support equipment, transportation and handling, technical data, facilities, system modifications, etc [1,4,5,6,7,8]

Operating and support costs are the most significant portion of the life cycle cost and yet are the most difficult to predict. The cost of operating and supporting an industrial machine tool for example may exceed the initial purchase price of that tool as much as five times. [9,10]

A product which is reliable and easily serviceable leads to maximum availability and maximum customer satisfaction. To improve customer satisfaction, it is important to address the issue of making products which can be maintained in the least time, at the least cost and with a minimum expenditure of support resources, without adversely affecting the product's performance or safety characteristics. Support resources are manpower utilization, spare parts, tools, test equipment, services, and support facilities. The larger and more complex a system, the greater is the capital investment it will represent and the greater its likely revenue-earning capacity. Each minute out of service is therefore going to result in considerable financial loss to the system user. [3,10]

Development, use and retirement of products require the use and conversion of material and energy resources. These activities cause waste to be released into the environment. Energy consumption, air pollution and waste management currently dominate public discussions. The legislation in EU countries is guided by the "originator principle": the one who inflicts harm on the environment has to pay for cleaning up the damage [11,12]. This together with other factors such as corporate image and public perceptions, consumers' demand for green products and rising waste disposal costs, has led to a increasing importance of retirement and disposal cost [13,14,15]. Life Cycle Assessment (LCA) is the framework that has been proposed for the evaluation of the impact products and processes have on the environment. LCA is an environmental and energy audit (accounting procedure) that focuses on the entire life cycle of a product from raw material acquisition to final product disposal of environmental emission. [13,14,15] Although LCA appears conclusive, in practice it has some shortcomings, as for example lack of reliable data and a difficult quantitative assessment of impact. The impact assessment within the LCA procedure includes the elaboration of an impact profile of assigned input/output data. This profile can be achieved by using models, which combine the input/output data from the inventory and a so-called indicator expressing the environmental effects or damages. In general, the indicators allow, in terms of being "units", for an aggregation of all emission-based contributions within each impact category. If appropriate, characterization factors are used to quantify the contribution of each single emission to the respective category. The models range from quantitative and internationally accepted ones to expert –or even value-based individual models. A complete model which contains all the necessary parameters and relevant data is very difficult to obtain and in the technical literature there is also stated, that a complete model does even not exist, because the results of the impact assessment are expressed as numerical indicator results with the underlying information usually not being related to space and time [16, 21, 22]. The design for life cycle approach described in this paper consciously abandons the option of a detailed consideration of all five major factors of a complete LCA (raw material acquisition, product and packaging manufacturing, consumer use, recycling and final disposal). We focused on the cost of energy and resource consumption during utilisation as well as assessment of recycling, remanufacturing and disposal cost. The assessment of the latter cost components bases on expert knowledge and survey of recycling companies.

In comparison to the existing efforts of extension of life-cycle assessment using LCC [23] the described approach uses the LCC methodology as basis and considers environmental costs as mentioned above.

2.3 Cost estimating

Just as in the design process lower level functional requirements are produced through functional decomposition to enable design solutions to be easily developed, cost decomposition on functional level was performed in order to determine function cost. The basic principle is that product functions can be quantified and the costs associated with a function are related to the life cycle costs caused be the functional units carrying the function. [8, 9, 10, 17]

The cost estimation model uses estimates of labour time and rates and also material quantities and prices to estimate the direct costs. An allocation rate is used to allow for indirect/overhead costs. For the prediction of maintenance and support cost the LCC model considers stochastic processes (e.g. Weibull distribution of failures considered as random variables) involving parameters such as reliability, maintainability and interest rates.

2.4 Integrating Quality Function Deployment and Value Analysis approaches

Quality Function Deployment (QFD) is “an overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production” [18].

In using the QFD approach to identify LCC-related potential for improvement, the aim is to improve customer-orientation by systematically integrating customer requirements and expectations throughout the process of product redesign. The heart of the situation is “the customer wants a function.” Thus, the language of function is the language of the product and cost optimisation.

QFD provides a framework for product optimisation to include all sorts of product requirements and break down the associated product redesign process in clearly defined steps to ensure a goal-oriented procedure in the definition of product properties [19] (see Figure 4). This demonstrates the process-orientation of the QFD approach. The linkage of the LCC to the QFD approach is based on the opinion that the design of products should not exclusively focus on the evaluation of historical data such as complaints or error statistics and life cycle cost. To complement such an analytic procedure, current and future customer requests, like explicitly voiced requirements, and even implicit customer requests should be taken into consideration.

When functions have been identified, clarified, understood and specified and knowing what it did cost in the past the greatest help would come from the answer to the question “How to achieve the functions for lowest overall cost”. Since value of a function means the lowest cost that would fully provide it, the Value Analysis method is the most appropriate to achieve the answer.

Value Analysis is a method that envisions analyses to be conducted at team level including workers from different affected areas in order to exploit their knowledge and ideas, as well as effects of group dynamics. The basic concept of Value Analysis is to assign “values” to functions and to find out the lowest cost that seems likely to accomplish all the functions that the customer wants [20]. Ideas for a more efficient functional performance are to be developed and put into practice, allowing for a life cycle-oriented optimisation of the functional design. Value Analysis focuses attention on the essential functions in a chosen design or construction objective and emphasizes meeting the essential function at the lowest life-cycle cost.

The first step of Value Analysis is to capture the as-is situation. This results in a list covering all functions of the product. The second step compares life-cycle cost and optimisation potentials of each function and develops cost-saving ideas boundaries and the entire product life cycle, thus promoting customer-orientation in thoughts and action. The elaborated solutions are tested for their feasibility. This requires a detailed analysis of all functions. At this point, the QFD approach is introduced to make the functions that the customer requires transparent. against specific profitability and risk criteria. The fourth step deals with working out clear-cut measures to implement the selected ideas.

The inter-disciplinary QFD approach helps to better understand problems that cut across departmental.

The focus of this combined approach is on determining and structuring customer requirements to provide a basis for all subsequent redesign steps. This systematic approach allows identifying product requirements, beginning with the detailed design of components, assemblies and product parts, and ending with process planning.

2.5 Design to Life Cycle by Value-Oriented Life Cycle Costing as a combined approach

The Value-Oriented Life Cycle Costing method combines the process-oriented Life Cycle Costing with the Value Analysis and QFD approaches (Figure 5). It includes the following procedural steps:

1. Evaluation of customer needs and wants and requirements resulting from the legal framework (pairwise comparison)
2. Matching of the most important requirements to product functions and prioritization
3. Determination of functional units that carry the product functions and evaluation with regard to their functional contribution
4. Calculation of historical product life cycle costs at functional unit level (process-oriented as far as possible)
5. Calculation of function costs and identification of cost optimisation potentials
6. Development of proposals for optimization of functions and functional units based on the target: minimisation of life cycle costs.

Working at functional unit level is very helpful in estimating life cycle costs. Opportunities for product cost optimisation are clearly pointed out before realising them by redesigning product components in an appropriate way. But the objective is not only to identify areas to optimise life cycle cost, but also to enable comparison of different product alternatives for the same operation area. Since the same functionalities in different product types are realised by different components, a comparison of the products at component level is inappropriate [11]. Moreover, using the classic approach of cost reduction by realising whole functionalities in a different way are not considered to be adequate.

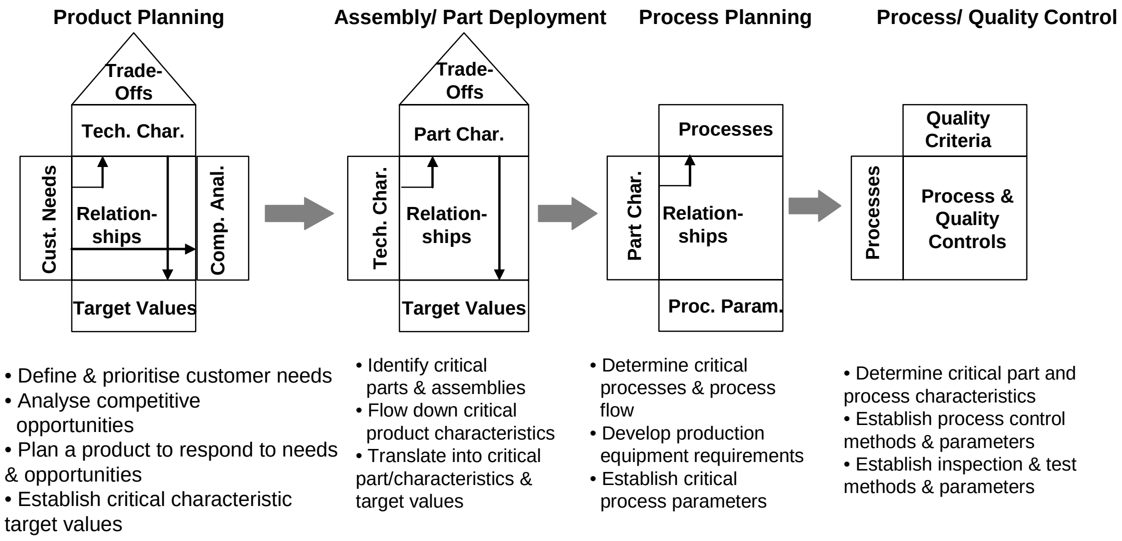

Figure 4: Four-Phase QFD Approach

3 IMPLEMENTATION

The method of Design to Life Cycle by Value-Oriented Life Cycle Costing described above has been implemented on medical devices used for imaging (digitizer for computed radiography). The first step considered the results of marketing studies on customer requirements and the customer-specific evaluation criteria. Also included were solution-affecting criteria formulated by the operator. Solution-affecting criteria are understood as additional requirements that are not fully described in actual or projected functions and their structures. They represent, however, additional attributes of the product assigned to the functions and are therefore fundamental evaluation criteria – restrictions – for the selection of suitable design solutions from the collection of ideas for the projected digitizer.

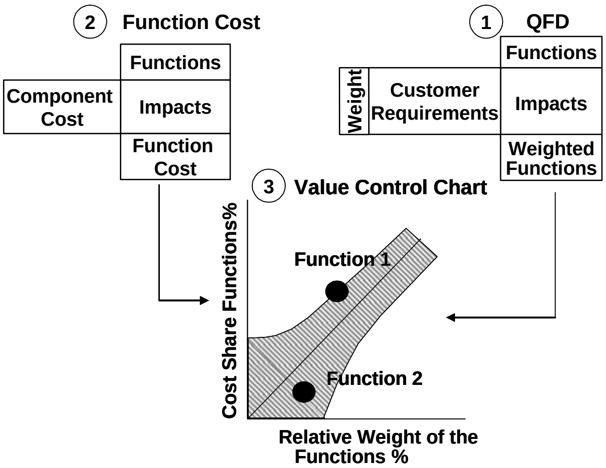

Figure 5: Functional approach for Value-Oriented Life Cycle Cost Control Chart

The evaluation and prioritization of these requirements has been done with help of pairwise comparison. The next step included the translation of customer requirements into the appropriate technical requirements, the latter expressed as functions. The function structure is a representation of the logical interrelations of functions in terms of application. Function classes were used to establish a hierarchy of functions. According to their importance, main functions were used such as “provision of adequate image quality”, “receiving imaging information” or “scan preparation”, which in terms of their application describe a particularly high weighted effect. Minor functions are effects that in terms of application have clearly lower weighting than a main function of the product. There were also determined undesired functions, which are avoidable (not serving the desired purpose) or unavoidable – for essential reasons – but nevertheless have unwanted effect on the digitizer. The third step included the determination of functional units that carry the product functions and evaluation with regard to their contribution to main and minor functions. The forth step was the most data-intensive step and included the calculation of historical life cycle costs at functional unit level (process-oriented as far as possible). Out of the determined life cycle costs for functional units and with the help of the weighting of units to their functional value, the function costs were calculated in the next step. Function costs determined this way represent the proportion of the costs of function carriers assigned to each function. The costs of a function carrier – components of the medical device – are divided among those functions which are realised by a function carrier. At functional unit level, the relationship between function costs and the interrelation of functions in terms of application was visualised with the help of value and cost control charts. As design optimisation at functional level (sixth step) allows more options open for cost reduction, a purely functional approach instead of the classic one is selected at functional unit level to determine the value control charts. Using an existing rough outline of the functional structure, a more detailed one is elaborated based on techniques from function analysis for the identified optimisation potentials. The product function structure is described hierarchically and the appropriate abstraction level (allow improvement on the one hand and enable new solutions at functional unit level on the other) is identified in an iterative. The determined functions are weighted in the House of Quality to get one part of the chart. Unlike the classic approach, functional costs now are estimated to complete the value charts. Therefore functional costs are extracted from real functional unit cost data. It is essential to consider the difference between the real expenses related to the components for product functions (in terms of value-analytical consideration) and the target function share of the component. The customer is not interested in a specific product but only in the fulfilment of the required functionalities. product operation depends on a lot of factors not considered when only customers' requirements for the product itself are regarded. However, there are several more specifications the product has to fulfil, e.g. statutory provisions or internal requirements of the operator. That's why inadequacies derived from the value control chart have to be validated against these aspects, too. In order to minimise the life cycle costs of the whole product it was necessary to optimise those functions which incur the greatest proportion of cost but are less important (Figure 6). The approach at the functional level with function costs allows the operator to compare in detail different types of digitizers with the same functionalities but different components.

4 SUMMARY

In order to understand how costs arise over the life cycle, a cost-effective approach that better describes costs and their relationship to cost-driving parameters is needed. The Value-Oriented Life Cycle Costing approach includes an analysis identifying and reducing costs by evaluating the most economic way of satisfying customer's needs and specified requirements. This way of cost reduction traces costs incurred by manufacturing, operation, maintenance, support and disposal. What drives or triggers costs, how these costs can be reduced, and how resources can be utilized more effectively and efficiently are important issues.

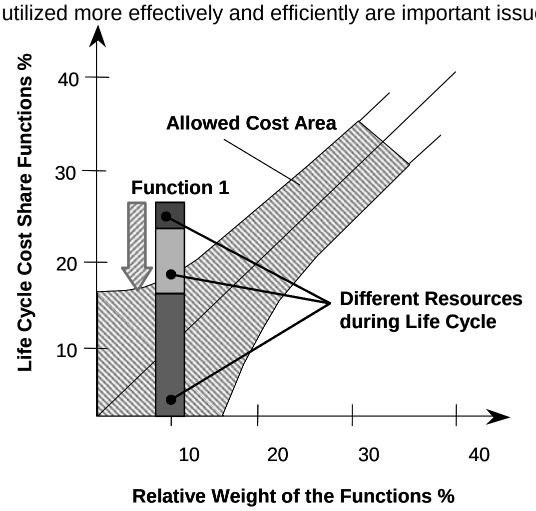

Figure 6: Optimization potentials

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A Product Lifecycle Costing System with Imprecise End-of-Life Data

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Abstract
The paper deals with a framework of the product lifecycle costing system, with an emphasis on cost estimating, for supporting decision making, especially the decision making on EOL strategy. In particular, the imprecise EOL data given in forms of interval, due to the lack of knowledge or the ordinary ambiguity of design in the early stage, is taken into consideration. In order to deal with interval data, the robust deviation criterion is applied to obtain a robust product design alternatives with the objective of optimizing the overall product lifecycle costs. It will give a conservative estimation of product lifecycle costs with the corresponding processes through its lifecycle. Consequently, it can be used as a design support tool to help new product development.

Keyword:
Product Lifecycle Cost; Disassembly Planning: Interval Data; Dynamic Programming

1 INTRODUCTION

Today's competitive business environment leads the concept for product lifecycle management (PLM) to help manufacturing firms manage all the activities related to a product in an integrated way across the lifecycle from customer need to product's end-of-life (EOL) strategy. Herein, product lifecycle cost is an important measure for PLM implementation. Product design can be improved by organizing continuous information feedback loops from product lifecycle to designers and manufacturers [1]. But, in an attempt to improve the design of products and reduce design changes and time to market, concurrent engineering or life cycle engineering has emerged as an effective approach. The principal unique aspect of life cycle engineering is that the complete life cycle of the product is kept in consideration and treated in each phase of the product development [2].

Product lifecycle costing (PLC) is concerned with optimizing the trade-off among all costs, which are attributable to a product from conception to those customers incur throughout the life of the product, including the costs of planning, design, testing, installation, production, marketing operation, support, maintenance and EOL treatment, to find the minimum lifecycle cost of the product. Especially, EOL strategy grows to be a new challenge in PLM, as environmental issues are becoming increasingly important to manufacturing firms, since legislation pressures for companies are increasing to protect the environment imposing the obligation to collect and upgrade such products in an environmentally conscious way.

However excellent a product may be environmentally, it would not come into wide use in the economy to realize its environmental load reducing potential unless it is also economically affordable. PLC is a tool to assess the cost of a product over its entire life cycle, and can be regarded as an economic counterpart of Life Cycle Assessment (LCA). A combined use of LCA and PLC would be imperative for assessing the sustainability of a product or product systems in the economy [3].

The life cycle costing (LCC) concept was initially applied by the US Department of Defense (DoD). Its importance in defense was stimulated by findings that operation and support costs for typical weapon systems accounted for as much as 75% of the total cost. However, most of the methodologies developed by the DoD were not intended for use for design but for procurement purposes [2].

For product lifecycle costing, the cost estimating method for each phase of product lifecycle, i.e., design, manufacturing of parts, production (assembly), and EOL treatment, is required. Particularly, this paper focuses on cost estimating of EOL phase, i.e., disassembly cost estimation, which considers the ambiguity of disassembly cost.

General procedure of product lifecycle costing is introduced in Section 2 with a brief literature review. And, a new cost estimation method for EOL disassembly is proposed in Section 3. Finally, the concluding remarks is followed in Section 4.

2 PRODUCT LIFECYCLE AND LIFECYCLE COSTING

With regard to the time of use, Layer *et al.* [4] distinguish three different types of cost calculation, originally quoted from the German Industrial Standard (DIN 32992 Teil 1):

- Pre-calculation.
- Intermediate calculation.
- Post-calculation

Pre-calculation estimates the future costs before the actual production and thus allows cost-based decision making. In contrast, 'post-calculation' — as a method of cost accounting — determines the actual costs incurred with these costs then serving as the base data for future pre-calculations. The data obtained from post-calculation will be used in the next pre-calculation phase as the input information. Pre- and post-calculation may utilize different kinds of information. For example, information from the shop floor management system or the purchasing department is collected to determine product costs for post-calculating. In contrast, pre-calculation

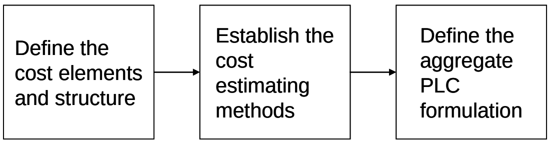


Figure 1: Product lifecycle costing procedure

is only able to access product describing data and, unfortunately, such data may be incomplete or uncertain. The use of such unreliable data necessitates suitable cost calculation methods if future costs are to be predicted accurately. During the product development cycle, pre-calculation calculations are carried out and applied for cost controlling purposes. Thus, while the methods for pre-calculation stem mainly from the field of engineering sciences, so called product lifecycle costing, intermediate and post-calculation methods have arisen from business administration concerns.

Although PLC comprises all the three calculation types above, in this paper, PLC focuses on pre-calculation, since PLC is mainly concerned in design phase. The procedure of product lifecycle costing is composed of 3 steps summarized in Figure 1.

2.1 Define the cost elements of interest and the structure

In Figure 1, the cost elements of interest are all the cash flows that occur during the product's life cycle. In fact, the cost elements are grouped and assigned according to the phase of product's lifecycle. Figure 2 shows a schematic description of the lifecycle of products. The life cycle of the product begins with the identification of the needs and extends through design, production, customer use, support, and finally disposal. There are several definitions about product's lifecycle, for example, six phases: need recognition, design development, production, distribution, use, and disposal.

In Figure 2, the 4 phases of lifecycle is adopted from [5]: design, manufacturing, use, and End-of-Life (EOL). In EOL phase, a product is disassembled to retrieve the parts or subassemblies that are recycled, reused, or remanufactured. Here, recycling implies material recovery without conserving any product structures, e.g., metal recycling from scrap and plastic recycling, and remanufacturing is the transformation of used products, consisting of components and parts, into units that satisfy exactly the same quality and other standards as new products. It implies that life cycle costing goes beyond the life of the product itself and simultaneously considers the issues of the processes and the product service systems. Life cycle costs comprise all costs attributable to a product from conception to those customers incur throughout the life of the product, including the costs of installation, operation, support, maintenance and disposal. For example, life cycle costs for a manufacturer include planning, design, testing, production, marketing, distribution, administration, service and warranty costs, apart from those costs caused by the purchaser [6]. The lifecycle cost of a product includes not only manufacturer's costs, but also the costs imposed to users and society.

The total lifecycle cost can be decomposed into cost categories shown in Figure 3 as an example. This decomposition is known as a cost breakdown structure [2]. The cost elements in the cost breakdown structure in Figure 3 are not always interesting to designer or manufacturer. Some are related to resource planning, production planning, or designing aspect too. The level of breakdown and the cost categories depends on the stage that is considered and the kind of information and data available.

2.2 Establish the cost estimating method

Once the cost element and the structure is determined, cost estimation should be carried out for each cost element. Figure 4 shows the classification of cost estimation approaches [7]. Niazi *et al.* [7] classified cost estimation methods into qualitative and quantitative. Qualitative cost estimation techniques are primarily based on a comparison analysis of a new product with the products that have been manufactured previously in order to identify the similarities in the new one. Quantitative techniques, on the other hand, are based on a detailed analysis of a product design, its features, and corresponding manufacturing processes instead of simply relying on the past data or knowledge of an estimator. Qualitative and quantitative methods are further classified as follows:

- The intuitive methods are based on past experience of the estimator. The result is always dependent on the estimator's knowledge. A domain expert's knowledge is systematically used to generate cost estimates for parts and assemblies. The knowledge may be stored in the form of case database, rules, decision trees, judgment, etc., at a specific location, e.g., a database to help the end user improve the decision-making process and prepare cost estimates for new product based on certain

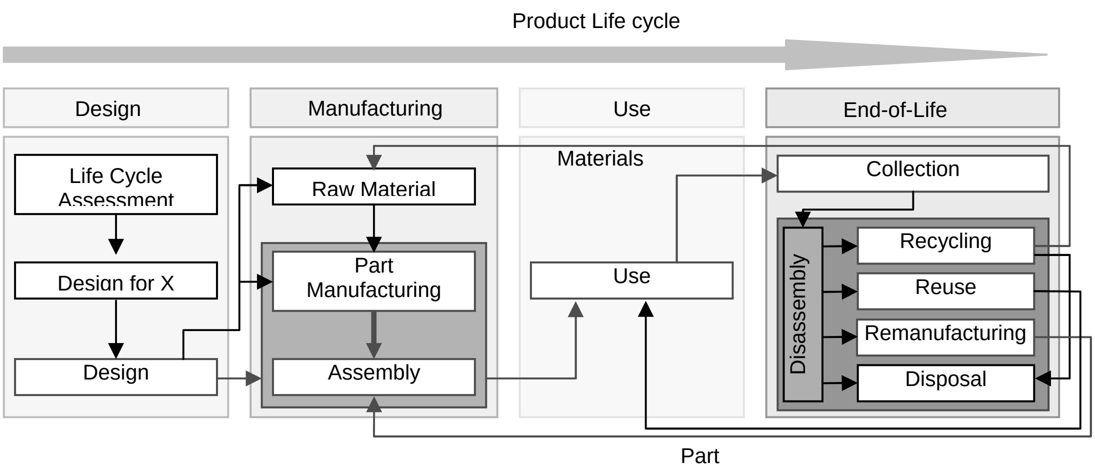


Figure 2: Product's life

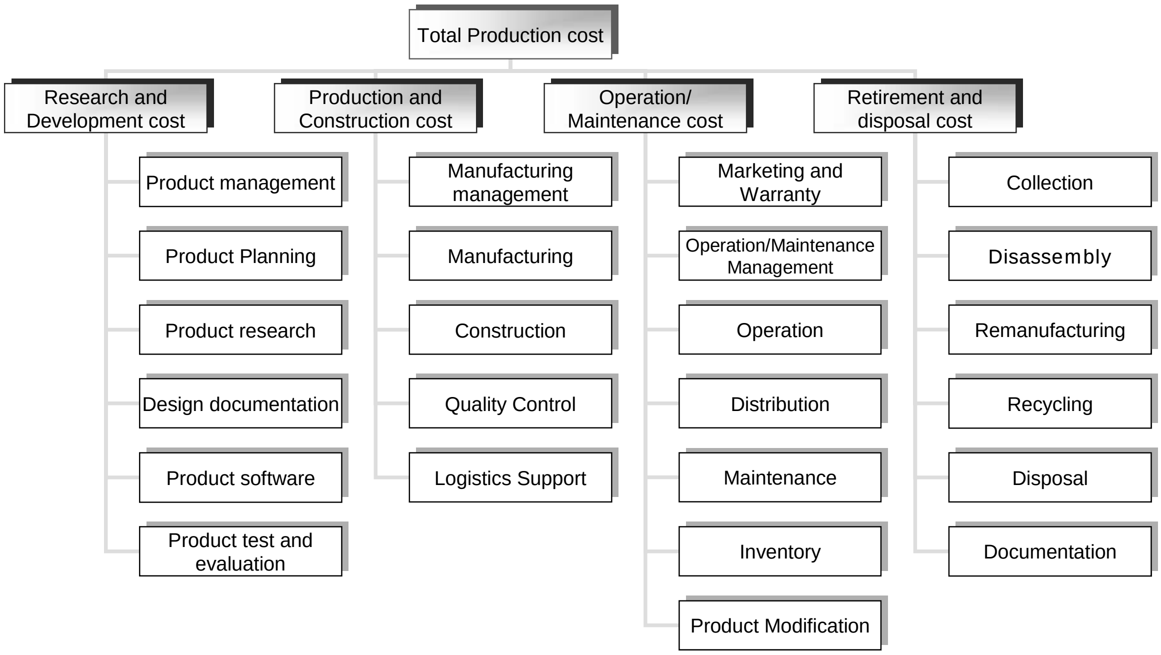


Figure 3: Cost breakdown structure

input information. The first method, which can be described as a 'rule of thumb' approach, also relies on the expert judgment of engineers familiar with the tasks being estimated. The experience accumulated by an engineer can constitute a large but unstructured´ knowledge base from which to assess the resources needed for a specific task. This experience is then often translated into 'rules of thumb' which are applied by the engineer for a rough sizing´ of costs. The creation of these 'rules of thumb' does not always follow a systematic process, but the technique is extensively used. As systematic process, case-based reasoning [8–11] and decision support systems [12] are also used.

- The analogical methods estimate the cost of products using similarity to other products with known cost. Basically, analogical methods use the statistical approaches using historical cost data for products with known cost, such as regression analysis models [13–15] and back-propagation neural network models as a surrogate method of regression analysis [14–21].
- The parametric methods estimate the costs of a product from parameters, which are usually used by the designers. In fact, parametric models are derived by applying the statistical methodologies and by expressing cost as a function of its constituent design variables. The parametric models can be distinguished form the analogical methods, since the parametric models can be developed in the form of non-linear equation, which is derived from the direct cost drivers [22].
- The analytical methods such as activity-based costing (ABC) allow evaluation of the cost of a product from a decomposition of the work required into elementary tasks, operations or activities with known (or easily calculated) cost. And, the total cost is expressed as a summation of all these components. These techniques can be further classified into different categories, e.g., operation-based approach – allowing the estimation of manufacturing cost as a summation of the costs associated with the time of performing manufacturing operations, nonproductive time, and setup times, break-down approach –summing all the

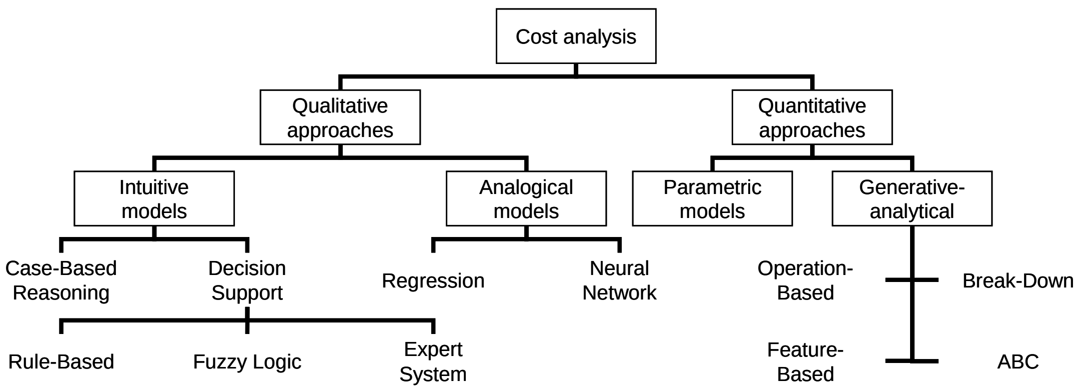


Figure 4: Classification of cost estimation approaches

costs incurred during the production cycle of a product, including material costs and overheads as well, feature-based cost estimation – dealing with the identification of a product's cost-related features and the determination of the associated costs, and activity-based costing (ABC) – calculating the costs incurred on performing the activities (including management cost, indirect cost, as well production cost) to manufacture a product [7].

For each cost element described in Figure 3, it is necessary to determine a proper method to estimate the corresponding cost. For example, case-based reasoning method is generally preferred to estimate manufacturing and construction cost, especially in conceptual design phase. When the detailed design is determined, analytical methods, i.e., feature-based method or operation-based method, give an accurate estimation. For the management-related cost elements, i.e., manufacturing management, quality control, marketing, warranty, etc., activity-based costing is generally used.

2.3 Determine the aggregated PLC formulation

The main feature of the PLC system is its principal role as a design support tool to estimate the cost of a product's entire lifecycle. The total lifecycle cost of product is the sum of the estimated costs of each breakdown cost. Therefore, pre-determined cost estimation methods are used as modules of the aggregated PLC system.

Total lifecycle cost of a given product is used for 1) helping decision-making through alternative selection, and 2) finding the trade-off formulation.

3 COST ESTIMATING FOR EOL PHASE WITH IMPRECISE DATA

EOL treatment and operations are faced with various uncertainties, such as the imprecise disassembly times, uncertain recycling and remanufacturing costs, uncertain yield ratio of recyclable or reusable parts, etc. Therefore, it is required to extend the research works to the stochastic version of cost estimation.

Disassembly planning corresponds to the estimation of EOL treatment costs except for collecting cost, since disassembly planning aggregates the cost of recycling, reusing, and remanufacturing as the EOL option of each components and subassemblies. In fact, disassembly is prerequisite of other EOL activities, and during disassembly planning, all other costs are entered as input information.

We focus on the problem with the objective of providing a conservative optimal cost estimation. The estimated cost can be obtained from the optimal disassembly plan. Disassembly planning is the problem of determining the disassembly level and the corresponding disassembly sequence for a given used or end-of-life product. Here, the disassembly level implies whether more disassembly operations are performed at each stage of disassembling a product, and the disassembly sequence begins with a product to be disassembled and terminates in a state where the entire product is disconnected into parts and/or components.

To deal with the interval objective coefficients, the *minimax regret criterion* which is one of the most credible criteria for decision making under uncertainty, is used. Here, the regret is defined as the difference between the cost obtained from the optimal solution and from the solution based on prior knowledge on which the particular real event will occur. Note that this criterion is conservative and especially useful for avoiding poor judgment. By applying the minimax criterion to the regret values, the original objective with interval coefficients is transformed into that of finding the least maximum regret, which is called the *robust deviation criterion* hereafter.

3.1 Problem Description

The problem considered here can be defined as *the problem of determining the optimal disassembly plan including the disassembly level, the corresponding disassembly sequence and the EOL options of remaining or retrieved components and subassemblies for a given product with the objective of maximizing the interval overall profit, while satisfying the precedence constraints among operations*. Here, EOL options are reuse, remanufacturing, recycling and disposal. The precedence constraints indicate that a set of operations has to be done prior to the accomplishment of the specified operation.

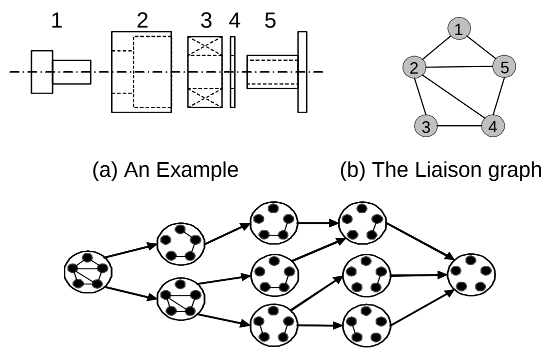
Without the interval objective coefficients, the problem can be represented using the *modified directed graph of assembly states*, which is shown in Figure 5(c), in which nodes represent assembly states, and arcs represent disassembly operations [23]. Figure 5(a) shows an example product obtained from Penev and de Ron [23], and its liaison graph is given in Figure 5(b). The root corresponds to the initial state, and each node can have child nodes corresponding to the states that can be reached from that node. See Kang *et al*. [24] for more details.

Let **G** = (**N**, **A**) denote the modified directed graph of the assembly states, where **N** is the set of nodes representing the assembly states and **A** is the set of arcs representing disassembly operations. An interval $[l_{ij}, u_{ij}]$, associated with each arc $(i,j) \in \mathbf{A}$, represents the range of possible profit for each arc. Now, the problem is to find the longest path from the source to any of the nodes in the modified directed graph of the assembly states. Note that the termination node in the path implies the disassembly level. A formal linear programming model is given below.

$$\textbf{(P)} \quad \max \quad \sum_{ij \in A} c_{ij} x_{ij} \tag{1}$$

$$\text{s.t.} \quad \sum_{0j \in A} x_{0j} = 1 \tag{2}$$

$$\sum_{ij \in A} x_{ij} \geq \sum_{jk \in A} x_{jk} \quad \text{for all } j \in \mathbf{N} \tag{3}$$



(a) An Example (b) The Liaison graph

(c) A Modified Directed Graph of Assembly State

Figure 5. Graphical Disassembly Representation

$$x_{ij} \in \{0,\ 1\} \qquad \text{for all } (i,i) \in \mathbf{A} \qquad (4)$$

where, $l_{ij} \le c_{ij} \le u_{ij}$, for all $(i, j) \in$ **A.** Cost c_{ij} represents the sum of the operation cost and the revenue of the assembly state *j*. A binary decision variable x_{ij} is equal to 1 if the disassembly operation (i, j) is performed and 0 otherwise. Equation (2) and (3) represent the node balance equations that are the same as those of common network flow problems, where the inequality allows for incomplete disassembly.

As stated earlier, we transform the original objective with interval coefficients into the minimax criterion to the regret values, i.e., the robust deviation criterion.

3.2 Dynamic programming algorithm

The problem can be solved by applying dynamic programming algorithm that can give the optimal robust disassembly sequence. First, the method to obtain the worst-case alternative for a given solution is presented. Then, based on the method, we formulate the problem as a dynamic program, and finally, the exact algorithm is presented based on the dynamic program [25].

The dynamic programming algorithm is proposed as follows:. Define:

$f_j(\Phi)$ = the regret value of the robust deviation path from *s* to $j \in \mathbf{N}$, while the set of arcs, Φ, is not contained in a worst-case alternative.

An initial condition for node *s* can be easily specified as:

$f_s(\Phi = \varnothing)$ = the length of the longest path from *s* to *t* in scenario *u.*

A recursive relation can be found for the rest of the root node:

$$f_j(\Phi) = \underset{i \in \mathbf{V}(j)}{Min}\{Max[f_i(\Phi) - u_{ij},\ f_i(\Phi \cup arc(i,j)) - l_{ij}]\} \qquad (5)$$

where, **V**(*j*) denotes the set of immediate predecessors of node *j*.

Equation (13) indicates that it is necessary to investigate two possibilities: either $\mathbf{y}^j$ contains arc(i, j) or not. The first term of the right-hand side considers that $\mathbf{y}^j$ contains arc(i, j), while the second term does not. The first term can be calculated directly. From Proposition 1, the second term can also be computed easily if $\mathbf{y}^j$ does not contain arc(i, j). In this case, $f_i(\Phi \cup \text{arc}(i, j))$ equals $f_i(\varnothing)$. The optimal solution can be obtained as $f_t(\varnothing)$. The complete algorithm is listed below.

procedure RobustLP ($\mathbf{G} = (\mathbf{N},\ \mathbf{A})$: directed acyclic graph; c: arc lengths);

begin

Initialization: compute the longest path $\mathbf{y}^s$ from *s* to *t* in scenario *u* and $\mathbf{x}^s := \varnothing$;

for *j*=*s* to *t* **do**

$\Phi := \varnothing$;

for each $i \in V(j)$ **do**

if $\mathbf{y}^j$ does not contain arc(i, j), $f_{ij}(\Phi) := f_t(\varnothing) - l_{ij}$;

else $f_{ij}(\Phi) := f_i(\Phi \cup \text{arc}(i, j)) - l_{ij}$;

$$f_j(\Phi) = \underset{i \in V(j)}{Min}\{Max[f_i(\Phi) - u_{ij},\ f_{ij}(\Phi)]\}$$

Update $\mathbf{x}^j$ and $\mathbf{y}^j$;

Output $f_t(\varnothing)$ as the optimal value for Robust Longest Path Problem

end.

In addition to the basic procedure given above, we used the concept of the midterm memory. While the recursive function $f_i(\Phi \cup \text{arc}(i, j))$ is obtained, the intermediate results are saved on each node. The intermediate results, i.e., the worst-case alternative from s to *k* excluding a set of arcs and its regret value, are referred to other paths since there are several paths from *s* to *j* that pass through node *k*. In the worst case, the recursive procedure iterates as much as the number of feasible paths from *s* to *j*. Then, when the outer ***for*** statement is reiterated, the midterm memory is refreshed.

4 CONCLUDING REMARKS

This paper dealt with the product lifecycle costing system (PLCS). The procedure of PLCS comprises 1) defining the cost element and structure, 2) establishing the cost estimating methods, and 3) defining the aggregate PLC formulation. As a module of PLCS, a proper estimating method for each cost element is required.

In particular, this paper proposed a cost estimating method for EOL treatment, which was a missed module of PLCS. Due to the ambiguity of EOL cost, the robust deviation criterion, as a conservative estimation criterion, was applied and the dynamic programming algorithm was proposed to find the optimal disassembly plan. As a result, the disassembly plan obtained from the dynamic programming algorithm estimates the EOL cost comprising the reuse, remanufacturing, recycling, and disposal cost, implicitly. Therefore, the propose method can be used as a module of PLC system to estimate EOL cost of product.

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A Life Cycle Cost Framework for the management of spare parts

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Abstract

In any industrial organization, the management of spare parts is very important because of functional and economic reasons. In order to have a good level of availability of the machine it is necessary to have a stock level of spare parts. On the other hand the efficacy and efficiency of maintenance policies depend on the ability to optimize the management of such supplies. Moreover, stock of spare parts represents for a company an elevated voice of cost, since it means to immobilize capital.

The aim of this work is to determine the optimal spare parts volume so to minimize the operating costs and of the lost production costs for unavailability. The work explores the classification criteria of spare parts by means of opportune Criticality Analysis. According to an appropriate "decision tree", spare parts are divided in a series of classes corresponding to different management policies, as RCM technique does with failure causes. Applying an algorithm of statistics management and by means of a technical-economic simulation methodology, we determined the optimal spare parts volume considering as key parameters the supply time and the level of service.

Keywords:

Life Cycle Cost, Spare Parts, RAMS, Monte Carlo Simulation

1 INTRODUCTION

In the last few year's important technological innovations have been achieved in almost all industrial products, those of which have emphasized the benefits of use on one side and the complexity on the other.

This evolution has made the choice of purchase extremely important, not only in considering the cost of acquisition but also in the costs connected to the use and the operating availability and the maintenance management. The customer can accept this complexity only if the components reliability and the operation time are high and required maintenance is low.

For this reason the supplier of the production system must be in a position to satisfy the customer from both a technical and economic view point by means of the development of products that are reliable and competitive, with respect to maintenance costs and at the same time optimizing the purchase costs and operating costs. From this point of view life cycle cost become essential to support the acquisition and to optimize the life cycle in the operating phase.

The LCC methodology utilizing data analysis is a major influence on the costs of life cycle (MTBF, MTTR, Productivity, rigid plans, etc.), allows us to understand the entire system behaviour, to gauge alternative designs, operations, maintenance management, to discover "The Best Choice" design solution.

Analyzing the various stages of the life cycle of a production system (Figure 1), it is clear that the supplier has a lot of leverage in order to act on the LCC in its various stages. This means that at acquisition stage it can be predicted what the future behaviour of the system will be in terms of stoppage costs for failures.

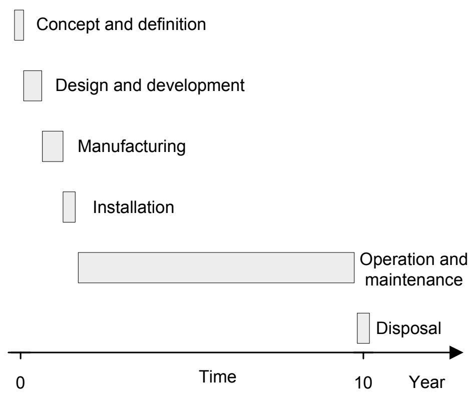

Figure 1:Life cycle phases

This work, focusing the attention on the stages of use and maintenance, produced a module that allows you to determine the best level of replacement parts, to keep in warehouse minimizing maintenance costs and lost production costs. Applying a management statistics algorithm with a methodology of technical simulation it has been determined the average monthly consumption of all the mechanical and electronic components used in the production line by means of reliable parameters including MTTF, MTTR, failure rate, etc. With this knowledge the advantage is twofold for both supplier and customers of the system.

The customers of the production system have obvious advantages to lessen the maintenance costs by applying the correct working methods and also optimizing warehouse management of the spare parts. The supplier of the production system, having a complete knowledge of all future failures of each component has the advantage to supply to his customers not just simple support but an improved after sales support [1] [2] [3] [4] [5].

2 LIFE CYCLE COST OF A PRODUCTION SYSTEM AND AFTERMARKET

A cost analysis of the life cycle of a production system has been carried out keeping into account an initial investment. Presuming an operating life equivalent to 10 years, it has been estimated a total LCC resulted for 6 times the initial investment.

The initial purchase price accounts 18% of the total cost, while the operating stage, labour costs included, materials "utilities and consumables" and expenses accounts for a 47%, maintenance accounts for 35%, including 8% for the replacement parts estimated through reliability and maintenance indicators.

Considering this, it is possible to assert that the value of the aftermarket, defined as after sales service supplied by the manufacturer of a production system, is estimated to be the double of the value of the initial investment, because it is determined mainly from the cost of the replacement parts, maintenance costs and the consumption of materials cost, used for maintenance.

The evolution of the markets and the increasing competitiveness of the products has moved an important part of the business of the distributer/producer from the sale of the new machine or the new systems to the after sales service; in fact by now the customer of the production system not only considers the quality of their product, but also bases his choice on quality and level of after sales offered. This sector of activity is continuously acquiring greater importance for the producer as it can guarantee a greater competitiveness in the market and therefore inducing customer confidence, which is also an important part of the business and therefore an ulterior source of revenues.

3 IMPORTANCE OF REPLACEMENT PARTS AND ACCUMULATED PROBLEMS

Management problems of replacement parts, is important for economic and functional reason. In fact to obtain an acceptable level of availability of the machinery it is necessary to maintain a supply of spare parts, and efficiency and effectiveness of the company policy of maintenance depends strongly on ability to manage in the most efficient way these supplies. The levels of supply of the spare parts are therefore conditioned from how the system is used and the maintenance is managed. Maintenance that demands a type of spare parts can sometimes be delayed or cancelled. This maintenance choice has an immediate impact on level of supply of that type of spare part. If the monitoring system of the operation conditions indicates that a given part of the system has been consumed, other policies can be to reduce the use of that particular component, for example, reducing the speed of production system. There has been much research and articles with respect to the problems of spare parts. Currently the evidence shows that management of spare parts is not based on optimization criteria and reduction of expense, but simply on avoiding going out of stock. This provokes stock accumulation because the system is calculating an excess amount in respect to real annual requirement. This fault depends fundamentally on four factors.

The first factor that negatively influences the estimation of the spare parts depends on the fact that it does no difference between the various failure mode of a single component. In other words the "failure rate" relative to failure mode that do not carry the necessary substitutions of the component, but that is only necessary to replace under parts of it has been inserted in the calculation.

For example if the failure mode is considered "card drive" for an electric motor, it involves only the substitution of the card and not of the complete electric motor. Therefore the "failure rate" of this type of failure do not have to be considered in order to estimate the amount of electric motors to keep in stock. Consequentially the initial estimate of the total "failure rate" for the considered components, and therefore its stock amount, is in excess.

The second cause of error depends on the consideration of all the components of the same type all in series and therefore to consider the "failure rate" of the complete series. The error resides in not taking into account of eventual inter operation buffer or of different productive rhythms between two consecutive stations, that would avoid stopping the whole system because of failure of a single component. This error leads to an estimation in excess of the system, and of the amount of annual spare parts necessary for the line.

An other source of error often derives from the structure of the database of many companies relating to spare parts. This last source is often composed by "families of components"; if the attention is focused on the pneumatic cylinder family, this family will contain cylinder different for function and constructive characteristics. They are often inserted in the DB with same value of MTTF and MTTR.

The last factor that produces an inaccurate estimate of the amount of spare parts derives from the consideration of lead time for the component. For spare parts that display a supply time considerably low, supplies do not have to be kept in stock, but in the majority of cases they are stocked anyway. Furthermore, for a correct estimation it would be also necessary to know the level of risk that the customer wanted to load itself with, so as to carry out a more precise determination of the supplies of spare parts.

The objective of this work has been to find an efficient management system of the replenishment of stock within warehouse that could achieve a cost reduction and at the same time can respond to all requirements.

4 ASPECTS AND CONDITIONS THAT INFLUENCE MANAGEMENT

The first phase that has allowed us to determine the supply of spare parts in the warehouse, has been to define the main aspects and conditions that determine management. Particular needs are listed as follows:

- Maintenance policy;
- Total number of redundant systems presents in the plant;
- Information about the reliability of the components;
- Criticality level of the plant;
- Failure rate of various components;

- Costs related to stock out of the spare parts due to a loss of production or problems of quality on the product;
- Value and dimensions. The number of parts to keep in supply resulting from their cost and the space that they occupy in the warehouse;
- Supply times and likelihood of finding them in the marketplace.

Known the main problems that induce to accumulate spare parts in the warehouse, the main aspects and conditions that determines management, we suggest the methods, described below, articulated in more steps, which allow us to define an operating system of rigorous management and at the same time simple, useable and fast [6] [7].

5 MONTE CARLO SIMULATION OF THE TIME TO FAILURE OF THE COMPONENTS

The first step allows the calculation of a medium monthly consumption of the components (electronical and mechanical) present in the system through a process of Monte Carlo simulation, which supplies dynamically the dates of every component failure.

With such method, through a generation of random numbers, the value of unreliability $Q(t)$ of the component is generated.

Therefore the generated numbers are inserted in the inverse function $Q(t)$. So future dates of failure can be estimated.

In order to make a simulation that reflects with a certain trust the real situation, it is necessary to have to handle all the available data of component reliability. A reliability function must be assigned to every component that defines it (Weibull, exponential, normal, etc.). This function supplies the relation between the life (at the time T) of a product and the probability of operation in that particular moment (T) of life [8] [9] [10] [11] [12].

6 MANAGEMENT POLICY BY MEANS OF DECISIONAL TREE

The next step of the simulation is to deal the spare part similar to what was done for the failure causes with the RCM technique, classifying the spare parts in series of classes corresponding to different management policies by means of an appropriate “decisional tree”.

After a careful analysis of the characteristics and conditions that influence management of supplies the main points that cannot be neglected are:

1. Criticality level of the component for the plant;
2. Easiness of finding them on the market;
3. Preventive supply times;
4. Failure monitoring;
5. Rate of use.

Starting from these considerations, it has been built the decisional tree, as shown in Figure 2, composed from more “branches” which lead to different classes. Each class is characterized by various management policies (Table 1), depending on the level of risk of accepted stock out [7].

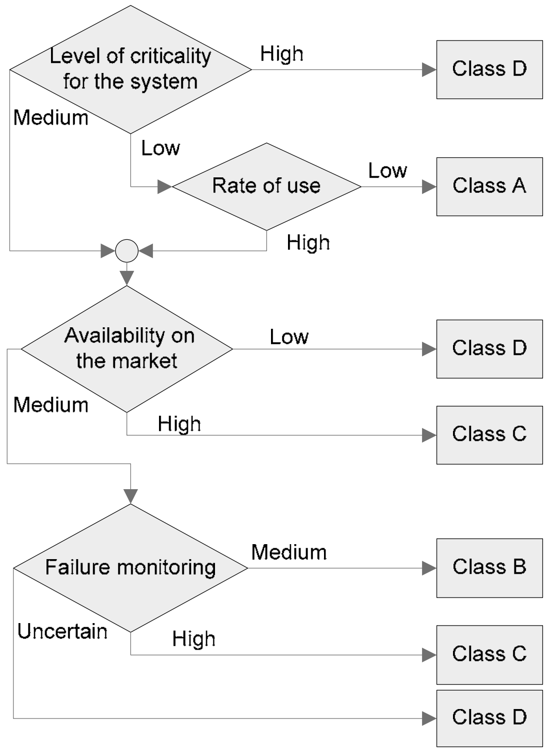

Figure 2: Decisional tree for the management of spare parts.

Class	Policy
Class A	Management of spare parts with high stock out risk level
Class B	Management of spare parts with medium stock out risk level
Class C	Management of spare parts with medium/low stock out risk level
Class D	Management of spare parts with low stock out risk level

Table 1: Management policy for each class.

The decisional tree leads to 4 different classes. Every class is characterized by a various level of risk of stock out.

6.1 Level of criticality for the system

Analyzing each item of the tree shown in Figure 2, we start to consider the “level of criticality for the system”.

We calculate criticality of the component using the equipment ranking method reported in Figure 3. For every elements of the schema (severity, quality, lost production cost, working, effects on the production, occurrence, maintainability) we have defined three criteria of identification of the rank:

A: Critically high;

B: Critically medium;

C: Critically low.

The criteria to evaluate final rank has been indicated in Table 2 for each element of Figure 3 [12].

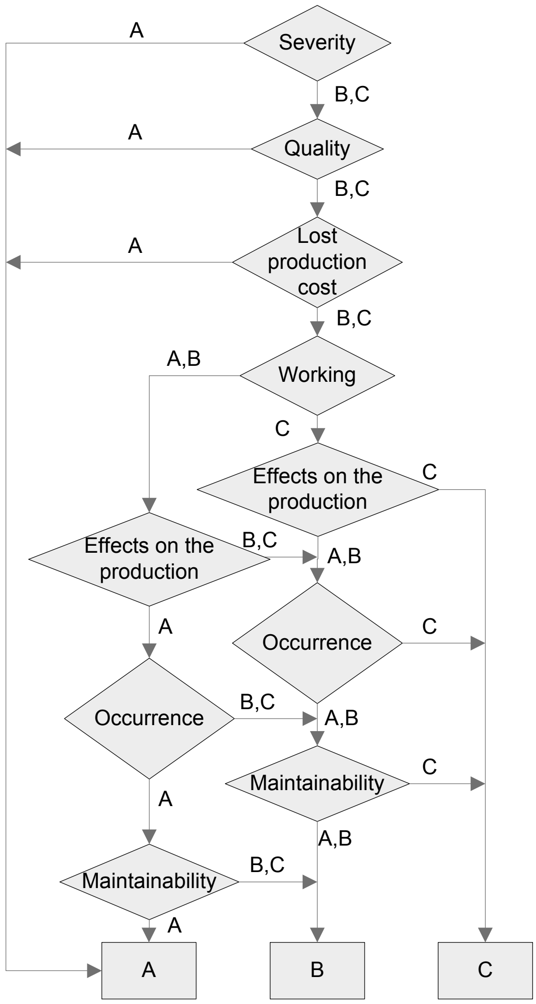

Figure 3: Flowchart for equipment ranking

	A	B	C
Severity	Failures mode affects operator safety and/or environmental safety	Not applicable	No discernible effects
Quality	Defects noticed by customers	Possible defects noticed by customers	No defects
Lost production cost	Lost production cost > 20000€	10000€ < Lost production cost < 20000€	Lost production cost < 10000€
Working	Preventive machine stop < 10 hours/month	10< Preventive machine stop < 300 hours/month	Preventive machine stop > 300 hours/month
Effects on production	Production stop of the line	Production stop of the single machine	No production stop
Occurrence	Critical failures > 1 per year	1/4 < Critical failures < 1 per year	Critical failures < 1/4 per year
Maintainability	MTTR > 6 hours	1 hour < MTTR < 6 hours	MTTR < 1 hour

Table 2: Identification rank for each element.

6.2 Rate of use

The second item of the decisional tree (Figure 2) is relative to the “rate of use” for the component. In Table 3 illustrates the distinction between a high and a low rate of use.

High rate of use	Use ≥ 5 pieces / year
Low rate of use	use < 5 pieces / year

Table 3: Rate of use identification.

6.3 Availability on the market

The following item of the tree is “availability of the market”. Common components such as bearing, seal, gascket, etc. will easily be available in few days, in comparison to a special component like pneumatic cylinder. The Table 4 identifies several the levels of availability.

Low	Supply time > 1 Month
Medium	Supply time within two weeks
High	Supply time within few days

Table 4: Availability levels on the market

6.4 Failure monitoring

The last item of the tree is “failure monitoring”. We have considered the possible failure modes and the different techniques of the control of the component.

High	High chance to detect a potential failure mode (continuous monitoring)
Medium	Moderate chance to detect a potential failure mode
No monitoring	No chance to detect a potential failure mode

Table 5: Failures monitoring levels

6.5 Management statistics of the spare parts

The estimation of the amount of spare parts to hold in supply has three different functional aspects:

- The probability of having a spare part in stock;
- The reliability of the component;
- The amount of components in the plant.

Spare parts are components “in low demand”, so we can use Poisson model to approximate their consumption [13]. Poisson formula is defined as follows:

$$p(x) = \frac{e^{-m}}{x!} m^x \quad (1)$$

7 CASE STUDY

The calculation model described in the previous section has been applied to an assembly plant of one of the biggest suppliers of the production systems for the automotive sector. The developed calculation model has been utilized to determine the optimal spare parts volume. The plant allows the assembly of the cylinder heads and it is composed by 9 manual stations, 2 semi-automatic station and 9 automatic stations. The friction roller transport line is 153 meters long. We assume that life cycle is 10 years and production is 230000 pieces per year with a cycle time of 70 seconds. The implemented labor organization politics is about 5110 labor hours per year on the basis of which the estimated production per hour, assuming an efficiency of 100%, is of 51,43 pieces/hours [4] [14].

7.1 Monte Carlo simulation to evaluate time to failure of component

In the following section we calculate time to failure of a ball bearing (considering 12 labor months of the plant) using Monte Carlo simulation [12]. Reliability parameters are reported in Table 6.

Eta	40000 hours
Beta	1,2
MTTF	37626 hours
Quantity	76

Table 6: Reliability parameters of ball bearing.

Time to failures of the ball bearing has been represented using a Weibull frequency distribution [5]. Distribution parameters are shown in Table 6. The cumulative distribution function (cdf) for the 2-parameter Weibull is:

$$Q(t) = 1 - e^{-(T/\eta)^{\beta}} \quad (2)$$

From the cumulative distribution function it’s possible to calculate time to failure T and Mean time to failure $MTTF$:

$$T = \eta\left[\ln\left(1/1 - Q_T\right)\right]^{1/\beta} \quad (3)$$

$$MTTF = \eta\Gamma\left(\frac{1}{\beta} + 1\right) \quad (4)$$

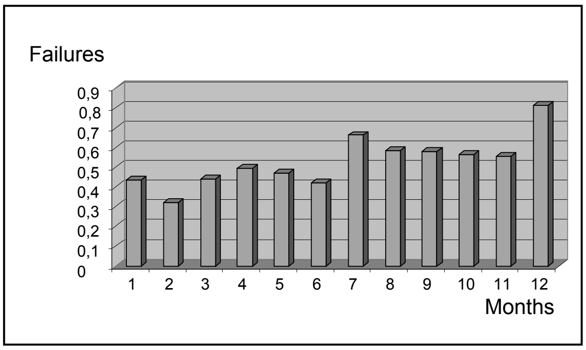

Figure 4: Failures of ball bearing (monthly).

7.2 Evaluation rank of ball bearing

Once calculated the amount of failures of ball bearing we applied "equipment ranking method" (see Figure 3).

Elements	Evaluation	Rank
Severity	Very law severity ranking. A failure mode doesn't reduce the level of performance	C
Quality	A failure mode can produce defects noticed by customers	B
Lost production cost	Very low lost production cost	C
Working	Continually working	A
Effects on the production	A failure mode causes lost production of the single machine	B
Occurrence	Few failures	C
Maintainability	MTTR about 1 hour	B

Table 7: Rank of each element.

Considering the rank of each element as shown in Table 7, we determined a low rank of criticality (**C**) of the component.

7.3 Management policy of spare parts

The procedure shown in Figure 2 continues considering:

- High utilization;
- Easy availability on the market;
- No failure monitoring.

the ball bearing belongs to the **C** class. The ball bearing can be managed with a level of medium/low stock out.

7.4 Spare parts optimization with Poisson model

Applying Poisson model, considering data shown in Table 6, 5110 yearly hours and 4 weeks of supply time we determined the optimal ball bearings volume presented in Table 8 [13].

Risk level stock out	Stock of spare parts
58%	0
21,30%	1
6%	2
1,20%	3
0,20%	4

Table 8: Risk levels for each stock of spare parts.

The optimal spare parts volume, calculated to minimize the operating costs and the lost production costs for unavailability, is 2 (risk level stock out of 6%).

8 CONCLUSIONS

The use of LCC model in the case study is an added value in the phase of the commission acquisition by the production system supplier and in the subsequent phase of the aftermarket service (maintenance and spare parts sale). Production supplier can evaluate various maintenance strategies (to assist product users) and know information concerning the failures of each spare part of the production system. So supplier can acquire a partnership for supplying spare parts (8% of the total LCC of the plant) and support to maintenance (27% of the LCC).

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