Allen H. Hu · Mitsutaka Matsumoto
Tsai Chi Kuo · Shana Smith *Editors*

Technologies and Eco-innovation towards Sustainability I

Eco Design of Products and Services

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Part I
Emerging Technologies and Sustainability

Chapter 1
Exchange of Modules Among Robot Manipulators Using Part Agents

Yuuki Fukumashi, Atsushi Nagasawa, Yoshinori Fukunaga, and Hiroyuki Hiraoka

1.1 Introduction

Currently, in order to solve environmental problems, a transition is required to a recycling-oriented society with smaller burden on the environment. However, among the 3Rs promoted to achieve a recycling-oriented society, reuse, in spite of its greater effect on the environment than recycling, has not been widely spread [1]. The reason for this is the difficulty for the user to know the level of deterioration in the function and performance of a reused product and its remaining lifetime, which disturbs dissemination of the reuse. To promote the reuse of parts, it is necessary to record and manage the usage history of the parts of a product, to predict the progress of deterioration and the failure of the part from the usage conditions of the parts, and to propose replacements of the part to the user.

In order to realize these functions, we are developing a part agent system using network agents and radio-frequency identification (RFID). In previous research, life cycle simulations of parts have been carried out based on the behavior of part agents [2–5]. In this research, in order to clarify the problems and the effects of the proposed system, a prototype has been developed, with part agents that are installed in modules of manipulators, to carry out experiments where simulated reuse activities are performed. This paper reports on its development and design.

Issues related to the promotion of the reuse of parts include the recognition of the status of a part, such as deterioration and the decision on when a part should be replaced with a used part. Methods used in predictive maintenance [6] can be applied to detection and prediction of the deterioration of a part based on acquired sensory, historical, and operational data. A part agent collects these data through related functions and stores them. The decision on exchanging a part with a used

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one is not only based on the state of the part but also on the availability of used parts and on the predicted operations and environments.

First, the concept of a part agent is described in Sect. 1.2. Then, the proposed mechanism of a part agent that provides advice on the replacement of a module is explained in Sect. 1.3. In Sect. 1.4, a planned experiment on module replacement is described. In Sect. 1.5, preliminary experiment with a manipulator with a single DOF is described with some results. Issues on the exchange of parts are discussed in Sect. 1.6, and the paper is concluded in Sect. 1.7.

1.2 Part Agent System

The proposed part agent system is based on the following usage scenario. The system uses the part agent to manage all information about an individual part throughout its life cycle. The proposal assumes the spread of networks and high-precision RFID technology [7].

The part agent is generated during the manufacturing phase of the main parts, when an RFID tag is attached to its corresponding part. The part agent identifies the RFID tag throughout the part's life cycle and tracks the part's transfer through a network. RFID tags were chosen for identification because they have a higher resistance to environmental stress than printed codes such as bar codes, which may deteriorate or become dirty over a part's life cycle. Moreover, one can read, write, and store data in an RFID. These functions are not feasible by other print-based identification methods.

In related research, a product embedded identifier (PEID) [8] has been developed, which involves a small computing chip, an RFID tag, and sensors to support the second half of a product's life. In contrast to the PEID system, our system aims to promote multiple reuse of individual parts that may go beyond the manufacturer's management. This requires a "lightweight" system that can be used repeatedly without maintenance of sophisticated hardware.

Figure 1.1 shows the conceptual scheme of the part agent. The part agent collects the information needed to manage its corresponding part by communicating with various functions within the network. These functions may involve a product database that provides product design information and applications that predict the deterioration of parts and provide logistic or market information. Furthermore, the part agent communicates with local functions on-site, such as sensory functions that detect the state of the part, storage functions for individual part data, and management and control functions of the product. Communication is established using information agents that are subordinate network agents generated by the part agents.

Based on this scheme, Tanaka developed a life cycle simulator of products that shows their behavior in the life cycle [2]. Nanjo proposed a method to predict future state of a part based on its life cycle and to evaluate options in maintenance activity [3]. Ueno proposed application of Bayes estimation for predicting state of a part to decide its replacement [4]. Yokoki added consideration of users' behavior based on

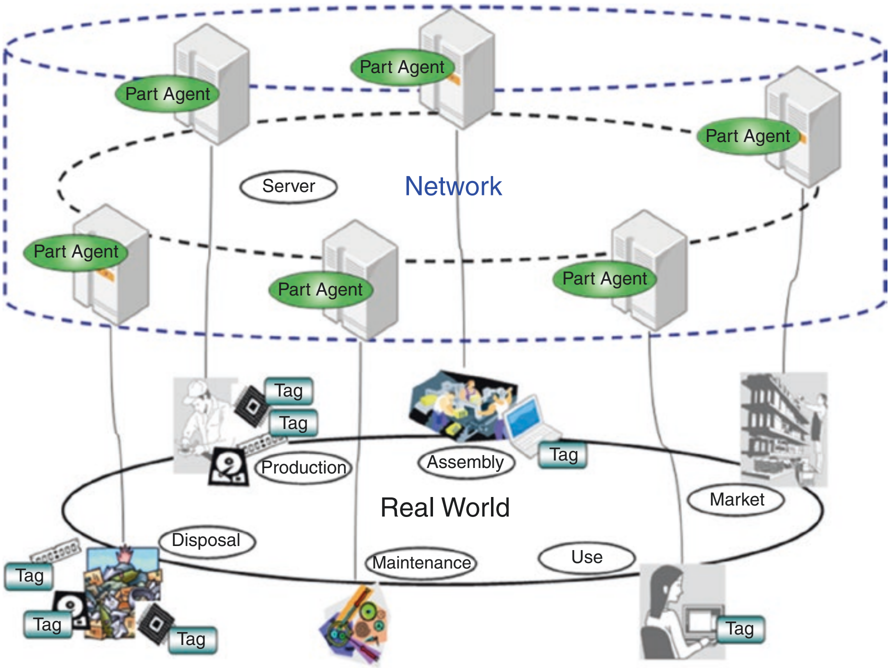

Fig. 1.1 Conceptual scheme of the part agent

Prospect theory in the replacement of parts [5]. These researches are based on simulation. Simulated state of parts includes deterioration, cost, profit, and environmental load all of which are based on simple models. No results have been reported on the implementation of actual part agent system with RFID.

1.3 Replacement of Manipulator Modules

Prototype systems of part agents have been developed for the prediction of deterioration and failures of modules as well as the generation of proposals on the replacement of modules based on simulation. In this paper, we report the development of an experiment system that is to carry out an experiment by which methods and activities that are proposed based on the results of the simulation are performed and evaluated.

Figure 1.2 shows the conceptual scheme of the experimental system for the replacement of modules. RFID tags are attached to modules that compose a product, which realizes identification of the modules and association between the modules and their corresponding part agents. A control computer collects the status of the modules through sensors attached to them. The computer sends the acquired information to the network database and the corresponding part agent. Based on the infor-

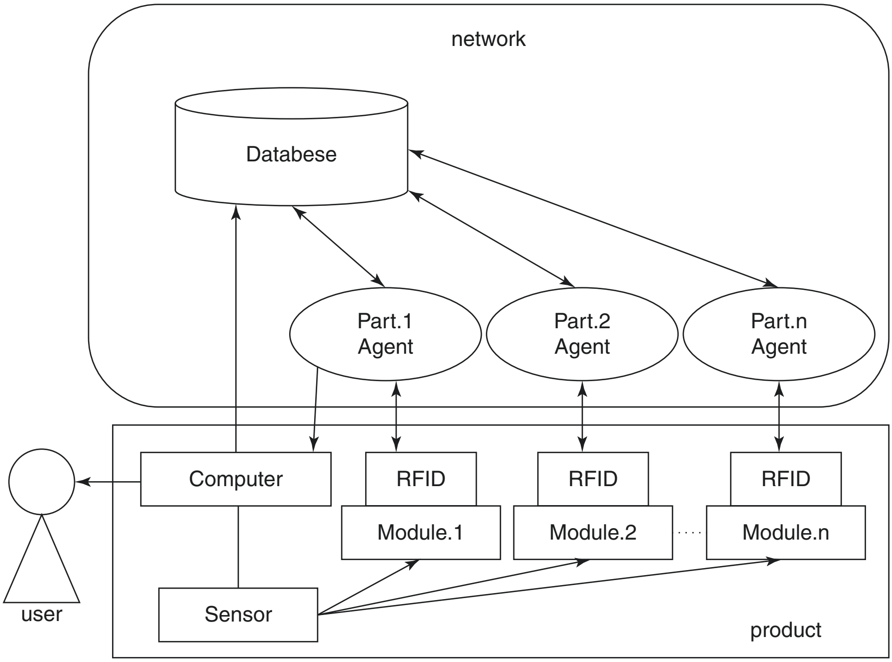

Fig. 1.2 System of modules replacement experiment

mation it contains and the information from the database, the part agent manages individual data on the corresponding module, predicts its deterioration, and acquires information from other part agents. By incorporating the information acquired, the part agent proposes the user an appropriate measure for the corresponding part.

Figure 1.3 shows the flow of module replacements. When a part agent detects the excessive deterioration of the corresponding module, based on the sensory data sent from the control computer, it sends a halt instruction to the manipulator that contains the module and searches an appropriate replacement module by consulting other part agents that manage the same type of module. When a replacement module is selected, the agent sends the user a proposal to replace the module, through the control computer. With this method, part agents stimulate the reuse of modules based on the management of modules and user support.

1.4 Experiment of Module Replacement

We are planning an experiment with ten robotic manipulators performing the task of carrying loads. The task varies for each manipulator in the weight of load and time allowed. Different content of work to be done by each manipulator results in different progress of deterioration for each module. Modules for replacement are selected

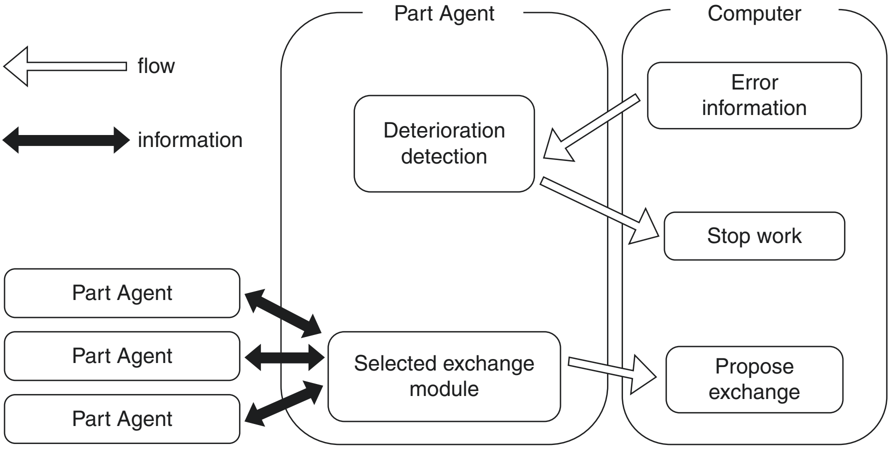

Fig. 1.3 Flow of module replacement

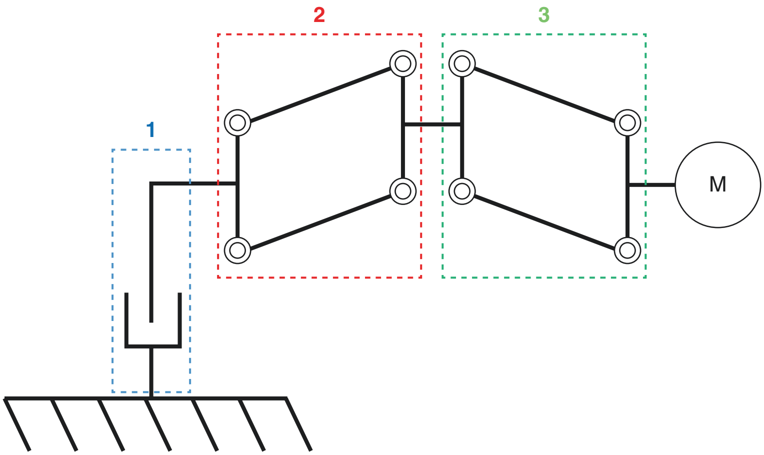

Fig. 1.4 Schematic plan of the manipulator

based on these different levels of deterioration. The prediction of deterioration is made based on data from sensors attached to the manipulator, the operating time of the manipulator, the operating environment, etc. When the part agent predicts excessive deterioration, it communicates with the part agents of similar modules and searches for a module suitable for replacement. When a replacement module is found, it suggests the user to replace the deteriorated module.

A simple robotic manipulator with three degrees of freedom is designed for the experiment. First, a prototype manipulator was designed and built to investigate design issues. See the appendix for the detail of the prototype. A robotic manipulator is newly designed as follows based on the experience from the prototype. Figure 1.4 shows the schematic plan of the manipulator. The rectangles with dotted lines denote the modules of the manipulator. Circled character M represents the load. Each module can be easily assembled and disassembled. It has a built-in DC motor and an angular sensor. The sensor is used not only for the control but also to gather control information. The module is controlled by feedback of the measured joint angle and by feed-forward of the torque required for the posture of the manipulator. The first module is for rotational motion around the axis, perpendicular to the ground. Modules 2 and 3 are for planar motion in a plane perpendicular to the ground, are identical, and can be interchanged. By using the same module in the manipulator, the number of replaceable modules is increased, and the exchange of modules is promoted. Modules 2 and 3 have the structure of a planar four-bar linkage that keeps the posture of the hand constant.

1.5 Preliminary Experiment

We assumed that the deterioration of modules is detected by monitoring its control value. In order to validate this assumption, we performed a preliminary experiment and checked how the deterioration proceeds by the motion of the manipulator and how the deterioration affects the changes in control values. For this purpose, a manipulator with one degree of freedom was designed as shown in Fig. 1.5, and it was equipped with a motor and a sensor to measure the angle of the link. The holes at the tip of the arm were designed for weights to be attached. Figure 1.6 shows the manufactured manipulator with one degree of freedom. We used a small computer Arduino and a motor driver to control the motor of the manipulator. Figure 1.7 shows the connection among devices. A commanding computer and Arduino communicate by a serial communication. Arduino changes the duty ratio of pulse width modulation (PWM) to control the motor according to instructions from the computer. It also obtains the angle value from the angle sensor and sends it to the computer. The computer then performs the control calculation.

Figure 1.8 shows the control block diagram of this manipulator that is controlled by proportional and gravity compensation control. Continuous movement of this manipulator causes deterioration. We observed the value of the angle sen-

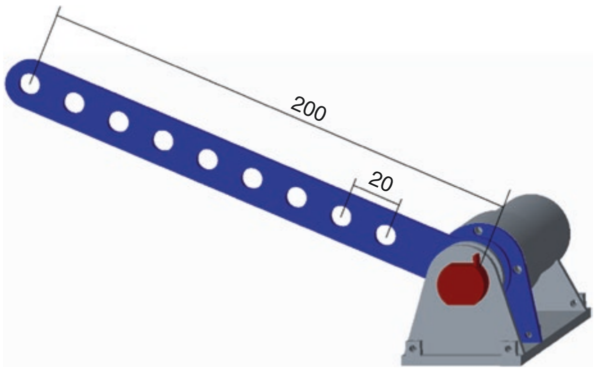

Fig. 1.5 Model of manipulator with one degree of freedom

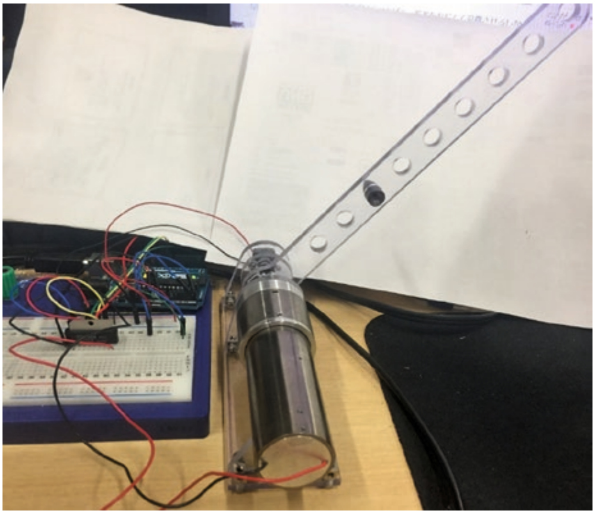

Fig. 1.6 Manufactured manipulator with one degree of freedom

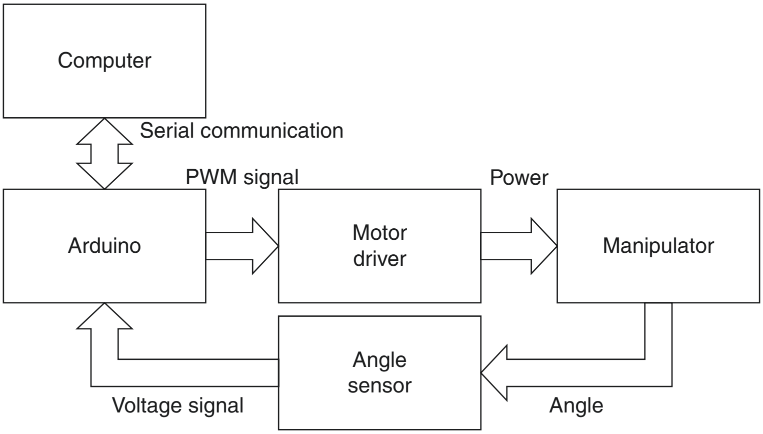

Fig. 1.7 Connection among devices

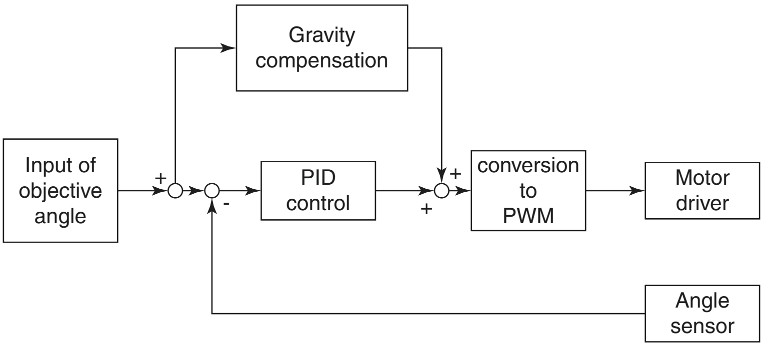

Fig. 1.8 Control block diagram of the manipulator

sor and the controlled variable, and we obtained the relation between the deterioration of the manipulator, the value of the angle sensor, and the controlled variable.

The experiment was executed where the link travels repeatedly between the angle 0° and 90° with the cycle of 90 s. For the first experiment that was performed without any weight for 7 h, i.e., for about 280 cycles, no difference is detected between the output to the motor observed at the start and that observed after 7 h. The next experiment was done with a weight of 10 (g) attached to the link at the point 60 (mm) from the joint, for 14 h, i.e., for about 560 cycles.

Figure 1.9 shows the result at the start of the experiment. The graph represents duty ratio (%) of PWM that is the output for the motor against time. The duty ratio changes between +100 (%) and −100 (%) because the output changes positive and negative with the change of rotation of the motor normal and reverse. Time from the start of experiment is shown in the horizontal axis. Peak value for each cycle is shown in the figure that is obtained when the link rises from the horizontal posture. Figure 1.10 shows the result after 14 h in the same way. The output observed after 14 h increased for 4.6% compared to the output at the start of the experiment. We consider the increase is due to the displacement between the center of the motor and that of the sensor occurred by the wear of the joint between the motor and the sensor, which leads to larger output required for the motion of the manipulator. The result shows the deterioration of a manipulator can be detected by the changes observed in the output to the motor.

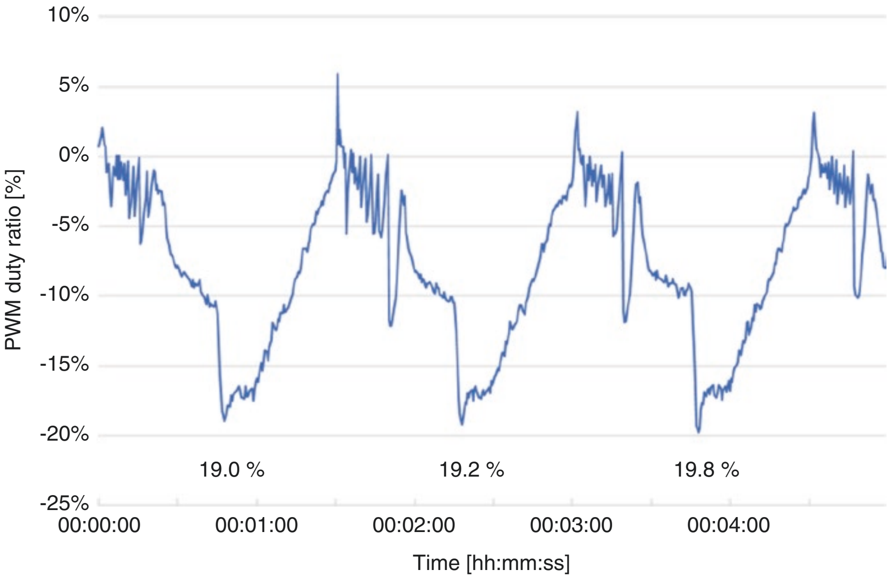

Fig. 1.9 Control output at the start of the experiment

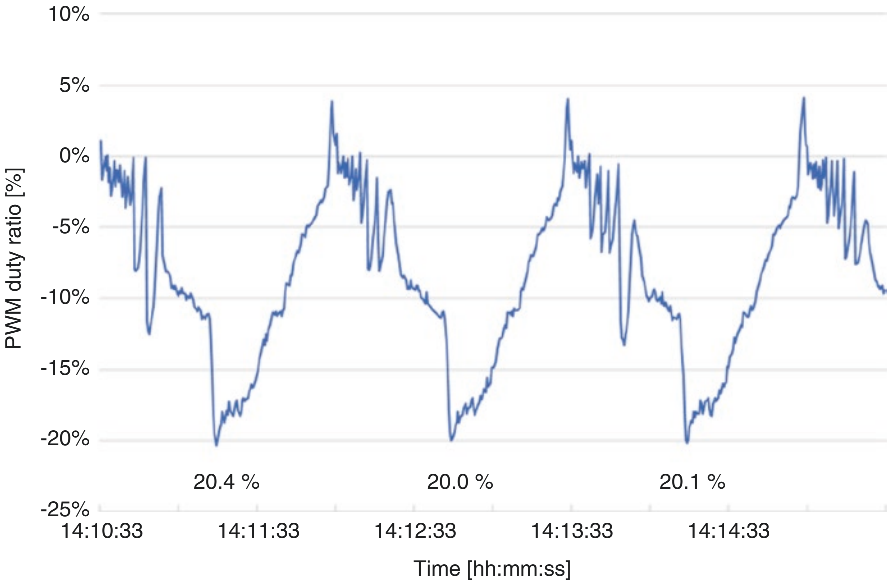

Fig. 1.10 Control output at 14 h after starting the experiment

1.6 Issues for Exchange of Modules

Issues are remaining to realize a system to exchange modules among manipulators to promote reuse of modules. We classify those issues into three categories, namely, details of exchange procedure, cooperation functions of part agents, and decision for exchange of modules.

First, procedure how to exchange modules should be elaborated in detail. For the procedure to collect the information on deterioration, we are considering that the commanding computer of the manipulator monitors the outputs for the motors for every control cycle, detects their peak values for every work cycle (i.e., every swing of the link for the manipulator with a single DOF in the above-described preliminary experiment), and distributes them to each part agent managing a module. However, the procedure should be examined from the viewpoint of appropriate detection of deterioration as well as sharing and integrating functions with control of manipulator.

The next category of the issues is cooperation of part agent with the commanding computer and with other part agents. In the phase of deterioration detection, appropriate cooperation based on the communication between each part agent for a module and the commanding computer is required. The appropriate communication is to be investigated including what information should be communicated, how the information should be represented, and how it should be communicated. The procedure of cooperation should be also elaborated when it is found that the replacement of a module is required. And it is also an issue how the cooperation among part agents in different manipulators are established and executed in selecting an appropriate module to be exchanged with the current module.

Decision on exchange of modules is an important issue. In a sense, the purpose of the system we are developing is to investigate an appropriate method for decision on exchange of modules. An appropriate strategy and methodology should be investigated and established for the decision on exchange of modules. Factors that may affect the decision include deterioration of the module, status of other modules within the same assembly, and availability of replacement modules. Method and procedure for decision on exchange of modules should be elaborated including the criterion, the threshold, and the assessment method for the decision. Though the preliminary experiment with a simple manipulator seems to work well in detecting the deterioration, the results need to be validated with accurate measurement. Selection of modules to be exchanged with the current module is another issue to be investigated. It includes how the candidate modules are chosen, how those candidates are compared on what criterion, and how they are ranked.

1.7 Conclusion

In this paper, we proposed a method to reuse mechanical parts with the help of a part agent system. We described the system in which a part agent proposes the replacement of part. A plan for an experiment is proposed where machine parts are modularized and are exchanged. Preliminary experiments were performed with a prototype manipulator, and their findings were reported. The remaining issues are discussed for development of the proposed experimental system. As the deterioration of the manipulator was confirmed in the preliminary experiments, we will proceed to manufacture ten manipulators and to perform the module replacement experiments.

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Appendix: A Trial Design of Module Replaceable Manipulator

Before building the manipulators for the experiment of module replacement, we developed a prototype of modularized manipulator to investigate points of attention in design. The purpose of modularization is to realize easy assembly and disassembly of manipulators in order to facilitate the reuse of their parts as well as to provide units of function. The module is the unit that is replaced and reused and to which a part agent is assigned.

Figure 1.11 shows the modularized manipulator prototype. It has four degrees of freedom with an end effector for grasping objects. It consists of four modules, a hand, two links, and a base. Each module is fixed on the flange of a motor and a shaft that is aligned with the output axis of the motor. This simplifies the connection and

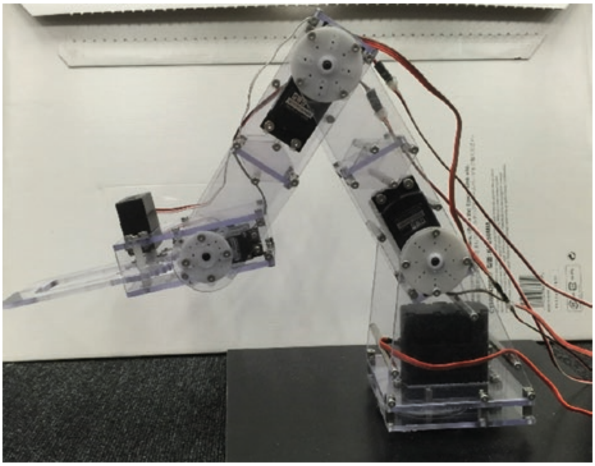

Fig. 1.11 Prototype modularized manipulator

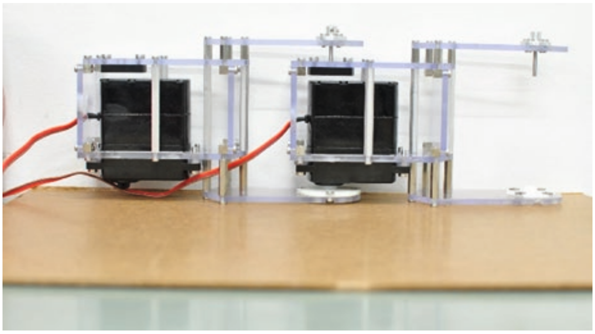

Fig. 1.12 Link modules

disconnection of the module by inserting or pulling it out of its rotational axis shaft. The link modules that were manufactured based on this design are shown in Fig. 1.12. We designed both link modules in the same way and mutually interchangeable to increase their reusability. For this purpose, the flange of the motor for link modules is fixed in the same plane as shown in the figure. This common plane ensures the interchangeability of the two modules. We confirmed that the modules are easily connected and disconnected by inserting and pulling them out of the shafts.

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Chapter 2
The Framework of the Integration of Carbon Footprint and Blockchain: Using Blockchain as a Carbon Emission Management Tool

Kun-Hsing Liu, Shih-Fang Chang, Wun-Hui Huang, and I-Ching Lu

2.1 Introduction

The carbon footprint is mainly produced by industrial activities such that how to manage the information to lower the carbon emission from supply chains is an essential issue [1]. The well-known enterprises such as Walmart, Nike, and Ikea requested the disclosure of carbon footprint from their suppliers in the past [2].

Under the increasing needs of products' carbon footprint calculation, the basic ability to calculate and disclose carbon footprint has become the important communication tools for government and industry to achieve carbon reduction targets, to declare its corporate social responsibility, and to market green product to the public [3].

For promoting and counseling the industry to disclose the product's carbon footprint and to evaluate the possibility of carbon reduction, many countries have started to construct not only the calculation standard or guidance but also the database for carbon footprint and life cycle assessment [3].

In Taiwan, a carbon footprint online database is thus constructed to enhance the basic ability to disclose and calculate the product carbon footprint of the domestic industry by providing the localizable and high applicable coefficients of carbon footprint [3]. However, the carbon footprint disclosure is still at high price about 120,000 to 200,000 NTD for each product. The disclosure is also time-consuming such as 12 months, especially when the composition of the tar-

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get product is complex. The life-span for some electronic products even ends before the completion of the disclosure.

The blockchain is an emerging technology now applied as a new transaction protocol with many innovative features such as decentralization, non-repudiation, irreversibility, data immutability, and transparency. As the product carbon footprint is involved in business behavior, the blockchain may bring a new opportunity or necessary change for the carbon footprint application [4, 5].

The two features of blockchain we focus on herein are decentralization and irreversibility. Decentralization means no central database will save the transaction data, and each transaction will be known to the public. Irreversibility means the information in the blockchain cannot be modified while synchronized universally.

Now the blockchain is mainly applied by banks for trade finance and cross-border payments. Other than financial field, blockchain can be implemented in any fields where agreement on shared state for decentralized and transactional data needs to be established [4].

If blockchain is accepted and used generally in the future, the carbon emission management is necessary to be enhanced to the next level because the carbon footprint may be then stored in the blockchain. For the decentralized feature of blockchain, the scattered information stored in the blockchain should be managed in one way that can be integrated and transformed for other aspects of carbon emission management. The framework is thus described, and the scenarios of carbon management are also discussed in the following sections.

2.2 The Framework

The framework illustrated as Fig. 2.1 includes three layers: the calculation layer, the blockchain layer, and the integration layer. This framework illustrates the connection of the data stream that the integration layer will retrieve the information from other two layers.

The calculation layer describes how an enterprise collects the data for carbon footprint calculation. There are two approaches happening in the layer: the traditional carbon footprint inventory and the automatic electronic data collection such as IoT (Internet of Things) technology. The data incorporate raw materials, energy and assisted resource consumption (water, electricity, fuel, or gas), and waste quantity.

After certified, the enterprise can claim the carbon footprint of the product that can be applied in trading, sale, or the demand of retailers by coding the carbon footprint in the blockchain. The blockchain layer provides three main functions: certification, consensus, and tracking. In theory, the data stored in blockchain is recorded and distributed that keeps the certification in each trading.

The information stored in the blockchain can open to the public to form a consensus if it is not encrypted. The consensus function is to raise the awareness of three types of stakeholders: the public, the industry, and the central or local

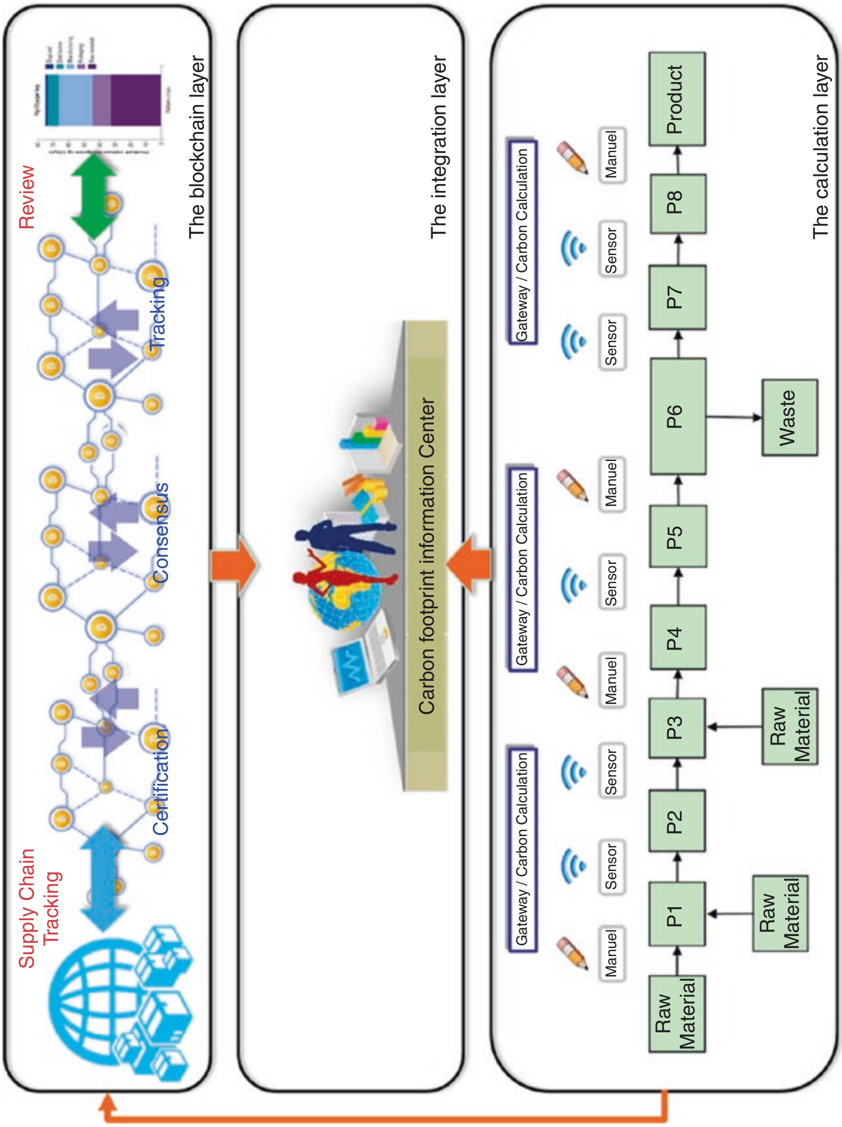

Fig. 2.1 The framework of the integration of carbon footprint and blockchain

governments. Once the carbon footprint is included in blockchain, the public, especially the environmental organizations, can search the information of the target products and adopt appropriate action to form the consensus of carbon reduction.

The integration layer herein is for retrieving the carbon footprint information of each enterprise via blockchain or the traditional reporting. When an enterprise needs to calculate the carbon footprint, it can search the information of the relevant parts of the target product if the carbon footprints of the parts are already recorded in the blockchain or reported in the database.

This database will try to retrieve or update the carbon footprint from the blockchain when it is renewed. In a certification process, the third party can use the database to speed up the process by the confidence the blockchain can provide. All carbon footprint information collected in the database is open to the public that makes the analysis and tracking possible.

In brief, the integration layer collects the scattered information from blockchain in an integrated and open database to provide the stakeholders the information they need.

2.3 The Carbon Footprint Online Database

The carbon footprint online database in Taiwan has been developed since 2013 [3]. The structure of the database is illustrated as Fig. 2.2. The database aims to provide the enterprise a calculation and storing tool for carbon footprint. It brings the benefits of the efficiency improvement of data management, the reduction of inventory cost and time, the promotion of carbon footprint inventory operation, and the enhancement of supply chain cooperation. Now the main companies have used this database such as China Airlines, Sino-American Silicon Products Inc., Taiwan Beer, and Cuprime Material Co., Ltd.

Illustrated in the aforementioned framework, the database connects the blockchain layer as another data source. The difference is the updating protocol that can connect to the blockchain-related technology used by banks and enterprise on commercial trading such as Corda [6] or Ethereum [7].

2.4 The Scenarios

2.4.1 Carbon Footprint Disclosure

In a traditional way, when an enterprise is requested to disclose the carbon footprint of the specific product, it will implement the carbon inventory process, and many relevant questionnaires and interviews arise that makes a tedious and time-consuming process.

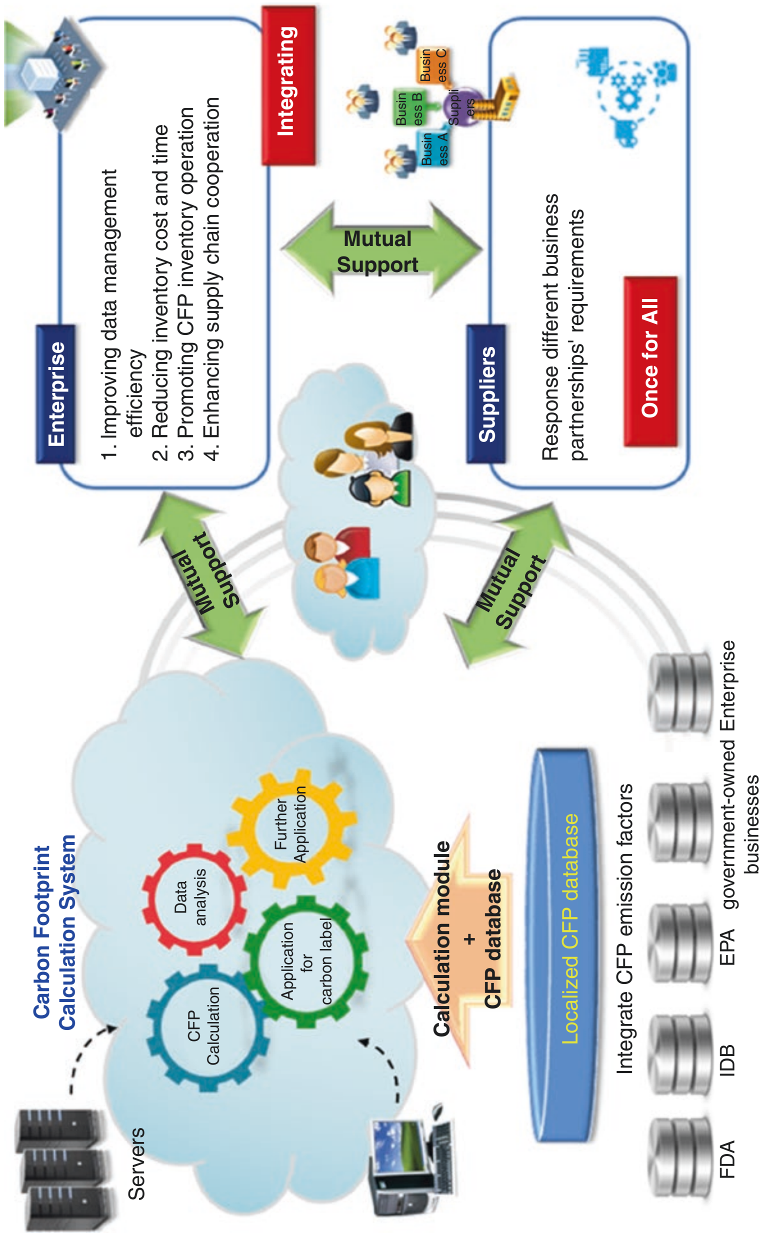

Fig. 2.2 The structure of the carbon footprint online database

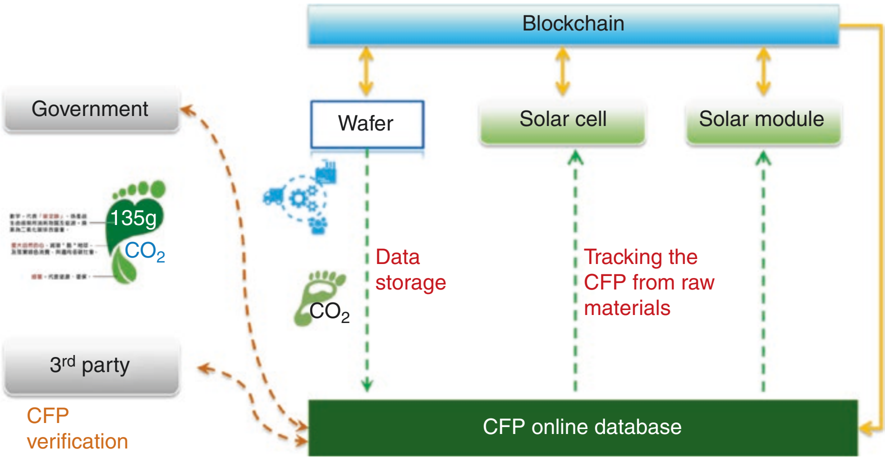

Fig. 2.3 The carbon footprint disclosure via the framework

Using this framework, as illustrated in Fig. 2.3, all companies can retrieve the certified carbon footprint for their target raw materials automatically. If the enterprise applies the IoT (Internet of Things), the certification will be enhanced more efficiently. After the certification and trading based on the blockchain, all the carbon footprint will be updated or added in the carbon footprint online database illustrated in the framework.

For third party audition, the institute can review the carbon footprint of the target product by the blockchain as a trustworthy source. The institute also can use the carbon footprint online database to benchmark of each part of the product if the carbon footprint information is existed.

2.4.2 Supply Chain Management

Supply chain management includes three types of stakeholders: the global or local industries, the government, and the environmental organizations. Their interaction is described as Fig. 2.4.

When the business of the enterprise is restricted by its buyer on the carbon emission issue, the enterprise can manage the carbon emission of the supply chain efficiently by using the framework. The enterprise can select its suppliers and raw materials with lower carbon footprint, while the carbon footprint is embedded in the blockchain and the carbon footprint online database update the relevant information constantly. Its buyer can trust the purchase process not only because the features of blockchain but also the carbon footprint online database that provide the tracking information if the buyer needs to review it.

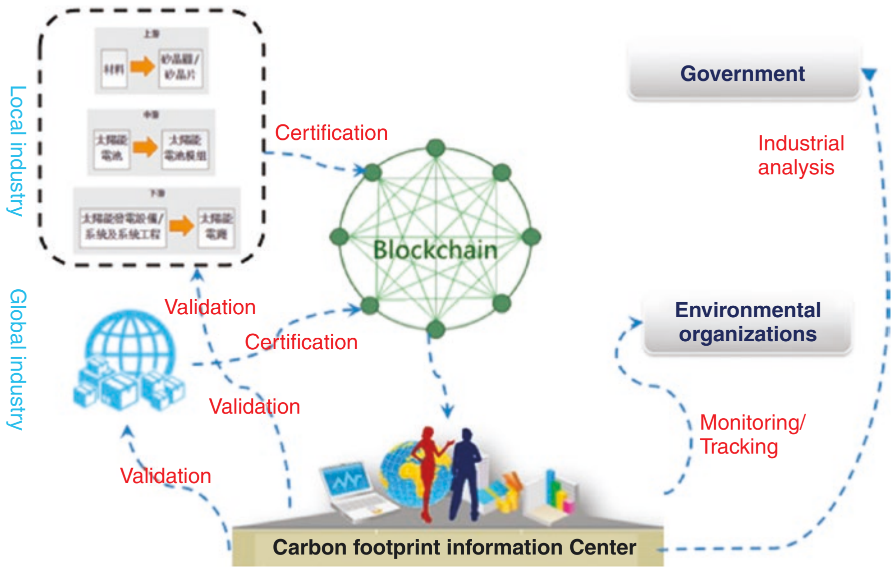

Fig. 2.4 The interaction of the management of supply chain using blockchain

This framework can also assist the government to make effective strategies to affect the whole industry. At first, the government can implement green procurement in itself to drive the low-carbon emission supply chain. When the carbon footprint and the blockchain are integrated more maturely, the government is able to evaluate and promote the target supply chain and the product comprehensively.

For environmental organizations, the framework is a convenient tool to monitor and track the carbon emission of the supply chains. It is easier for the environmental organizations to form a phenomenon to promote the low-carbon products in the country.

2.5 Conclusion

Now blockchain is a future technology that can provide a better and faster management tool in terms of carbon emissions and supply chain management by its feature as a distributed and irreversible database. When carbon footprint information is incorporated in the blockchain, it seems that the information is open to public, but it is not readable for the people without information technology expertise.

The stakeholders, i.e., companies, governments, and environmental organizations, still need a tool such as the carbon footprint online database aforementioned that can collect and integrate the relevant information to satisfy their demand for carbon footprint calculation, supply chain management, and the review of products.

By the credibility and efficiency the blockchain can provide, we believe the carbon emission management can be tracked, planned, and implemented in an easier and more systematic way in the future.

Above all, there are two main advantages of the integration of blockchain and carbon footprint information summarized: (1) The distributed information can be retrieved and integrated from transactions for governmental decision-making. (2) The industries can analyze the supply chain to find the bottleneck and the relevant strategies, and after the implementing the strategies, the industries can observe if the carbon footprints are improved in the long term. Besides the advantages, the technical issues will be the main challenges for the implementation of the framework in the future, such as which blockchain technology the financial system adopts, the multiple blockchain technologies integration when two or more technologies are adopted by different financial systems, data consistency for the blockchain, and the transformation of the carbon footprint online database.

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Chapter 3
Bayesian Estimation for the Reuse of Mechanical Parts Using Part Agents

Yoshinori Fukunaga, Yuuki Fukumashi, Atsushi Nagasawa, and Hiroyuki Hiraoka

3.1 Introduction

In recent years, it has become apparent that change in industry is necessary to achieve a sustainable society. To realize effective reuse of mechanical parts for sustainability, it is essential to manage individual parts throughout their life cycle. Manufacturers need to estimate the quality and quantity of parts to be returned for reuse when producing on a reuse basis [1]. However, due to the uncontrollable nature and unpredictable diversity of user behavior, it is difficult to predict the quality and quantity of secondhand parts. Moreover, product users have difficulty in properly maintaining various parts in the product. Addressing these considerations, we propose a scheme whereby a part manages itself and supports users' maintenance activities. Network agents have been developed that are programmed to follow the actual partner's part throughout the life cycle. These network agents are called "part agents" [2–9]. Part agents provide users with appropriate advices on reusing parts and promote circulation of reusable parts.

The deterioration of parts varies depending on factors in their usage environment such as temperature, as well as factors related to their usage levels such as frequency and intensity of use. However, the quantitative relationship between the occurrence of failure and those factors cannot be clearly determined owing to its probabilistic nature. To deal with this problem, a Bayesian network [10] is employed to capture the causal effects of the factors on the failures of parts [4–7].

Bayesian estimation is used to determine the probability of the occurrence of failure of a product, based on the probability of events that are caused by user's actions, and a system that informs the user about reuse of the product was proposed. We believe that it would be possible to use Bayesian estimation to propose

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appropriate behavior of the user based on expected values calculated from the evaluation of the life cycle of the product.

In this paper, to confirm that it can be applied to mechanical parts, we create a Bayesian network to estimate deterioration of mechanical parts.

The concept of a part agent is described in Sect. 3.2, wherein we explain the mechanism by which a part agent advises users on the reuse of parts. In Sect. 3.3, we explain life cycle simulation of parts. In Sect. 3.4, we describe the evaluation of reused parts using Bayesian network of example cases. We discuss the future issues in Sect. 3.5, and we conclude the paper in Sect. 3.6.

3.2 Part Agent System

A part agent manages all data about its corresponding part throughout its life cycle. This Scheme [3] assumes the spread of networks and high-precision RFID technology.

A part agent is generated in the manufacturing phase of core parts, when an RFID tag is attached to each corresponding part. The part agent identifies the ID of the RFID tag during the part's life cycle and tracks the part through the network. We chose to use an RFID tag for identification because RFIDs have higher resistance to smudging or discoloration than printed bar codes and are more likely to last the prolonged period of a part's life cycle.

Figure 3.1 shows the conceptual scheme of the part agent [3, 6, 9]. The part agent communicates with various functions within the network and collects the data necessary for the management of its corresponding part such as product design information, predicted deterioration of parts, logistic information, or market information. It also communicates with local functions on-site, such as sensory functions that detect the state of the part, storage functions for individual part data, and management and control functions of the product. Communication is established using information agents that are subordinate network agents generated by the part agents.

3.3 Life Cycle Simulation

Part agent requires a function to predict future state of the corresponding part in order to generate appropriate advices on the part for the user. For this purpose, part agent performs simulation of life cycle of the part based on acquired information [3, 8, 9].

Figure 3.2 shows a simple life cycle model that is used as an example in this paper. We define life cycle of part consisting of life cycle stages and life cycle paths connecting them. Circles represent life cycle stages that are produce, sell, use, repair, and dispose. Arrows represent life cycle paths.

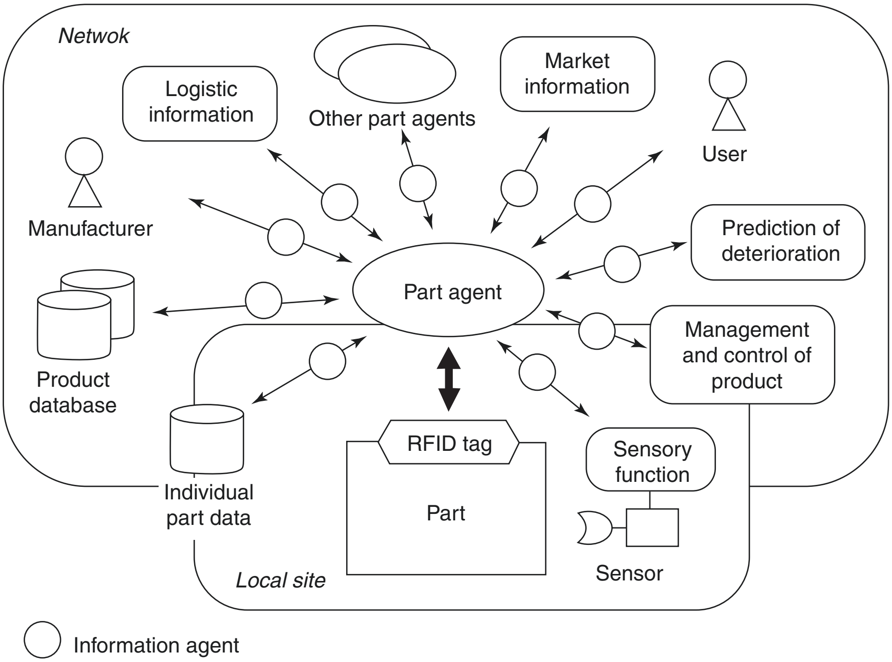
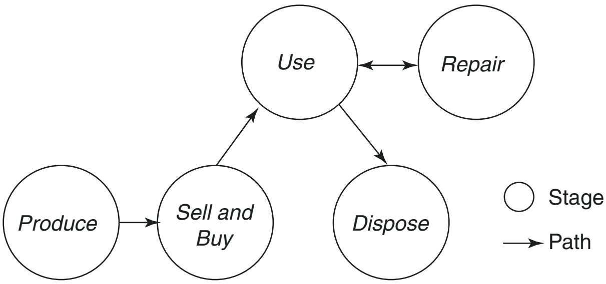


Fig. 3.1 Conceptual scheme of the part agent

Fig. 3.2 A simple life cycle model



Part agent expands the life cycle of the part into an expanded life cycle. It represents possible changes in the life cycle of the part over time. Figure 3.3 shows an example of an expanded life cycle of the life cycle of the part that is expanded starting from "use" stage. In the expanded life cycle, each expanded stage has properties that are profit, cost, and environmental load of the part, and each expanded life cycle path has probability for the part of taking that path.

Based on the information of thus expanded life cycle, part agent calculates the expected values for candidate stages starting from the current life cycle stage. Expected value is obtained by accumulating product sum of the values of stages and the probability of paths branching from the candidate stage.

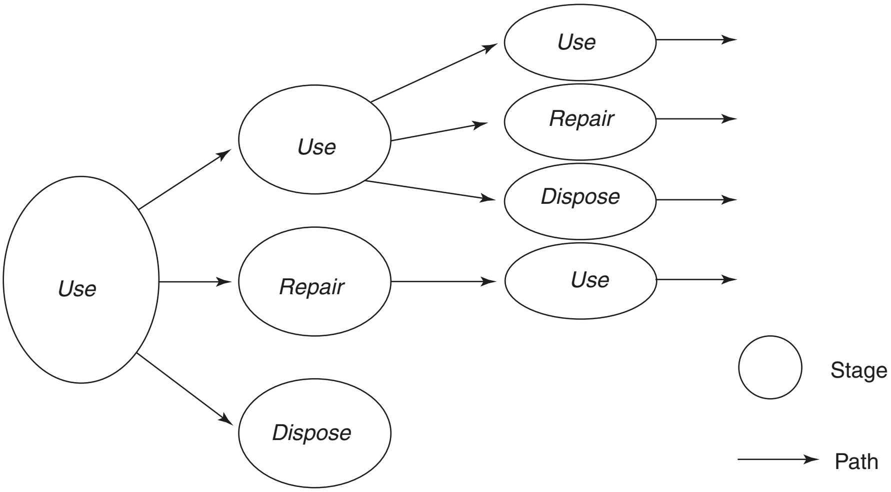


Fig. 3.3 Expanded life cycle model

The value, such as cost and profit, for a life cycle stage may be estimated based on the state of the part in the stage using calculations or through simulations of part behavior. However, it is difficult to estimate the probability attached to a life cycle path. In order to deal with this problem, we are planning the application of Bayesian estimation and Bayesian network that can estimate uncertain events as described in the following sections [6, 8, 9].

3.4 Evaluation of Used Parts by Bayesian Estimation

3.4.1 Overview of Experiment

The relationship between the operating conditions of parts and failure cannot be judged easily in most cases. For example, regarding failure of hard disk drives (HDDs), although the relationship of an operating condition (temperature) and failure has been shown to exist to some extent by an investigation of a Google company, the relationship has a statistical probabilistic nature; the cause-and-effect relationship between operating conditions and failure is not clearly established. Moreover, the difference in deterioration is also related to the type of HDD.

When parts are evaluated in consideration of consumers' characteristics, the decision on the employment of a product depends not only on the state of the parts detected by the part agent but also on the behavior of each consumer. The behavior of consumers is also stochastic.

To estimate the influence of factors on used parts, dependencies and causal relationships between variables are represented by a Bayesian network that is used to perform probability reasoning including uncertainty.

A system is verified by an example of simple parts [4]. The state of parts changes with consumers' operations, and the system deduces the machine part that requires repair as a result.

First, an experiment is performed with a simple causal model. Then the system is applied to a HDD.

3.4.2 Simple Casual Model

Figure 3.4 shows a Bayesian network representing simple causal relations among related events.

Two events in the network that can be observed are states 1 and 2 (Observed state 1, 2). Operations 1, 2, and 3 are input from the user. The network represents the following causal relations: Operations influence the occurrence of Defects 1 and 2. Defect 1 affects the occurrence of Observed state 1 and Defect 2. Defect 2 affects in turn the occurrence of Observed state 2 and Maintenance required.

We calculate and compare the probabilities of maintenance on a part with the occurrence of Observed state 1 and on a part with the occurrence of Observed state 2, P(M|Os1) and P(M|Os2), respectively, for consumers (Users 1 to 8) who have different prior probabilities on operations. The probabilities take a low probability of 0.10 and a high probability of 0.90 as shown in Table 3.1. Conditional probabilities are shown in Fig. 3.5.

Figure 3.6 shows the calculation results of the P(M|Os1), P(M|Os2), and P(M) for each user. A comparison between the P(M|Os1) and P(M|Os2) shows that P(M|Os1) is lower for Users 1,2,4, and 6 and P(M|Os2) is lower for Users 3,5,7, and 8.

Fig. 3.4 Representation of casual relations

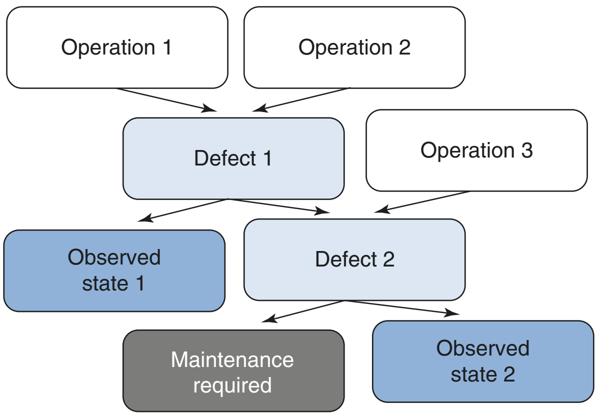


Table 3.1 Prior probability of users

	P(Op1)	P(Op2)	P(Op3)
User 1	0.1	0.1	0.1
User 2	0.1	0.9	0.9
User 3	0.1	0.9	0.1
User 4	0.1	0.1	0.9
User 5	0.9	0.1	0.1
User 6	0.9	0.1	0.9
User 7	0.9	0.9	0.1
User 8	0.9	0.9	0.9

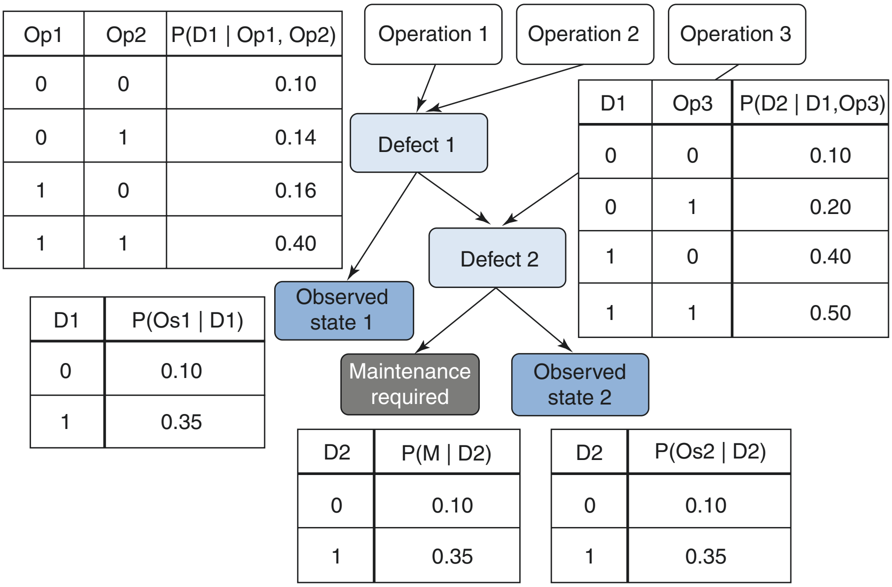


Fig. 3.5 Conditional probability table

This means that when we have a reused part A with occurrence of Observed state 1 and a reused part B with occurrence of Observed state 2, the probability of need for repair would be low if Users 1, 2, 4, and 6 use the reused part A and Users 3, 5, 7, and 8 use the reused part B.

The probability of the occurrence of Maintenance required varies, depending on a combination of the consumer's usage levels and the state of the part. As shown in this example, you can estimate an appropriate used part that fits with a consumer using the Bayesian network.

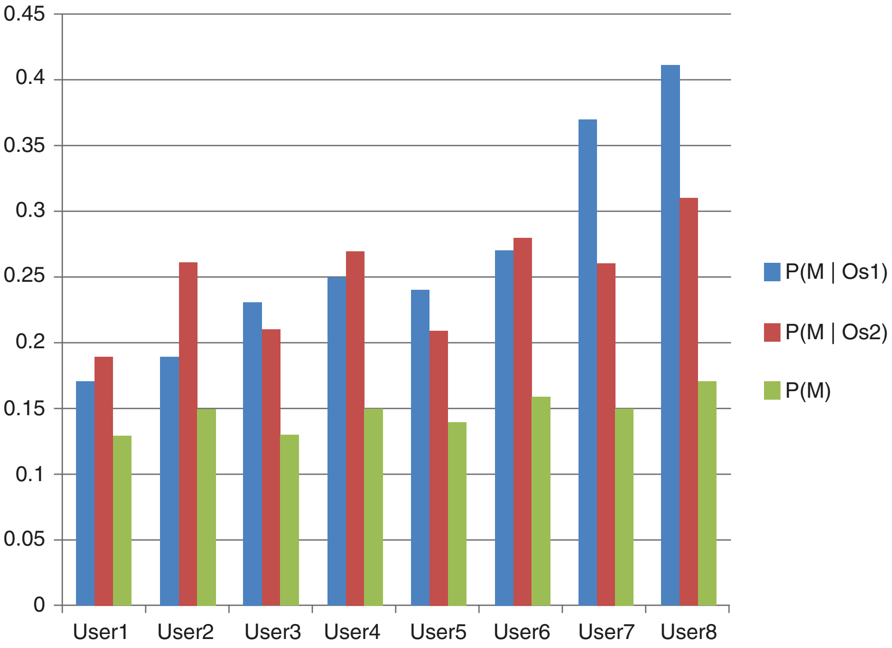


Fig. 3.6 Posterior probability of maintenance required

3.4.3 Application to HDD Model

We created an example to evaluate the applicability to various situations using a Bayesian network different from the above example. We envision the utilization of the Bayesian network within the part agent system we are developing. The target is deterioration for HDDs. Figure 3.7 shows a Bayesian network representing deterioration relations. The events from A to G in Fig. 3.7 are Bad environment, High temperature, Vibration, Decrease of magnetic force, Decrease in reading speed, Abnormal sound, and Partially of bad sectors, respectively. Input events are A, B, and C, unobservable events are D and E, and observable events are F and G.

Assume that the prior probabilities of A to C and 8 users are same as in the previous example shown in Table 3.1. When Abnormal noise occurs, we calculate the probability of occurrence of events D and E that cannot be detected, P(D | F) and P(E | F). The conditional probabilities are shown in Fig. 3.8. The results are shown in Fig. 3.9.

From the results in Fig. 3.9, we found that when an abnormal sound was heard, what happens in the HDD is different by the user. Users 1, 2, 3, 4, and 8 are more likely to have a decreasing in reading speed, and users 5, 6, and 7 have a high pos-

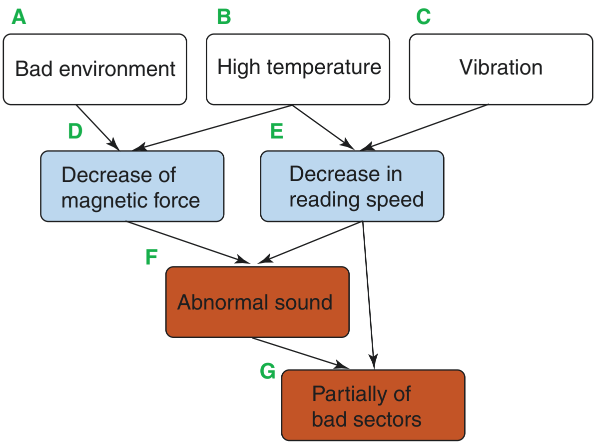


Fig. 3.7 Representation of deterioration relations

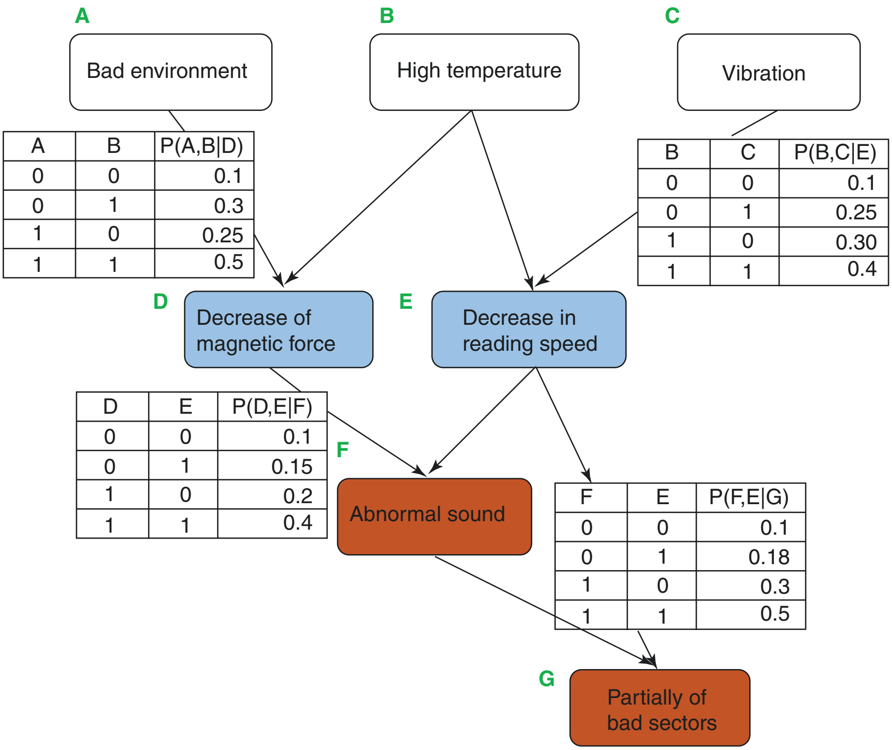


Fig. 3.8 Conditional probability of deterioration

sibility that a decreasing in magnetic force occurs. Hence, we can predict the occurrence of unobservable events, which is useful for users when they reuse the HDDs.

From the two examples, it was found that it is possible to predict occurrence against malfunction and undetectable event. We think that these things can be incorporated into life cycle simulation. The idea is described in the next chapter.

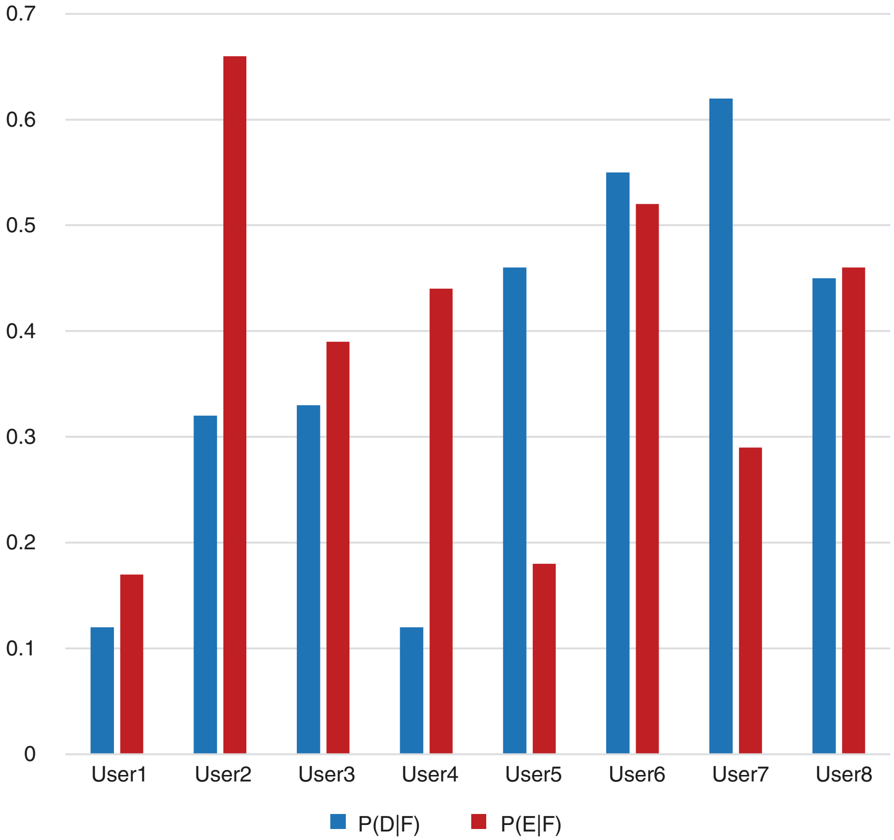


Fig. 3.9 Posterior probability of abnormal sound

3.5 Discussion on Future Issues

As described in Sect. 3.3, the probabilities of life cycle paths, i.e., transitions between life cycle stages in the expanded life cycle, are required in order to calculate expected values in the life cycle simulation. We consider the method of Bayesian estimation described thus far is applicable to obtain these probabilities.

Figure 3.10 describes a proposed scheme how probability of a life cycle path is calculated using Bayesian estimation in the life cycle simulation. Because a life cycle stage represents a specific state of the part, different life cycle stage is characterized by different inputs or observed events relating to the part. In the figure, these events are depicted as small squares in the circle representing a life cycle stage. Hence, probability of the path starting from a life cycle stage, namely, the probability of the occurrence of an event that leads to the transition to another stage, can be estimated using Bayesian method based on the set of events existing in the stage.

We are developing a life cycle simulation based on this scheme.

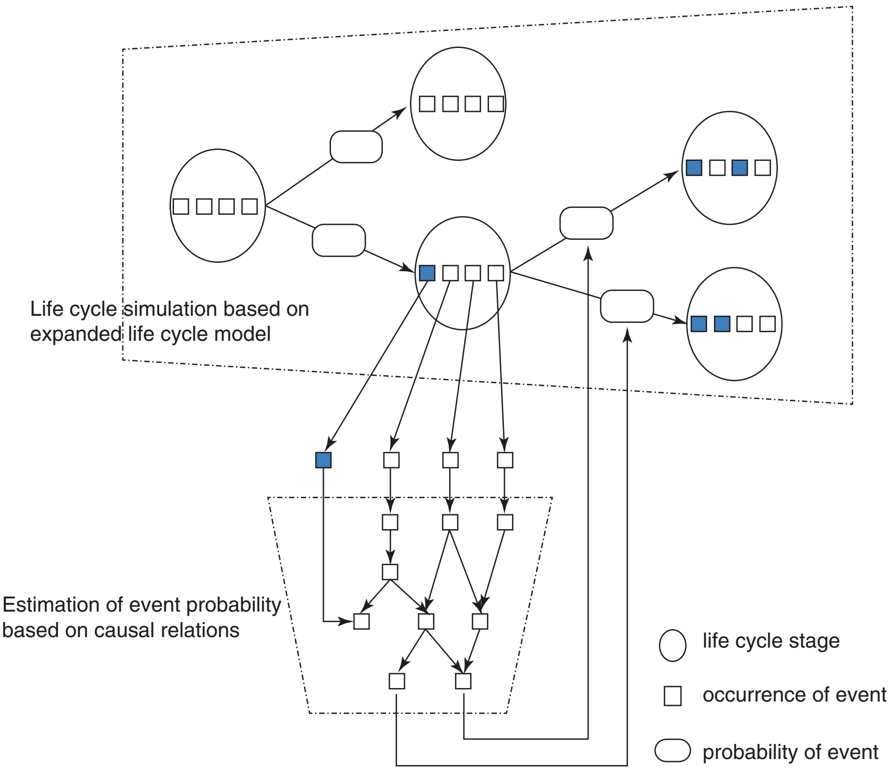


Fig. 3.10 Posterior probability of abnormal sound

Another important issue for using Bayesian network is the creation of the appropriate network including conditional probabilities. Methods are proposed in the literature that creates a Bayesian network based on a large amount of observed data. We think it is not practical as we may not expect large amount of data on deterioration of specific part. For this reason, we are planning the updating of existing causal network based on observed events. We still have to solve many issues to develop a system that updates the causal network such as the interval of renewal and the criteria for the updating.

3.6 Conclusion

In this paper, a proposed method is described that applies Bayesian estimation for prediction of the state of mechanical parts. Experimental simulation is performed successfully for the deterioration of HDD. Future works are discussed including integration with life cycle simulation and updating a Bayesian network representing causal relations among events.

Acknowledgment This work was supported by JSPS KAKENHI Grant Number 15 K05772.

Appendix Bayesian Network

Predicting failures of a part is an important function of the part agent to support the effective reuse of the part. However, it is also a difficult issue due to its probabilistic nature caused by its dependency on the level of usage by the consumer and on environmental conditions. To deal with this problem, we have applied an estimation method based on a Bayesian inference.

Consider the causal relation exists between events *A* and *B* where event *A* affects event *B*. The probability of the occurrence of an event *A* before the occurrence of related events is called the prior probability of *A* and is denoted by *P*(*A*). The probability of the occurrence of an event *B* after the occurrence of event *A* is called the conditional probability and is denoted by *P*(*B*|*A*). If we know the prior probability *P*(*A*), *P*(*B*), and the conditional probability *P*(*B*|*A*), we can estimate *P*(*A*|*B*), namely, the probability of the occurrence of *A* when you know event *B* occurred, by Bayes theorem represented by the following Eq. (3.1):

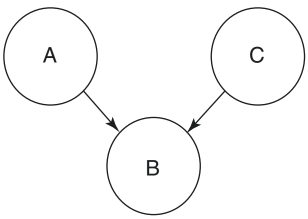
$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{3.1}$$

This probability is called the posterior probability. It is an improved estimation of the probability of the occurrence of an event based on the knowledge of the occurrence of related events.

When multiple events affect an event, the causal relations among the events form a network. It is called a Bayesian network that is represented by a noncircular directed graph where each node is equipped with a table representing the conditional probabilities of related events called the conditional probability table.

Figure 3.11 shows a simple example of a Bayesian network. The graph shown in the left of the figure depicts that the probabilities of events A and C affect the occurrence of event B. The conditional probability of an event B or P(B|A,C) varies with the occurrence (shown as 0 and 1 in the table) of events A and C, which is summarized in the conditional probability table shown in the right of the figure

In a Bayesian network, there are three types of events that are input events, observable events, and unobservable events. The probability of the occurrence of unobservable events in the network can be estimated using Bayes theorem described



A	C	P(B|A,C)	
		0	1
0	0	p11	p21
0	1	p12	p22
1	0	p13	p23
1	1	p14	p24

Fig. 3.11 An example of Bayesian network with conditional probability table

above if we have conditional probabilities of events and gather evidences on the occurrences of input events and observed events.

We represent probabilistic causal relationships between failures of a part and their factors using this Bayesian network in order to obtain the probability of the failures.

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Chapter 4
Turning the CPPS of the World’s Largest Automotive Research Factory ARENA2036 into a Data Gold Mine for Eco-Design

Daniel Wehner, Max Hossfeld, and Michael Held

4.1 Introduction

4.1.1 ARENA2036: Future Mobility and Production

ARENA2036 is the world’s largest research factory dedicated to the future of mobility and its creation. It serves as a key enabler for the European Automotive Industry by disrupting and redesigning the entire value chain. The ARENA2036 campus therefore not only incorporates state-of-the-art workplaces for all kinds of knowledge-based work but also a flexible full-scale model factory.

Given the long-term horizon of ARENA2036’ research program—viz., the year 2036, i.e., the 150-year anniversary of the automobile—sustainability is at the very heart of its mission. Fully aware that unlocking the disruptive potential of engineering science comes along with radical changes, ARENA2036 not only focuses on shaping the future of mobility and of its creation but also addresses, analyzes, and shapes the future of man in its workplace. Taken together, this means that ARENA2036 accepts the social, environmental, as well as scientific responsibilities that come with the challenges stemming from rapid technological development and change, by providing holistic perspectives and answers on future questions. In order to integrally respond to these challenges, issues regarding data collection, handling, and storage have to be resolved first, before turning to an actual life cycle assessment

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(LCA) that allows addressing all aspects of future products along the lines of so-called eco-design activities.

So as to provide such an answer, we will subsequently first localize the CPPS concept within the framework of current research, before turning to further considerations regarding its relation to eco-design more generally. Finally, we will discuss how CPPS as a high-quality data provider fosters sustainability with regard to the product as well as to its production by integrally encompassing the entire value chain.

4.1.2 Sustainability of Personalized Mobility: Opportunities, Challenges, and Risks

Personalization offers great opportunities to tap new potentials for sustainability by tailoring products to the actual demand of individual users instead of designing for non-existing average users or user groups. In the automotive field, this can be illustrated with reference to lightweight design. Even though the production and processing of lightweight materials are often associated with an increase in costs and environmental impacts compared to standard materials [1, 2], lightweight designs offer great net savings regarding costs and environmental impacts for cars with high mileage. However, such an approach requires the availability of low-cost yet high-quality baseline data regarding trends in user demand, specific individual product use, and end-of-life characteristics as well as reliable predictions regarding the impact of design decisions on the manufacturing of a high number of individual products from cradle to gate. Therefore, strong analytics are required to extract high-value insights for deployment in future product development activities from historic manufacturing data. Failing to meet these requirements bears the risk of out-of-control life cycle environmental and cost impacts, hence failing to tap the sustainability potentials through product personalization.

4.1.3 Demand for Improved Eco-Design Approaches

Today, a great number of methods and tools are already established in various industries, in order to facilitate eco-design activities. In the field of life cycle assessment of environmental impacts, the standards DIN EN ISO 14040 [3], DIN EN ISO 14044 [4], or VDI 4800 [5] provide generally appropriate methods. Life cycle costing and social life cycle assessment [6] supplement LCA with economic and social aspects. Typical for these methods is their focus on the retrospective description of life cycle impacts. Integration with methods from the field of advanced analytics has so far only been addressed in a small number of specialized cases even though many user-friendly advanced analytic tools have been available for several years [7]. Well-established tools for LCA-based eco-design are the GaBi Software [8], Umberto [9], or SimaPro [10] as well as many other more specialized eco-design tools. For example, the easy-to-use web application ENDAMI [11] can be considered a forerunner in this group. It supports aircraft developers with a direct feedback regarding the environmental impact of particular design choices and made a major progress in the automation of the analysis of sustainability KPIs. However, the integration of product- and plant-specific data in ENDAMI still requires significant manpower for data preparation and modeling. Moreover, ENDAMI does not feature capabilities in the field of advanced analytics or options allowing easy integration with respective applications. Further advances in the field of eco-design approaches and tools have been demonstrated with regard to integration of LCA in product life cycle management [12, 13].

With regard to tapping sustainability potentials by way of personalization, the abovementioned approaches show major deficiencies in the following areas: (1) failing to integrate or to efficiently integrate with detailed information from in-house manufacturing operations, (2) widely relying on averaged and imprecise input information with regard to the to be supported eco-design cases, (3) requiring input data which only becomes available when most design decisions are already frozen (e.g., details on manufacturing), and (4) no or limited capabilities to integrate with methods and tools in the field of advanced analytics.

4.2 Development-for-Life-Cycle-Sustainability in the Age of Data Abundancy (DfLCS)

4.2.1 Concept Overview

The concept "Development-for-Life-Cycle-Sustainability in the age of data abundancy (data-abundant DfLCS)" consists of the following three elements targeted at providing the various stakeholders involved in the product development process with application appropriate, reliable information to improve the sustainability of their developments: (1) the high-quality data foundation provides the basis of the concept and ensures the reliability of information services; (2) with advanced sustainability analytics, the necessary insights to support a particular application are extracted; and (3) application-tailored information services for decision support ensure seamless integration into the development process by providing comprehensible information on sustainability-related decision consequences without significant additional effort for decision makers.

Figure 4.1 illustrates the concept. Its elements are further described in the following chapters.

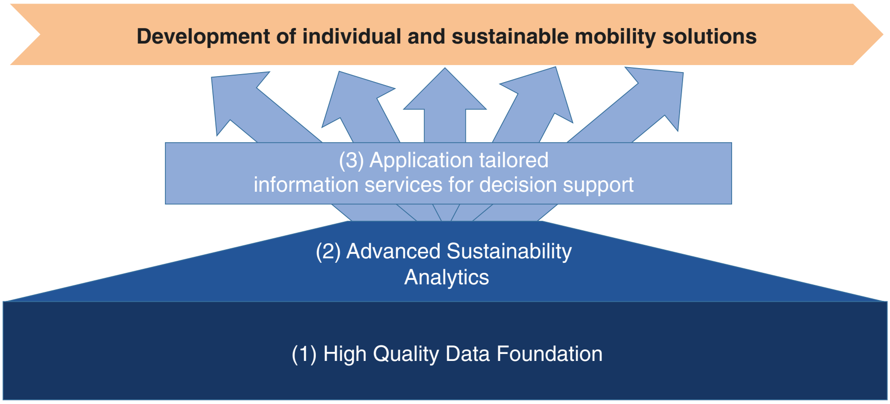

Fig. 4.1 Data-abundant DfLCS concept overview

4.2.2 High-Quality Data Foundation

High baseline data quality is essential for the reliability of the targeted sustainability decision-support information services. The data-abundant DfLCS concept relies on high-quality baseline data with regard to the activities along the whole life cycle of products as defined in the international standards for life cycle assessment (LCA) DIN ISO 14040/14044 [3, 4] and detailed in the ILCD handbook [14]. These activities comprise the manufacturing processes to create the product from cradle to gate, the operation of the product including maintenance, and the repair activities as well as end-of-life operations for recycling or disposing the different elements the product is composed of. In LCA, mass and energy balances for each of these activities are elaborated. The mass and energy flows of the activities are further distinguished in elementary flows (those that are exchanged with the environment) and technical flows (those that are exchanged between the different activities). While elementary flows are used for the assessment of environmental impacts, technical flows are necessary in order to build quantitative system models describing the life cycle of products as well as for the evaluation of life cycle costs. System models are typically distinguished in the foreground and the background system. The foreground system comprises the activities that have to be addressed with specific data in order to meet the goals of the LCA study or that offer to be actively managed. These are typically the activities of the company commissioning the LCA study and may include tier-1 operations. The remaining activities are allocated to the background system and typically addressed with averaged data aggregated in cradle-to-gate datasets, which can be found in commercial databases such as the GaBi or ecoinvent database.

The data-abundant DfLCS concept enhances the LCA approach to meet the requirements for creating the high-quality data foundation necessary for decision support in the development of individual mobility solutions. Figure 4.2 illustrates

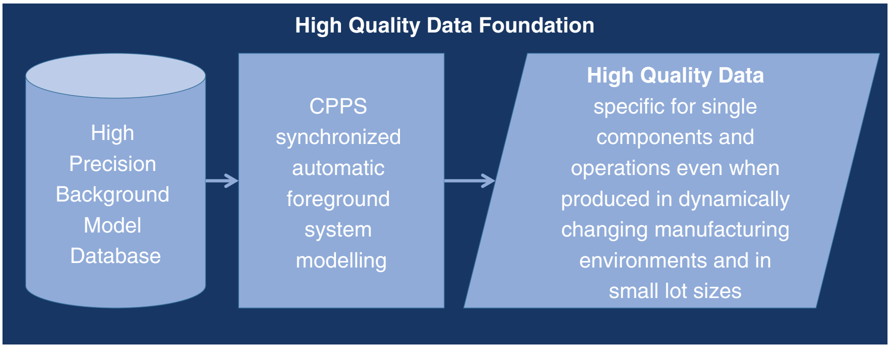

Fig. 4.2 Concept for generating the high-quality data foundation necessary for data-abundant DfLCS

this enhanced approach. The enhancement consists of several elements, which are described in the following sub-chapters.

4.2.2.1 Increased Specificity of Assessment Results

The first element is increasing the specificity of the assessment results. This means that the material and energy flows of activities as well as the environmental impacts associated with these flows are tracked specifically for single components and operations even when produced in dynamically changing manufacturing environments and in small lot sizes. Moreover, the assessment results are enriched with manufacturing and design metadata. This is essential for gaining meaningful results through advanced sustainability analytics (see Chap. 4.2.3) that offer high added value when deployed in decision support (see Chap. 4.2.4), e.g., identifying processing conditions or design aspects that are associated with poor environmental performance or high costs. Additionally, the specificity of use and end-of-life data has to be increased. In this regard, ARENA2036 cooperates with the "High-Performance Center Mass Personalization" where this aspect is extensively addressed. It is therefore not further detailed in this publication.

4.2.2.2 CPPS Synchronized Automatic Foreground System Modeling

While the effort for manual modeling of the foreground system by an LCA expert has been acceptable for mass production—where one LCA result was good enough to describe up to hundred thousands and millions of identical products using the same production steps and processes—it is intolerable when results specific for small lot sizes or even individual products are required. The data-abundant DfLCS concept addresses this requirement by automating the foreground system modeling through synchronization with the CPPS and the associated data storage of the ARENA2036 research factory, which serve as a hub to link environmental and cost information with manufacturing and design data.

Storing and transferring data along the value chain are part and parcel of the ARENA2036 project Digital Fingerprint. The core idea is to describe and improve each process step by employing information from all steps of the process: beginning with the first idea, continuing with design, and manufacturing all the way to in-service and end-of-life data. Hereby, the product itself becomes an industry 4.0 component due to its integrated intelligence by way of using sensors and automated interpretation. Such smart structures are able to exactly know and analyze their performance over their life instantly, thus being transferrable as real-field data and as such usable for quantification steps such as simulation. This opens possibilities like an automated product evolution by using in-service data or the improvement of the manufacturing process by monitoring the product during its creation. Vice versa, an LCA for each product itself can be done autonomously based on the stored information of each process step.

The CPPS approach establishes the foundation for closing the optimization loop and achieving a production system, which permanently operates at the optimal operating point. The LCA yields knowledge regarding current production performance of the entire production chain. This knowledge can be used for a holistic optimization of the entire production system, if the production system is built as CPPS. In traditional manufacturing systems, many process sequences are defined in hardware. The behavior of subsystems is defined centrally in control units such as PLCs. The effects of adapting these global control laws on the entire system performance are hard to assess as they affect different components. On the contrary, the CPPS is a software-defined manufacturing system whose behavior emerges from the interplay of smart products and production assets. As control functionality is encapsulated in the smart products and production assets, the results of the LCA can be utilized for optimization of the value chain with minimal interference on other components and processes. Furthermore, knowledge can be continuously aggregated in these components through machine learning leading to a continuous improvement of their performance. This means that local decision laws and their decision parameters evolve continuously over the life cycle of the employed technologies and assets.

4.2.2.3 High-Precision Background System Model Database

In order to expand the system boundaries of the assessment to the entire life cycle, the foreground system results need to be supplemented with appropriate background system data. While averaged background system data (typically averaged for product groups produced in the year prior to publication) is available for a wide range of commodities in commercial LCA databases, studies like [15–17] have shown a great variability of results (up to several hundred percent) depending on the exact conditions the commodities are produced in.

As these boundary conditions are rapidly changing (e.g., due to the shift toward electricity production from renewable energies, improvement in manufacturing technology, etc.), available background data is neither appropriate to support development decisions that concern production—which may lie up to several years in the future nor to tap optimization potential in the manufacturing network beyond a company's own system boundaries (e.g., considering locations and technological capabilities of suppliers and service providers). Therefore, the target of the data-abundant DfLCS concept is the development and implementation of a high-precision background system database. The approach builds on mass and energy flow models for the manufacturing of products from most sectors of industry that were created by the department life cycle engineering of the University of Stuttgart in almost 30 years of intensive research on product environmental impacts. Based on the thorough technical understanding of production systems, the approach foresees enhancing these models with submodels regarding the future development of the key technologies of a production system. Furthermore, the background system models are to be enriched with market and in-house supplier data (e.g., from the International Material Data System [18]) to properly reflect the breadth of commercially available commodities.

Figure 4.3 shows the prototypal application of this approach on the example of commercially available titanium ingots.

For the analysis, the following elements were integrated to create the high-precision background system: (1) material and energy flow models for the cradle-to-gate production of titanium alloys including the production of master alloys, (2) data on the composition of commercially available titanium ingots from the ASM Alloy finder [19], (3) country-averaged models for electricity production from the GaBi database including predictions on the developments of key electricity grid mixes from today until 2050 [8].

By integration of these models, about 500 k cradle-to-gate production system models of commercially available titanium inputs were computed and assessed for GWP potential. No quantities for the GWP are given as the purpose of this prototypal application is to demonstrate the general capability for generating high-precision background data.

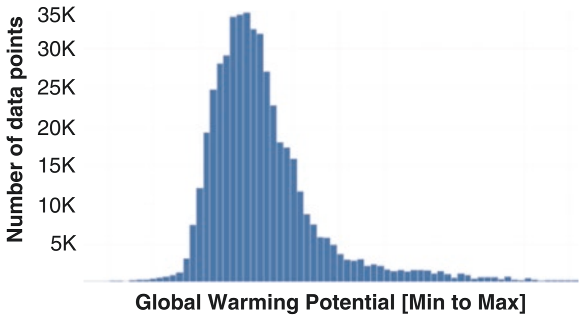

Fig. 4.3 Relative global warming potential (GWP) of commercially available titanium ingots

4.2.3 Advanced Sustainability Analytics

As shown in the previous chapter, increasing the specificity and precision of the assessment of production systems can easily lead to multimillion assessment results (e.g., the titanium ingot would only be one of the various inputs to a production system operating in varying conditions). Therefore, traditional, manpower-intensive interpretation of single assessment results is no longer viable for data-abundant DfLCS. In consequence, the data-abundant DfLCS employs the methods and tools commonly applied in the field of diagnostic and predictive analytics [20] to extract the necessary insights for deployment in decision support. Thereby diagnostic analytical methods (e.g., cluster analysis, drill-down, etc.) are used to understand sources and reasons for unfavorable environmental or economic behavior based on the mostly historic data of the high-quality data foundation. To make the gained results readily deployable in decision support, predictive analytics are used to train algorithms (e.g., using classification or regression algorithms) to predict potentially unfavorable consequences of design decisions. In cases with very sophisticated baseline data, the training of prescriptive algorithms (e.g., suggesting most sustainable design options based on the description of a design problem) may prove a viable option for deployment. For training predictive or prescriptive models, the supervised learning scheme shown in Fig. 4.4 is followed.

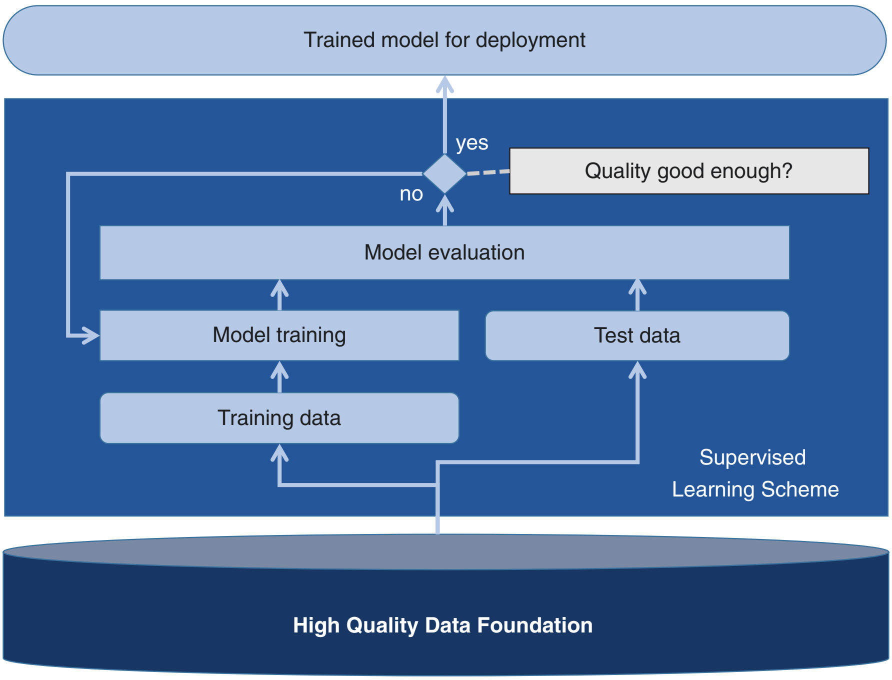

Fig. 4.4 Supervised learning scheme employed in data-abundant DfLCS

Training data is used to identify correlations between selected attributes and the so-called label (the attribute the algorithm/model is to predict). Depending on the targeted deployment (see Chap. 4.2.4), the label may be an indicator describing the environmental or cost impacts of decision options or key instantiating data inputs to compute indicators using the underlying data models of the high-quality data foundation (e.g., predicting information on the most likely pursued process routes for manufacturing as instantiating input to integrate existing mass and energy flow process models to a production system). Sources for correlating attributes are preferably those that are directly associated with the decisions to be supported. Therefore it is necessary to enrich the assessment results of the high-quality data foundation with respective design and manufacturing metadata (see Chap. 4.2.2).

The test data is used to evaluate the predictive quality of the trained algorithm by comparing the predictions of the trained algorithm to the actual results in the test dataset. If the results of the *model evaluation* do not meet preset standards, changes to model training (using alternative algorithms, algorithm settings, and/or training and test data) may be tested for achieving higher-quality results. If the model evaluation delivers satisfying results, the model is ready for deployment in sustainability-related decision-support information services (see Chap. 4.2.4).

4.2.4 Application-Tailored Information Services for Decision Support

Supporting the various stakeholders involved in the major product development decisions to create more sustainable product solutions is the ultimate goal of the data-abundant DfLCS approach. While the DfLCS elements "high-quality data foundation" (see Chap. 4.2.4) and "advanced sustainability analytics" (see Chap. 4.2.3) are predominantly focused on the necessary reliability of the decision-support information, the aspect of "application tailoring" addresses the issue of seamless integration of gained insights INTP product development. This requires efficient generation of supporting information without adding significant effort for decision makers. Moreover, results need to be communicated in a comprehensible way for the decision maker. Both aspects highly depend on the nature of the decision (e.g., which type of information is readily available at the point in time when a decision is taken or prepared, the importance of a decision, the available budget for its preparation, etc.) as well as the personal preferences of the decision maker (e.g., preference regarding workflow, technical units, etc.). Therefore, it is essential to build the decision-support information services on a solid understanding of the business context of the decision. The Cross Industry Standard Process for Data Mining (CRISP-DM) provides the basic methodology for building up such data-driven information services based on sophisticated business understanding. It is commonly used in projects that are targeting to create business value from big data. The methodology of the CRISP-DM is structured in the following steps: (1) business understanding, defining goals and requirements as well as the deduction of the analytical problem definition; (2) collecting data and understanding the needs for data preparation; (3) data preparation, generating the datasets as necessary for modeling; (4) modeling, application of modeling techniques; (5) evaluation by comparing results with the requirements; and (6) deployment of the results.

The data-abundant DfLCS concept builds on this methodology following the approach suggested by [21] who interpreted the CRISP-DM standard for LCA-related problems in the context of industry 4.0. For the implantation of the data-abundant DfLCS concept in the context of ARENA2036, the methodology of the CRISP-DM is employed as follows:

Business understanding (1) is gained by involving key players along the whole automotive value chain, such as Daimler, Bosch, BASF, HP, Siemens, or KUKA. This allows covering a broad range of development decisions and roles.

The *CRISP-DM steps (2) to (5)*, namely, data collection, understanding, preparation, and modeling, provide a wide range of generally useful advice (e.g., selecting problem appropriate algorithms) which is used in support of the creation of the high-quality data foundation (see Chap. 4.2.2) as well as for implementing advanced sustainability analytics (see Chap. 4.2.3).

For *deployment of the results (6)*, decision-support information services are used. These information services are integrated with the applications the supported users routinely work with when preparing or taking the decision supported by the information service. This approach is illustrated in Fig. 4.5 [22].

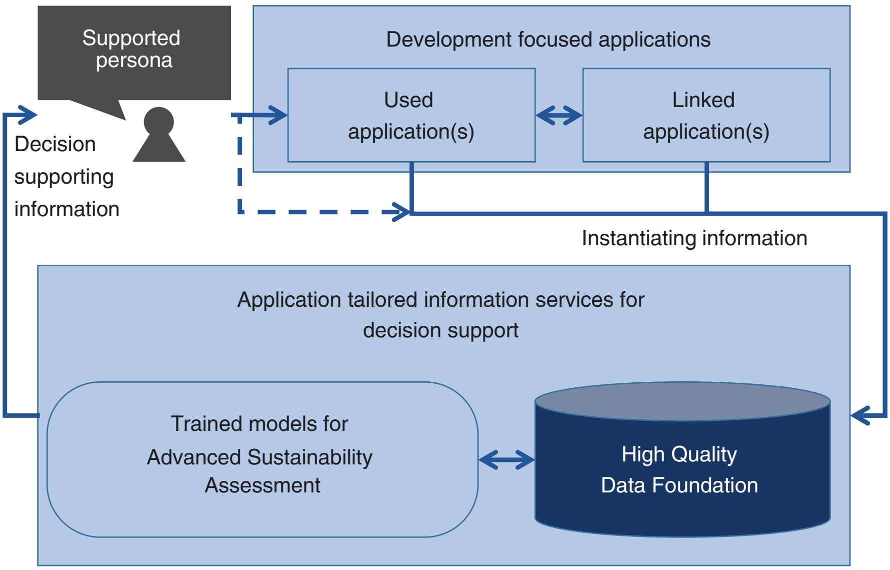

Fig. 4.5 Data-abundant DfLCS approach to deploying application-tailored information systems for decision support

In this approach, the information for decision support is provided by an application-tailored information service. Depending on what delivers the best results for a particular decision-support case, the information services are built from the trained models for advanced sustainability assessment (see Chap. 4.2.3), particular elements of the high-quality data foundation (see Chap. 4.2.2), or a combination of both, trained models and elements of the data foundation (e.g., using an algorithm to instantiate a mass and energy flow model of the data foundation). In order to ensure a minimum additional effort solution, the instantiating information for the information service itself should preferably be provided by the application the supported user uses anyways in preparing the decision (e.g., a CAD software). Hence, only minimal additional user input is required, if unavoidable (indicated by the dashed line in Fig. 4.5).

Additional instantiating information should rather be provided by linked applications instead (e.g., databases containing material or supplier information). Such an integrated approach requires a highly flexible IT architecture that allows a quick and safe connection of different applications. The IT architecture employed in ARENA2036 uses a layered approach spanning from computational heavy-lifting carried out in data centers to fast and lean computational resources physically located on the shop floor. It allows the generation of encapsulated cells connecting service providers and service users while protecting data of both stakeholders against third parties. Services can be deployed dynamically in the layered architecture. This allows locating services in the spots where an optimum of computational resources and latency can be achieved. This deployment of local control and decision laws is vital for the realization of the decentralized CPPS approach. In this way the seamless integration in the development workflows as well as availability of the required input information to deploy the data services is ensured.

4.3 Conclusion

ARENA2036 is the world's largest research factory dedicated to shape the future of mobility and its creation, accepting the social, environmental, as well as scientific responsibilities associated with this challenge. Pivotal to this challenge is tapping new potentials for sustainability by tailoring products to the actual demand of individual users. With regard to tapping these potentials, current eco-design approaches and tools, however, show major deficiencies in the areas of data quality, the effective use of advanced analytics, and the seamless integration of insights in product development. Therefore, this paper introduced the concept of data-abundant DfLCS as a means to integrally respond to the challenge of overcoming these deficiencies. Addressing the data quality issue, the fundament of the concept is formed by a high-precision database, directly linked to the detailed in-house manufacturing information from the CPPS and the associated data storage of the ARENA2036 research factory. This does not only enable the production of personalized, functionally fully integrated, autonomous, and crashless lightweight vehicles. It also turns the factory itself into a data gold mine for eco-design by delivering high-quality manufacturing data, specific for single components and operations, even when produced in dynamically changing manufacturing environments and in small lot sizes. Moreover, the concept showed how high-precision results also for upstream (supply chain) and downstream (use phase, end-of-life) processes are ensured by tapping on the achievements of almost 30 years of intensive research on the environmental impacts of all kinds of products at the department life cycle engineering of the University of Stuttgart. Furthermore, the concept showed how, based on the high-quality data foundation and the use of advanced analytics, high-value information services can be created and seamlessly integrated along the whole life cycle of products—from major direction giving strategic decisions via early and detailed design to production planning, optimization, maintenance, and recycling.

4.4 Outlook

While eco-design in the age of severe data scarcity had to follow the paradigm of limiting the need for gathering and managing information to the absolute minimum necessary to gain basic insights, ARENA2036 embraces the age of digitization with implementing the concept for data-abundant design for life cycle sustainability. By the involvement of key players from science and along the whole automotive value chain, such as Daimler, Bosch, BASF, HP, Siemens, or KUKA, the Arena2036 concept ensures rapid transfer from research to practical application in industry. With the implementation of the data-abundant DfLCS concept in the full-size production facilities of ARENA 2036 and by making use of the latest production technology and industry 4.0, it will be demonstrated how the concept caters to the industry demand for the high-quality data foundation necessary to manage the increased complexity in product design and manufacturing, which goes along with capitalizing on digitization by addressing individual customer wishes with personalized production. While the data-abundant DfLCS concept was developed for and will be implemented in the context of personalized vehicle production, its central elements, the CPPS-driven gathering of high-precision data, the use of advanced analytics to gain insights, and the solutions for seamless integration of insights into product development are relevant for any complex product manufacturing industry progressing toward personalization.

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Chapter 5
Between the User and the Cloud: Assessing the Energy Footprint of the Access Network Devices

Nils F. Nissen, Lutz Stobbe, Nikolai Richter, Hannes Zedel, and Klaus-Dieter Lang

5.1 Introduction

The energy consumption of telecommunication networks and data centers is a considerable cost factor and of growing environmental concern. The 2015 study by Stobbe et al. [1, 2] predicts that by 2025 roughly 50% of the total ICT-related power consumption in Germany will be allocated to telecommunication networks and data centers (see Fig. 5.1). This projection might not be a surprising statement considering the continuously increasing data traffic and utilization of the Internet [3]. Earlier studies had less detail on networks and concentrated on data centers and end devices [4–6].

However, what exactly are the contributing factors and mechanisms that influence total energy and resource consumption? To what extent will the component and equipment selection, the dimensioning and configuration of the support infrastructure, as well as the operational conditions and power management influence the energy performance of networks and related data centers?

In this paper, the authors will initially discuss the necessity for quantifying the energy and overall environmental impacts of the Internet, cloud computing, and their main infrastructure elements including telecommunication networks and data centers. They will underline the value of such quantification. The focus lies on the corporate perspective, in particular the informational benefits of environmental assessments for planning of technology migration process and other related decision-making.

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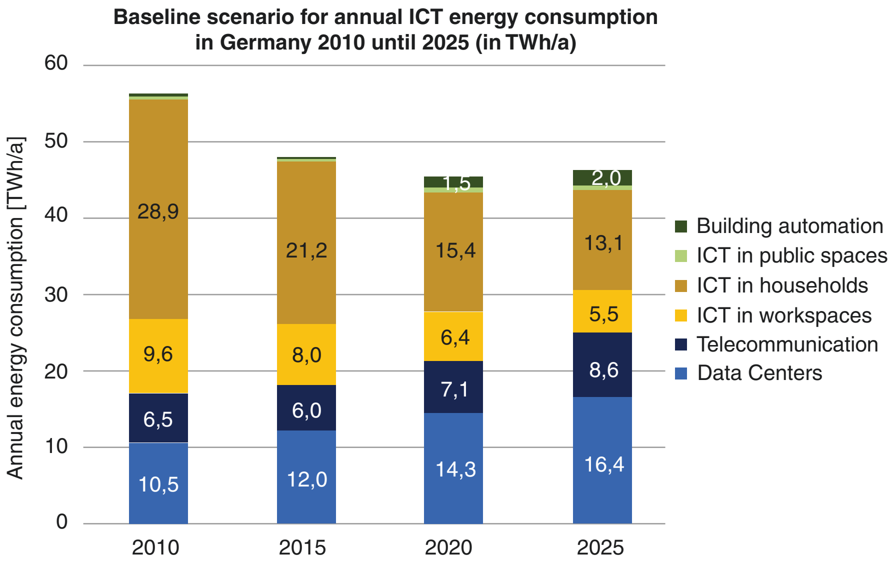

Fig. 5.1 Annual ICT energy consumption [1]

The second part of the paper presents a novel concept for modeling the energy and environmental footprint of telecommunication networks and data centers with reasonable effort and in realistic dimensions. This concept strongly reflects the complexity of life cycle inventories and the usually limited data availability, two reasons why so few environmental assessments are carried out in the telecommunication and data center sector.

The paper then outlines the general principles that substantiate the modeling approach. It explains the approach for reducing the complexity and data requirements in conjunction with an inventory model that only requires stock data of the dominant technical components and operational conditions. Finally, the modeling approach will be exemplified on the background of radio access networks (RAN) in a simplified manner.

5.2 Eco-Assessments for the ICT Sector

The findings in [1] indicate that the primary reason for the increasing environmental and financial impact is the steadily growing end-user demand for massive broadband communication, full coverage, and highest availability of service. Data traffic is driven by high- and ultrahigh-definition video, IPTV, online gaming, and social networks (push services). The industry is starting to utilize the Internet and telecommunication infrastructures as well (Industry 4.0). Smart factories, the Internet of things, connected vehicles, and urban security are the next topics of the digital

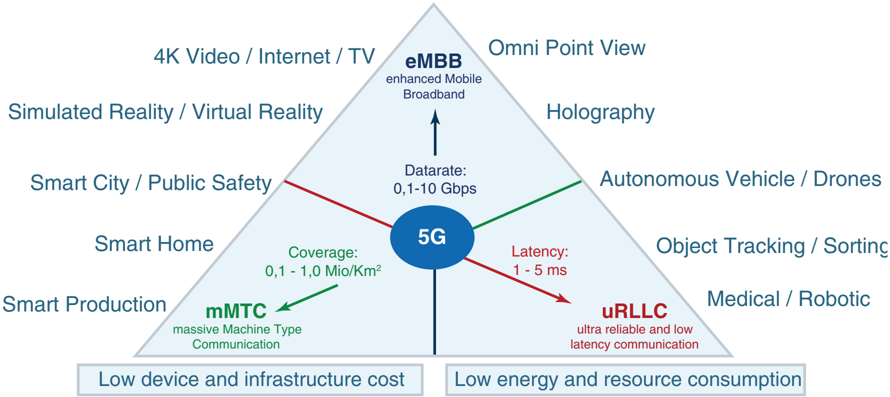

Fig. 5.2 Technical core aspects and main applications of 5G

agenda. The fifth generation of mobile communication (5G) is a key-enabling technology platform in that respect. Figure 5.2 shows the technological highlights and application areas of 5G.

Meeting future demand regarding mobile broadband communication, coverage, and latency, new 5G networks will utilize millimeter wave spectra (>6 GHz) and highly complex modulation technology for spectral efficiency. Furthermore, 5G will deploy a very high number of small cells with massive MIMO antennas. This technology spectrum is potentially leading to more installed hardware and subsequently more resource consumption.

In order to assess this potentially changing energy and resource demand of the ICT sector effectively, a simplified but still comprehensive environmental assessment methodology is proposed. The approach aims to identify environmental hotspots of ICT systems (telecom and data center) and relate them to their components, configuration, and control elements. By adequately quantifying the environmental impacts with respect to the function and location (e.g., within a specific telecommunication network), it will be possible for the management to address oversizing and other inefficiencies. A more effective distribution and configuration of hardware based on the assessment can lead to a reduction of the environmental as well as the financial impact of the given network. The assessment results could also be utilized to communicate environmental performance indicators to customers.

Over the past two decades, an increasing number of environmental assessments for ICT products such as smartphones, notebooks, and television sets were published. However, there are hardly any environmental assessments of telecommunication equipment, servers, and storage equipment. The few existing assessments indicate that the primary impact on greenhouse gas emissions is attributed to the use phase emissions. Based on the current equipment's lifespan, the use phase typically contributes over 90% of the total life cycle carbon footprint. This might change in the future due to the accelerating technology development, which could lead to shorter cycles of replacing older devices with the newest hardware generation.

Additionally, the predicted use of more hardware with less individual energy consumption will shift the ratio between the environmental impact of manufacturing and operation.

Especially the manufacturing of semiconductor components contained in electronic equipment is a very energy- and resource-intensive process involving ultraclean manufacturing conditions and environmentally critical materials. Therefore, the consideration of the production phase is required for a profound environmental assessment.

To account for that, it is deemed necessary to consider at least the following impact categories:

- Global warming potential (GWP) in kg CO_2 equivalents.
- Cumulated energy demand (CED) in MJ.
- Abiotic depletion potential (ADP) in kg Sb equivalents.
- "Virtual water" in l (optional)

The global warming potential (GWP) or carbon footprint is currently the most established impact category because it allows assessing the manufacturing as well as the use phase with one indicator. There is already a public and political interest and a general understanding of this parameter, which often led to a reduction of LCAs to product carbon footprints in the last few years. However, this simplification is not considered sufficient for the assessment of telecommunication networks. For instance, in the case of supplying the network completely with renewable energy, the consequently low carbon footprint would not account for the resource effort for supplying this amount of energy. Furthermore, from an operator's perspective, identifying energy hotspots by knowing the actual cumulated energy demand (CED) is beneficial for deriving specific optimization measures.

For the same reason, but concerning resource expenditure, an ADP value provides additional insight into the environmental impact of the material usage. With respect to current political concerns, indicating (virtual) water usage is proposed as an option.

5.3 Challenges

The implementation of the presented concepts leads to potential challenges of environmental assessment projects that need to be addressed. It is best to do this in an early stage to prevent any negative consequences. These challenges will be discussed from the present point of view without claims of completeness since external conditions may change over time.

5.3.1 Data Acquisition

A precise quantification of the infrastructure's parameters—such as data volume, energy consumption, and installed hardware—would require substantial measurement campaigns and effectively the collection of large amounts of data that are typically considered business secrets. Sensitive data has to be handled with utmost care and security. Therefore it is essential to communicate confidentially with the operators of the network and the equipment manufacturers in order to jointly implement standardized and anonymous questionnaires or data input masks for the data acquisition. This data will then be aggregated to conceal the sources and create averaged data sets that enable a considerable reduction of the subsequent workload (a further elaboration on this topic can be found in Sect. 4 "Modeling Approach"). However, it is important to maintain the right balance between convenient simplification and ensuring anonymity on the one hand and preserving the necessary precision and granularity as well as scientific replicability on the other hand. The optimal trade-off has to be adjusted depending on the scope of the assessment and the involved stakeholders.

5.3.2 Quantification of Qualitative Requirements

In the case of the end-user devices, environmental assessments have shown that technological progress in the form of miniaturization on the hardware level and power management on the software level systematically improved the power consumption and therefore energy efficiency in the use phase. Similar technology optimizations are basically available for telecommunication equipment and data centers, but the conditions under which telecommunication systems operate are considerably more complex. Since the performance of a network is determined not only by measurable energy and data traffic parameters but also by the user experience, relating the quantified data to unquantifiable network characteristics such as quality of service and functionality poses another challenge. This will be addressed by the definition of scope, functional unit, and the boundary conditions.

5.3.3 Complexity and Variability of Telecommunication Networks

The continuous technical evolution of telecommunication networks with substantial changes in network architecture, equipment, and configuration in conjunction with increased utilization is altering the energy and environmental footprint constantly. This is the main reason why up-to-date environmental data for ICT equipment is scarce in existing LCA databases. An analysis of conventional LCA guidelines and tools, which are primarily meant to assess individual products, has also shown that these are only partly suitable to assess the complex interdependencies and variability of telecommunication networks.

All of that leads to the need of a new modular and application-oriented approach.

5.4 Modeling Approach

The basic principle for the environmental impact modeling concept derives from existing process flow models which are typically used for technical cost modeling [7]. A process flow model consists of input-output inventories for all the individual steps or activities in the respective sequence of a particular process. This creates a linked chain or network depending on how many activities are carried out in parallel (scaling). The process sequence and scaling is specified by the selected technologies on the one hand and a particular business scenario on the other hand. The business scenario dictates qualitative requirements and other framework conditions (see Fig. 5.3).

In the proposed method, however, the process steps represent the different telecommunication network elements and nodes along which the signal or information (data traffic) is transported. The specific sequence of the network elements in end-to-end communication creates what will be called the data path. The data path is corresponding to the data plane or data channel in a network. The control plane or signal channel can also be modeled in the same way.

In a cloud computing scenario, the data path typically starts with the user equipment, which can be a personal computer or mobile phone. In the case of a mobile phone, the data path continues with the radio access network, followed by the aggregation and core transport network of the telecommunication network provider. Depending on the destination and service, the data path runs through multiple networks up to its final destination. For example, the data path of a cloud application might terminate in a data center.

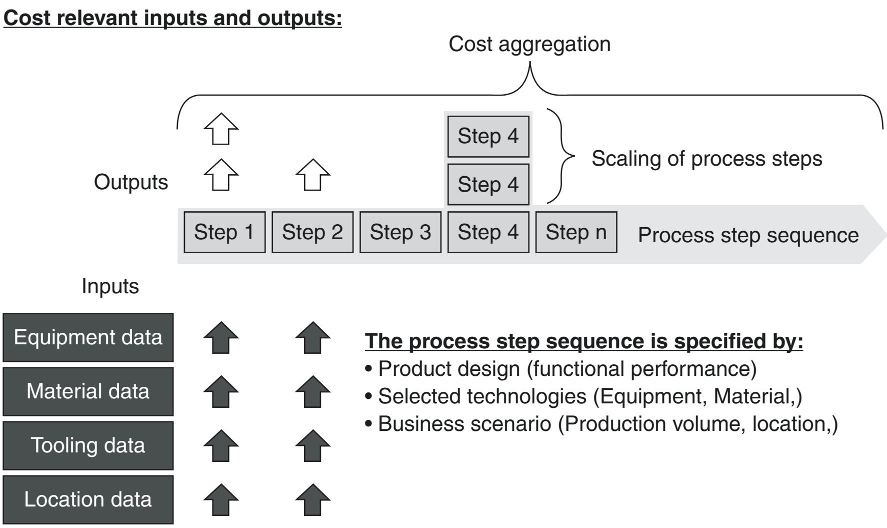

Fig. 5.3 Process flow model

Along such a data path, the information is processed by a variety of telecommunication and computing equipment. These technology elements include radio nodes, switches, routers, gateways, optical transport, monitoring equipment, and others. On data center level, the technology elements include network equipment, servers, and data storage systems. Furthermore, potentially energy- and resource-intensive support equipment such as heating, ventilation, and air conditioning (HVAC) as well as uninterruptable power supply (UPS) need to be considered as well. This type and configuration of the support equipment can be an indicator of qualitative business requirements such as network availability and resilience.

Figure 5.4 schematically visualizes this principle modeling approach. Similar to a process flow, a particular sequence of telecommunication, computing, and (if applicable) considerable support equipment along the data path is modeled. The data path and respective equipment sequence is determined by an actual business case or scenario. In other words, the business case defines the goal and scope of the environmental assessment. With this definition of the inventory's boundaries, the task is to obtain and allocate data for assessing the manufacturing and use phases. Empirical data indicates that these two life cycle phases typically have the largest impact.

The environmental impact of the use phase is mainly related to the accumulated power consumption over a period of time (energy). The power consumption specifications of the equipment are determined by (a) technical parameters including type and generation of the equipment (technology data), (b) individual power consumption per mode (energy data), and finally (c) the application environment and actual mission profile or workload over a defined period of time (location data).

The power consumption on the equipment level is determined by the following technical parameters:

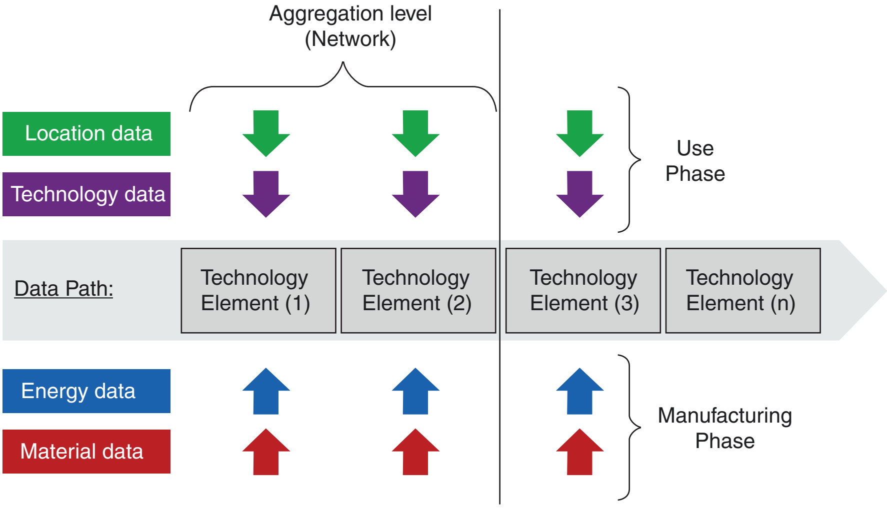

Fig. 5.4 Data path model

- *Components*: The active electronic, photonic, and electromechanical components that draw electricity. A focus is placed on larger integrated circuits (ICs), high-frequency ICs, and power converters. Active electronic components have a defined dynamic range between lowest and highest operating power consumption. The dynamic range is an indicator for load adaptiveness and energy efficiency.
- *Configuration*: The actual type and number of components that create the functional performance. The configuration determines the power consumption limits in active, idle, and standby mode. It also determines (in conjunction with the system dimensions and form factor) the thermal design effort and power usage effectiveness (PUE).
- *Control*: The dynamic range of the system and the specific power management capabilities under operational conditions. Ideally the power consumption curve matches the workload curve. Power management options for timely adaptation of network and computing resources (activation/deactivation) are key to energy efficiency.

Existing life cycle assessments of electronic products suggest that integrated circuits (ICs) and printed circuit boards (PCBs) are the largest contributors to the environmental impact with respect to the manufacturing phase. The broad mix of materials including precious metals and rare materials, the amount of process chemicals and tooling, as well as the necessity of clean room production environments contribute to the relatively large amounts of energy, water, and other environmentally relevant resources needed in the manufacturing process.

Furthermore, with even smaller dimensions (line/space) and more complex production processes, the testing and quality assurance is becoming a key effort in electronics manufacturing. This too demands growing amounts of equipment, floor space, and energy contributing more and more to the environmental footprint of the manufacturing phase.

With respect to the proposed modeling approach, the basic components are determined by their functional parameters (technology data) on the one side and the material and manufacturing energy (material data) on the other side.

Finally, it is necessary to consider the average active use life of the equipment, meaning the span of time from rollout to removal. The authors propose using a fixed time period (e.g., 6 years) for the main equipment categories. Similar to cost modeling where the capital costs for purchasing the equipment are distributed evenly as depreciation over a fixed period of time (a defined number of years), the manufacturing impact of the equipment (e.g., CED or GWP) is distributed evenly (per year or month) over the active use life. With this approach it is possible to partially allocate the manufacturing phase to the use phase when assessing, for instance, the annual environmental impact of an equipment or network in a holistic way.

5.5 The Inventory Structure

In this paragraph a more detailed description of the inventory model is provided. As mentioned before, the proposed approach is reflecting not only the increasing necessity for effectively assessing the environmental impacts of telecommunication networks and cloud computing but also the general lack of environmental data in this ICT sector. The inventory modeling approach is therefore utilizing known principles and contributors that provide a granularity of data sufficient to derive viable recommendations. It is the intention of this approach:

- To reduce the data collection effort to a useful minimum.
- To identify data gaps and define necessary data sets.
- To provide the option of using generic and specific data.
- To provide a logical structure for data aggregation while maintaining realistic dimensions.
- To correlate technical performance and use conditions including qualitative requirements with specific environmental impacts as indicators for improvement measures.

In the following section, the structure of the inventory model is exemplified on the example of a telecommunication network (see Fig. 5.5). The site category (e.g., residential area) and subnetwork type (e.g., access network) determine the general topology of technology units. Those (e.g., 4G LTE) consist of varying technology elements (functional hardware such as routers) which then comprise of basic components with unspecific generic functions (e.g., IC, PSU).

The main attributes of the five hierarchical layers of the inventory model are listed below:

1. *Site category*: describes the local conditions as well as the expected data mission profile.
2. *Subnetwork type*: describes the position of the network equipment in the data path sequence.
3. *Technology unit*: describes the technical specification according to the supported communication standard.

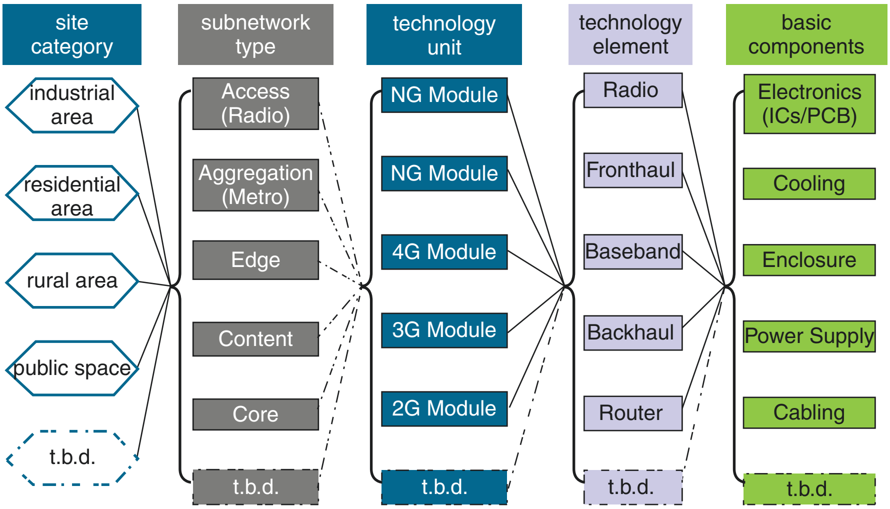

Fig. 5.5 Inventory model

4. *Technology element*: describes the function and principle component configuration of the equipment.
5. *Basic components*: describe the physical composition of the equipment including main parts and materials.

The following description of each layer on the example of radio access networks (RAN) has the intention of providing a more thorough understanding of this multi-level inventory modeling approach.

The site categories provide a useful framework for describing the conditions of the technical application and external factors such as workload profiles (use patterns), coverage in terms of cell size or number of supported end-user devices, signal absorption values due to building or vegetation density, geographic topology, and others. We are proposing to distinguish industrial areas, residential areas, rural areas, and public spaces. It is possible to define other site categories. It is important to reflect metastable load patterns (daily, weekly, or seasonal) first when defining a site category.

Figure 5.6 shows the parameters related to the site category.

A second increasingly important aspect is the speed and amount of movement of the end-user terminals within the cell. With growing mobility the network density typically increases as well as the compute capacity in support of massive MIMO, beamforming, small cell management, and other network control functions. Some specific conditions with respect to the site location are the seasonal climate (which might determine the cooling concept) and the type of energy that is locally available and used. Figure 5.7 shows differentiations of the specific subnetwork type regarding the general function of the network section.

In our example of radio access networks, the performance characteristic is defined by the mobile communication standard. This in turn is scaling the number

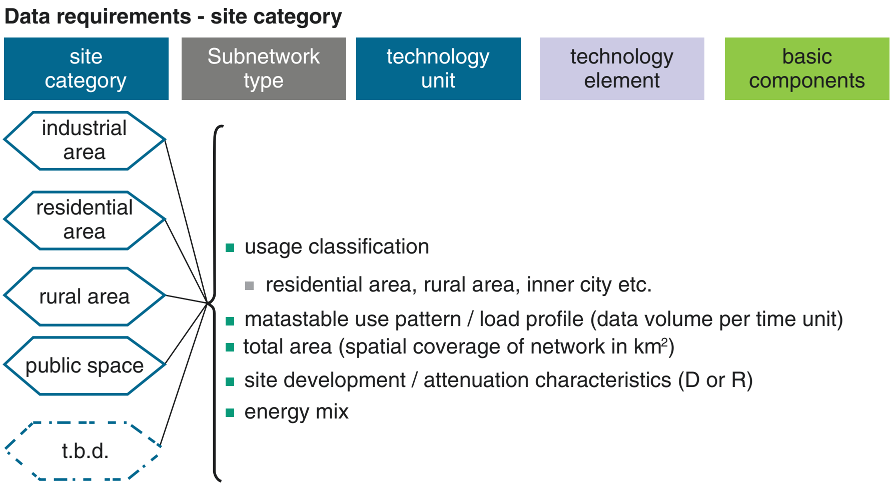

Fig. 5.6 Data requirements—site category

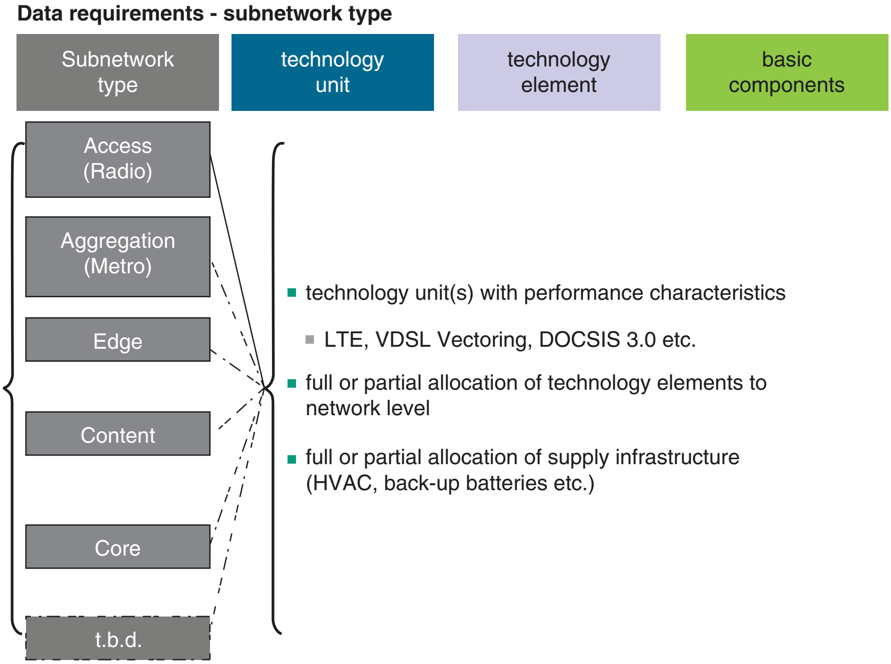

Fig. 5.7 Data requirements—subnetwork type

of radio base stations in order to cover a certain area. The network type will also provide the blueprint for the type and number of technology elements and support infrastructure and equipment. With new network architectures and the 5G development in particular, the static network layout will change considerably. The network configuration can vary from standalone 5G systems to non-standalone hybrid 5G systems. New control principles including network function virtualization (NFV) and software-defined network (SDN)—which allow for easy network slicing—will dramatically influence the hardware configuration and utilization within the same type of network. Therefore we created further subcategories in conjunction with the technology unit.

Figure 5.8 lists parameters and data requirements for the third level of the inventory: the technology unit.

The technology unit reflects the characteristics of a specific network and communication standard. The technical parameters are essential for linking the environmental performance in terms of energy and resource consumption to the real-life performance of a particular technical system. The appropriate dimensioning of the network regarding the local conditions provides a substantial eco-design potential—also on complex systems such as a radio access network. Furthermore, when utilizing environmental assessments in the planning phase and for rolling out a new network technology, it can provide useful information for reducing capital costs (CAPEX) and operational costs (OPEX).

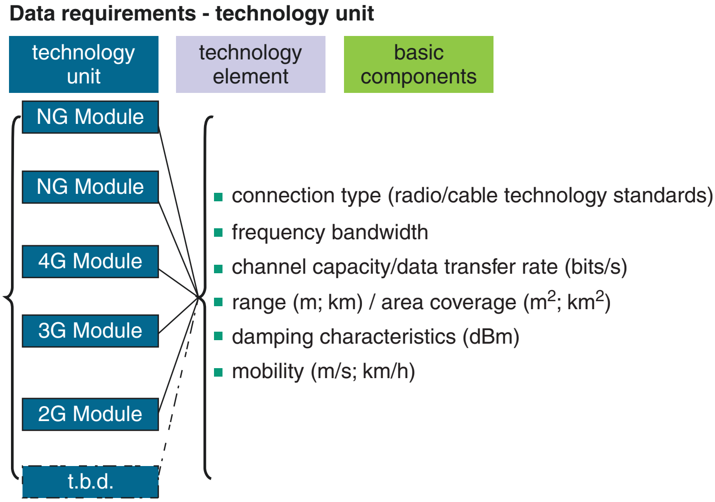

Fig. 5.8 Data requirements—technology unit

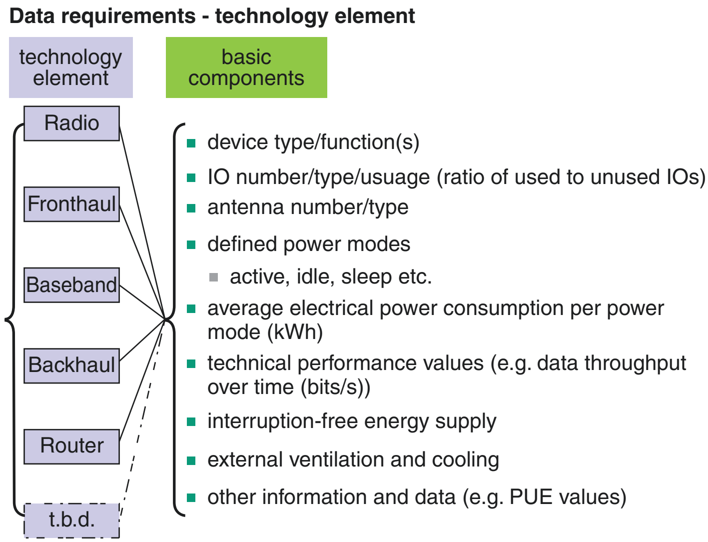

Fig. 5.9 Data requirements—technology element

Figure 5.9 further differentiates the functional technology element.

The functionality determines not only the position in the data path but also the number of interfaces and therefore the topology of the network. Despite obvious aspects such as power consumption in various operation modes, the technology element could also reflect qualitative aspects like resilience and availability. Another aspect is the infrastructure overhead (UPS, HVAC). Over the past years, this overhead has been conveniently aggregated by the PUE metric. In the future, a more detailed understanding of the interaction between the thermal management require-

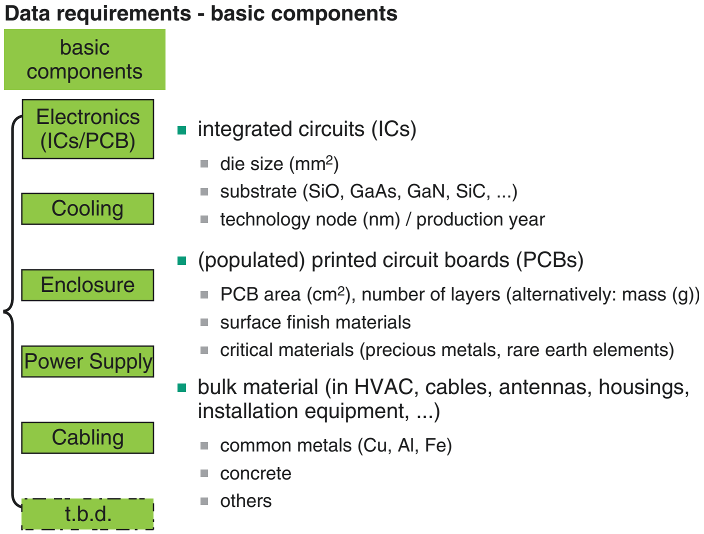

Fig. 5.10 Data requirements—basic components

ments of the network equipment and the local climate conditions might require a higher data granularity for expedient assessments.

Figure 5.10 finally shows how technology elements can be broken down to basic components.

As explained in the previous section, each network element can roughly be broken down to a few very basic components and materials. These include the ICs and PCBs in the electronic equipment as well as copper (Cu), aluminum (Al), iron, and steel (Fe), respectively, and possibly other environmentally relevant materials that appear in great amounts in the site infrastructure (e.g., buildings, masts), installation equipment (e.g., enclosures, mounting rails), antennas, and cables.

By focusing on basic components that are known for having a considerable environmental impact, a reduction in overall data is intended. For the manufacturing phase—e.g., for ICs and PCBs of various sizes and complexities—only a very limited number of data sets are available. Using unsuited and old data compromises the precision and expedience of life cycle-oriented environmental assessments. By placing a focus on the environmentally most contributing components, it is intended to provide an incentive for strategically collecting data together with the semiconductor and panel manufacturing industry.

5.6 Application Scenario

Since the effort of analyzing each telecommunication site in a given region in detail is not manageable, the authors propose to dissect and analyze exemplary sites and equipment, hence creating representative data sets for typical configurations on each layer. Such representative data sets are then used to freely scale the model to any topology to allow quick and economic assessments in realistic dimensions. This flexibility to scale the model to varying scopes represents the core advantage of the modular approach.

To ensure a fair comparability, it is important to develop standardized energy measurement methods as well as guidelines for the granularity of the product tear-downs when compiling material lists. To simplify the subsequent scaling process, these numbers will be normalized in relation to the corresponding area, period of time, and data throughput. From there it will be assumed that, e.g., similar residential areas (in terms of data load and mission profiles) will contain a similar amount of radio base stations which consist of a similar setup of routers and so forth. Preliminary analyses during the data acquisition process determine how many different typical configurations are needed for each layer to maintain the optimal balance between simplicity and precision (regarding how accurate the area/device is modeled).

It is suggested to use a customized spreadsheet—which is yet to be developed—where all the data and quantities can be submitted into a preexisting standardized data path model. Since every actual addressed network segment will probably differ more or less from the standard preset, it is necessary to allow individual adjustments to the typical data sets by overriding the default values. These data sets already contain all the environmental data so that the overall environmental impact of the given network segment can be calculated automatically for each impact category without further adjustments. This provides the opportunity to quickly and economically determine magnitudes and environmental hotspots within the network segment. These results are the starting points for defining improvement measures, key performance indicators, and performance monitoring systems.

In conclusion, the modular approach provides the foundation for calculating an energy or environmental footprint of individual sites, regional networks, or complete services spanning end-to-end. The model allows scaling the inventory according to network topologies of real-life application scenarios (business case). This can be done by looking at a given region/site/device, choosing the most fitting-prepared configuration, and submitting information on the most relevant characteristics (e.g., amount of units, area coverage, and data throughput). Figure 5.11 shows these principle approaches for utilizing the modular inventory model by illustrating examples of the typical configurations on all network levels. It also shows how all of these can be broken down into the same basic components being ICs, PCBs, bulk materials (copper, aluminum, iron/steel, etc.), and the HVAC overhead. The red highlighting indicates the two approaches for a life cycle assessment, either by the total amount of equipment in an area or along the network nodes of the service's data path.

5.7 Summary

In this paper a modular inventory model supporting an effective and life cycle-oriented assessment of the environmentally relevant attributes and impacts of networks and cloud computing has been presented. The structured modular approach

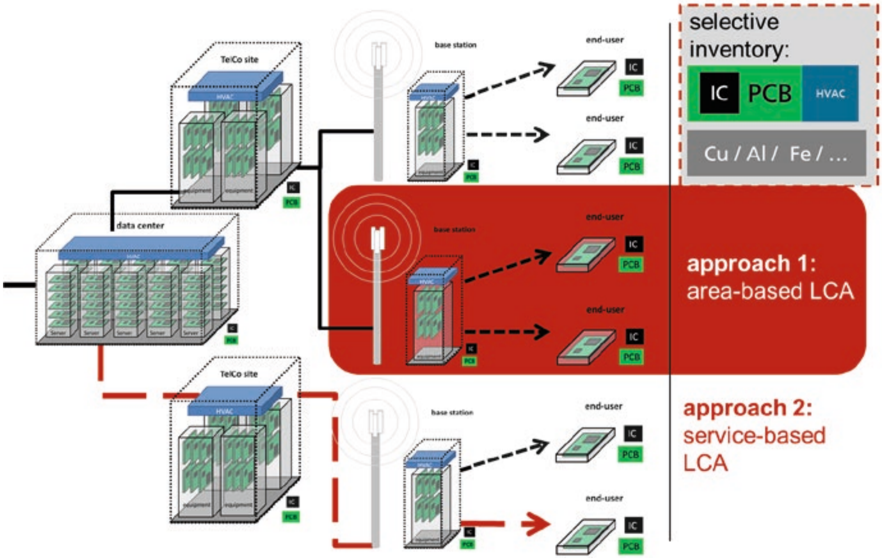

Fig. 5.11 Application of the modular assessment approach

of mapping complex telecommunication networks and their technical components, performance characteristics, and local site conditions derive from an increasing understanding of technical systems that build telecommunication networks.

Recent estimates indicate that the energy and resource consumption of telecommunication networks and related data centers will increase in the coming years. Environmental assessments have a potential to support technology decisions and actual planning of new networks. The site location costs and energy costs are already driving the economic balance sheet of the telecom providers. These two aspects directly translate into resource and energy consumption. The impact of the manufacturing phase might become more dominant in the overall assessment as the number of specialized devices is increasing drastically and should continuously be addressed (on the background of having less than 10% share in past analyses).

By respecting the limited data availability and adjusting the inventory's granularity, the proposed approach tries to overcome existing shortcomings in life cycle-oriented assessments. The modeling approach is designed to create meaningful results with minimal data requirements. Considerable challenges particularly with respect to data acquisition remain nonetheless. The approach also tries to reflect on qualitative requirements by translating them into technical performance parameters. The adjusted process flow model for mapping equipment topologies along a technically defined data path allows analyzing different levels of complexity and functionality of a network down to the equipment level. Figure 5.12 shows an aggregated overview of the modeling approach.

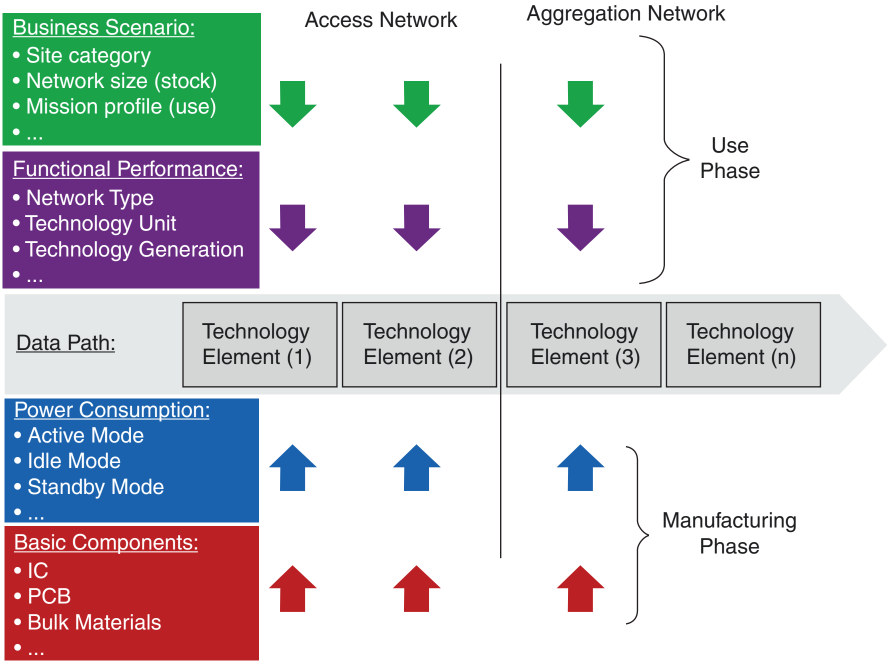

Fig. 5.12 Overview of the methodological approach

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Chapter 6
Monitoring Energy Consumption of Individual Equipment in a Workcell Using Augmented Reality Technology

Nicholas Ho and Chee-Kong Chui

6.1 Introduction

Manufacturers are modifying their business and operations model to move towards environmental sustainability. The reasons for this trend include stricter regulations (due to climate change issues), a need to increase competitive advantage, a need to protect and strengthen brand/reputation and financial incentives from grants, subsidies and cost savings [1]. For instance, increasing operational efficiency and the need to protect and strengthen their brand and reputation are some of General Motors' motivations to adopt an aggressive sustainability approach [2].

Monitoring and controlling energy consumption of electrical appliances are important processes in energy management systems (EMS). Such systems are widely utilized in buildings, homes and factories to achieve optimal energy efficiency [3–5]. On top of this, these systems provide users a breakdown of their energy usage so that they are able to better respond by controlling the energy consumption of relevant appliances with high-energy usage. Likewise, monitoring energy consumption of equipment in a manufacturing workcell is part of an important process of energy consumption control.

Sophisticated and advanced energy sensors have made it possible to effectively monitor energy consumption of equipment in the workcell via a smart device in real time. For instance, Moreno et al. [6] developed an IoT-based, smart building energy management system (BEMS), using a combination of RFID and IR sensors to monitor energy consumption. Their case studies illustrated that energy savings of about 23% can be achieved when this system is utilized.

However, it is worthy to note that in a manufacturing setting, stakeholders like new workers, eco-consultants and/or authorities are unfamiliar with the equipment terms,

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thus making it challenging for them to visualize the energy consumption of each equipment in the workcell from the smart device. These challenges increase further when it comes to complex manufacturing operations like the production of hybrid medical devices (e.g. CNT-PDMS (carbon nanotubes-polydimethylsiloxane) based on artificial trachea prosthesis [7–9]), which make up of a combination of both synthetic and biological components. Such manufacturing processes involve many uncommon equipment which terms are usually unknown to these stakeholders, thus making it difficult for them to consult or regulate manufacturers on their energy control efficiencies.

AR technology's potential use for monitoring purposes has been investigated by various researchers. Zollmann et al. [10] introduced an approach to utilize AR technology for on-site construction site monitoring. Their field tests results confirmed great potential for the proposed methodology in other industries. In another work by Fard et al. [11], the authors proposed a four-dimensional AR model for automated construction progress monitoring. Their preliminary results proved potential benefits of utilizing this technology for progress monitoring in the construction industry. On a side note, AR technology has already started being utilized for assembly training and inspection purposes in some manufacturing companies. For instance, in a Harvard Business Review case study by Abraham and Annunziata [12], it has been reported that Boeing is utilizing AR technology for wiring harness assembly, and this led to an increase in productivity by 25%. As such, an AR-based energy monitoring concept will add value with minimum cost because of its easy integration in the inbuilt system together with these features. Moreover, either most of these proposed AR-based methods have a prefixed data programmed or they require manual updating of data in the system. Hence, there is also a need to consider an AR-based approach that allows automatic, real-time updating of data in the system.

In order to aid this group of stakeholders in the monitoring of energy consumption process, we propose a novel, augmented reality (AR) and Internet of Things (IoT)-based energy monitoring conceptual design. It aims to not only give users an option to have an overall view of the energy consumption in the workcell but also to allow users to visualize energy consumption of each equipment in the actual field. With the help of AR technology, one can immediately pinpoint equipment with constant high consumption rates while walking in real environments and give better advice to control energy consumption by exploring ways to reduce their energy usage. With IoT technology, automatic, real-time updating of data in the system is possible. This paper highlights the potential of the proposed energy monitoring conceptual design in aiding users to better visualize the energy consumption patterns of individual equipment in the workcell.

6.2 AR Energy Monitoring Architecture

Figure 6.1 shows the AR energy monitoring architecture which consists of three main components: (a) the equipment set, (b) the processor and (c) the AR display device. Figure 6.2 is the system flowchart.

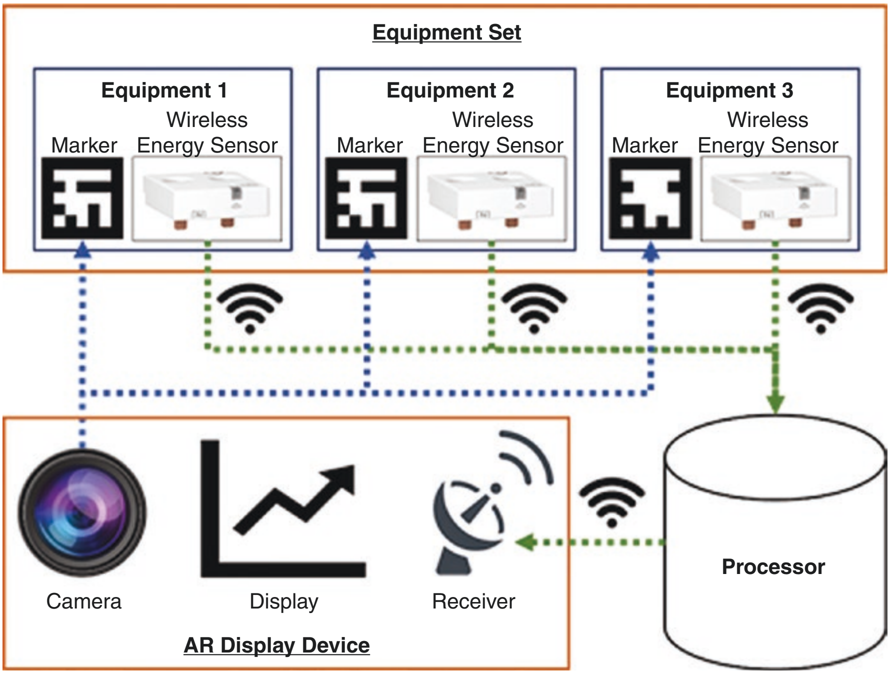


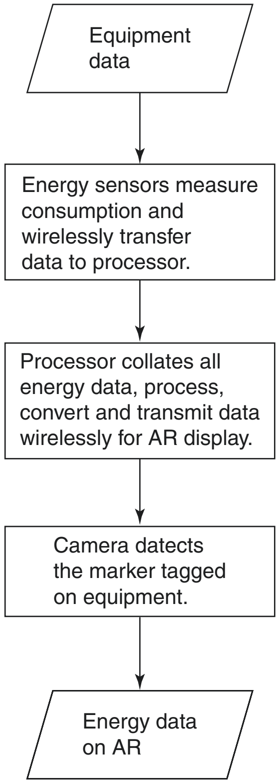
Fig. 6.1 AR energy monitoring architecture. Energy data transfer is indicated by green line; visual detection of marker(s) is represented by blue line

The equipment set comprises of all the equipment that require energy usage. Each equipment will be tagged with a unique marker for identification purposes [13]. On top of this, each equipment is attached with a wireless energy sensor to enable real-time measurements of energy consumption and convenient energy data transfer [14]; this energy data will be wirelessly transferred to the processor. Next, the processor will collate the energy data from all equipment, and process and convert them to display mode for AR (e.g. graphical and chart forms that will be augmented on the AR display device). The reason for having this conversion process is to provide better visualization for users at a later stage, thus allowing them to easily identify equipment with high-energy usage and to compare energy usage among all equipment [15]. Subsequently, the processed energy data (in display mode) is wirelessly transferred to the AR display device.

The AR display device, which is usually a lightweight, and a portable device (e.g. smartphones, tablets, head-mounted display (HMD), AR glasses) [16–18] are utilized to present the processed, well-packaged energy data to the user while he/she carries the device around in the real workcell environment. When the device's camera detects the marker tagged on the equipment, the AR display of the energy data will appear to the user on the device [19].

In summary, the proposed AR energy monitoring architecture aims to allow users to better visualize energy consumption levels of each equipment in the actual field.

Fig. 6.2 AR energy monitoring system flowchart



Using markers to identify each equipment and using a processor to produce well-packaged energy data for each equipment, it is technically possible to adopt this approach with the aid of an AR display device.

6.3 Conceptual Illustrations

In order to illustrate the concept of the proposed AR energy monitoring architecture, we utilized a small-scale workcell with various equipment.

6.3.1 Description of the Small-Scale Workcell

The small-scale workcell is located in an equipment room in our laboratory. We selected three various equipment that consume different amounts of energy. Equipment 1 is a Panasonic refrigerator-freezer, model NR-BN221SNSG, that is used to store chemical agents. Equipment 2 is an Akarui Digi 38L dry cabinet that

Fig. 6.3 Small-scale workcell with various equipment and their respective marker designs

is used to store items that are sensitive to humidity and dust. Equipment 3 is a regular Dell personal computer. All these equipment are switched on 24/7 and tagged with different marker designs. The small-scale workcell and the respective marker designs are illustrated in Fig. 6.3.

6.3.2 AR Energy Monitoring

We used an Android tablet and an MS Windows laptop for the AR display device and the processor, respectively. An application using the software Unity3D and Vuforia 3D is built to enable marker detection and to augment the virtual processed energy data on the tablet.

The virtual processed energy data is illustrated in Fig. 6.4, and the AR energy monitoring process is illustrated in Figs. 6.5 and 6.6. In Fig. 6.4, the energy data, which are collected from the sensors, are converted by the processor to display mode for AR. Figure 6.4a–c represent the energy consumption pattern graphs for equipment 1, 2 and 3, respectively. Figure 6.4d represents the overview comparison of energy consumptions among the three equipment. These processed energy data will be presented to the user appropriately via the AR display device when he/she aligns the device's camera vision with the respective tagged marker as clearly illustrated in Fig. 6.5.

The AR energy monitoring process requires two steps: (1) finding the tagged marker on the equipment of interest and (2) aligning the device's camera vision with the marker. Figure 6.5a–c illustrates the monitoring process for equipment 1, 2 and 3, respectively, step 1 on the left and step 2 on the right side of the figure. Figure 6.5d, on the other hand, illustrates how the user can activate the overview comparison chart by 'pressing' on the virtual 'overview' button. Figure 6.6 illustrates an overview of how the user can utilize the system to effectively monitor energy consumption levels of individual equipment in the workcell.

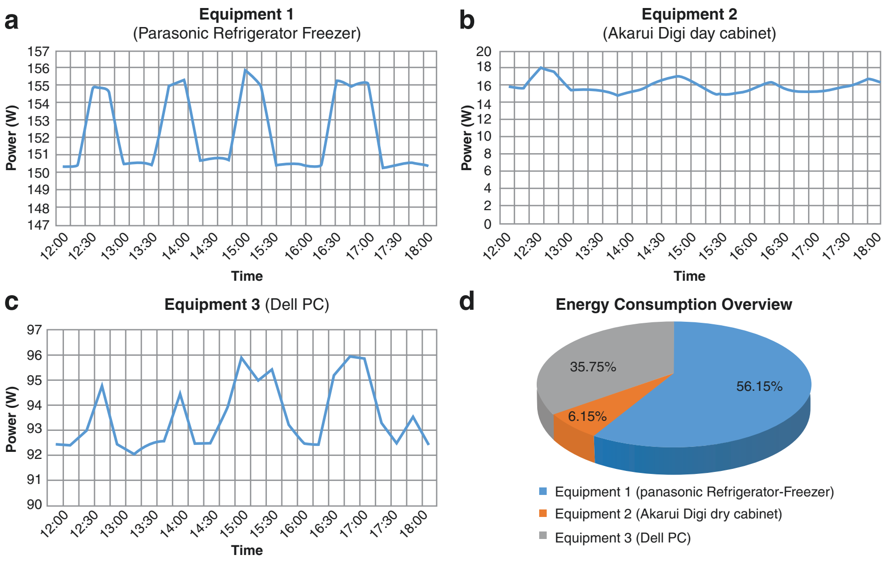


Fig. 6.4 Virtual processed energy data: energy consumption patterns for (**a**) equipment 1, (**b**) equipment 2, (**c**) equipment 3 and (**d**) overview comparison chart

6.4 Discussions

From above, we demonstrated that the proposed AR energy monitoring architecture is feasible and effective. Firstly, from Figs. 6.4 and 6.5, we can observe that the system provides better visualization to the user via the virtual processed energy data; the graphical and chart data formats make it easier for the user to analyse data. Secondly, the system provides real-time and accurate energy data to the user. As such, the user does not need to estimate energy consumptions for each equipment based on electricity bills and/or equipment power ratings. Thirdly, the system allows the user to conduct on-site monitoring. As such, the user is able to immediately pinpoint equipment with constant high consumption rates while walking in real environments. The system also provides convenience to the user as it involves wireless technology and lightweight and portable devices. The involvement of wires and bulky and heavy devices will hinder the monitoring process in the workcell.

Nevertheless, the proposed system has several limitations. Firstly, the additional costs of wireless energy sensors and AR display devices may deter manufacturers to adopt this system [20–22]. Nevertheless, we believe that with rapid technological advancements and increasing production efficiency, these costs will decrease significantly over time. Secondly, the system heavily relies on markers. The disadvantages of using markers for identification purposes are having unstable tracking and limited tracking range; its tracking system is based on a few features; and the range of camera vision from which the markers are visible is limited [13]. Thirdly, the illustration example utilizes a tablet as the AR display device. Although

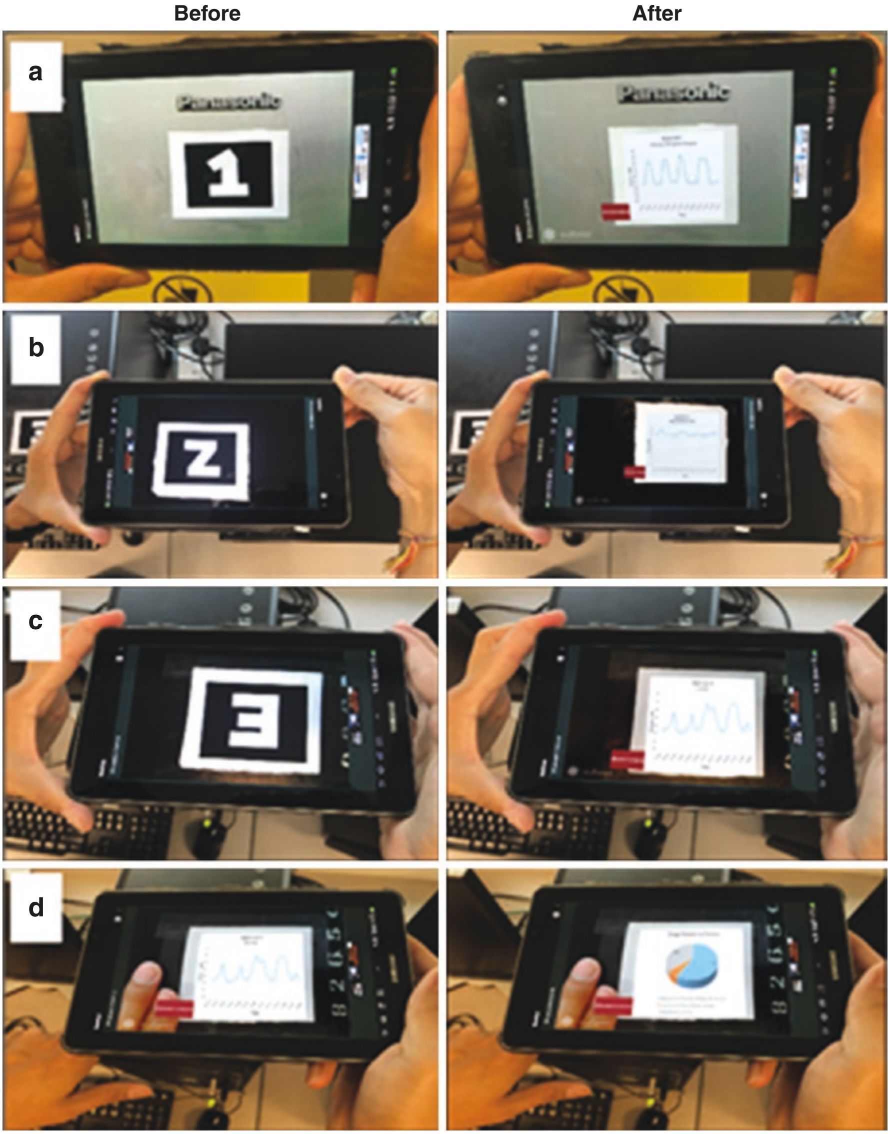


Fig. 6.5 Conducted AR energy monitoring process for (**a**) equipment 1, (**b**) equipment 2, (**c**) equipment 3 and (**d**) activation of overview comparison chart

the tablet is lightweight and portable, it still poses a hassle for the user as it has to be carried around on hand in the workcell [21, 22]. Lastly, the amount of virtual processed energy data (as shown in the illustration example) that is provided to the user may not be sufficient enough to reach an accurate conclusion on energy usage. This is because energy consumption measurements can be done in varying units (e.g. kWh, joules, kgoe) and in varying time periods (e.g. annually, monthly, daily)

Fig. 6.6 Overview of user's monitoring experience during experiment

Table 6.1 Advantages and limitations of proposed AR energy monitoring architecture

Advantages	Limitations
Better visualization	Higher setup costs
Real-time and accurate energy data	Reliance on markers
On-site monitoring	Carrying hassle of tablets
Convenience	Insufficient energy-related data

[23–25]. Including these variations as part of the provided virtual processed energy data may enable better judgement of the energy consumptions by the user. Table 6.1 summarizes the advantages and limitations of the proposed AR energy monitoring architecture.

6.5 Conclusion

The increasing need for manufacturers to move towards environmental sustainability calls for an urgent need to improve energy management systems that include the monitoring and control of energy consumptions. Although smart systems have the potential to effectively manage energy levels, it can be foreseen that with increasing competition and costs, manufacturers will face with a dilemma between maintaining energy consumption levels and increasing output. As such, stakeholders like eco-consultants and authorities play an important role to constantly keep these manufacturers in check.

As this group of stakeholders can be unfamiliar with the equipment terms in a complex manufacturing setting, it will be beneficial to consider an energy monitoring system that will effectively aid users in visualizing the energy consumption patterns of individual equipment in the workcell. In this paper, we illustrated the potential of the proposed AR energy monitoring concept that enables users to immediately pinpoint those equipment with constant high consumption rates while walking in real environments. Hence, this also allows them to give better advice to control energy consumption by exploring ways to selectively reduce energy usage.

Further studies and development are required for the proposed system. Hardware aids such as head-mounted display (HMD) and AR glasses could be used to enhance effectiveness and user experience. Wearing headgears, as compared to carrying portable smart devices around, may be a more convenient and visual solution. We also intend to improve the presentation of the virtual processed energy data by including more data in varying units and time periods. Marker-less tracking system will also be considered to reduce the reliance on markers. Testing the fully developed AR energy monitoring system on human subjects and comparing the user experience between utilizing the proposed AR energy monitoring system and the conventional method of analysing data from a device in an enclosed space (e.g. office, laboratories) are important.

The proposed system will enable users to better visualize the energy consumption patterns of equipments within a workcell. The collected data could be analysed over time. It is a platform for us to research and develop visual cues for effective monitoring and control of equipment energy consumption. Computational intelligence software is used to generate the appropriate visual cues.

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Chapter 7
An Intelligent Robotic System for Handling and Laser Marking Fruits

Chih-Hsing Liu, Ta-Lun Chen, Tzu-Yang Pai, Chen-Hua Chiu, Wei-Geng Peng, and Chia-Chun Weng

7.1 Introduction

Price look-up (PLU) codes [1] have been used to identify bulk produce since 1990. The International Federation for Produce Standards (IFPS) is the organization that assigns and maintains PLU codes to produce items (such as fruits, vegetables, dried fruits, herbs, and nuts). PLU codes are usually four-digit numbers and appeared on a small sticker applied to the skin of an individual piece of produce. The four-digit PLU codes are randomly assigned between 3000 and 4999, which can be used to identify the type, variety, and size of conventionally grown produce. For example, PLU code 4173 represents small Royal Gala apples; the photo of Royal Gala apples with PLU code 4173 stickers can be seen in Fig. 7.1. The five-digit PLU codes are also used by IFPS. For example, a number "9" in front of the four-digit PLU code indicates that the produce is organically grown. So far, there are over 1400 PLU codes assigned to produce items. The use of the PLU codes is not compulsory. But most supermarkets and grocery stores do use PLU codes as a simple way to manage inventory and pricing. The use of the PLU codes can make checkout and inventory control easier and more accurate, which can ensure that the correct price is paid by consumers and also remove the need for cashiers to identify the produce product. A complete list of PLU codes can be found from IFPS website [1].

Instead of the use of stickers applied to the skin of produce items to label the PLU codes, Drouillard and Kanner [2, 3] proposed the method and system for laser marking of produce items by using a laser with a controllable high-intensity light beam along a predefined path on produce skin and controlling the laser to etch the produce skin such that the generated mark does not penetrate completely through the produce skin to the meat of the produce. An identifying mark such as PLU codes can be generated by laser marking. The ink-free approach provides an ecologically

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Fig. 7.1 Apples with PLU code stickers (PLU code 4173 represents small Royal Gala apples)

friendly, inventory-free, and rapidly changeable option to packers for replacement of adhesive labels. Griffiths and Fox [4] proposed method and apparatus for laser marking eggs. Eggs are commonly packed in cartons that have expiration dates printed on the surface of egg cartons. However, consumers may remove the eggs from a carton and put them in the egg holders of their refrigerator and therefore lose the expiration date information. In addition, there might be instances where certain establishments may remove eggs from one printed carton and placed in another having a later expiration date. To resolve abovementioned problems, a particularly desirable way is to mark an expiration date on the shell surface of the egg using laser, which results in a permanent mark that cannot be removed from the egg itself.

Marx et al. [5] investigate the benefits of direct laser marking and identify the factors influencing the achievement of useable markings by testing various laser wavelengths to mark a simple 9-mm^2 sized 2-D barcode on the surface of apple fruits. The readability of the marked patterns is high at low laser power levels of about 5–10 W (CO_2 laser). The risk of tissue shrinkage, water loss, and fungal infection increases with high laser powers. By using suitable laser marking energy per pattern, it is possible to minimize the damage on the surface of produce.

In order to develop an intelligent robotic system for automatically handling and laser marking fruits, the development of a nontraditional robotic gripper for picking and placing produce with size and shape variations and without causing damage to the grasped products is one essential task in the implementation of the system. Pettersson et al. [6] develop a robot gripper mounted on a six-axis robot that utilizes the effects of a magnetorheological (MR) fluid to grasp produce such as apples, carrots, strawberries, broccolis, and grapes. In the gripping process, pouches filled with MR fluid are molded around the object. Through the activation of an electromagnet in the gripper arm, a large increase in the MR fluid yield stress confines the object in the mold produced by the gripper. A hygienically designed force gripper for handling of easily damaged natural food products has also been developed [7]; a magnetic coupling is used to transfer the gripping motion to the gripper arms; this concept enables a complete encapsulation of the actuator mechanism and thus also the construction of a washable parallel arm electric force gripper for food handling.

The development of a dexterous soft robotic gripper or hand to perform the pick-and-place task for objects with different shapes and sizes has drawn considerable attention over the years. For example, the SDM hand proposed by Dollar and Howe [8] is a single actuator, compliant grasper for adaptive grasping applications. Petković et al. [9] propose a passive adaptive gripper which can accommodate various concave and convex objects. Deimel and Brock [10] propose a compliant underactuated hand with pneumatic PneuFlex actuators [10, 11] which can provide grasp adaptability and low control complexity. Liu et al. [12] present an optimal design procedure to synthesize compliant mechanisms with maximum geometric advantage (which is defined as the ratio of output displacement to input displacement). A soft-add topology optimization algorithm [12, 13] is developed to synthesize the optimal layout of an adaptive compliant gripper. A size optimization procedure combining augmented Lagrange multiplier method and simplex method is also proposed to maximize the geometric advantage of the synthesized compliant mechanism. The formulation of the topology optimization method to design compliant mechanisms with one input and two target output ports is also proposed by Liu et al. [14], which can consider both geometric advantage and mechanical advantage (which is defined as the ratio of output force to input force) of the synthesized compliant mechanism with adjustable control parameters. The usage of the soft materials is one common characteristic of the abovementioned grippers and hands. Generally, the compliant hands and grippers are able to prevent possible damage of the grasped objects, which is particularly important in handling of delicate food products [6, 7, 15–17].

Topology optimization is one major numerical method to synthesize compliant mechanisms. The numerical algorithms of topology optimization are extensively investigated during the past decades [18–22]; it can be used to optimize material layout within a given design domain with specified loading and constrained boundary conditions. Traditional topology optimization algorithms are usually based on the finite element method. For example, evolutionary structural optimization (ESO) method [23, 24] is one traditional method in topology optimization which is based on the simple concept to gradually remove inefficient elements from the analysis domain until the iterative result converges to an optimum under prespecified constraints and boundary conditions. A later version of ESO method, bi-directional evolutionary structural optimization (BESO) [25–27], is also proposed which allows to remove and add elements during the optimization procedure. Further, in order to improve the computational efficiency in topology optimization of compliant mechanisms, a constant volume fraction method [28, 29] is proposed to synthesize designs. After a design is obtained, explicit dynamic finite element analysis can be used to predict the performance of various designs involving dynamic and contact conditions [12, 29–35].

This paper aims to develop an innovative robotic system for handling and laser marking fruits. The laser marks on fruit skin are expected to replace the widely used fruit stickers (as can be seen in Fig. 7.1) which can provide specific information for fruit products. The developed system consists of a compliant gripper, a robotic arm, a machine vision module, a laser marking unit, a conveyor, and a robot controller. A topology optimization method is utilized to design a compliant gripper for grasping fruits. From a sustainability perspective, the developed robotic laser marking system can reduce significant amount of stickers being used on produce. The remaining part of this paper includes the following content: The formulations of the topology optimization method and the optimal design of a topology optimized compliant gripper are provided in Sect 7.2. The intelligent robotic system for handling and laser marking fruits is introduced in Sect 7.3. Finally, a summary is made in Sect 7.4.

7.2 Topology Optimization Design of a Soft Robotic Gripper

7.2.1 Formulations for Topology Optimization

A topology optimization method is used in this study to design an innovative compliant gripper for grasping fruits. The flowchart of the proposed topology optimization method is given in Fig. 7.2. The first step is to discretize the analysis domain using finite element formulation with prespecified boundary conditions; then finite element method is used to solve the force equilibrium problem. The sensitivity

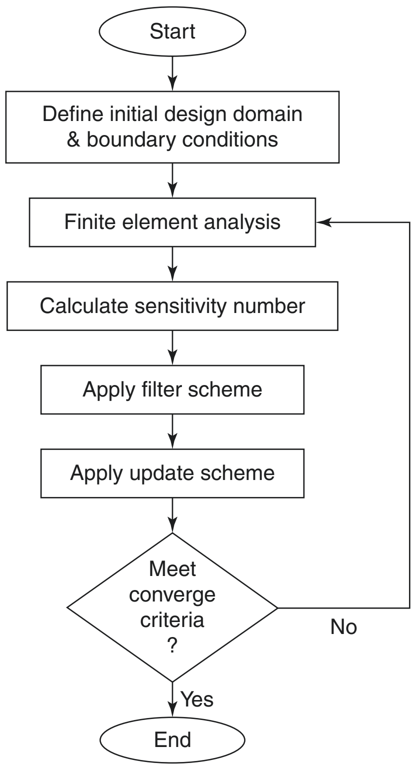


Fig. 7.2 Flowchart of the topology optimization method

number is defined as the gradient of objective function with respect to design variable for each element. A filter scheme is used in the topology optimization procedure to avoid the possible checkerboard pattern problems. A soft-add update scheme [13] is used to update sensitivity value and density for each element. A convergence criterion is used to calculate the variation of objective values until convergence.

The optimization problem in this study is to synthesize compliant mechanisms with one input and two output ports, which can be formulated as [14]:

$$\text{Maximize:}\quad c=\frac{(1-\zeta)S_{\text{mut},1}+\zeta S_{\text{mut},2}}{2\eta S_{\text{in}}+2(1-\eta)\left[(1-\zeta)S_{\text{out},1}+\zeta S_{\text{out},2}\right]} \tag{7.1}$$

$$\begin{aligned}\text{Subject to:}\quad & \mathbf{KU}_1=\mathbf{F}_1;\ \mathbf{KU}_2=\mathbf{F}_2;\ \mathbf{KU}_3=\mathbf{F}_3\\ & \sum_{i=1}^{N}x_iV_e=V^*;0<x_{\min}\le x_i\le 1\\ & 0<\eta<1;\ 0<\zeta<1\end{aligned}$$

where c is the objective function which consists of three types of strain energy (S_{in}, S_{out}, and S_{mut}) and two control parameters (η and ζ); S_{in}, S_{out}, and S_{mut} are input strain energy, output strain energy, and mutual potential energy, respectively; η is the advantage control parameter; ζ is the output control parameter; $\mathbf{K}$ is global stiffness matrix for the analysis domain; $\mathbf{U_1}$, $\mathbf{U_2}$, and $\mathbf{U_3}$ are the displacement vectors corresponding to the force vectors $\mathbf{F_1}$, $\mathbf{F_2}$, and $\mathbf{F_3}$; x_i is the pseudo density of the ith element; V^* is the target volume; $x_{\min}$ is a small positive value; V_e is the volume of an element; and N is the number of elements in the analysis domain.

The pseudo density (x_i) is the design variable of the optimization problem. The output control parameter (ζ) controls the target output ratio of the two output ports. The advantage control parameter (η) allows the optimization problem to maximize mechanical advantage and geometric advantage of the analyzed compliant mechanism. According to the study from Krishnakumar and Suresh [36], decreasing advantage control parameter (η) increases the mechanical advantage and decreases the geometric advantage of the synthesized compliant mechanism (and vice versa).

Further, the formulations for the input strain energy (S_{in}), output strain energy (S_{out}), and mutual potential energy (S_{mut}) can be formulated as:

$$S_{\text{in}}=\frac{1}{2}\int_{\Omega}\sigma(u_{\text{in}})\varepsilon(u_{\text{in}})\,\mathrm{d}V \tag{7.2}$$

$$S_{\text{out}}=\frac{1}{2}\int_{\Omega}\sigma(u_{\text{out}})\varepsilon(u_{\text{out}})\,\mathrm{d}V \tag{7.3}$$

$$S_{\text{mut}}=\int_{\Omega}\sigma(u_{\text{out}})\varepsilon(u_{\text{in}})\,\mathrm{d}V \tag{7.4}$$

The formulation of the global stiffness matrix **K** is given below:

$$\mathbf{K} = \mathbf{K}_s + \sum_e x_i^p \mathbf{K}_e \tag{7.5}$$

where $\mathbf{K}_s$ is the stiffness matrix for the numerical springs [13, 28] placed at the input and output ports of the synthesized compliant mechanism, p is a penalty factor, x_i is element density, and $\mathbf{K}_e$ is stiffness matrix for an element [13].

The sensitivity value for each element ($\alpha_{e,i}$) can be calculated by the gradient of the objective function (c) with respect to the design variable (x_i):

$$\alpha_{e,i} = \partial c / \partial x_i \tag{7.6}$$

The filter scheme in BESO method [27] is used to avoid the checkerboard pattern problems in this study. The BESO filter scheme starts from calculating the nodal sensitivity number ($\alpha_{n,j}$):

$$\alpha_{n,j} = \frac{\sum_{i=1}^{n_e} \alpha_{e,i}}{n_e} \tag{7.7}$$

where $\alpha_{e,i}$ is the sensitivity number for the ith element obtained in Eq. (7.6), i is element number, j is node number, and n_e is the number of elements connected to the jth node.

The filtered sensitivity number for an element can be formulated as:

$$\tilde{\alpha}_{e,i} = \frac{\left(\sum_{j=1}^{n_r} w_{ij} \times \alpha_{n,j}\right)}{\left(\sum_{j=1}^{n_r} w_{ij}\right)} \tag{7.8}$$

$$w_{ij} = \max\left(0, r - r_{ij}\right) \tag{7.9}$$

where w_{ij} is a weight factor, $\alpha_{n,j}$ is nodal sensitivity number obtained in Eq. (7.7), r denotes the filter radius (which is about the center of an element), n_r is the number of nodes within the circle of the filter radius, and r_{ij} denotes the distance between the jth node and the center of the ith element. In addition, the filtered elemental sensitivity numbers obtained in Eq. (7.8) for every two successive iterations are averaged to stabilize the iterative results.

After that, the soft-add scheme proposed by Liu et al. [13] is applied to update the sensitivity numbers and pseudo densities. The calculated volume for each iteration, V^{iter}, can be formulated as:

$$V^{\text{iter}} = \min\left(v_{\text{f}}, \text{Ar} \times \text{iter}\right) \times V_0 \tag{7.10}$$

where v_f is the pre-defined volume fraction constraint which represents the target volume divided by the full volume of the analysis domain, Ar is a predefined variation value, iter is iteration number, and V_0 is full volume. The calculated volume in Eq. (7.10) for each iteration is initially determined by multiplication of the variation value (Ar), iteration number (iter), and total volume (V_0). The calculated volume (V^{iter}) is linearly increased with the iteration number (iter) until the pre-defined volume fraction constraint (v_f) is reached. After that, the calculated volume (V^{iter}) remains constant until the computation is converged. According to the soft-add update scheme given in Eq. (7.10), the elements are equivalent to be numerically added into the analysis domain.

A threshold value for sensitivity number for each local iteration (it) is defined as:

$$\alpha_{th}^{it} = \left(l_1^{it} + l_2^{it}\right) / 2 \tag{7.11}$$

where $l_1^{it} = \tilde{\alpha}_{e,\max}^{iter}$ and $l_2^{it} = \tilde{\alpha}_{e,\min}^{iter}$ when $it = 1$..

Initially, the pseudo density of each element is assigned with the value of $x_{\min}$. If the filtered sensitivity number of the ith element is larger than the threshold value as in Eq. (7.11), the pseudo density of the element (x_i) is increased by one increment (Δx) in the local iteration (it). Otherwise, the pseudo density of the ith element is decreased by one increment. The pseudo density for each element can only be varied from $x_{\min}$ to one. The above rule can be formulated as:

$$x_i = \begin{cases} \min\left(1,\ x_i + \Delta x\right) & \text{when } \tilde{\alpha}_{e,i} > \alpha_{th}^{it} \\ \max\left(x_{\min},\ x_i - \Delta x\right) & \text{when } \tilde{\alpha}_{e,i} < \alpha_{th}^{it} \end{cases} \tag{7.12}$$

The calculated volume defined in Eq. (7.10) for each global iteration (iter) can be calculated by:

$$V^{iter} = \sum_{i=1}^{N_e} x_i V_e \tag{7.13}$$

where x_i is the pseudo density of the ith element, V_e is the volume of an element, and N_e is the number of elements in the analysis domain. If the value calculated in Eq. (7.13) differs from the previous value obtained in Eq. (7.10), the threshold value α_{th}^{it} as in Eq. (7.11) can be updated according to the following rules for l_1^{it} and l_2^{it}:

$$l_1^{it+1} = \begin{cases} l_1^{it} & \text{if } \sum_{i=1}^{N_e} x_i V_e > V^{iter} \\ \dfrac{l_1^{it} + l_2^{it}}{2} & \text{if } \sum_{i=1}^{N_e} x_i V_e < V^{iter} \end{cases} \tag{7.14}$$

$$l_2^{\mathrm{it}+1} = \begin{cases} \dfrac{l_1^{\mathrm{it}} + l_2^{\mathrm{it}}}{2} & \text{if } \sum_{i=1}^{N_e} x_i V_e > V^{\mathrm{iter}} \\ l_2^{\mathrm{it}} & \text{if } \sum_{i=1}^{N_e} x_i V_e < V^{\mathrm{iter}} \end{cases} \tag{7.15}$$

At the end of the topology optimization procedure, the following rule is used to check for termination:

$$\left| \frac{\sum_{n=\mathrm{iter}-9}^{\mathrm{iter}-5} c_n - \sum_{n=\mathrm{iter}-4}^{\mathrm{iter}} c_n}{\sum_{n=\mathrm{iter}-4}^{\mathrm{iter}} c_n} \right| \le \mathrm{err}, \mathrm{iter} \ge 10 \tag{7.16}$$

where c is objective function value, n is number, iter is iteration number, and err is a tolerance value.

7.2.2 *Topology Optimization Design of a Compliant Gripper for Grasping Fruits*

The topology optimization method introduced in Sect 7.2.1 is used to design a two-finger compliant gripper with high mechanical advantage. From Fig. 7.3, it can be observed that there are one fixed port, one input port, and two output ports defined for the compliant finger. The design domain as given in Fig. 7.3 is a trapezoidal area. The desired output port#1 is at the fingertip, and the desired output port#2 is at the midpoint of the finger length as indicated in Fig. 7.3. To ensure the existence of elements at the gripping jaw, a non-design domain (80 mm length region) is defined at the expected contact region (which is also the length of the finger). The pseudo densities for the elements in the non-design domain are pre-defined as one throughout the iterative process, whereas the pseudo densities for the elements in the design domain are initially assigned with the same value as $x_{\min}$.

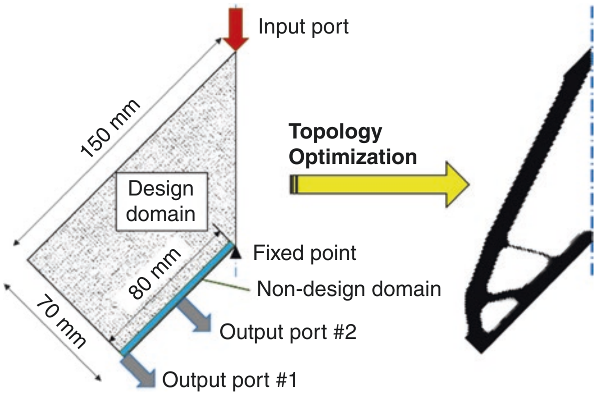


Fig. 7.3 Design domain, boundary conditions, and topology optimization result

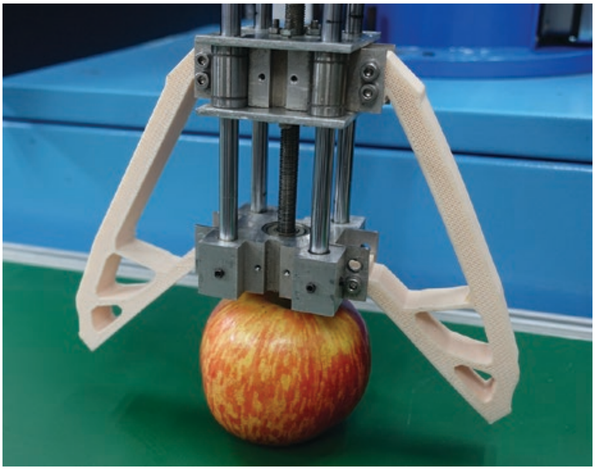
The parameters used in topology optimization include elastic modulus = 11.6 MPa, Poisson's ratio = 0.45, $\eta = 0.01$, $\zeta = 0.225$, $V^* = 0.2$, $p = 3$, $r = 7$, Ar = 0.01, $x_{min} = 0.001$, input force = 1 N, and numerical spring stiffness = 10^{10} N/mm. The dimension of each element is 1 mm × 1 mm. The topology optimization process for this analysis case is converged after 165 iterations. The topology optimization result for the compliant finger is given in Fig. 7.3, where the dark layout denotes elements with pseudo densities equal to 1.

7.3 An Intelligent Robotic Grasping and Laser Marking System for Fruits

The optimal finger design in Fig. 7.3 from topology optimization is prototyped by 3D printing using flexible thermoplastic filament. The prototype of the soft robotic gripper is given in Fig. 7.4. The compliant gripper module consists of one main frame structure and two identical compliant fingers. The thickness of the compliant finger is 20 mm. The input port of the finger (as denoted in Fig. 7.3) is mounted on the top moving platform of the main frame structure which can move along axes. A gear motor is used to drive the moving platform to move downward (or upward) to provide displacement input for the gripper. Both compliant fingers can deform elastically after the displacement input to perform the gripping motion. Figure 7.5 shows the photo when an apple is grasped by the soft robotic gripper.

The setup of the developed robotic grasping and laser marking system can be seen in Fig. 7.6. The automated system consists of the compliant gripper, a six-axis robotic arm (made by LIMING), a machine vision module, a laser marking unit (SYNTEC 70SB, laser power: 20 W), a conveyor, and a robot controller. The objects are initially placed on a moving conveyor passing through a machine vision camera as in Fig. 7.7(a); then the object position and size can be obtained. The robotic arm

Fig. 7.4 Prototype of the 3D-printed soft robotic gripper



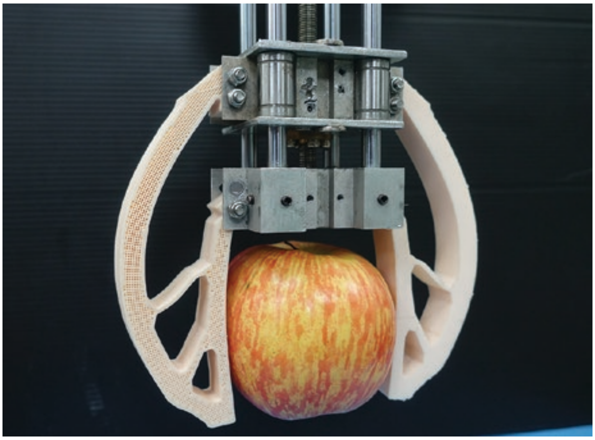


Fig. 7.5 Grasping object (an apple) using the developed soft robotic gripper

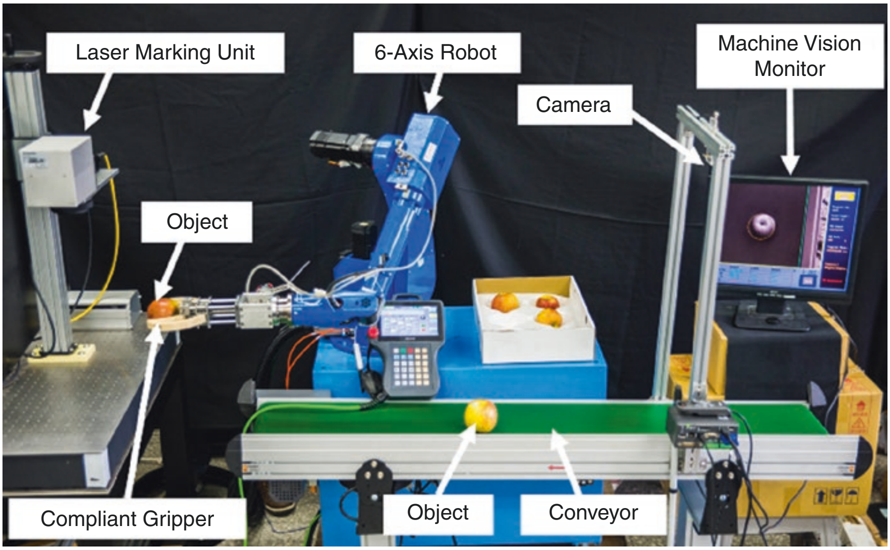


Fig. 7.6 Robotic grasping and laser marking system

can be guided using the machine vision module to move to the object location and grip the object. After that, the robot moves the object to the laser marking unit as shown in Fig. 7.7(b) to permanently create marks (such as PLU code) on fruit skin. Finally, the object is placed in a carton box as can be seen in Fig. 7.7(c). The objects used in this study are large Fuji apples (PLU code 4131); the laser marking result is shown in Fig. 7.8. Figure 7.9 shows the laser marking results on pomelo and peeled coconut.

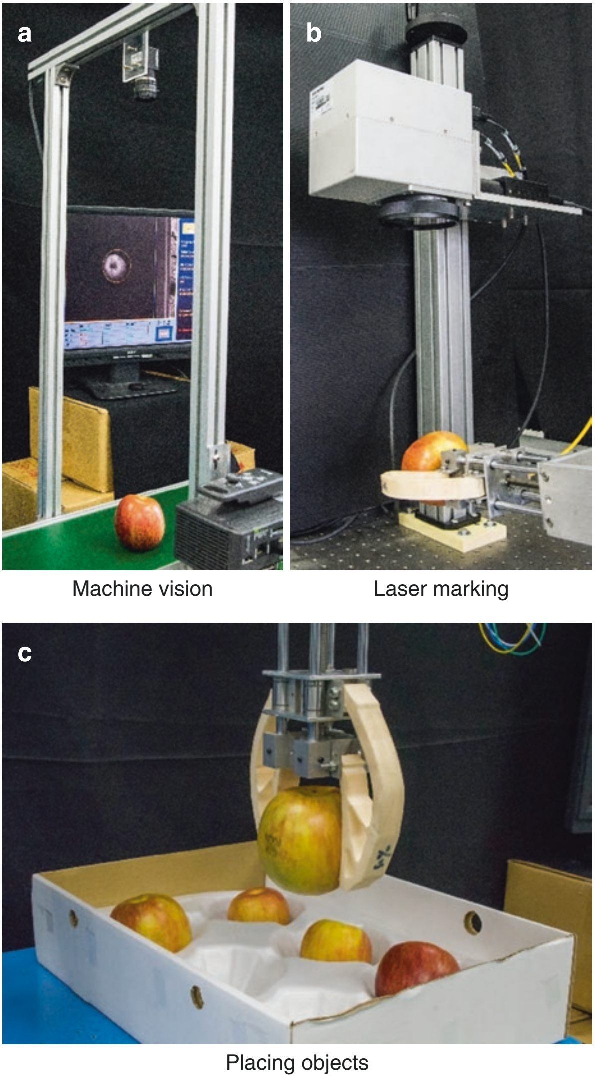


Fig. 7.7 Object detection, laser marking, and placing: (**a**) machine vision module to detect the object (apple) on a moving conveyor, (**b**) laser marking a gripped apple, and (**c**) placing objects

Fig. 7.8 Laser marking result on Fuji apple (PLU 4131)

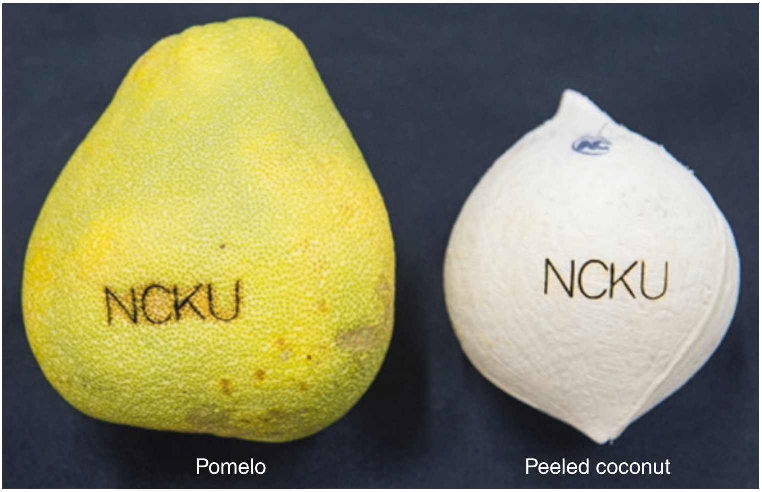


Fig. 7.9 Laser marking results on pomelo and peeled coconut

7.4 Summary

The prototype of an intelligent robotic grasping and laser marking system for fruits is implemented. From an environmentally friendly and sustainability perspective, the proposed system can minimize the usage of printed sticky labels on produce, as well as to avoid the possible falling off problem for PLU stickers. An innovative 3D-printed compliant gripper is also developed to pick and place a variety of objects with shape and size variations. Most importantly, the proposed gripper can be used for handling of delicate objects without causing damage. One of the critical issues in developing the system is to control the laser marking parameters (such as power, duration, and speed) to etch the produce skin such that generated laser marks do not penetrate completely through the produce skin to the meat of the produce. These laser marking parameters vary with the fruits. A systematic method to identify the optimal laser marking parameters for different fruits should be further investigated.

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Part II
Circular Economy

Chapter 8
Implications of the Circular Economy for Electronic Products

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8.1 Introduction

The European Commission has set the goal for the European Union to transition to a circular economy, in which linear production and consumption patterns of "take, make, dispose" are replaced by a circular approach, in which the value of products, components, and resources is maintained for as long as possible and the generation of waste is minimized. To enable the transition to a circular economy, the Circular Economy Action Plan of the European Commission [1] proposes actions aimed at supporting each step along the value chain—from production to consumption, repair and remanufacturing, waste management, and the production and usage of secondary raw materials. The Action Plan highlights the significance of electronic products for their content of valuable resources. Critical raw materials, as defined by the European Commission [2], and plastics are further identified as priority areas which face specific challenges in the context of the circular economy.

There is a wide consensus that the design of products needs to be adapted and that design is pivotal to the transition to a circular economy. Yet, few examples are available in the electronics industry, and of those a majority could be characterized to address niche markets or experimental stages. Specific examples start with something as simple as choosing materials with an established end-of-life (EOL) strategy and including postconsumer recycled (PCR) plastics during the production stage. More complex examples are design trade-off decisions between more robust

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designs which may extend the first use cycle of a product, and more modular designs to accommodate enhanced repair, reuse, and material recycling. This paper explores the following themes and questions: What are the key elements of the Circular Economy Action Plan with relevance to electronic products? How can reparability, upgradability, reusability, durability, and recyclability be integrated into the design of electronic products? How can remanufacturing of such complex products technically be addressed? How can a market for secondary raw materials such as high-grade plastics be fostered? For each of these themes, the paper explores which aspects are currently discussed with regard to possible new requirements under the European Ecodesign Directive and which approaches are currently being investigated and put into practice by companies and the scientific community.

8.2 Relevant Key Elements of the Circular Economy Action Plan

The Circular Economy Action Plan acknowledges the significance of the product design phase, in which the environmental impacts of the product life cycle are largely predetermined. Better design can make products more durable or easier to repair, upgrade, remanufacture, or recycle and thus help to save resources. Consequently, it is foreseen to promote better design by emphasizing circular economy aspects in future product requirements under the European Ecodesign Directive [3]. The objective of the Ecodesign Directive is to improve the efficiency and environmental performance of energy-related products. To date, requirements have mostly focused on improving the energy efficiency of electric and electronic products in scope of the Directive. However, the Action Plan explicitly states the goal to emphasize issues related to material efficiency, such as reparability, durability, upgradability, and recyclability. The provision of economic incentives to manufacturers whose products are easier to recycle, based on the end-of-life costs of their products, is suggested as another conceivable instrument to guide design decisions.

Material and energy efficiency aspects of production processes are foreseen to be addressed by promoting the socially and environmentally sustainable sourcing of raw materials. Further, enhanced remanufacturing is highlighted as a high-potential area to be funded via the EU's Horizon 2020 program, among others. The Circular Economy Action Plan also puts emphasis on the importance of consumption and the role of consumers in the transition to a circular economy. To this end, the communication of sustainability aspects of products toward consumers will be improved, for instance by including information on the durability of products via the existing energy efficiency label. Additionally, shared economy concepts and selling services rather than products are mentioned as viable approaches. With regard to material recycling at EOL, the need for quality standards to enable the increased use of secondary raw materials in the production processes, particularly recycled plastics, is highlighted. Furthermore, the need to stimulate sufficient demand for recycled materials is emphasized.

In summary, it can be said that the Circular Economy Action Plan takes the entire life cycle of products into focus, including closing the loop for components and materials, rather than focusing on recycling of EOL products only. However, in a survey of EU Member States, the EEA found that the majority of policy approaches employed to closing material loops across different life cycle stages has this far focused mostly on waste-related aspects and recycling [4]. Product design and measures aiming to enable reuse, repair, refurbishment, and remanufacturing activities were not found to be extensively reflected in policy approaches (Fig. 8.1).

Considering that WEEE is one of the fastest growing waste streams worldwide [5], focusing on waste management and recycling is essential but may not be the only approach to effectively address material efficiency. It has been shown that for some products, the environmental impacts embedded through resource extraction and manufacturing activities are much higher than the impact of all other life cycle phases. This is especially true for mobile ICT products, such as smartphones, tablets, and laptops, which are frequently highly energy efficient in the use phase [6]. Typically, the life cycle profiles of such devices show that the clear majority of environmental burden is associated with the manufacturing activities, while EOL processes only contribute minor shares while frequently recovering only minor shares of the complex material mixtures found in such products. This is illustrated via the example of a life cycle assessment of the Fairphone 2, a smartphone that follows a modular approach, and which emphasizes social and environmental values. It has been found that extending the time the product stays in the use phase,

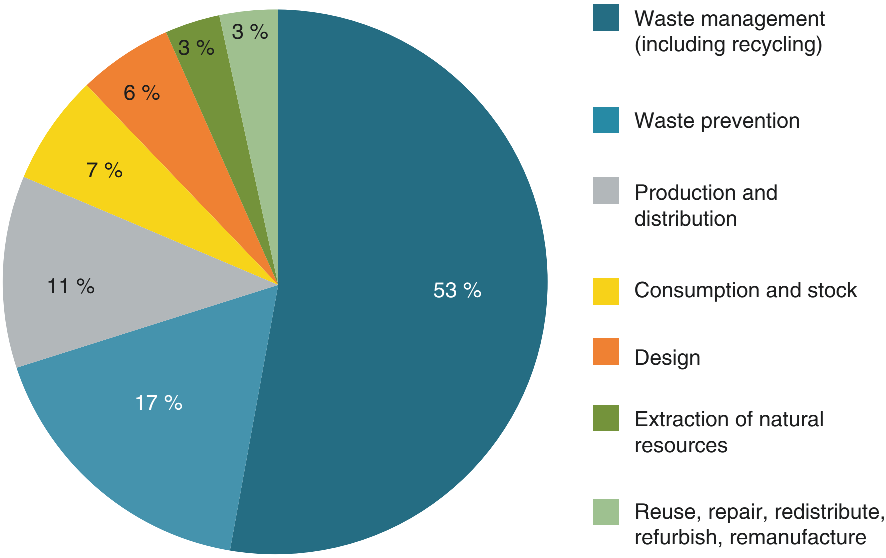

Fig. 8.1 Distribution of responses on policy approaches to closing material loops in a survey of Member States conducted by the European Environment Agency [4]

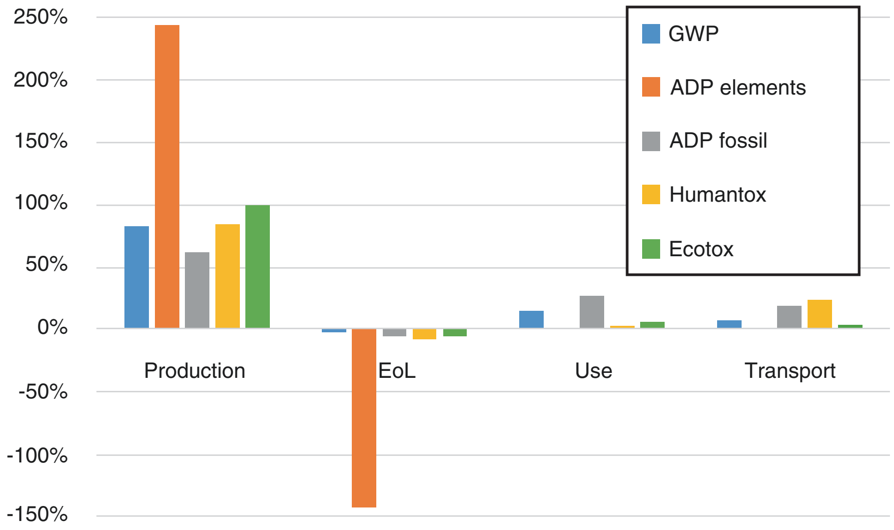

Fig. 8.2 Relative impacts of the different life cycle phases per impact category for the Fairphone 2 smartphone [7]

e.g. through design for reparability, is an effective path to mitigate environmental burden caused during the manufacturing phase [7] (Fig. 8.2).

8.3 Reparability, Upgradability, and Reusability of Electronic Products

For some product categories, particularly mobile ICT devices such as smartphones, tablets, and notebooks, the trend in product design in the past years has been to design increasingly slimmer and more integrated devices. One of the most extensively discussed components in this context are device batteries. This is because firstly, their functionality inevitably degrades over time and secondly, the concentration of valuable materials such as cobalt, lithium, and graphite, is relatively high. For the product groups mentioned above, it has become commonplace to integrate batteries into the products as opposed to designs which allow the user to easily remove and replace the battery without the use of tools. Depending on the design approach chosen by the manufacturer, this practice has the potential to considerably complicate the repair process once the battery needs replacement, in addition to removal of the battery at EOL for dedicated battery recycling. Determining factors for the ease of disassembly and separating the battery are mostly the joining techniques applied in the device and to fasten the battery (e.g. use of screws, clips, or adhesives) (Fig. 8.3).

While RAM and mass storage units are typically soldered directly onto the mainboard in smartphones and tablets, the same design choice can increasingly also be observed in notebooks. This trend further extends to notebook CPUs and GPUs,

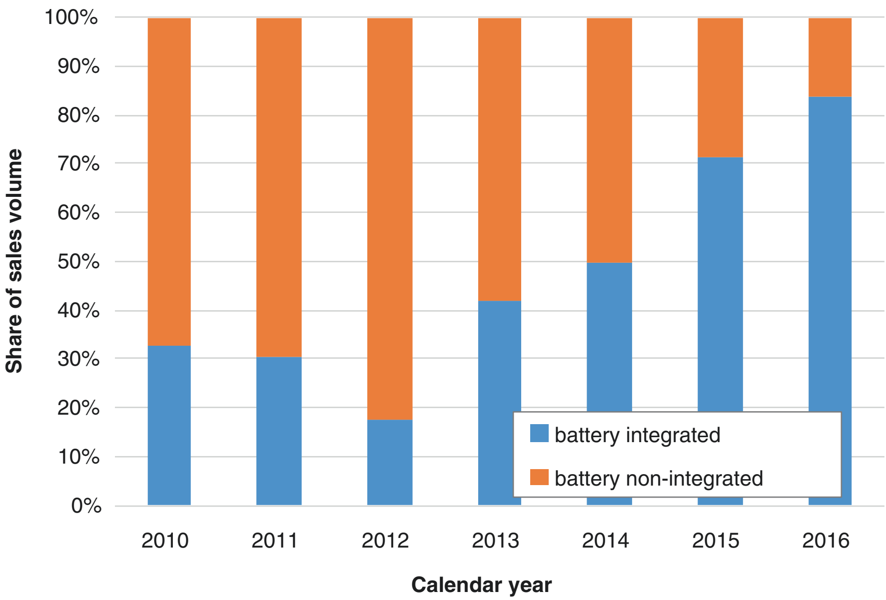

Fig. 8.3 Share of sales volume of best-selling smartphone models in Europe with integrated batteries and non-integrated batteries in the years 2010–2016 [8]

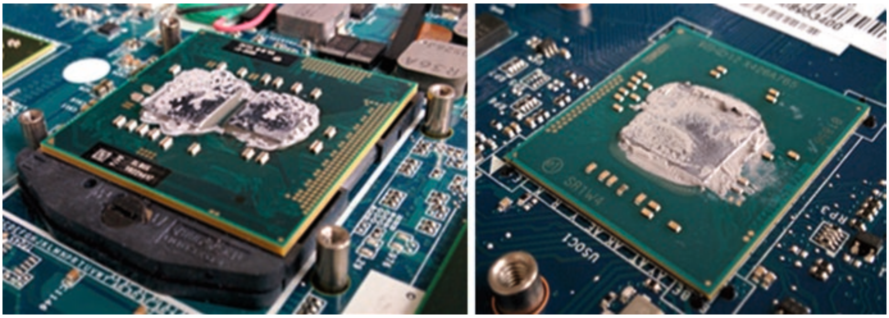

Fig. 8.4 Examples for integrated circuits on a notebook mainboard connected via PGA fitted into a socket (left) and directly soldered onto the mainboard via BGA (right)

which are moving away from technologies that reversibly join those components to the PCB, such as pin grid arrays (PGA) fitted into a socket, toward permanent joining techniques using soldering, such as ball grid array (BGA) technology. This approach may significantly complicate upgrade and repair activities for those components and can potentially be considered counterproductive to the objectives of the circular economy. On the other hand, more integrated solutions often also require less material, such as copper and gold, for electrical connections between components (Fig. 8.4), and may in some cases be more resitant to external stressors.

The Ecodesign Directive has been identified in the Circular Economy Action Plan to address such design aspects which influence aspects such as reparability, upgradability, and reusability of products. To this end, current preparatory studies and revisions of existing regulation under the Ecodesign Directive are introducing corresponding measures. Specifically, product groups in scope of such studies are electronic displays, including television sets [9]; computers, including notebooks and tablets [10]; and enterprise servers and network equipment [11]. For example, several draft requirements prohibit the use of welding (soldering) and gluing for certain components. In the case of desktop and notebook computers, the following components are explicitly mentioned: batteries, internal power supply units, display, mass storage system, memory, keyboard, trackpad, network interface board, and wireless LAN board. For tablets, soldering and gluing are not eligible for batteries and display. However, the use of adhesive tapes to adhere batteries is exempted from this requirement. The draft requirements further suggest making the provision of accompanying repair information by manufacturers mandatory. This includes, among others, exploded diagrams showing the location of listed components in a product and documentation of disassembly and reassembly operations.

The Fairphone 2 smartphone can serve as an example of an ICT product that employs a modular approach for improved reparability. The fact that the consumer can easily replace individual modules significantly lowers the barrier for do-it-yourself repairs and thus potentially allows the products to stay in use longer. The life cycle assessment of the Fairphone 2 demonstrated that although modularity implies a slightly increased impact associated with the manufacturing phase due to a slightly increased material usage, the enhanced reparability likely leads to significantly lower total life cycle impacts over an extended product lifetime [7] (Fig. 8.5).

The benefits of modular design in environmental terms ultimately depend on the user behaviour. The design strategy only fully pays off if the use period is indeed

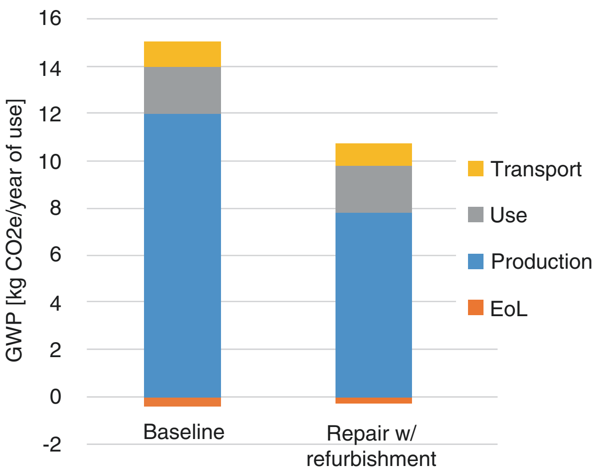

Fig. 8.5 Global warming potential of the Fairphone 2 life cycle per year of use (left, baseline scenario in which only the battery is replaced once in the use time of 3 years; right, repair scenario in which further components are replaced to extend the use phase to 5 years) [7]

extended, e.g. by swapping broken parts or upgrading components, or when components are separated at the EOL to enter dedicated recycling paths.

8.4 Durability of Electronic Products

Product longevity may be increased by the abovementioned design strategies for reparability, upgradability, and reusability, but manufacturers may also choose to design their devices for maximum robustness and reliability to extend the technical lifetime. For smartphones, tablets, and notebooks, this may mean constructing a compact device designed to withstand adverse events such as drops by the user and minimizing the risk of ingress of foreign matter such as dust and liquids. As is well known, certification for international protection (IP) according to the international standard IEC 60529 [12] is increasingly employed for smartphones and other devices to warrant ingress protection. However, constructing devices in such a way may require further integration of components into devices, as discussed in Sect. 8.3, potentially hampering the ability to repair and upgrade. Hence, contradictions between different design strategies appear inevitable, which may require manufacturers to prioritize one strategy over another. The Ecodesign Directive currently has only a limited number of requirements in place which aim at product durability. The approach is to target components in products that are considered to fail most frequently. In the case of vacuum cleaners for instance, the hose is required to be able to endure at least 40,000 oscillations under strain, and the operational motor lifetime is required to be greater than or equal to 500 hours [13]. New durability requirements have also been suggested in the above-mentioned draft requirements for computers [10] regarding the device battery: It is suggested that manufacturers communicate the remaining capacity the device battery can hold after withstanding 500 charge/discharge cycles during testing carried out according to the relevant IEC standard. While this is an information requirement rather than a specific threshold value for minimum durability, it is designed as an intermediate step toward a more concrete future requirement, as data can be collected to be used in setting a specific threshold in the future. Additionally, based on a draft technical report by the Joint Research Centre [14], it is suggested that manufacturers pre-install a software on notebooks which allows the users to limit the maximum state of charge of the battery to reduce the negative impact of high voltages on battery durability.

These examples show that the durability of devices needs to be evaluated on a case-by-case basis, as each product category may have different components most prone to failure, either due to technical reasons (battery) or due to common use patterns (displays with smartphones and tablets). Whether this is an efficient approach to product durability or whether other instruments may prove more practical, such as extended producer warranties, remains to be seen.

8.5 Remanufacturing and Cascade Reuse of Electronic Components

Keeping products in the use phase for as long as possible has been identified as a priority on the path toward a circular economy. However, it can be assumed that virtually all products will eventually be disposed of. Organizations involved with collecting and recycling WEEE commonly assess the potential for reuse of electronic devices and components. If reuse requires extensive repair and is not economically viable, components may be harvested for spare parts. Accounting for the fast pace of technological development, especially in the ICT sector, another application of functional components from EOL electronics may be cascade reuse in less demanding applications. Again, the viability of component harvesting depends on the joining technique applied, and soldered or adhered components may make this process considerably more complex, as the effect of subjecting ICs and printed wiring boards to additional soldering processes is not planned for in the original product design stage and may be detrimental to the product's functional integrity.

Nevertheless, desoldering flash memory components from smartphones for a cascaded reuse in applications such as USB memory devices is currently under investigation in the EU project sustainablySMART [15]. Desoldering of such BGA components is challenging as there is the trend to use increasingly underfillers for these packages, which enhances reliability of the assembly, but results in residues at the point of desoldering. This is actually a good example of trade-offs in a circular economy: Better reliability of assemblies is beneficial for an extended first product life. However, repair and a second component life face an additional barrier through the use of underfillers (Fig. 8.6).

Under these conditions a circular economy strategy needs to define whether to prioritize a longer first life or a component second life. Another challenge is the number of reflow cycles a BGA component undergo in such efforts: Typically, BGA components are qualified for a limited number of reflow cycles, which correspond to first production, and a component rework in first production might already go

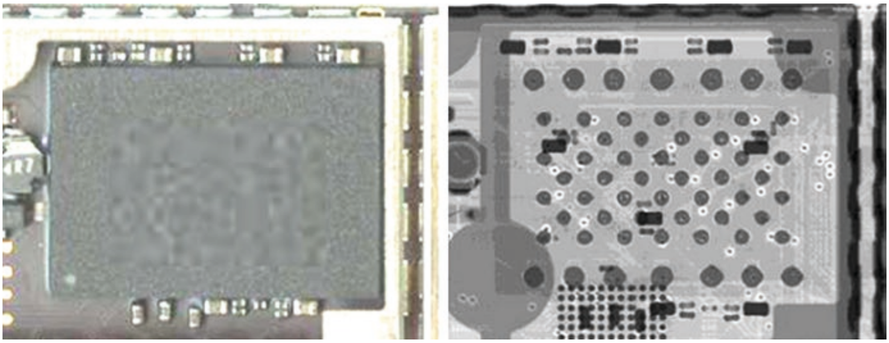

Fig. 8.6 Flash memory BGA (left, photo with underfill meniscus visible on the left side; right, X-ray image with solder balls visible underneath the component) [15]

beyond the number of soldering cycles the component is designed for. For a second life, another sequence of desoldering, reballing, and resoldering processes is required, which leads to additional stress on the component. Sitek et al. [15] at least report that investigated memory BGA packages withstand numerous reflow cycles and still pass quality and functional tests.

Another aspect of concern is data erasure from memory components for a second life. Recently, cases were reported in which data could be retrieved from newly manufactured USB sticks, and it was found that the storage units stemmed from discarded smartphones [16]. The project sustainablySMART also investigates data erasure routines to reliably erase data from BGA flash memory components. The challenge is that eMMC technology used for smartphone flash memory is based on an integrated memory controller in the memory package. This controller governs access to the actual memory, and any data deletion process has to be adapted to the internal memory controller.

Another step forward is to consider reuse scenarios as early as in the product design stage. Circular Devices, for instance, the company behind the PuzzlePhone concept, has thought up several ways in which components can be used if they are no longer fit to satisfy the demands of users in their primary function. These include the integration of the "brain module," containing the main computing elements, into a supercomputer-like cluster, as is illustrated in Fig. 8.7 [17].

Conclusively, reuse approaches have a great potential to maximize the efficiency of resources incorporated into products and components; however, there seems to be a long way ahead before the practice can become commonplace. Compatibility of components between different products and product generations is an issue that could be addressed by modularity in conjuction with standardization of aspects such as form factors, electrical connectors, and software.

8.6 Plastics in a Circular Economy

Of the estimated 20–50 million tons annual waste of electric and electronic equipment (WEEE), an average of 21 % by weight are plastics [18]. While valuable metals from WEEE are frequently recovered at high rates, the same cannot be said about plastics. For one, the economic value of plastics from WEEE is orders of magnitude below the value of metals such as gold, silver, and platinum and well below metals such as copper, cobalt, and gallium [5]. Additionally, the variety of available combinations of polymers and polymer blends, as well as additives such as flame retardants, plasticizers, and reinforcing agents, makes an efficient and effective separation and recovery challenging. The dominating approach to separating polymers from shredded WEEE fractions is the sink and float method. One or several sequential salt-containing solutions keep materials below a defined density afloat, while materials with a higher density will sink to the ground. Density separation is usually designed to keep the polymers most commonly found in WEEE afloat, i.e. ABS, PS, and PP, while other materials, such as glass and plastics

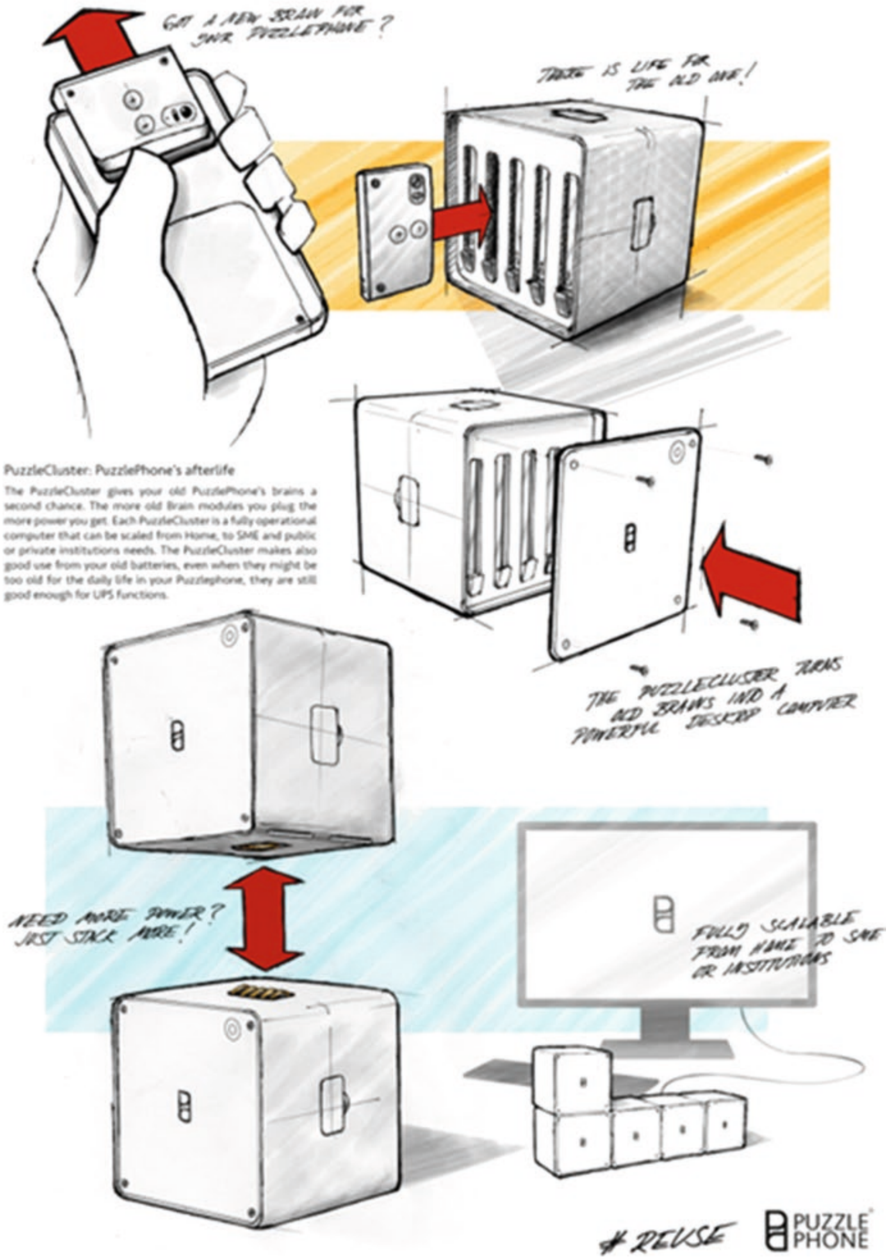

Fig. 8.7 Design concept showing reuse of compute modules enabled through high integration technologies [17]

containing flame retardants, sink [19]. Other solutions to separate different plastics include optical techniques such as NIR and MIR or selective solvent extraction, such as Fraunhofer IVV's CreaSolv® process. The latter can even separate additives, such as brominated flame retardants or antimony trioxide, which are typically lost in electronics recycling processes despite the fact that antimony is on the European Commission's Critical Raw Materials agenda. The process is under research in the Horizon 2020 project CloseWEEE [20].

One barrier to closing the loop for plastics in EEE is the use of materials that are currently not recyclable from a technical or economic point of view, such as polymers reinforced with glass fibers and carbon fibers. Co-molded plastic parts are also of concern. The circular economy, particularly in the case of postconsumer recycled (PCR) plastics, also has a conflict to solve between high recycling rates and removing potentially hazardous substances from the material cycle: Thresholds under European RoHS, POP, and other directives are usually defined on the basis of detection limits. In the case of recycled polymers from postconsumer plastics, there is always a share of historic waste, which still contains banned materials. Although no hazardous materials are intentionally added to the recycled polymers, concentrations will be higher compared to virgin polymers, which never have been brought in contact with said substances. Furthermore, not all brominated flame retardants are banned or regulated, but NGOs and industry frequently require "halogen-free" material—which, depending on the defined threshold, is a clear barrier to use recycled plastics in new products.

Another gap to closing the loop for plastics in EEE has been stated to be the demand side of recycled polymers [1]. While several manufacturers of EEE have incorporated recycled plastics in their devices for many years, large-scale integration of PCR plastics is not yet commonplace. Manufacturers require materials with reliable and consistent quality and a stable supply at reasonable prices. The latter implies that recycled materials should be available at equal or below the cost of virgin materials. As recycled polymers are not necessarily equal to virgin materials in terms of material purity—ABS can reportedly be separated with 99% and PS with 98.5% purity [19]—virgin materials may be regarded by manufacturers as the more reliable choice. Consequently, an absence of incentives may be the reason for the lack of a large-scale implementation of WEEE PCR plastics in newly manufactured EEE.

The use of recycled plastics in new applications on a large scale is an endeavor with high complexity and influenced by many different yet interlinked factors—not only the quality but also a guaranteed availability and stable price of recycled plastics influence the decision whether or not the final user will select PCR plastics over virgin materials. In an economic system, where recycling is a for-profit activity, product design and material choices can result in favorable or unfavorable economics of the recycling processes and final material price. Even if a product is technically recyclable, but the process of material liberation and recycling does not result in positive economic value, products are not likely recycled [21]. Mindful material selection paired with product design, linked to disassembly, material liberation, and economically running sorting and recycling processes could contribute positively to increased yields of high-quality recycled plastic and overall improvement of the economics across the value chain.

Several voluntary schemes currently list PCR plastics content in their criteria. For example, EPEAT lists the declaration of postconsumer recycled plastic content as a required criterion and the actual implementation of PCR plastics in products in ranges of either 5 %–10 % or above 25 % as optional criterion for imaging equipment [22]. TCO criteria for displays require a minimum of 85 % postconsumer recycled plastic for cutting-edge products [23]. However, in terms of European legislation, obligatory requirements are currently not in place. Preliminary suggestions for revised requirements under the Ecodesign Directive for printers suggest a tiered approach, requiring the use of PCR plastics from WEEE in printers starting with a low percentage to be increased over time [8], in order to stimulate a growing market for PCR plastics and ultimately close the loop.

8.7 Conclusions and Outlook

The EU's Circular Economy Action Plan sets the goal of transitioning from a linear to a circular economy and identifies concrete actions to facilitate this transition. Some of the identified actions have already been taken up in defining new product-level requirements under the European Ecodesign Directive. This approach will in the future be supported by a set of standards, which has been commissioned to the EU's standardization organizations under standardization request M/543. This work will produce calculation and test methods with reference to product durability, upgradability, reparability, and reuse and remanufacturing [24]. However, the efficiency and effectiveness of prohibiting or prescribing certain technologies for specific product categories in the scope of the Ecodesign Directive may be questioned. Moving to an approach in which the goal is prescribed, while the process to get there is left to manufacturers, product designers may eventually yield better solutions. For instance, if extended producer warranties were to be prescribed, the technical solutions to achieve the target may be left to the manufacturers. A further step may be to set performance indicators on company level with goals to lower the primary material input per unit of product produced and thus pushing the market to new solutions for material efficiency.

What's more, changing product design and enhancing the recycling rates are just one puzzle piece in the big picture. To truly transition from a linear to a circular economy, the way we do business eventually needs to change. New and innovative business models are needed that generate benefits for the company, the prosumer, and other stakeholders while minimizing negative impacts on the environment. The guiding principle is to preserve the highest possibly integrity of the product to retain its possibly highest value. In order to retain this value for as long as possible implies moving away from selling a product, toward providing the product as a service for as long as possible, including repair and refurbishment activities. Furthermore, products should be used more efficiently through multiple use by different users (sharing) or (cascade) reuse of the product (in different applications). In such circular economy business models, revenue is generated through pay-per-service, lending, or contracting models, rather than selling as many units as possible. The idea behind this is that, all things considered, following the efficiency, sufficiency, and consistency strategy will be better for the people, the planet, and for business alike.

Until this vision of a circular economy becomes a reality, technological solutions can be expected to be incrementally implemented by frontrunning companies, such as Fairphone and others, and via new requirements set out by political instruments such as the Ecodesign Directive. The path toward a circular economy has been set, and the implications on electronic products are undeniably taking shape.

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Chapter 9
Modeling and Analysis of Material Flow Toward a Better E-Waste Recycling System in Malaysia

Mohamad Afnan Haziq and Nozomu Mishima

9.1 Introduction

9.1.1 Background

The term "e-waste" refers to electrical and electronic devices that have reached their end-of-use (EOU) stage. E-waste is often categorized as a type of hazardous waste because it contains hazardous materials such as lead, cadmium, and chromium [1]. Thus, e-waste is dangerous and considered harmful to human health, as well as to the environment, if it is not disposed of properly. While it comprises various hazardous materials, it also contains different precious metals. Metals such as gold, copper, and silver can be recovered from e-waste [2], but if e-waste is disposed of in an improper way, such as landfilling, these precious metals cannot be recovered. This may lead to the issue of depletion of precious metal resources.

Some examples of the e-waste problem are appliances and devices that have reached their EOU stage being hoarded in houses, e-waste being improperly recycled by unlicensed parties and premises, and illegal importation and exportation of e-waste [3]. One significant consequence of these issues is a scarcity of data on e-waste. This particular problem occurs in most countries, and it only gets worse when it comes to developing countries. The problem of not having e-waste data available is that we cannot take appropriate and effective measures to address a country's emerging e-waste problems.

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9.1.2 E-Waste in Malaysia

In the year 2005, new regulations—the Environmental Quality (Scheduled Wastes) Regulations 2005—were established in Malaysia. Under the new regulations, e-waste was not defined specifically but falls within the scheduled waste category of SW110 [4]. Thus, any waste that is listed as scheduled waste shall be disposed of and treated in prescribed or licensed premises only. The Environmental Quality (Scheduled Wastes) Regulations 2005 have been enforced mainly in the industrial sector. Hence, e-waste produced by the industrial sector is mostly being managed properly and treated in an environmentally sound manner. Data on e-waste in the industrial sector are also recorded. In contrast, there is no specific regulation or management system designed for the household sector in Malaysia. As a result, no data on e-waste produced from the household sector are available.

The lack of data on the household sector suggests that issues such as discarding e-waste as normal municipal solid waste and keeping used products on personal premises after upgrading to a new product are occurring in the household sector in Malaysia. Both of these problems result in serious adverse effects on both the environment and the economy. The potential economic harm caused by hoarding of used products may be undervalued by users, but for a circular economic model to function effectively, loss of resources and value within the loop must be reduced. It stands to reason that any leakage, including hibernation (referred to as "hoarding" in this paper), will have manifold effects because not only are precious resources lost for reinvestment as remanufactured components or reused products but also the shortfall in materials will necessitate a rebalancing with virgin stock [5]. In December 2013, one of the leading consumer electronics chain stores in Malaysia, Senheng Electric (KL) Sdn. Bhd., launched its e-Waste Alam Alliance Recycling Program to aid and promote recycling awareness among Malaysian consumers. The program provides two services: it offers cash vouchers for nonbulky e-waste items brought into any Senheng outlets, and it operates a free on-call e-waste collection service [6]. However, despite these efforts, data on the household sector, such as the e-waste collection rate and recycling rate, are still scarce.

9.1.3 Study Objective

The objective of this study is to clarify the flow of e-waste in Malaysia by creating an e-waste flow model and estimating the scarce data. Also, from analysis of the estimated data, we hope to propose an idea or two for a better recycling system in Malaysia. The scarce data can be listed as follows:

(a) The amount of e-waste that is recycled.
(b) The amount of e-waste that goes to landfill or is improperly recycled.
(c) The amount of e-waste that is reused.
(d) The volume of unused appliances and devices that are stocked in houses.

Most previous studies have focused only on one particular consumer sector in Malaysia—either the household sector or the industrial sector. In this study, we try our best to consider and include both sectors as the main e-waste generators in order to get a clearer image of how e-waste flow works on a national scale in Malaysia.

The case study is divided into two parts according to the appropriate e-waste generator sector. For the industrial sector, any product that can be listed as scheduled waste as per the Environmental Quality (Scheduled Wastes) Regulations 2005 is part of the case study. The case study for the household sector includes televisions, refrigerators, air conditioners, washing machines, personal computers (both desktops and laptops), and mobile phones. We use the term “e-waste” to summarize all of the case studies involved in this study. Most previous studies on e-waste have focused on one specific product, such as televisions or personal computers, for their case study, but we have decided to stick with the decision to use “e-waste” as the terminology in our case study.

9.2 Methodology

The main method implemented in this study is called material flow analysis (MFA). MFA is an established methodology used to characterize the flows of materials in a defined system [7]. It involves making a model that represents how a certain material moves around within the targeted system and characterizes the movement of the material by filling the necessary data into the model. Here, the movement of the material is called “flow.” Therefore, by implementing MFA in this study, we can clarify the actual flow of e-waste within Malaysia. On top of that, e-waste data are also needed in order to characterize the flow of e-waste in Malaysia. As mentioned earlier, e-waste data in Malaysia are very scarce, which means that data on e-waste need to be estimated.

The e-waste flow model for this study is shown as in Fig. 9.1. In Malaysia, municipal solid waste and scheduled/hazardous waste have a higher probability of containing e-waste than clinical waste. Both come from the household sector and

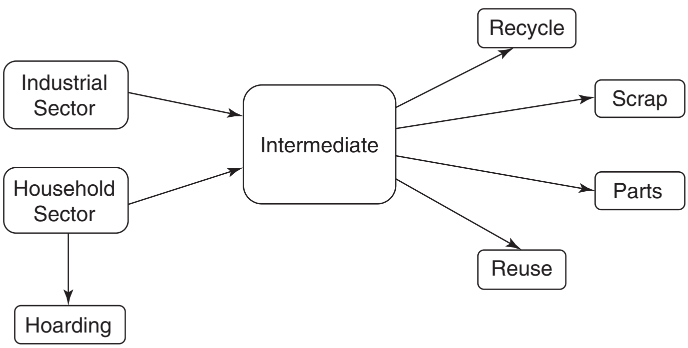


Fig. 9.1 E-waste flow model for Malaysia

the industrial sector, respectively; hence, we use them as the flow model's two main e-waste generators.

The "intermediate" sector is an assumed sector setup designed to organize and simplify the flow model. The actual flow between e-waste generators and e-waste disposal destinations is very complex, and by simplifying the flow model, it is easier to understand e-waste flow in Malaysia without having to focus on insignificant information. The "intermediate" sector in the flow model includes all of the actions, processes, and premises that are involved between the e-waste generators and the e-waste disposal destinations.

Importation and exportation of e-waste are not included in the flow model because this study is intended to focus on domestic e-waste data. We believe that focusing on internal e-waste flows is the very first step toward establishing a better e-waste management system in Malaysia.

9.3 Data and Results

9.3.1 Data Estimation

The data have been collected and estimated from various prior studies. The previous years' data on the industrial sector have been collected from the Department of Environment's website and other previous studies [8], while the data on e-waste from the household sector have mainly been collected from a survey report conducted by the Sustainable System Design Institute [9]. Scenario analysis has been implemented to estimate the amount of e-waste that goes to each of the e-waste disposal methods: "recycle," "scrap," "parts," "reuse," and "hoarding."

9.3.1.1 Extrapolation and Scale-Up Calculations

The only available e-waste data are the previous years' data from the industrial sector. The available data only show the weight of e-waste generated by the industrial sector in Malaysia from 2006 until 2011. In order to project e-waste data from the industrial sector in 2012, a linear extrapolation method is implemented. The calculation is as follows:

$$\begin{gathered} W_{2012} - W_{2006} = \frac{W_{2011} - W_{2006}}{Y_{2011} - Y_{2006}} \left(Y_{2012} - Y_{2006} \right) \\ W_{2012} = 150,033\,\text{tonnes} \end{gathered} \tag{9.1}$$

W_{2012} is the weight of e-waste generated by the industrial sector in 2012, W_{2011} is the weight of e-waste generated by the industrial sector in 2011, and W_{2006} is the weight of e-waste generated by the industrial sector in 2006. Y_{2012}, Y_{2011}, and Y_{2006} are the years 2012, 2011, and 2006, respectively.

Next, data on e-waste generated by the household sector in 2012 are estimated. The survey report conducted by the Sustainable System Design Institute is used as the main reference to estimate the weight of e-waste produced from the household sector on a national scale. The calculation is as follows:

$$\begin{aligned} W'_{2012} &= \frac{W'_{2011}}{PP_{2011}} \times PM_{2012} \\ &= \frac{15{,}149}{1{,}601{,}000} \times 29{,}240{,}000 \\ &= 276{,}675\ \text{tonnes} \end{aligned} \tag{9.2}$$

W'_{2012} is the weight of e-waste produced by the household sector on a national scale; W'_{2011} is the weight of e-waste produced by the household sector in Penang state. PP_{2011} and PM_{2012} are the population of Penang in the year 2011 and the population of Malaysia in the year 2012, respectively.

9.3.1.2 Scenario Analysis

The scenario analysis is a scenario-based estimation method. A scenario-based coefficient needs to be determined for every e-waste disposal method in the model flow, which will be used to estimate the scarce data. The scenario-based coefficients are shown in Table 9.1. These coefficients have been determined on the basis of previous studies that mainly focused on consumers' preferred e-waste disposal options. Once again, those studies focused only on a specific state for their case study, so we try our best to accumulate these kinds of studies as much as possible to use them as references so we can estimate the scarce data on a national scale.

Thus, multiplication of the coefficients by the weight of e-waste produced corresponding to its sector will give data on the weights of e-waste that flow to "recycle," "scrap," "parts," and "reuse." As for estimating "hoarding," the average numbers of hoarded e-waste units are derived from a prior study [10]. Thus, the data can be calculated as follows:

$$\begin{aligned} &\text{Total of hoarded e-waste} \\ &= \text{Average numbers of hoarded e-waste units per household} \times \text{Number of households in 2012} \\ &= 0.28 \times 6{,}800{,}000 \\ &= 1{,}915{,}333\ \text{units} \end{aligned}$$

Table 9.1 Scenario-based coefficients for each sector

Sector	Recycle	Scrap	Parts	Reuse
Industrial	0.75	0.07	0	0.18
Household	0.0395	0.2150	0.2003	0.5452

Table 9.2 Details of "hoarding" calculations

Type of product	Percentage of e-waste disposed of (%)	Number of e-waste units hoarded	Average weight per unit (tonnes)	Weight of e-waste hoarded (tonnes)
TV	38.40	735,488	0.0316	23,241
Refrigerator	14.34	274,659	0.0350	9613
Washing machine	5.395	103,332	0.0650	6717
Air conditioner	25.41	486,686	0.0480	23,361
Personal computer	15.62	299,175	0.0067	2004
Mobile phone	0.8361	16,014	0.0001	2
Total				64,938

The calculation above shows the number of hoarded e-waste units in Malaysia. Hence, to use the number in the flow model, conversion of units into tonnes is necessary to match up with the other estimated data. First, the numbers above need to be broken down into the amount of e-waste hoarded for each different type of product disposed of by the household sector (Table 9.2). Then, by multiplying the average weight of every e-waste product, the total weight of hoarded e-waste can be calculated.

9.3.2 Results

The completed flow model is shown in Fig. 9.2. In the year 2012, a total of 427,000 tonnes was disposed of, of which 150,000 tonnes and 277,000 tonnes came from the industrial sector and the household sector, respectively. From these numbers, 123,000 tonnes of e-waste was sent to recycling facilities for appropriate processing; 70,000 tonnes of discarded e-waste ended up in landfill; 55,000 tonnes of e-waste was disassembled into parts for reuse purposes; 178,000 tonnes of e-waste was reused in various ways, such as being donated or resold as secondhand products; and 65,000 tonnes of e-waste was estimated to be hoarded or kept on personal premises. This number only shows the estimated volume of hoarded electrical and electronic appliances no longer in use.

9.4 Analysis of the Results

The household sector became Malaysia's largest e-waste generator in 2012, as it generated almost twice as much e-waste as the industrial sector. Of the total amount of e-waste generated by both the industrial and household sectors, 42% was reused,

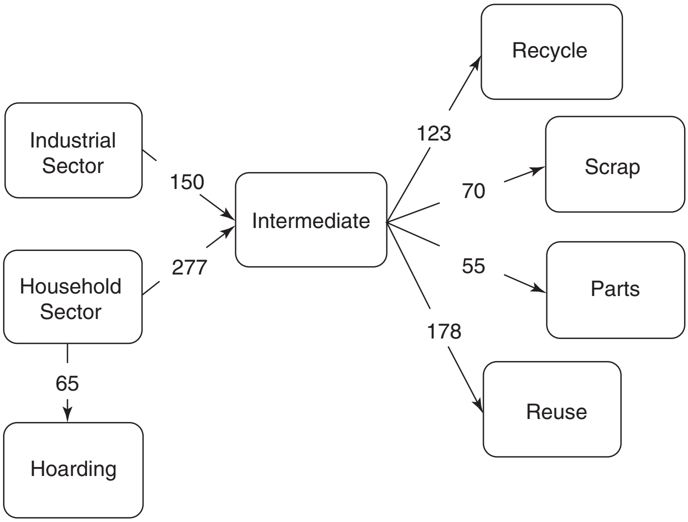


Fig. 9.2 Completed e-waste flow model; all numbers are rounded to the nearest kilotonne unit

making "reuse" the most preferred e-waste disposal method. The next preferred disposal option was "recycle," with 29% of e-waste being discarded for recycling purposes. "Scrap" and "parts" came in third and last as disposal methods, respectively, with only a slight difference in their percentages (16% and 13%, respectively).

From comparison of the e-waste data for the industrial and household sectors (Fig. 9.3, top panel), it is obvious that e-waste in the household sector is not being managed properly at present. Although 29% of the e-waste from both sectors goes to "recycle," only 9% of the recycled e-waste comes from the household sector; the rest comes from the industrial sector alone. This indicates that the industrial sector in Malaysia is currently excelling in managing the e-waste it disposes of. Next, of all of the e-waste that goes to "scrap," 15% and 85% originate from the industrial sector and the household sector, respectively. Fifteen percent of the e-waste that originates from the industrial sector is actually the remaining unrecoverable materials from e-waste that has undergone dismantling, separation, and metal recovery processes in licensed facilities. Hence, the e-waste from the industrial sector that flows into "scrap" can be considered less dangerous than the e-waste from the household sector that goes to "scrap," because the latter does not undergo any filtering processes. As for the "parts" and "reuse" e-waste flows, both are dominated by e-waste from the household sector: 100% and 85%, respectively. All of these percentages show that the household sector's e-waste management is in bad condition. In addition, by looking at the household sector data alone, it can be shown that the e-waste collection rate in the household sector at the national level is in a severe condition, with only 3.95% of e-waste being delivered to licensed recycling facilities, while 19.2% of all e-waste from the house-

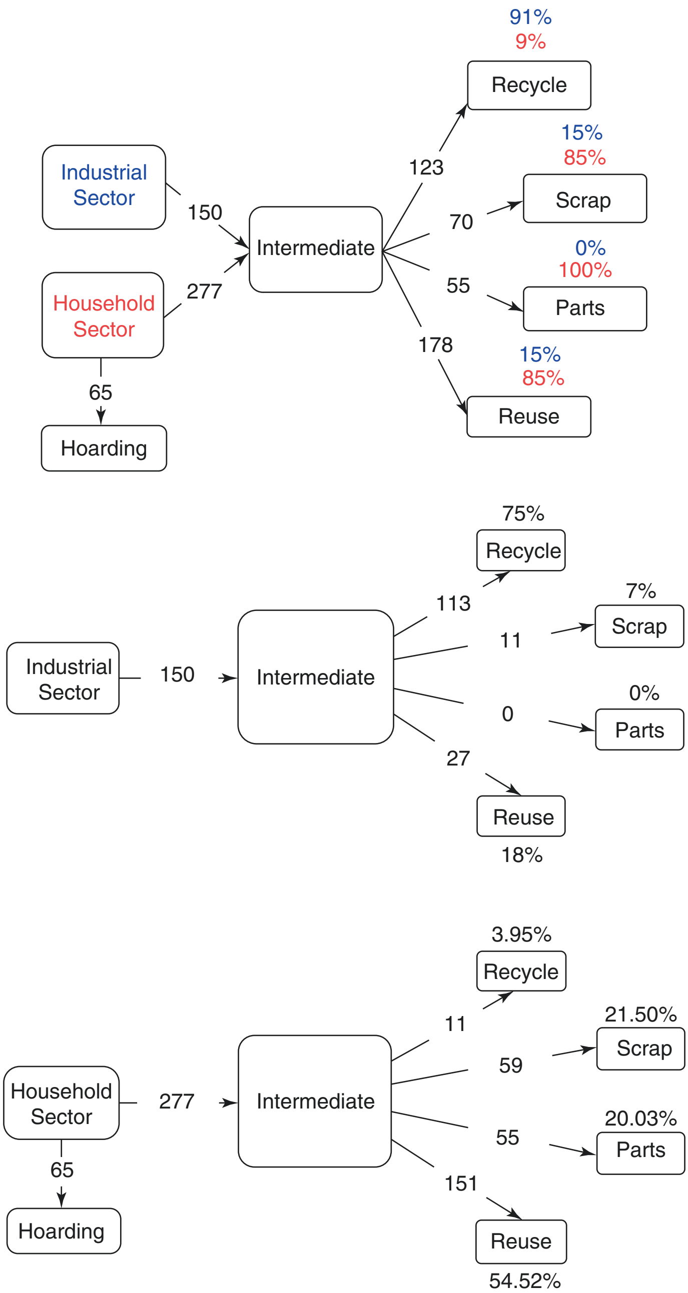


Fig. 9.3 E-waste flow from the industrial and household sectors, expressed in kiloton units and percentages. *Top:* Comparison of e-waste flow from both sectors. *Middle:* E-waste flow from the industrial sector. *Bottom:* E-waste flow from the household sector

hold sector is being hoarded in houses. The detailed percentages of e-waste flowing into each EOU option from each sector are shown in Fig. 9.3 (middle and bottom panels).

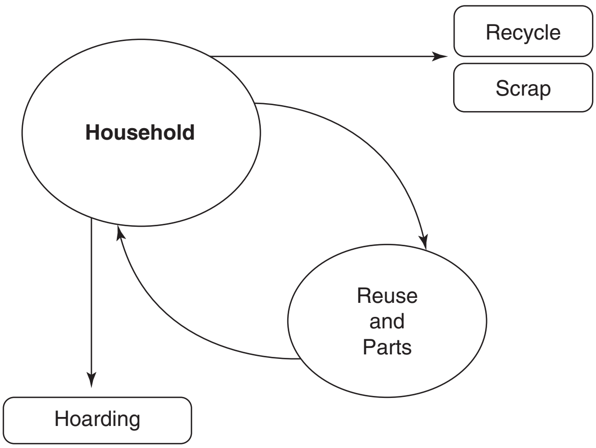
9.5 Idea Proposal

According to our analysis of the results, it is clear that the management of e-waste in the household sector in Malaysia is currently below par. Thus, we would like to propose ideas to contribute to a better e-waste management system in Malaysia, especially in the household sector. The main objective of this idea proposal is to maximize the proportion of e-waste that flows into recycling facilities for recycling purposes. The main target of this idea proposal is the household sector.

From this study's results, we realize that there is a specific pattern of e-waste flow in Malaysia's household sector, which is shown in Fig. 9.4. "Reuse" and "parts" are definitely not the last destinations of e-waste discarded by households. What these disposal methods do is delay the arrival of e-waste reaching other disposal destinations. These disposal methods are commonly regarded as alternatives to recycling; thus, "reuse" and "parts" cannot be considered a problem for the e-waste management system. Therefore, the other e-waste disposal options that remain are "recycle," "scrap," and "hoarding." On the basis of this study's results, "recycle" is the least preferable option of the three options mentioned earlier. As a result, we can conclude that the problems that need to be addressed are "scrap" and "hoarding."

We propose that "scrap" should not be considered a "disposal option"; instead it should be recognized as a "source" of resources—at least by the Department of the Environment (DOE)—to promote urban mining. The main task is to separate

Fig. 9.4 E-waste flow pattern in the household sector



e-waste from other municipal solid waste before landfilling takes place. Such separation and filtration processes should be conducted near or at every landfill site, and the separated e-waste should be transported to nearby e-waste recycling facilities so as to minimize the cost of transportation of e-waste between the landfill and the place where such separation occurs. Moreover, on the basis of this study's data, televisions, air conditioners, refrigerators, and computers should be given higher priority in separation of e-waste from other municipal waste because of their abundance in terms of volumes (see Table 9.2).

Hoarding is also one of the problems that are detrimental to urban mining. Increasing the e-waste collection rate is the best way to address this issue. The general idea is to increase the number of e-waste recycling facilities so the e-waste collection rate in the household sector will rise. According to data reported by the DOE in 2012 [11, 12], a number of e-waste recycling facilities have indeed been established. Moreover, the DOE has provided 309 recycling bins to collect unused mobile phones in different locations—for example, supermarkets, universities, and government offices [13]—but the fact that the e-waste collection rate is still below par cannot be ignored. Therefore, our idea is to conduct an investigation to identify which areas have severe e-waste hoarding problems, so that recycling collection bins and processing facilities can be relocated in those identified areas. Most of the facilities that are listed by the DOE are located in industrial areas, and recycling bins are located in urban areas. However, there are no studies indicating or showing that urban areas in Malaysia have a much more severe e-waste hoarding problem than rural areas. We believe that without identifying the problem areas first—for instance, urban or rural—we cannot increase the efficiency of e-waste collection programs.

9.6 Conclusion

Sound e-waste management is a significant factor in maintaining sustainable ecology. According to our e-waste flow model and comparison of the data for the industrial sector and the household sector, e-waste management in Malaysia, especially in the household sector, is still inadequate. Malaysians tend to reuse their e-waste instead of taking it to recycling facilities for recycling purposes. Landfilling e-waste also still occurs, as does hoarding of e-waste on personal premises. In addition, the e-waste collection rate in Malaysia's household sector is still at a low level. Hence, this study proposes that separating e-waste from landfilling sites and increasing e-waste collection rates by identifying areas that have severe e-waste hoarding problems might be a solution to help maximize the volumes of e-waste flow into recycling facilities [14].

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Chapter 10
Component Recoverability Analysis in Product Design Using System Dynamic Modelling

Novita Sakundarini, Nur Shafieza Riwayat, Christina May May Chin, Eng Hwa Yap, Raja Ariffin Raja Ghazilla, and Salwa Hanim Abdul-Rashid

10.1 Introduction

Component recoverability analysis aims to examine a product at its conceptual design stage to determine the ease of its recovery at its EOL. With many EU directives such as energy-related product (ErP) [1], end-of-life vehicles (ELV) [2], and waste electronic and electrical equipment (WEEE) [3] in place, manufacturers are obligated to design eco-friendly products for the consumer market. A component at its EOL can be remanufactured to an almost new condition after disassembly, sorting, cleaning, inspection, recycling or refurbishment, reassembly, and testing [4].

Although there are many studies focusing on manufacturing eco-friendly products for cleaner disposal and sustainable manufacturing, very few emphasise on offering tools at the design stage to manage the conceptualization of recoverable design of the product as opposed to managing its disposal or manufacture. Within the last 20 years, conventional disposals of WEEE through incineration and landfill are causing pollution, depletion of resources, and overcapacity of landfills [5, 6]. Thus, it is imperative that products are designed not just for its application or dis-

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posal but also with its recovery in mind. To incorporate recovery effectively into a product's life cycle, variables that can affect recoverability must be considered early at the conceptual design stage. This will allow for reiterations in design to achieve a highly recoverable product.

The variables needed for the SDM and recoverability factor can be obtained easily from the computer-aided design (CAD) model of the product and general information on costs and prices of materials. Through the CAD model, information needed such as the bill of materials, mating features, dimensions, and component positioning can be obtained. This paper presents a method to analyse the product's recoverability through several metrics including material compatibility, disassembly complexity, geometric positioning of parts, time taken to disassemble the product, depth factor, generic factor, energy consumption, resource usage, cost from cradle to grave, and landfill consumption.

The motivation of this study is to provide a convenient evaluation tool that incorporates recoverability aspects into product design and be able to use concurrently during CAD drawing.

10.2 Literature Review

This research investigates significant parameters in product recoverability at its EOL. These variables should be considered when improving the product at the conceptual design stage to ensure the optimisation of its components' recoverability.

Both Tonnelier [7] and Cheung [8] agree that the most crucial part in ensuring the recoverability of a product lies in its design concept. However, Tonnelier [7] focuses on criteria that allow a product to be treated at its EOL to be reused as energy, part, or material, while Cheung [8] concentrates on identifying disposal costs from the original equipment manufacturer (OEM) viewpoint. The novelty of this research is that it incorporates both viewpoints by measuring various criteria that affect the recyclability of a product into its original material and the production, disposal, and recovery costs from the OEM's perspective.

EOL treatment of a vehicle is divided into two families of criteria—one related to its material and another to its disassembly potential [7, 9, 10]. The material-linked criteria consider the material compatibility and the ease at which they are separated, the recovery network, the number of materials in the product, and the existence of contaminants that cause pollutions of the materials [7]. In turn, the second criteria related to the disassembly potential consider the component orientation, the existence of predetermined breaking points, the compatibility and accessibility of the fasteners and components, component modularity, fastener integration, standardisation, and the optimum number of fasteners. A product that adheres to all these variables is considered easier to recover at its EOL, hence a positive recovery potential [7]. Certain criteria related to the product design such as the material compatibility and component modularity are considered for this project. However, criteria such as the existence of contaminants and recovery network are deemed insignificant as this paper focuses on optimising the design of a product at its design stage as opposed to selecting the most appropriate EOL strategies.

Cheung [8] considers an alternative approach whereby the only information required are on cost-sensitive components and their approximate location in the entire product. While the study describes the method to estimate the cost of EOL of EEE at their design stage, it was concluded that the estimated refurbishment cost derived from Zhou [11] is too subjective and difficult to quantify. This is due to subjective variables such as degradation rate, fastener failure probability, and part failure probability.

Fang [12] provides a product remanufacturability assessment model comprising of several metrics including disassemblability, disassembly accessibility, recoverability, and product complexity. However, the metrics depend entirely on the CAD model of the product, and variables like fastener accessibility and disassembly metrics are too complicated and impractical to be applied in real life. Their definition of recoverability also refers to the probability that a product or component is restored to its original condition—not to be recovered or reclaimed as a new product or remanufactured. Nonetheless, its disassembly complexity metric is adapted into this study as a variable for the recoverability factor. This study provides a solution to designing a product prior to even modelling it on a CAD software by presenting values such as the number of compatible materials, optimum number of fasteners, and generic factors of the components.

Sakundarini [13] presents optimised modular designs as an EOL strategy where components are clustered into units that are independent in function but common in design that can create unique product variants. Three stages to generate modular design that consider EOL strategies are developed, namely, the evaluation of modular cluttering drivers, optimisation, and evaluation of EOL strategies. A mathematical formulation was devised to generate modular design alternatives that consider EOL strategies. Various combinations of components in a module are illustrated using modular hierarchy.

However, it was determined in this study that although geometric positioning developed by Sakundarini [13] is important, there are multiple other factors derived in this paper with more significant effects on product recoverability. Hence, the geometric positioning index was adapted into this paper but adjusted to have a lower weightage on the overall recoverability factor.

Staikos and Rahimifard [14] developed an EOL support tool for recovery in the footwear industry. However, the drawbacks are that their paper focuses specifically on the footwear industry and the decision support tool was vague and generalised, while the assessment modules are too subjective and difficult to quantify. For example, the environmental impact (EI) score is dependent on individual perception. Their paper also focuses on assisting recycling and recovery parties in selecting the appropriate EOL measures for post-consumer footwear—not optimising the product for recovery at the design stage itself. To improve on Berzi [15] proposes the evaluation of EOL performance for hybrid scooter with applications of recycling and recovery assessment methods. The recoverability of hybrid vehicle was approached from two perspectives. The first is through the ISO 22628 standards to determine the recycle rate (RR) and recyclability and recoverability rate (RRR) for M1 and N1 class vehicles. The second is through Union des Industries Ferroviaires Européennes (UNIFE) assessment to consider technological limitations which was adapted from the railway sector. Similarly, their paper only investigates a particular product and focuses on EOL applications after the products are used as opposed to evaluating the products at the design stage itself with recovery in mind.

10.3 Methodology

The methodology used in this study consists of four parts:

Part 1—identifying recoverability parameters. In this stage, lists of recoverability parameters are identified by literature search and interviews to relevant companies. These parameters are then weighted and formulated, and a final metric called recoverability formula is created by integrating all related parameters together.

Part 2—developed all parameters into a single numerical metric. This value is used to compare the recoverability of two or more products (Sect. 10.3.1).

Part 3—a system dynamic model is developed to illustrate the resources used to manufacture a product. The system dynamic modelling reflects the manufacturing of the product from the resource recovery perspective, which is explained in Sect. 10.3.2.

Part 4—as part of the case study, a product will be selected and examined, and improvements are made to the design of the product from the recoverability perspective.

10.3.1 Recoverability Factor

The recoverability factor is defined as the rate of product that can be recovered at its end of life (EOL). The recoverability factor formula is developed through extensive research to quantify the recoverability of a product, and it is unitless. This recoverability factor can be used to compare two (or more) products to determine which of those will have a higher possibility of recovery at its EOL. The recoverability factor is a function of variables, namely, material compatibility, disassembly complexity, geometric positioning of components, disassembly time, depth factor, generic factor, and energy consumption improvement.

The material compatibility measures the relationship between the different components in terms of the materials they are made of. A higher number of similar materials in multiple components will increase the ease of recovery. It is calculated using the compatibility factor, C_{M}.

$$C_M = \frac{\Sigma\left(\mathrm{MCI}_{i,j}\right)}{p \times n} \tag{10.1}$$

where $\mathrm{MCI}_{i,j}$ is the Material Compatibility Index (MCI) between components i and j, p is the number of parts, and n is the number of materials (Table 10.1).

The disassembly complexity, M_{COM}, is adapted from Fang [12]:

$$M_{\mathrm{COM}} = \sum_{i=1}^{N_t} \log_2\left(N_{f(i)} + 1\right) \tag{10.2}$$

Table 10.1 Material Compatibility Index (MCI)

MCI	Description
3	Components of interest (COIs) are made from the same material
2	COIs are made from materials that are compatible with one another
1	COIs are made from materials that are somewhat compatible
0	Incompatible materials

Table 10.2 Geometric positioning of component of interest

f_{geo}	Description
0	COI is inside another COI
1	COI is constrained by 2 other COIs
2	COI is in contact with 1 other COI
3	COI has no direct relation to another COI

Table 10.3 Standard Component Index (SCI)

SCI	Description
1	COI can be used in other types of products without having to completely break it down to its original materials, e.g. old bedsheets can be resewn into a bag
2	COI is manufactured specifically for the product that can be used in similar products without having to completely remanufacture it, e.g. old tyres can be retreaded to be reused as new tyres in other cars
3	COI must be remanufactured/recycled into its basic material and reproduced into a new product for it to be functional and have value, e.g. aluminium casing from laptops can be remelted and remoulded into new products
0	Nonrecoverable components

where N_t is the number of joining types and $N_{f(i)}$ is the number of fasteners of type i. This approach is selected for simplicity.

The geometric positioning, f_{geo}, of the components is measured using a scale of 0 to 3. As stated in the literature review, the metrics developed by [13] are adapted into this study, but the weightage was reduced from 0, 1, 3, and 9 to 0, 1, 2, and 3, and the definition for each index is altered. This is done to reduce the effect of geometric positioning on the recoverability of the components as it was determined that there are other variables more significant than f_{geo} (Table 10.2).

The generic factor, f_{gen}, measures the modularity of the different components in the product which is quantified using a Standard Component Index ranging from 0 to 3 (Table 10.3).

The depth factor, f_{depth}, is adapted from Cheung [8]:

$$f_{depth} = \frac{\text{Number of assemblies to disassemble}}{\text{Total number of assemblies}} \tag{10.3}$$

The disassembly time, t, is the time taken for all the components to be completely separated from the main assembly. It is estimated either through detailed observation of the disassembly process, literary study, or by gathering data from technicians involved in product repair and recovery. The units may vary depending on the product being reviewed. For example, the disassembly of a watch may be measured in minutes, but the disassembly time of a television may take hours. Hence, it is important to note the time unit in the final recoverability factor.

It is important to consider the decrease in energy consumption involved in the production of the materials if the product were to be recovered. This energy saving can be illustrated using the energy consumption improvement factor (ECI):

$$\mathrm{ECI} = \frac{\sum_{i=1}^{n} \begin{pmatrix} \text{Percentage of energy saved} \\ \text{by recycling material } i \end{pmatrix}}{n} \tag{10.4}$$

where n is the number of materials.

When deriving the recoverability factor, R_f, it is noted that ECI would have the most significant impact on the product recoverability, and a zero or negative ECI would result in a zero or negative R_f, respectively. It is also noted that the three f variables, i.e. f_{geo}, f_{gen}, and f_{depth}, have equal importance to one another and should be a function of the number of COIs. It is also noted that a larger disassembly time implies lower recoverability.

Therefore, the recoverability factor is

$$R_f = \frac{C_{\mathrm{M}} + \dfrac{\sum f_{\text{geo}} + \sum f_{\text{gen}} + f_{\text{depth}}}{p}}{M_{\text{COM}} + t} \times \mathrm{ECI} \tag{10.5}$$

where C_M: compatibility factor

f_{geo}: geometric position

f_{gen}: generic factor

f_{depth}: depth factor

p: mass of product

M_{COM}: disassembly complexity

t: Disassembly time (hours)

ECI: energy consumption improvement factor.

10.3.2 System Dynamic Model (SDM)

To simulate the product's impact on the environment, an SDM tool is developed to provide a graphical illustration from a biocapacity or sustainability perspective over time.

The SDM is divided into two main systems and multiple material systems. The two main systems are the main product and the landfill systems. Each material system is further classified into four subsystems: energy consumption, resource consumption, financial aspects, and landfill capacity. Each subsystem is a function of multiple variables that are interrelated to one another whereby the variables loop across different subsystems, i.e. one variable may be a function that exists within two or more subsystems.

Variables in the SDM tool are interrelated with each other through integral equations. Examples of integral relationships between the variables in the plastic resource consumption subsystem are as in Eqs. (10.6)–(10.9).

$$p = \int_0^t \left(p_{\text{produced}} - p_{\text{used}} \right) dt + p_{\text{initial}} \tag{10.6}$$

$$p_{\text{produced}} = \int_0^t \left(p_{\frac{\text{mass}}{\text{product}}} \times PR + p_{\text{recovered}} \right) dt + p_{\text{initial}} \tag{10.7}$$

$$p_{\text{used}} = \int_0^t \left(p_{\frac{\text{mass}}{\text{product}}} \times PR - p_{\text{recovered}} \right) dt + p_{\text{initial}} \tag{10.8}$$

$$p_{\text{recovered}} = p_{\text{EOL}} \times p_{\text{pctrec}} \tag{10.9}$$

where

p: mass of plastic available

p_{produced}: mass of plastic manufactured

p_{used}: mass of plastic used for production

$p_{\text{recovered}}$: mass of plastic recovered

p_{initial}: initial mass of plastic available

$p_{\frac{\text{mass}}{\text{product}}}$: mass of plastic per product

PR: production rate of product

P_{EOL}: mass of plastic at its EOL

p_{pctrec}: percentage of plastic recovered

t: disassembly time (hours).

The variables forming the entire system are given in Tables 10.4 and 10.5. Note that underlined variables are inputs and non-underlined variables are automatically generated outputs. All outputs generated can be viewed in graph format to show their respective predicted projections after time t.

It can be seen from Fig. 10.1 that the glass energy consumption is a function of two variables, i.e. energy for production of glass and used glass, while the energy saved by recycling glass is a function of three variables, i.e. energy for production of glass, percentage of energy saved by recycling glass, and produced glass. With recovery in place, the recovered glass will be reprocessed and resupplied into the

Table 10.4 Main systems and their variables

Main product system Products, production, EOL products, *product lifetime*, *production rate*
Landfill system Available landfill area, available landfill volume, required landfill area, required landfill volume, *landfill height*, *original landfill volume*

Table 10.5 Material subsystems and their variables

Resource consumption system Material *i*, *mass of material i per product*, produced material *i*, used material *i*, recovered material *i*, *percentage of material i recovered*, percentage of material *i* scrapped, waste material *i*, EOL material *i*
Energy consumption system Material *i* energy consumption, total energy consumption, *energy for production of material i*, *energy saved by recycling material i*, *percentage of energy saved by recycling material i*
Financial aspect system Total disposal cost of material *i*, total recovery cost of material *i*, total expenditure of material *i*, total production cost of material *i*, *price/kg of scrap material i*, *price/kg of material i*, *price/kg of recycled material i,* total cost of product
Landfill capacity system *Waste material i density*, waste material *i* volume

produced glass available for production of specific components, after which it will be considered used glass post its EOL. Therefore, in this SDM tool, the variable recovered glass is looped back into the variable produced glass which subsequently affects the energy saved by recycling glass. It is this type of looping that makes the SDM tool developed valuable for engineers to work on product designs. These interrelated values are difficult to be quantified or measured without the SDM tool (Fig. 10.2).

10.4 Case Study

A case study is conducted on two phone models, namely, the iPhone 7 Plus and Sony Xperia Z4 with the intention of recovering their external housings or casings, buttons, and display screens. The phones are modelled on Autodesk Inventor with emphasis given on materials, dimensions, and all components (including buttons) attached to the casings and displays. The information gained from the CAD models are used in the recoverability factor formula and the SDM to compare their recoverability to one another. For the purpose of this case study and consistency on both phones, the production rate is set at 7500 models per month, and the SDM simulation was set on a 24-month model.

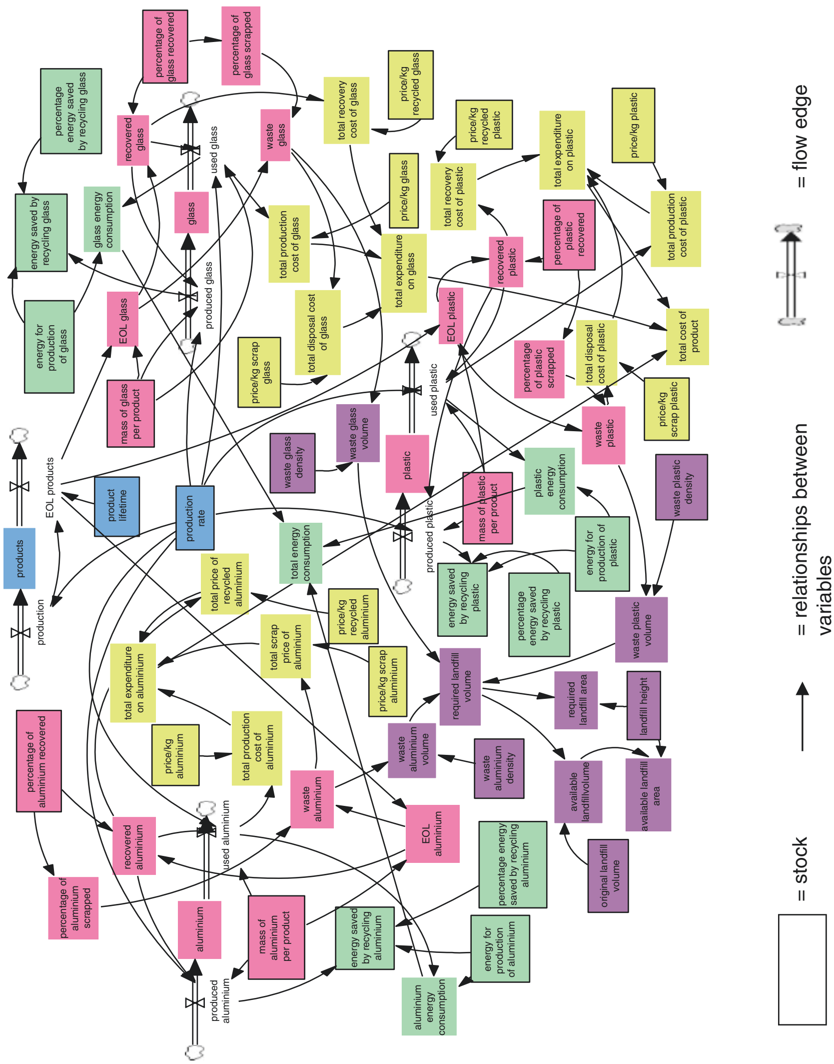

Fig. 10.1 Full SDM tool for component recoverability analysis

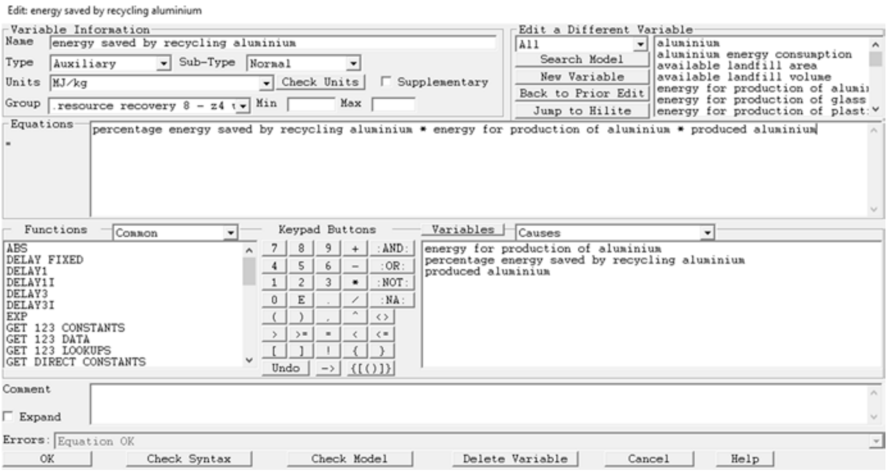

Fig. 10.2 Window for the variable "energy saved by recycling aluminium"

10.4.1 iPhone 7 Plus Phone Model

There are 13 components in this model, namely, two sensor covers, two cameras, an aluminium housing, a camera cover, a glass housing, a display screen, a sim tray cover, and four buttons (i.e. home, ringer, volume, and wake buttons). The two cameras are not recovered but modelled to calculate the MCI. All other 11 parts modelled are considered COIs in the study (Fig. 10.3).

As there are five glass, five aluminium, and one plastic components, the compatibility factor is:

$$C_M = \frac{3\left({}^{5}_{2}C\right) + 3\left({}^{5}_{2}C\right) + 1(0)}{11 \times 3} = 1.8181 \tag{10.10}$$

As there are no fasteners on the external body and components, the disassembly complexity is:

$$M_{\text{COM}} = \sum_{i=1}^{N_t} \log_2 (0+1) = 0 \tag{10.11}$$

The geometric position factor for the 11 COIs is:

$$\sum f_{\text{geo}} = 1(3) + 1(2) + 9(1) = 14 \tag{10.12}$$

It was found that the SCI for the display screen is 2 as it can be used in other phones without having to completely remanufacture it, and the SCI for the other 10 COIs is

Fig. 10.3 iPhone 7 Plus CAD model on Autodesk Inventor

1 as these components would have to be remanufactured or recycled into their raw materials to be recovered. The generic factor is therefore:

$$\sum f_{\text{gen}} = 0(3) + 1(2) + 10(1) = 12 \tag{10.13}$$

The time taken to disassemble the iPhone 7 Plus is obtained by gathering information from iFixit.com technical writers and the repair technicians at Fast Fix Solution. The disassembly time is $t = 1.5$ h.

Since there is only one assembly to disassemble, the depth factor is $f_{\text{depth}} = 1$.

By recycling aluminium, 95% energy can be saved in its production. Similarly, recycling glass and plastic would save 30% and 90% of energy for production, respectively [16–20]. The energy consumption improvement is given by:

$$\text{ECI} = \frac{0.95 + 0.3 + 0.9}{3} = 0.7167 \tag{10.14}$$

Therefore, the recoverability factor is:

$$R_f = \frac{1.8181 + \dfrac{14 + 12 + 1}{11}}{0 + 1.5} \times 0.7167 = 2.0415 \text{ h}^{-1} \tag{10.15}$$

By inputting the values obtained from the CAD model and CES EduPack into the SDM, the effects of recoverability on the iPhone 7 Plus production can be illustrated. Two scenarios were studied, one with recovery in place (red lines) and one without recovery (blue lines) which can be observed in Figs. 10.4, 10.5, 10.6, 10.7. The simulation was run on all materials in the COIs, but for conciseness, only aluminium is shown.

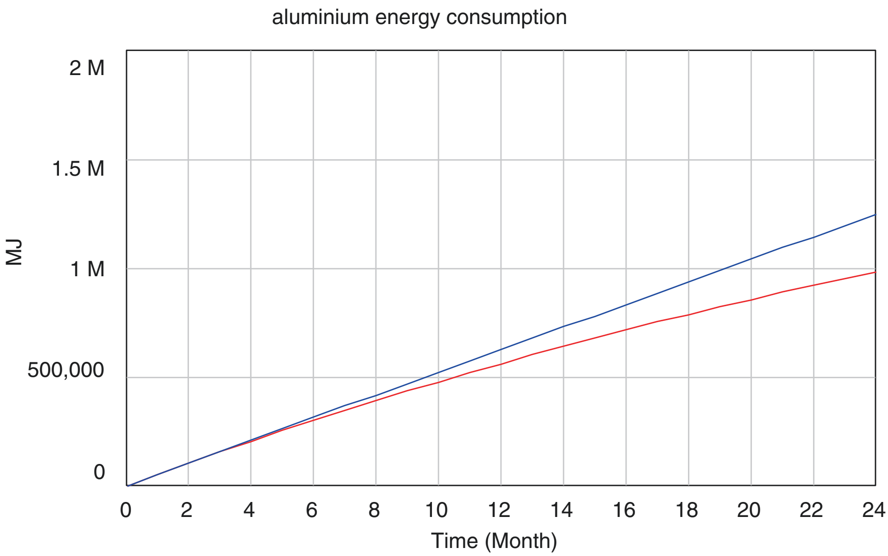

Fig. 10.4 Total energy consumption for production and recovery of aluminium

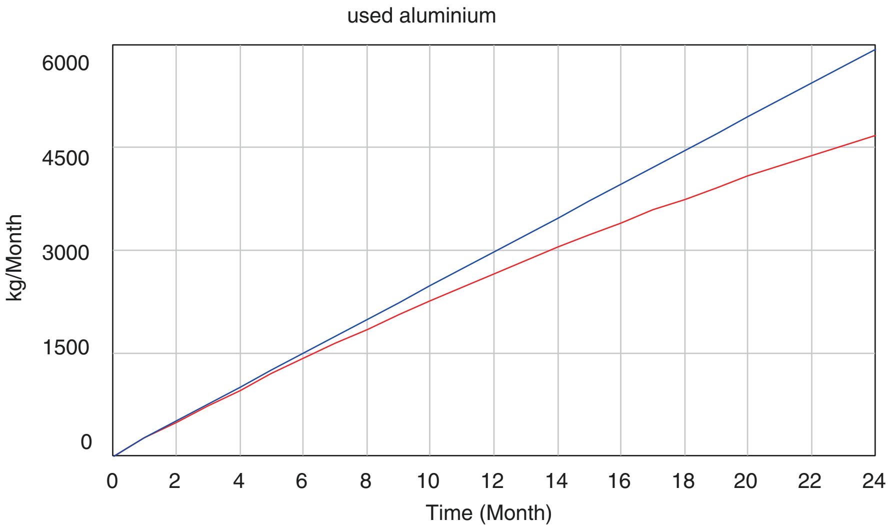

Fig. 10.5 Total aluminium used for iPhone 7 Plus

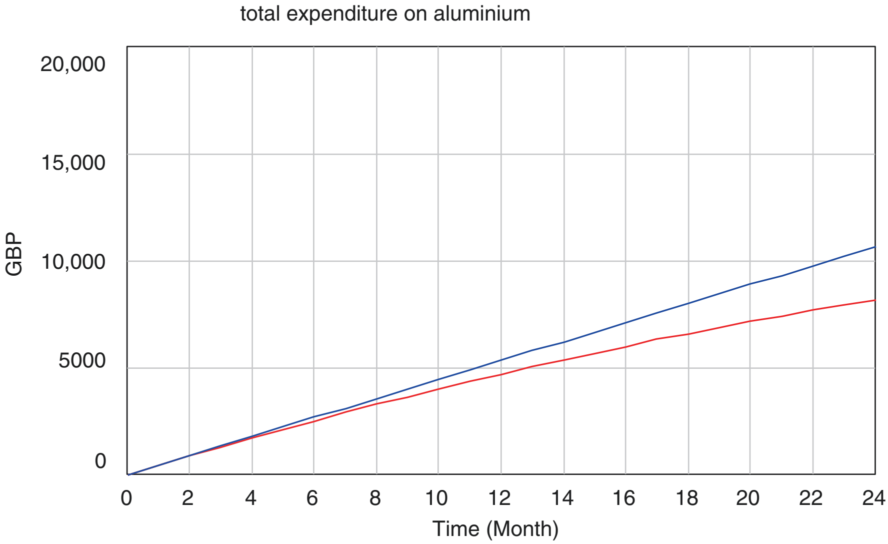

Fig. 10.6 Total expenditure on aluminium

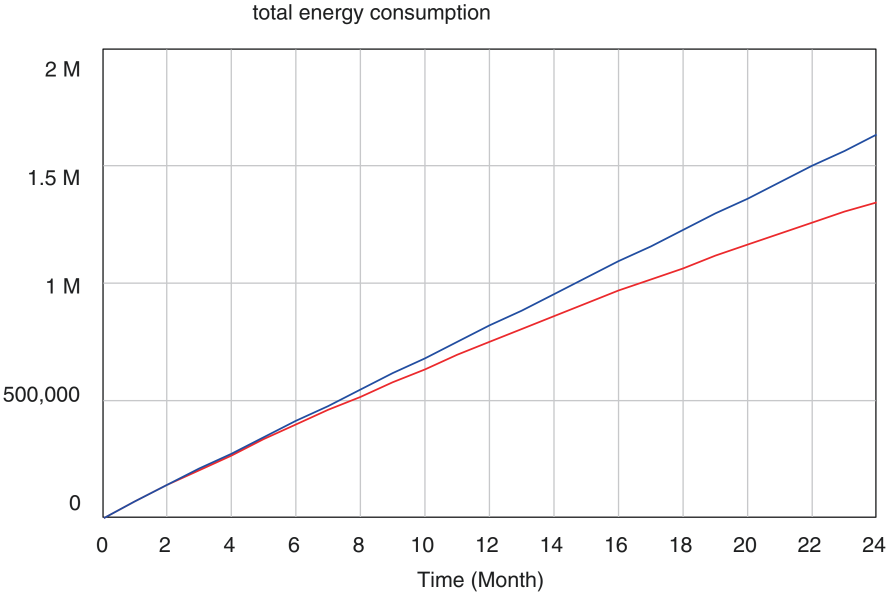

Fig. 10.7 Total energy consumption for production and recovery of iPhone 7 Plus COIs

To improve the recoverability of this phone model, it is suggested that the aluminium housing is replaced with magnesium AM60A. The red and blue lines illustrate the scenarios for the usage of aluminium and magnesium housings, respectively, with recovery in place (Figs. 10.8 and 10.9).

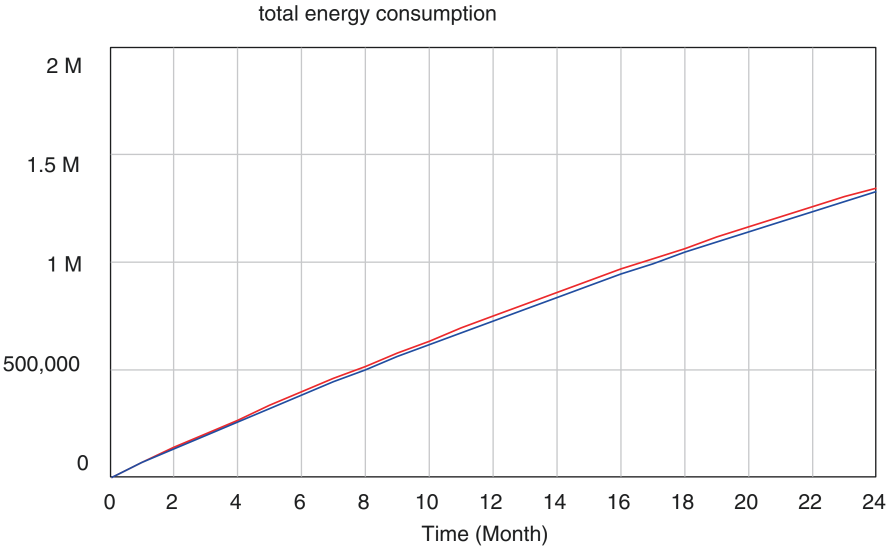

Fig. 10.8 Total energy consumption for production and recovery of iPhone 7 Plus COIs

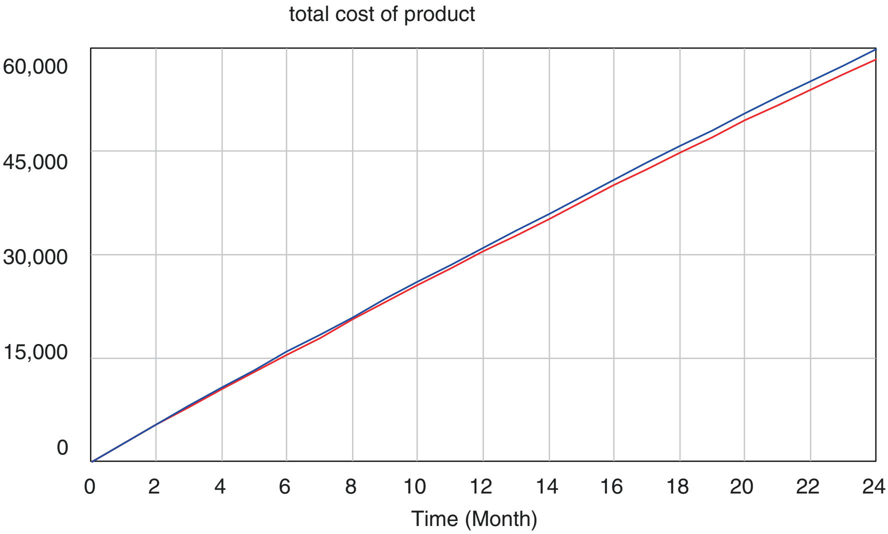

Fig. 10.9 Total cost of iPhone 7 Plus COIs

Table 10.6 Total energy consumption and total cost for iPhone 7 Plus COIs after 24 months

Material	Total energy consumption (MJ)	Total cost (£)
Aluminium	1.34663×10^6	58497.80
Magnesium	1.32562×10^6	59814.50

Replacing the aluminium casing with magnesium reduces the total energy consumption; however this causes the total cost of the COIs to increase (Table 10.6).

10.4.2 *Sony Xperia Z4 Phone Model*

Similar methods and resources used for iPhone 7 Plus were used to obtain all the information required for Sony Xperia Z4 (Fig. 10.10).

The compatibility factor is:

$$C_M = \frac{\sum\left(3\left({}_2^2C\right)+3\left({}_2^5C\right)+2\left({}_2^2C\right)\right)}{9\times 3} = 1.2963 \tag{10.16}$$

The disassembly complexity is:

$$M_{\text{COM}} = \sum_{i=1}^{N_t} \log_2\left(0+1\right) = 0 \tag{10.17}$$

The geometric position factor for the 9 COIs is:

$$\sum f_{\text{geo}} = 2\left(3\right)+2\left(2\right)+5\left(1\right) = 15 \tag{10.18}$$

The generic factor:

$$\sum f_{\text{gen}} = 0\left(3\right)+1\left(2\right)+8\left(1\right) = 10 \tag{10.19}$$

The disassembly time is $t = 1$ h.

The depth factor is $f_{\text{depth}} = 1$.

The energy consumption improvement is given by [16–20]:

$$\text{ECI} = \frac{0.95+0.3+0.9}{3} = 0.7167 \tag{10.20}$$

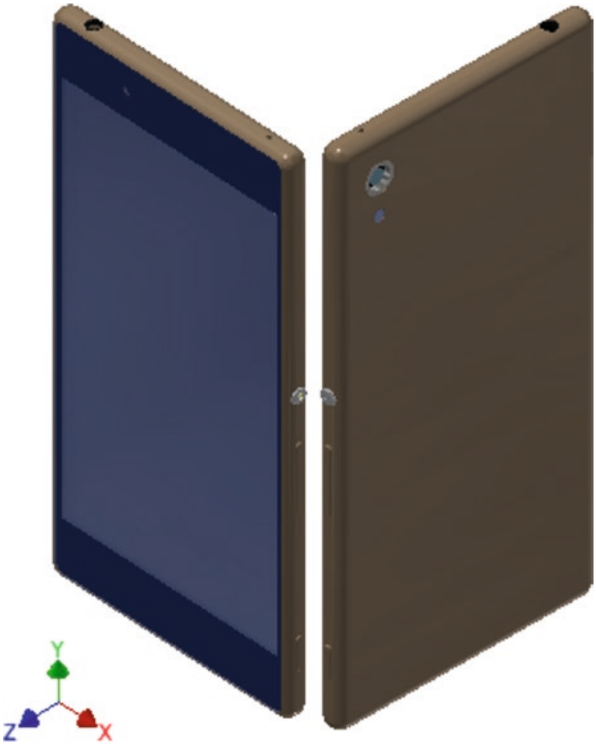

Fig. 10.10 Sony Xperia Z4 CAD model on Autodesk Inventor

Therefore, the recoverability factor is:

$$R_f = \frac{1.2963 + \dfrac{15+10+1}{9}}{0+1} \times 0.7167 = 2.9995\text{h}^{-1} \tag{10.21}$$

Based on the SDM, the Sony Xperia Z4 with recovery in place is significantly more sustainable than the iPhone 7 Plus even with recovery in place and the usage of magnesium housing. This is simply due to the smaller size of Sony Xperia Z4 which allows it to use less materials, thus reducing the required landfill area. When comparing the two phones using the recoverability factor, it is apparent that the R_f for Sony Xperia Z4 (2.9995) is higher than the iPhone 7 Plus (2.0415). This is mostly contributed by the better geometric positioning of the COIs in Sony Xperia Z4 and its short disassembly time.

10.5 Conclusion

Many manufacturers neglect sustainable design mainly because recoverability and sustainability are considered complex to quantify especially in the early stages of design. This project provides two simple tools that can be used to evaluate the recoverability of a product at any stage, which is beneficial principally when conceptualising a product. Information required for both tools can be obtained easily from the CAD models without having to build a prototype or finding intricately ambiguous values such as the angle of approach when disassembling each fastener. However, the SDM tool can be further expanded to include more material subsystems for larger or more complex products such as automobiles and computers. As product complexity increases, more variables can be added to the systems such as different types of EOL strategies and their costs, e.g. incineration, recycling, landfill, or refurbishment.

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Chapter 11
The Effects of Collection Promotions on Resource-Efficient Utilization and Resource Sustainability of Mobile Phone Market: A System Dynamics Approach

Juntao Wang, Wenhua Li, and Nozomu Mishima

11.1 Introduction

Since the revolution of industrialization, the world had been stepping into the booming of various products. Consequently, resource consumption and waste generation are rapidly increasing. The serious results are the prediction of resource supply shortage and heavy landfill burden. Undoubtedly, sustainable development is vital in the consumption of resources and development of the product market. As mentioned by the UN (1987), "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1].

Accordingly, a series of measurements and promotions have been taken. One of the useful ways is to promote the circular utilization of products, which include reuse, remanufacture, refurbish, and recycle. Circular utilization is the process of incorporating moving goods from their typical final destination for the purpose of capturing value or proper disposal [2, 3]. One of the keys for the promotion and improvement of circular utilization is the guarantee of post-product collection and supply. However, from literature review and observation, the evidence highlighted that even in some countries with good collection system and regulation system, the collection rate of post-products is still relatively low. For example, the EEA (2016) pointed out that in 2010, the average collection rate of WEEE (waste electrical and electronic equipment) for the entire EU was 37% [4], let alone many countries without environmental consideration. Among all the collection categories, it's noticed that SEEE (small electrical and electronic equipment) is

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the one with the lowest collection rate in most countries. One outstanding reason is its small volume, making the disposal with mixed waste or hibernated inside any corner of the house easy [5–8]. Regardless of informal collection, some researches have already been presented successful collection systems in developed countries, such as Japan, the USA, and so forth [9]. Since the fate of the post-products, hibernated or returned to the collection system and so on, is decided by the attitude and behavior of consumers, then it becomes important for stimulating the engagement of consumers. De Brito et al. (2003) have outlined that the role of "corporate citizenship" is the motive for post-product collection [10]. Various promotions have been put forward and recognized helpful for achieving the goal directly or indirectly, such as deposit refund, old-for-new, and other incentives for return [11–15]. Consequently, the world is noticing an increase of post-product collection. However, along with different policies, some side influences on the whole society are noticed instead of solely improving post-product collection. Take policy of old-for-new as an example; even though some companies announced that it's useful for improving the end-of-life products and may be benign for the environment, there's no doubt that the promotion may enlarge the demand for new products which is the driving force for the companies to implement the policy. If the policy failed designed well from the whole resource-consumption perspective, undoubtedly, the resource consumption and waste generation will be enlarged with the blind consumption. From the sustainable development perspective, this is not an efficient way to conduct resource consumption and utilization. And obviously it is not the original vision for improving the collection of post-products.

Considering these, this research is conducted based on the analysis of mobile phone market through system dynamics. For one reason, the total quantities of mobile phones are huge, and the demand is still increasing. According to [16], by the end of 2015, the number of mobile phone subscriptions worldwide is expected to reach almost seven billion subscriptions. Among the sales of mobile phones, the sales of smartphones are huge, nineteen percent of the sales in 2010 were smartphones [17]. Considering mobile phones consuming various resources, such as gold, tin, copper, nickel, lead, and so forth [18, 19], even though the average weight of one product is relatively light, the total resources consumed and waste generated are very huge. Moreover, the life span of one mobile phone is quite short, which estimated to decrease from 4 years to around 2 years [20–22]. All of these may cause a huge attention on the resource supply shortage and environmental issues of waste treatment. For another reason, the collection rate of mobile phones is relatively low. Comparing with the big EEE, the lower collection rate is mainly caused by hibernated in house for its small size as well as privacy reason [16]. To promote the collection rate, some promotions have been proposed. Since the generation of one post-product normally happened on the basis of purchasing a new one, if the promotions failed designed well, the demand of new products may be enlarged more or less by decreasing the utilization time of olds. And absolutely the resource consumption and waste generation may be increased, which is similar to the Jevons paradox or rebound effect [23]. Since then, a comprehensive understanding of the collection system, as well as the influences of collection promotions on resource-efficient utilization and sustainability, is becoming crucial. According to the best knowledge of the authors, there's no specific research related to the analysis and comparison of different collection promotion policies from the influences on the closed-loop supply chain of mobile phone market. Besides, even though an increase of post-products collected has been noticed, there's still a space for further improvement. Considering these, the main objectives of this research are to depict and analyze the influences of collection promotions on resource-efficient utilization as well as to propose suggestions to help further improve the collection of post-products to improve the resource sustainability.

The paper is organized as follows: Methodology employed in this paper is introduced in Sect. 11.2. As one of the system dynamic analyses, CLDs are built to conduct the comprehensive analysis. With the building of CLDs, several results and discusses would be drawn and made in Sect. 11.3. Finally, Sect. 11.4 sets out our conclusion.

11.2 Methodology

11.2.1 System Boundary

System dynamics (SDs) is a powerful methodology for obtaining insights into problems of dynamic complexity and policy resistance [24, 25]; moreover, it can be effective and useful to identify strategic interventions to improve system behavior [26]. Qualitative and quantitative analyses are always used in system dynamics. Qualitative analysis is useful to describe the problem and identify potential solutions, while quantitative analysis helps to visualize and investigate the effect of different interventions using mathematical modeling [27]. The application of system dynamic modeling and CLDs has been used in many fields, such as capturing stakeholder perspectives with respect to watershed management and planning [28], setting strategies for recycling healthcare waste [26], conducting the analysis and formulation of policies for municipal solid waste facilities [29], and so forth. Moreover, Spengler and Schroter (2003) have presented a closed-loop supply chain using SDs [30]. And the effects of environmental parameters on the closed-loop supply chain have been analyzed with reuse or recycling, respectively [31, 32]. However, to the best knowledge of the authors, even though SDs have been widely applied, the analysis of effects of collection promotions, especially a specific analysis on mobile phone market considering the obvious characteristics of mobile phones, such as privacy, function updating, and so on, has not been conducted till now. Considering sustainable development, as well as improving the collection rate of post-products, this research is conducted by incorporating the closed-loop supply chain with two different sales channels of new and reuse products.

11.2.2 Identification of Key Elements

In reality, the closed-loop supply chain of mobile phones is very complicated. There're many stakeholders involved in the whole chain, including manufacturers, transporters, distributors, retailers, consumers, collectors, and so forth. Meanwhile, there're a bunch of brands of mobile phones. For each brand, there're several kinds of products sold at the same time. And each product has different functionalities and appearances as well as the prices may vary from each other. Taking one model of mobile phone as the case study, new and reuse products can be distinguished along the closed-loop supply chain. To model the differences of the sales of new and reuse products, two different sale channels are planned. In reality, the new products are always sold at the same time with the reuse products regarding the long-existing time of one product. As for the closed-loop supply chain, the sales of new products are very important for the forward supply chain. Meanwhile, the sales of reuse products are recognized useful for determining the products accepted for reusable products. And once collected, all the products will be controllably disposed by environmentally benign methodology if not accepted for reuse or recycling. To depict the influences of collection promotions within the closed-loop supply chain, we will analyze and discuss the influences of collection promotions on the demand of new and reuse products by incorporating the price factor and market behavior. In order to analyze the resource-efficient utilization, the natural resources consumed, the sales of new products, the uncontrollably disposed products, and so forth will be the main objectives that are focused on.

To conduct the system dynamic analysis, the CLDs are depicted with the free version of Vensim software. In CLDs, the "+" means positive (reinforce) effect, while the "−" means negative (balance) influences.

11.3 Model Structure and Discussion

11.3.1 Model Structure

In former researches, Georgiadis and Vlachos (2004) had illustrated the SD diagram of a forward-reverse logistic system considering the remanufacturing. Based on the model, they studied the impacts of the environmental policy and the corporate image of environmental practices on market behavior [31]. According to their work and other researches [31–33], considering the aiming of this research, the CLDs are modified to incorporate the sales of new and reuse products in two different sale channels at the same time, as showed in Fig. 11.1 (B1, B2, B3, B4, and B5 are used to represent the new product supply circled in dark blue, while B9, B10, and B11 are for reuse supply depicted in light blue). The reinforce loops and balance loops are marked with the letter R and B, respectively.

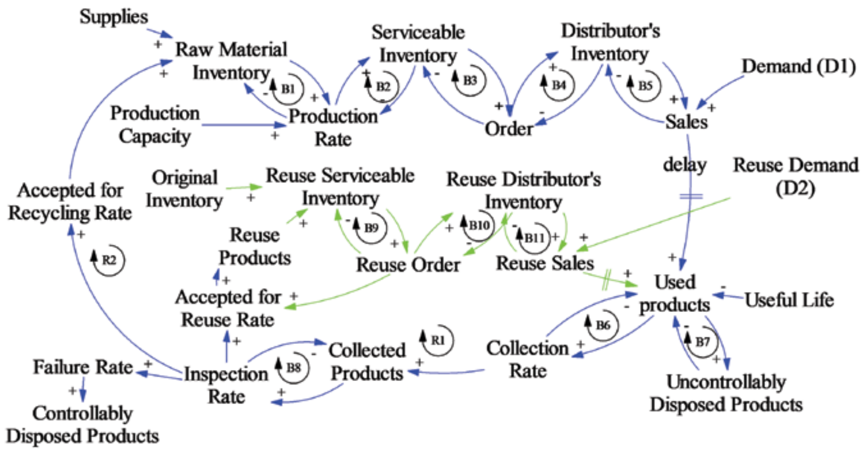


Fig. 11.1 Influence diagram for a closed-loop supply chain considering two different sale channels

In these CLDs, the sales of new and reuse products are conducted through two different supply chains to satisfy with the demand (D1) and reuse demand (D2). To make the sales of reuse products keep at the same pace with the sales of new products, the parameter of original inventory in the reuse supply chain is designed. Eventually, the reuse sales will drain the reuse distributor's inventory, and reversely the reuse sales will be guaranteed to increase by the reuse distributor's inventory as a balance process showed in B11. The behavior is similar to the one between sales and distributor's inventory showed in B5. And the new products or the reuse products will be collected regarding the collection rate after the specific time delay (see the two arrows with two cross lines for each), while the uncollected products will be disposed uncontrollably. Through the inspection, the collected products will be divided into three flows based on the accepted for reuse rate, accepted for recycling rate, and accepted for failure rate. From the resource-efficient consumption point of view, it's vital to decrease the supplies from the nature, as well as to reduce both the controllably and uncontrollably disposed products, which are outside of the system boundary. Meanwhile, in order to achieve the absolute reduction of resource consumption and waste generation, the attention needs to be focused on the raw material inventory and the used products.

In the original model, there're two different demand sources. To make a well study of the system, two scenarios related to the two demand sources are designed. In Scenario 1, there're no interactions between the D1 and D2 considered, as showed in Fig. 11.1. While in Scenario 2, the demand of new products and reuse products is related to the potential in use in the system, which can be partly depicted in Fig. 11.2 as two balance loops. Both D1 and D2 will be enlarged along the increasing of the

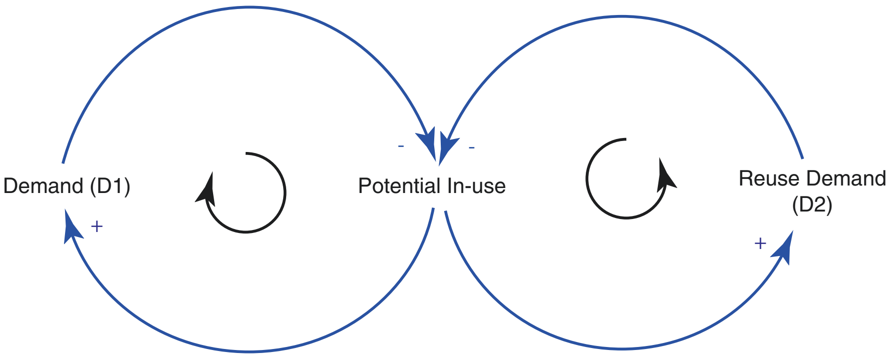


Fig. 11.2 The interactions between the demands of new and reuse products

potential in use, and conversely the potential in use will be decreased through demand satisfaction.

11.3.2 SD Diagrams Incorporating the Influences of Collection Promotions

Based on the structure model proposed above, two kinds of collection promotions named old-for-new and deposit-refund are discussed in the following. Old-for-new is widely employed in mobile phone market at present [34, 35]. The national old-for-new Home Appliances Replacement Scheme (HARS) policies in China are originally aimed at promoting the replacement of older home appliances in urban areas and the collection of those older appliances [36]. Different from old-for-new, deposit-refund is one economic instrument used for environmental protection with the goal of incentive to return post-products. Most of the researches related to deposit-refund are focusing on packages and containers collection [37–39]. Under deposit-refund, the consumers return the post-products and then receive refunds, and a high recovery rate can be attained with low monitoring costs [40]. However, Kansai (2003) mentioned that it may decrease the sales of products due to the addition of deposits to price [41]. From the definition of the two policies, one obviously common characteristic for both of them is the economic effect. And the influences of the two policies are mainly from two sides: one is through the payoff to consumers who return the used products to incentive the collection rate, while, on the other side, it may change the demand structure by adding or reducing the price of the products that waited to be purchased by consumers. To depict the influences of promotions on the collection rate as well as the demand, the price decrease factor and payoff factor are designed. The SD diagrams incorporating the influences of the collection promotions within the closed-loop supply chain are modelled in Fig. 11.3. The variables in rectangle are originated from variables depicted in Fig. 11.1. The red arrows that lie between the demand and reuse demand describe the relationship considering the two scenarios mentioned above. The green arrows are used to

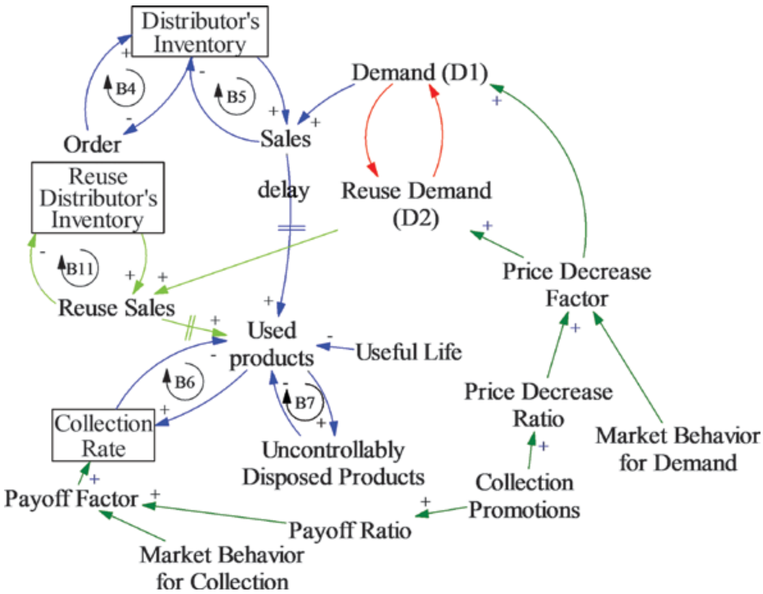
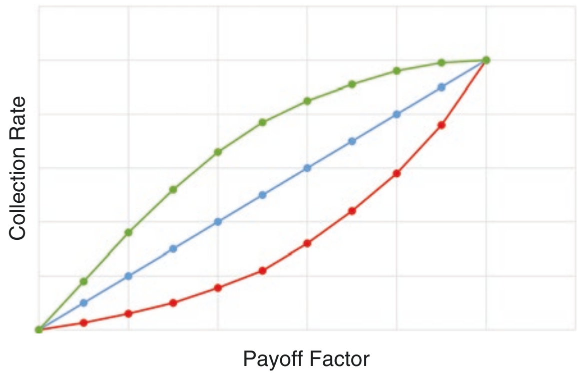


Fig. 11.3 The SD diagrams incorporating the influences of the economic collection promotion

Fig. 11.4 Three plausible relationships between the collection rate and the payoff factor



represent the influences of the collection promotions on the whole system. As the green arrows indicate, the collection promotions are designed to positively affect the demand and the collection rate through the price decrease factor and payoff factor, respectively. And the price decrease factor is determined by the price decrease ratio and the market behavior for demand, while the payoff factor is influenced by the payoff ratio and market behavior for collection.

Considering the fact that the higher the payoff, the higher the collection rate, in this study, three plausible adjustment behaviors are recognized to depict the relationships between the collection rate and the payoff factor in Fig. 11.4. In the figure, the upper curve means that the collection rate is highly sensitive to a low payoff ratio and the middle line means that the collection rate is proportional to the payoff ratio, while the left curve means insensitive behaviors between the collection rate and the payoff ratio. Besides the influences of collection promotions on collection rate, the relationships between the price decrease factor and the demand are also analyzed. In economics, the relationships between the price of a certain commodity and the amount of it that consumers are willing and able to purchase at any given price are depicted by the demand curve [42]. For simplicity, in this qualitatively analysis, we simply treat the relationship of the price decrease factor and the demand based on the basic demand curve, and as the increasing of the price, the demand will decrease at a certain proportion.

11.3.3 Systemic Analysis and Discussions

In Scenario 1, there's no interaction between demand (D1) and reuse demand (D2). Then the demands will be affected by the fluctuant price. If the price increases, then both the demands will be decreased, and conversely, they will be increased. Since, in fact, old-for-new to a certain extent decreases the price of new type products, finally it will stimulate the demand (D1). Finally more resource consumption can be anticipated. However, as Kansai (2003) mentioned, deposit-refund may decrease the sales of products due to the addition of deposits to price [41]. This will be helpful for decreasing the total resource consumption. Moreover, the decrease of the demand can be on the other hand understood as that the utility time of mobile phones will be prolonged. It will absolutely improve the resource-efficient utilization. In terms of the collection rate, no matter which of the three plausible curves happened, the collection rate can be improved by the two promotions. The increasing of the collection rate will be good for reducing the natural resource supplies from the outside of the study system boundary in the long run. And as the stabilization of the collection rate, finally the supplies of natural resources will be reduced to a stable level considering the relatively low demands under the deposit-refund promotions. However, the situation will be a little different with the promotions of old-for-new policy. It is clear that the supplies of natural resources will keep increasing to compensate the discrepancy between the increasing of demands and recycling rate, regarding to the loss of resources during the recycling process. Besides, if the increase of the reuse demand grows more slowly than the potential increase of the accepted for reuse products, then more potential reuse products will flow to recycling, and this will accelerate the resource consumption speed and the coming of the resource supply shortage.

The results vary once considering the interactions between the demand (D1) and reuse demand (D2), as explained in Scenario 2. Considering the potential in-use keeping constant, then there're two situations that need to be analyzed, which are the dominance of the demand (D1) and the reuse demand (D2). And the dominance of demand (D1) means the priority effect from the promotions. Then if the demand of new products is dominant in the system, the increase of the demand of new products will squeeze the demand of reuse products under the promotions of old-for-new. As the demand increases (D1), as well as the collection rate increases, then more and more products with potential reuse quality will be sent to recycling. Even though the increasing of recycling is environmentally friendly and is good for recovery resources from waste, this process on the other hand accelerates the resources consumption speed; as a result, more controllably and uncontrollably disposed products will be accumulated. From a long-time point of view, the consumptions of natural resources are stimulated to increase. If the demand of reuse products is dominant, from a short run, it will increase the utilization extent of the resources and decrease the consumption of the supplies of natural resources from the outside of the system. And as the collection rate stabilized in a certain extent, the reuse amount will keep constant; if the reuse products can be guaranteed, then the total resources will decrease to a relatively low level, and at the same time, the controllably and uncontrollably disposed products will be reduced. It is definitely beneficial for the resource-efficient consumption. Considering the influences of deposit-refund, almost the opposite effects induced comparing with the old-for-new promotions regarding the two situations in Scenario 2. If the situation of the demand of new products is dominant, the demand (D1) will be reduced because of the increase of the price. Then the consumption of natural resources will be restrained. And as the collection rate increases, especially the reuse sales, the utilization extent of the resources will be enlarged. From a resource-efficient consumption point of view, it is very helpful for the development of the sustainable society. If the reuse demand (D2) dominates the system, even though the collection rate is increasing, the reuse demand (D2) is reduced. And undoubtedly, not only the resource consumption will be enlarged, but also the controllably and uncontrollably disposed products will be increased. This is the worst condition considering the resource consumption and utilization.

According to the analysis and discussions, there's no doubt that the collection rate of post-products can be improved by both the two promotions. Since the influences on the demands also considered and studied in the depicted SD diagrams, most of the results showed that the resource-efficient utilization cannot be achieved. Overall, the deposit-refund seemed to perform better than the old-for-new promotion. However, as Kansai (2003) mentioned, deposit-refund may decrease the sales of products due to the addition of deposits to price [41]. And this should not make the promotions welcomed and popularized well in the system. Considering this, some supplementary promotions are regarded helpful. Take old-for-new for an example, except for increasing the utilization extent of the products by enlarging the reuse demand, the specific content regarded to the old-for-new collection can be modified. In reality, the payoff to the collected products through the old-for-new promotion is determined by the performance and appearance of the product, we can add the utilization time of the products as one factor once conducting the collection, and moreover, we can make a difference of the payoff by setting a series of time intervals to increase the utilization extent of products. However, to improve resource-efficient utilization by applying circular utilization, a further study needs to be conducted by employing both qualitative and quantitative analyses of influences on the system based on system dynamic analysis.

11.4 Conclusions

In this research, several CLDs are established to make a system dynamic analysis of the influences of post-product collection promotions on resource-efficient consumption from the closed-loop supply chain perspective. Accordingly, the system dynamic diagrams regarding two different sales channels and the interactions are modelled. Moreover, the two kinds of promotions that are helpful for improving the collection rate of the post-products are recognized and analyzed in the model, which mean old-for-new and deposit-refund, respectively. In this study, the authors treated that the promotions will make sense according to their economic influences on the consumption behavior. And the influences will work from two sides, which are demands and the collection rate. The relationships between the collection rate and the payoff factor are depicted based on the three plausible adjustment curves, while the relationships between the demands and price decrease factor are designed according to the basic demand curve. In order to conduct the analysis, two different scenarios are designed. In Scenario 1, there're no interactions between demand (D1) and reuse demand (D2) considered, while a negative effect exists between the two demands based on the constant in-use products in the system that is studied in Scenario 2.

According to the SD diagrams and the interactions depicted within the diagrams, a qualitative study of the two promotions is conducted. From resource-efficient consumption point of view, it is important to reduce the consumption of natural resources and maximize the utilization extent of the resources. And to achieve sustainability of the society, we need to cut down both the controllably and uncontrollably disposed products. However, even though both the old-for-new and deposit-refund are good for the improvement of collection rate, the demands are also noticed affected by the influences of them. More seriously, in some extent, the resource consumption and disposal products can be stimulated to increase. And the resource-efficient consumption and utilization cannot be improved. It is necessary to well consider the system and improve the resource-efficient utilization regarding the potential resource supply shortage and harmful influences caused by waste disposal.

Based on the analysis and results, some supplementary policies are proposed to the existing system. Instead of discouraging the demand directly, the more effective methodology is to control the utilization extent of the products. In order to improve resource-efficient utilization, new promotions or supplementary needs to be proposed, such as controlling the payoff of the returned products by considering the utilization time. In terms of the limitations of this research, more concrete suggestions to help improve the resource-efficient consumption are not analyzed and discussed. In the future, a quantitative study including mathematical calculation and case study related to the influences of promotion based on system dynamics will be conducted, and it will be more useful to reveal the interactions within resource consumption as well as to help improve resource-efficient consumption.

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Chapter 12
Toward a Circular Economy: An Analysis of Innovation in Taiwanese Small- and Medium-Sized Enterprises

Shiang-Ruei Hsu, Guo-Liang Chen, and Tsai-Chi Kuo

12.1 Introduction

Small- and medium-sized enterprises (SMEs) are often referred to as the backbone of Taiwanese economy for the performance of SMEs in 2015 accounted for 97.69% of all enterprises in Taiwan. In addition, the number of employed persons in SMEs represented 78.22% of all employed persons and contributed 30.36% of the total annual sales of all business enterprises in Taiwan [1]. At present, Taiwan's economy is seeking to transform and upgrade, and circular economy is one of the innovative industries actively promoted by the government. As addressed in President Tsai Ing-wen's inaugural speech, the Tsai government will bring Taiwan into an age of circular economy [2]. Green products and/or services are carriers of circular economy, and eco-design of products and/or services is the key to achieving the goals of green growth [3]. Therefore, innovative research of green products and/or services in Taiwanese SMEs is an important indication toward the promotion of circular economy.

The foci of this paper are listed below:

1. To understand the interrelationship between technological innovations and circular economy movements.
2. By means of secondary data analysis of SMEs and their innovative products and/or services with the concept of circular economy as the basis of further in-depth case interviews.

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3. Through in-depth case interviews to comprehend the interrelationship of circular economy and the innovative research of SMEs.
4. With the summary of the above interviews to develop circular economy models and strategies that are best for Taiwanese SMEs to adopt.

12.2 Literature Review and Study

Green products use materials safer to the environment, are recyclable, and require less energy throughout extraction, production, distribution, use, and disposal stages of product life cycle [4]. Green products and/or services are carriers of circular economy [3]. The core concept of circular economy is to achieve the goals of economic development, sustainable resources, and environmental protection by means of resource conservation, resource efficiency, and circular recycling [5]. Properly designed environmental standards can trigger innovations that lower the total cost of a product or improve its value. Such innovations allow companies to use raw materials and energy more productively, thus offsetting the costs of improving environmental impact, making companies more competitive, and ending the stalemate of environmental protection and economic development [6].

Accenture, a leading global professional services-providing company, identified five business models driving the circular economy and creating impacts that transform different links of a value chain. The five models impacting a supply chain from upstream to downstream according to Accenture are defined as follows [7]:

1. Circular supplies: Provide renewable energy, bio-based or fully recyclable input material to replace single-life cycle inputs.
2. Resource recovery: Recover useful resources/energy out of disposed products or by-product.
3. Product life extension: Extend working life cycle of products and components by repairing, upgrading, and reselling.
4. Sharing platforms: Enable increased utilization rate of products by making possible shared use/access/ownership.
5. Product as a service: Offer product access and retain ownership to internalize benefits of circular resource productivity.

The World Economic Forum (WEF) has been working in partnership with the Ellen MacArthur Foundation and with the support of McKinsey & Company on Project MainStream, a multi-industry, chief executive officer-led global initiative to accelerate a series of business-driven innovations [8]. The Global Competitiveness Report 2011–2012 published by WEF indicated that the economy development of Taiwan has entered the innovation-driven stage [9]. According to the *Asian Development Outlook 2011* published by Asian Development Bank (ADB), Taiwan is expected to reach developed-country levels by 2030 with the support of innovation-driven production which accounts for more than 50% of economic development [10].

To encourage SMEs to engage in innovative research development, improve technical and service standards, and boost competitiveness, the Ministry of Economic Affairs (MoEA) has set out criteria for SME Innovative Research Award. Since established in 1993, the Innovative Research awardees were products and/or services that were composed of eco-design or circular economy concepts [11]. As a result, analyzing the awarded products would produce an indication in Taiwan's circular economy movements.

12.3 Methodology

This study focuses on the SME Innovative Research Awardees between 2009 and 2016 with a total of 237 awarded products and/or services as studying subjects. For the purpose of secondary research analysis for this study, the 237 awardees are divided into five categories of products, techniques, production, process, and services with regard to the case studies of SME Innovative Research Award Hall of Fame published by MoEA and then cross-referenced with the five business models of circular economy. The resulting list of enterprises are the suggested targets for in-depth case interview (Fig. 12.1).

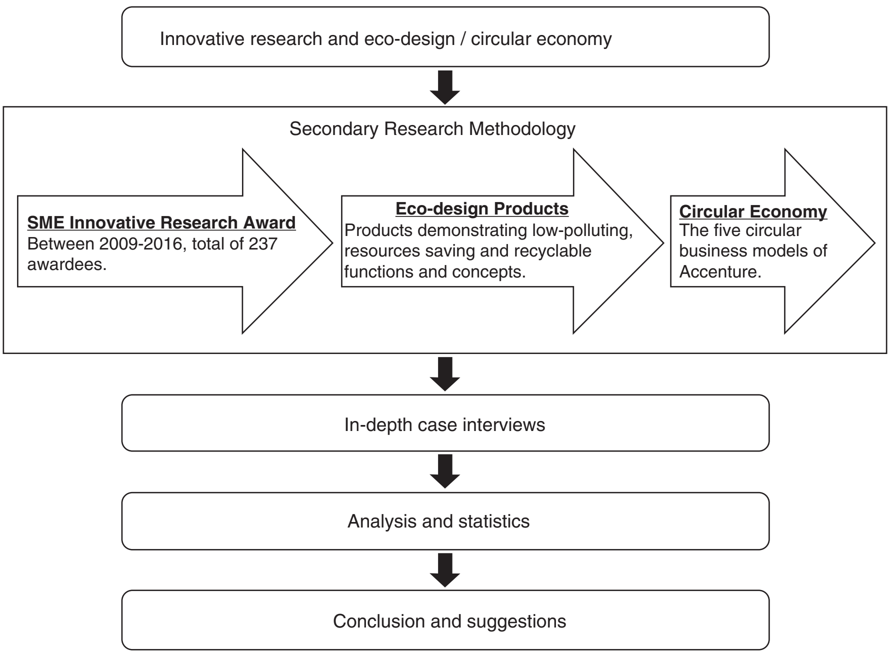

Fig. 12.1 Study methodology

12.4 Results and Analysis

The results of secondary research analysis of 237 SME Innovative Research Awardees between 2009 and 2016 are summarized below.

12.4.1 Characteristics of Eco-Design Products Among SME Innovative Research Awardees

The awarded product commentary section of the SME Innovative Research Award Hall of Fame details the innovative features of the awarded products and/or services. As a result, the awarded products and/or services are to be identified as to whether or not they demonstrate the characteristics of eco-design products of being low-polluting, resource-saving, and recyclable.

1. A total of 86 awarded products demonstrate the characteristics of eco-designed products and account for 36.29% of the 237 SME Innovative Research Awardees (Table 12.1).
2. Out of the 86 awardees categorized as eco-designed products, 20 belong to the machinery and equipment manufacturing sector ranking first, 12 from the electronic part and component manufacturing sector ranking second, and 10 from the manufacturing-not-elsewhere sector ranking third (Table 12.1).
3. Among the awarded eco-designed products, 18 are characterized as resource-saving ranking first, 8 are recyclable ranking second, and 5 are low-polluting ranking third (Table 12.2).

The above findings reveal that most innovative products are energy-saving machineries and equipment demonstrating the importance of energy conservation and carbon reduction to enterprises. The economic incentives from energy saving definitely are a strong market drive in innovative researches.

12.4.2 Analysis of Eco-Designed Products and the Circular Economy

The 86 awarded eco-designed products characterized with low-polluting, resource-saving, and recyclable concepts are then cross-referenced with the five business models of circular economy from Accenture.

1. Twenty-two out of eighty-six awarded eco-designed products fit the profile of circular economy business models, which account for 9.28% of the total 237 SME Innovative Research Awardees (Table 12.1).
2. The sector of manufacturing-not-else ranking first for having seven awardees justify as circular economy business models, chemical product manufacturing,

Table 12.1 Number of awarded products (by industrial sectors), eco-designed products, and eco-designed products that fit in the circular economy business models

Industrial sectors	Number of enterprises	Eco-designed products	Circular economy
Electronic part and component manufacturing	14	12	1
Computers, electronics, and optical product manufacturing	28	6	1
Machinery and equipment manufacturing	57	20	1
Nonmetallic mineral product manufacturing	4	0	0
Chemical product manufacturing	10	6	3
Pharmaceuticals and medicinal chemical products	9	3	1
Basic metal manufacturing	11	2	0
Plastic product manufacturing	9	5	1
Rubber product manufacturing	1	1	0
Other transport equipment manufacturing	11	3	0
Pulp, paper, and paper products	2	2	0
Leather, fur, and related products	3	3	1
Printing and reproduction of recorded media	1	1	0
Food manufacturing	5	0	0
Textiles mills	5	5	3
Manufacturing not elsewhere	30	10	7
Informational services	33	7	3
Services	4	0	0
Total	237	86	22

Table 12.2 Statistics of eco-designed products in subcategories

Eco-designed product subcategories	Low-polluting	Resource-saving	Recyclable
Number of enterprises (may be applicable to more than one category)	17	74	11

Table 12.3 Statistics of the five circular economy business models

The five circular economy business models	Manufacturing-driven		Business-driven		
	Circular supplies	Resource recovery	Product life extension	Sharing platforms	Product as a service
Number of enterprises	0	10	7	1	4

textiles mills, and informational services each containing three enterprises in the circular economy business models ranking second (Table 12.1).

3. Out of the 22 enterprises fit for the profile of circular economy business models, 10 belong to the resource recovery business model and account for 45.5% and 7 in the product life extension business model and account for 31.82% (Table 12.3).

4. The five circular economy business models can be further divided into manufacturing-driven and business-driven. Of the above 22 enterprises, 10 are categorized into the manufacturing-driven business models where the circular process occurs in the manufacturing stages, which account for 45.45%. The other 12 enterprises belong to the business-driven business models where the circular pattern occurs in the business concept rather than the manufacturing stages and account for 54.55% (Table 12.3).

In contrast to the eco-designed awardees, most enterprises which fit the circular economy business models are in the manufacturing-not-else sectors which encompass environmental engineering, medical and biotechnology, design services, etc. This result is a demonstration of the versatility of circular economy and enterprises of all types and size which are able to move toward circular economy. At present, the statistic shows that "resource recovery" is the most dominating business model, which reflects on the well-established resource recycling value chain in Taiwan. Since the awardees of SME Innovative Research Award mostly focus on the innovative improvements of consumer goods, hence it resulted in zero count in the "circular supplier" category. Among the business-driven models, "sharing platform" is currently the least applied in Taiwan.

12.4.3 In-Depth Case Interviews

12.4.3.1 DA.AI Technology Co., Ltd.

The awarded products are "Dope-dyed DA.AI Grey Eco Blanket" (2013 awardee) and "R2R PET chip" (2016 awardee) demonstrating the "resource recovery" characteristic.

The recycled PET bottles used as the raw materials were collected, sorted, and cleaned by a recycling platform which consisted of more than 200 thousand Tzu Chi Foundation volunteers and 50 partnering recycled material recovery enterprises. After sorting, cutting, and cleaning, the flakes undergo granulation process and are being made into yarn and finally turned into blankets.

Textile manufacturing is an important industry in Taiwan. However, the waste textile from production is treated as industrial waste and resulted in great negative impacts on the environment. DA.AI invested researching efforts trying to develop cradle-to-cradle design techniques to minimize the disposed fabric. DA.AI has successfully recycled and reversed disposed fabric back into its PET chip form and named it "R2R® (recycle 2 recycle) PET chip" and "R2R® PET DA.AI eco fabric." The eco fabric is used in the manufacturing of blankets, vests, and scarves, and the zipper of the vest is also made with the R2R® PET chip.

The key points of the in-depth interview are:

1. Material identification capacity of recycled resources. During the recycling process, many different types of materials are mixed together. The ability to identify the types of materials correctly determines the rate of these materials being successfully entered the remanufacturing routes.

2. Pollution control in the resource recycling processes. The resource recycling and remanufacturing of recycled resources may cause secondary pollutions. To prevent secondary pollution during the reverse cycle requires the cooperation between recyclate-treating equipment industry and the adjustments of environmental regulations.
3. Value creation of products made by recycled resources. Adding value to the products made by recycled resources is the best incentive to push forward industrial chain to shift from linear production to circular economy. Value creation can be achieved by product eco-design, green marketing, and the wide awareness of green consumption.

12.4.3.2 EcoTech Solutions Engineering, Co., Ltd.

The awarded "Cloud Monitoring Service" (2010 awardee) is a web-based remote monitoring platform. Instead of providing the customers with wastewater treatment equipment, the service provides leasing of the cloud monitoring functions, thus characterized as "product-as-a-service" business model.

The web-based cloud monitoring service transmits the signals of a wide variety of sensors onto the cloud and allows users to monitor and control through web browsers. Each signal is to be time-controlled. When abnormalities occur, users receive SMS notification and are able to actively control remotely through SMS notifications. Customized software packages can be added to enforce professional knowledge of different industries. Currently, wastewater level control and pumping water level control are applied to cater for wastewater treatment system monitoring service for housing, factories, buildings, schools, and hospitals in the Greater Taipei area.

The key points of the in-depth interview are:

1. Integrated industrial chain. In order to provide a complete service capacity, industrial chain requires to be integrated before applying either product-driven or business-driven business models.
2. Business model of circular supplies. To date, Taiwan industries have exhibited some advanced recycling technologies. However, with the limitation in industrial waste-related regulations, certain types of recycled resources are not allowed to be reused in the manufacturing of new products.
3. Current business model. The current business model of EcoTech is to promote the lease of water management equipment that is designed with easy maintenance in mind to prolong the product lifetime.
4. Talent training. The engineers are restrained by the technological knowledge and only focus on advancing the product functionality without the holistic view of combining circular economy with total solution.

12.4.3.3 3RTW International Corporation

The awarded "Reusable Cloth Diaper" (2011 awardee) exhibits the essence of "product life extension" business model.

The reusable cloth diaper is made of special functional fibers with a unique design for environmental protection. In addition to being a green product, the diaper minimizes natural resource consumption to meet the global trend. With its quality materials and design improvement, it keeps users (infants or the elderly) dry to ensure physical health and comfort of the sensitive skin. In addition to the adjustable feature which enables the diaper to grow with the infants to prolong product life span, the functional material makes the product easy to wash. 3RTW even provides product maintenance service to further extend product life.

The key points of the in-depth interview are:

1. Innovative technologies. Utilizing the techniques of combining functional textile with high-absorbing capacity of polymers in a cloth diaper.
2. The Green Mark. The preexisted Green Mark category of cloth diaper requires the target to contain at least 50% of cotton. The awarded reusable cloth diaper, however, does not fulfill this requirement, hence the inability of applying for the Green Mark.
3. Policy incentives. According to 3RTW's estimation, four million disposable diapers are thrown away daily, and most end up in the incinerators. If there is a policy in place to encourage the use of cloth diaper over disposable diapers, the load on incinerators would be greatly relieved.
4. Consumer attitudes. Although consumer acceptance of cloth diapers is not yet widespread, the comments are quite positive from consumers who have used them. As a result, the innovative business models of circular economy need to be made aware by the mass consumers through all channels.

12.4.3.4 My Happy Farm

The awarded product of "Happy Farm Lease Platform for Adoption" (2014 awardee) presents the characteristics of "sharing platforms."

The happy farm lease platform connects the land to the people in two folds. First, the farm owners become a service provider offering consumers the experiences of organic farming and disseminate the traditional Taiwanese land culture. Second, the young generation of farmers are able to pass on the land heritage with Internet applications. Through the support of Happy Farm Lease Platform, the consumers have a new source of fresh organic produce, and at the same time, the struggles of independent organic farmers can be relieved and continue with determination of sustainable farming.

The key points of the in-depth interview are:

1. Sharing platforms. Integrate spare resources of stakeholders on the sharing platform to offer consumers with business-driven circular economy model.
2. Incorporate public welfare. The business models of circular economy can be incorporated with social or environmental issues to promote public welfare initiatives with economy.
3. Regulation amendments. Some related regulations, such as "The Company Act," need to be amended to meet the current innovative business models.

12.5 Conclusion and Suggestions

From the above analysis, many Taiwanese SMEs are keen on utilizing the professional core technology coupled with determined innovation in designing products that are low toxicity, resource efficient, and recyclable and services compliant to the international circular economy trends. However, during the process of circular economy promotion, many hindrances are yet to be resolved. On the basis of secondary research of the innovations of 237 SME Innovative Research Awardees and in-depth interviews with the selected enterprises, utilizing circular economy business models, the conclusion and suggestions are as follows:

1. Suggestions to the industries. Moving from linear production to circular economy requires cross-industrial integration, for instance, the convergence between circular supplies and resource recovery and the incorporation of sharing platform with eco-designed products.
2. Suggestions to the governmental agencies. Amendments of regulations are essential for adapting and encouraging the movements of circular economy. For example, "Waste Disposal Act" and "Regulated Recyclable Waste Auditing and Certification Regulations" need to be adjusted for implementation of circular economy, "Public Procurement Laws" require to add more recognition and incentives toward circular economy, and the Green Mark and "Company Act" must adapt to the innovative business models of circular economy.
3. Suggestions to the educational institutions. Professional and technical trainings are the foundation of circular economy promotion, as in cross-industrial professional training and the use of information technology to assist the traditional industries in application trainings. Not until the basis of circular economy infiltrates all levels of education will the public understand, accept, and join the circular economy movements.

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Chapter 13
Policy for Circular Economy: Prestudy for Improved Policy Development

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13.1 Introduction

Circular economy (CE) is a rapidly adopted concept to improve resource efficiency and sustainability, with Braungart et al. one of the early contributors [1]. In order to reach CE, there is a need for a lot of changes in society, which will have a lot of consequences both for industry and for society. The Ellen MacArthur Foundation has been working intensively to create an awareness of that [2, 3]. There are a lot of actions to be done in order to drive the transition, for example, implementation of new regulations and policies, but also systematic attempts to enhance the engagement and request for more circular products and offers among customers and suppliers along the supply chain.

The "Polcirkeln project" within the research program RE:Source, funded by the Swedish Energy Agency, Vinnova and Formas, was a preparatory study, to be used as a base for further research. The study was carried out as a collaborative research project with 19 company representatives covering the value chain. The aim of the project was to study the current situation and possible future effects of various policy measures for a circular economy on circular flows of products, materials and wastes, using Sweden as the "test case" [4]. Among others, the EU's proposed policy package for a circular economy has been studied [5]. Today's products, materials and waste flows constitute a starting point, and challenges and possible effects have been formulated and analysed based on experiences and views from different actors in the value chain (mainly from industry) and other experts. While the project addresses

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predominantly policy aspects, earlier research related to ecodesign by Boks et al. [6] points to a crucial role of language and communication for implementation and the under-researched link between ecodesign proponents and executors (technical experts, decision makers and marketing experts). Thus aspects of communication and cooperation were addressed in interviews and questionnaire. Methods used in the study are, for example, mapping of flows based on statistics, interviews, a web survey based on questionnaires, workshops and scenario analysis.

13.2 Methodology

In order to evaluate the consequences of policies on material flows, three material flows were chosen to study more in depth. The three were chosen based on a first survey of the amount of policies having an impact on circular economy for each material flow. Material flows chosen were:

1. Textiles.
2. Electronics.
3. Plastics from the building industry (construction and demolition).

In this paper material flows related to electronics have been chosen as the sample, since the data available were most complete and reliable for that material flow.

The study was using an iterative approach. Information was gathered and analysed in several steps, starting with mapping the current situation regarding material flows and existing legislation and in parallel interviewing project partners from industries about challenges. Then a web survey was carried out with a larger population including non-participants to gather a wider view about identified challenges and what consequences existing policies have on product design, material selection and end of life and thus on material flows. Intermediate results were then discussed in a workshop, after which complementing interviews were held. Based on the results, a first version of scenarios was developed which considered increased implementation of CE policies and its impact on flows of products, materials and waste. Finally the scenarios and other results were discussed and elaborated in a workshop with actors along the value chain and further developed based on the results of the workshop.

13.2.1 Study of Current Situation

13.2.1.1 Current Material Flows

Current flows of products, materials and waste were studied in order to get a better understanding of the prerequisites for existing and coming policies. This was based on market data, statistics from the Swedish government and information from recycling, refurbishment and selling companies. It was obvious that the data that are publicly available were not detailed and complete and therefore not sufficient to give a clear picture. In order to address this shortcoming, the data quality was described for the different figures given. The final pictures can still be used to analyse the magnitude of effects and thus show which policies will have a high impact on resource efficiency.

13.2.1.2 Existing and Suggested Policies

A study of existing and suggested policies was done, with a focus on policies having an impact on material flows, directly and indirectly. Global, European and Swedish policies were gathered and studied, covering legislation, tax regulations and other incentives, mainly from governments.

13.2.2 Web Survey

A web survey was developed with the objective to gather information from a large amount of stakeholders within the industry, covering all steps along a circular system, including raw material producers, product manufacturers, service providers, users, collecting actors and actors in waste treatment, including incineration.

The questionnaire was sent out to about 200 possible respondents within the project network, covering the intended stakeholders.

13.2.3 Interviews and Workshops

In order to let the stakeholders of the project elaborate their ideas about how policies work today and what possible consequences suggested policies could have, 15 interviews with representatives from different stages along the supply chain and the waste treatment were carried out. One main objective was to find out what stakeholders see as main challenges that have to be overcome in order to change to a circular economy.

The challenges were then listed and elaborated further in two steps at two workshops, where the stakeholders in the project were gathered. One notable aspect is that the stakeholder group was very keen to contribute to the research and to provide positive suggestions about possible solutions to the challenges identified.

13.2.4 Scenario Analysis

In terms of future effects, uncertainty is inherent. However, this does not mean that we should avoid discussing possible futures. Concerning circular economy measures and impacts on consumption, material and waste streams as well as material and energy recovery, it may therefore be appropriate to develop different scenarios for possible future flows and related effects.

Different types of scenarios have been presented by, among others, Dreborg [7], Börjeson et al. [8] and Bishop et al. [9]. Overall, all of these types can be divided into probable, possible and desirable future scenarios.

Since the purpose of this study was to link the Commission's action plan to the effects that this has on future consumption and waste flows, four scenarios were developed where existing and future policies were summarized in packages.

Current flows of products, materials and waste and the challenges described by the industry and other actors in the interviews and workshops were used as a base when developing the scenarios.

1. Scenario 1 (S1): Current situation.
   (a) Existing national, European and international policies having an impact on the transition to a circular economy were collected and analysed regarding their impact on the actual outcome as regards material flows and sustainability. The specified date to define existing policies was that they were published and implemented on September 1, 2016.
2. Scenario 2 (S2): Including CE package.
   (a) The same as S1, but adding the EU's proposed policy package for a circular economy [5].
3. Scenario 3 (S3): Including CE package and suggestions that have been developed as intermediate results from the project *Polcirkeln* (workshop).
4. Scenario 4 (S4): "Goal" or best-case future scenario, where sustainable circular flows of products, materials and waste are in place. This was used as a benchmark to understand the outcome of the other scenarios.

13.3 Results and Discussion

13.3.1 Results of the Study of Current Situation

The research of the current situation gave some interesting flow pictures, where the flows of today were described. Due to data quality reasons, we use electronics as the example (Fig. 13.1).

The study shows that the picture is very complex, but that the main flows of materials for electronics are dominated by import and export. It also shows that even with the Waste Electronic and Electronic Equipment (WEEE) directive in force, circular flows are today mainly implemented through recycling.

An aspect that is difficult to handle in the assessment is the area of informal recycling and illegal material flows, for example, the illegal export of electronics, since that data is not gathered in any statistics. Specifications of numbers are varying very much; the actors involved in Polcirkeln assume that numbers for Sweden are low.

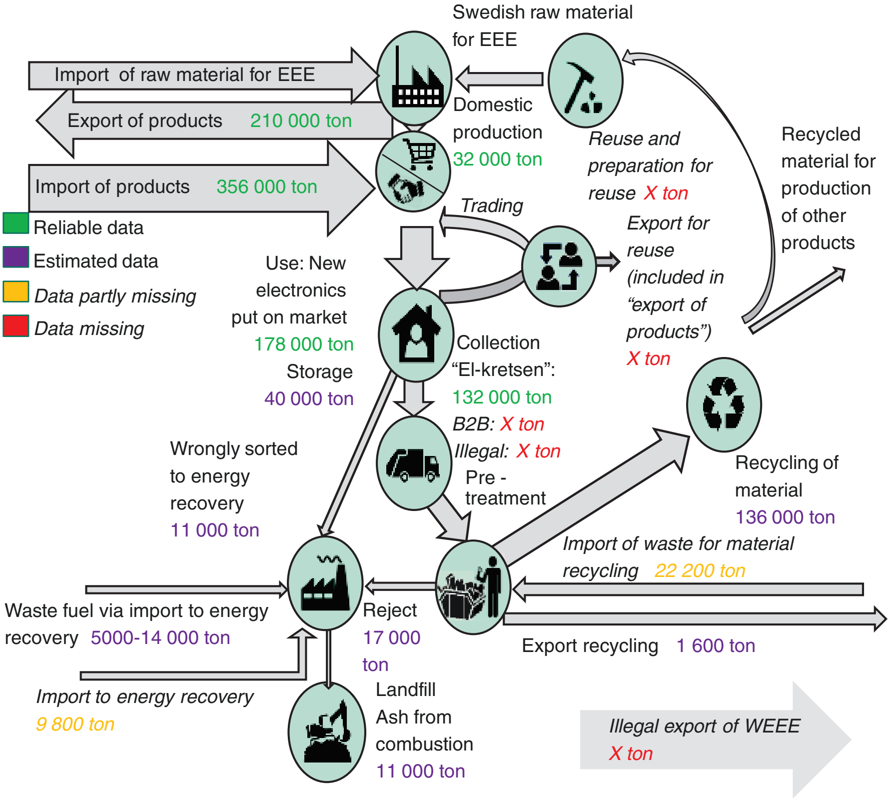

Fig. 13.1 A visualization of current flows of products, materials and waste for electronics

13.3.2 Results from the Web Survey

The web survey was answered by 76 respondents, of which 50 gave full answers to all questions. Results show what companies find most important in relation to a circular economy, with focus on what drives and stops them from increasing reuse, recycling, remanufacturing and recycling.

Respondents could select multiple answers. The main results from the survey is given in the diagrams below (Figs. 13.2 and 13.3).

13.3.3 Results from the Interviews and Workshops

In the following, results are highlighted separately for both rounds of interviews.

General challenges from first round of interviews.

List of identified general challenges with impact on possible flows of products, materials and waste according to the stakeholders

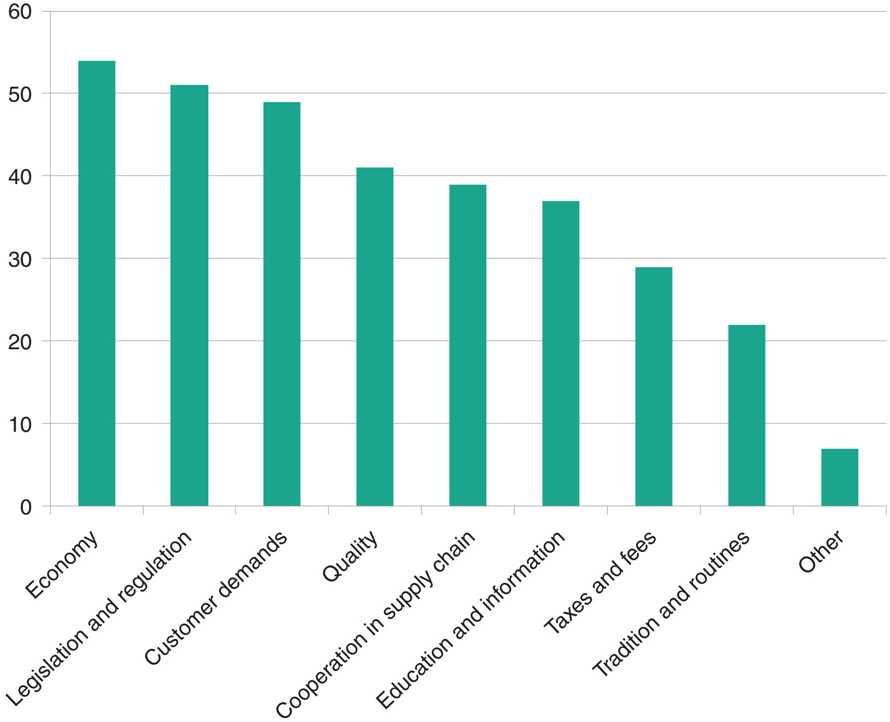

Fig. 13.2 The most important factors (% of responses) which support the reuse of products and components today (from web survey)

1. Design, production, cooperation:
   (a) Material content
   (b) Material demand
   (c) Design of products and components
   (d) Cooperation between actors
2. Consumption and waste prevention:
   (a) Procurement (public and private)
   (b) Collection
3. Demand for reused/remanufactured product
4. Information and labelling
5. Waste management and recycling
6. Infrastructure
7. Secure information treatment
8. Market surveillance
9. Definitions and measurements

Further discussions at workshops and through complementing interviews gave details listed below

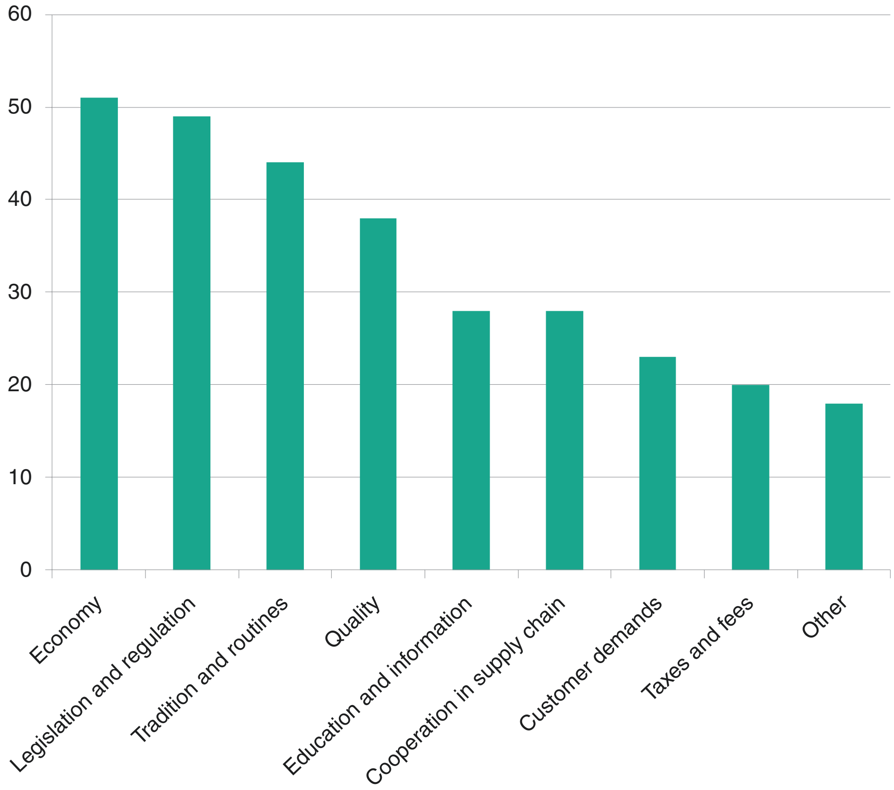

Fig. 13.3 The most important factors (% of responses) that prevent an increased recycling of products and material today (from web survey)

1. There is a need for a more holistic view. Today many of the existing policies address a specific issue/sector and distinguish between improved waste management or product design and waste prevention. They do not consider a systematic picture.
   (a) For example, the general goal to recycle and reuse electronics does not consider hazardous chemical substances used in the past. An example are flame retardants based on brominated compounds, which make the electronics fulfil fire-resistance legislation and regulations, but are no longer compliant.
2. Cooperation between companies is a key to circular economy, and the systems of today, for example, business models and regulations, are adapted to linear economy and thus quite often barriers for cooperation. It is therefore a request from the industry that the policymakers try to push cooperation through policies and through simplified rules (e.g. for shared values).
3. There is a need for an increased knowledge, not least among SME, regarding existing and coming legislation and regulations; specifically there is a lack of knowledge regarding legislation and regulation affecting other actors part of the own value chain.

4. There is a lack of enforcement and monitoring of existing legislation, making the "good" companies suffer on behalf of the "bad" ones, since it is costly to fulfil the requirements, while those who do not follow the rules can get away with it (e.g. illegal export of WEEE).
5. Definitions and regulations connected to the definitions are very important, and we see that they can even be a barrier to circular economy:
   (a) For example, in Sweden, only municipalities have the right to collect municipal solid waste (originally because of hygienic reasons). Items that are brought to recycling centres are defined as waste and are then forbidden by legislation to be reused, remanufactured or refurbished but only recycled as material or energy.
   (b) At the same time, it is forbidden for shops to collect waste except for electronics within WEEE—this is a large obstacle for initiatives by textile retailers to increase reuse, remanufacturing or refurbishment.
6. Labelling—The industry points out a wish to have a standard regarding quality of reused and/or remanufactured products.
7. The industry also has a wish for standardized systems for information regarding the material content.
8. When asking the industry which are the most important factors for reuse of products and components, the answers in interviews and workshops were very similar to the ones in the web survey:
   (a) Economy
   (b) Legislation
   (c) Attitude
9. Leading companies already working on improving circularity foresee market possibilities and increased competitiveness due to their efforts, where they also see existing and future policies as an opportunity rather than a challenge.

13.3.4 Results from the Scenario Analysis

The scenario analysis showed that existing regulations and policies of today (scenario 1) do not address the identified challenges for reaching circular flows. We conclude that this is precisely why the challenges have been identified and prioritized during the project. This result applies to all three researched material flows: electronics, textiles and plastics from construction and demolition.

The powerful policy instruments Sweden (and other countries) has had for a long time, for example, producer responsibility and landfill bans for organic and combustible materials, contribute to a well-developed waste treatment system but do not reach the higher levels in the waste hierarchy or the internal circles of the flows.

If we include the EU's proposed policy package for a circular economy [5], we will come one step further, and therefore we conclude that the EU's circular economy package addresses several of the challenges. This happens through, for example, economic incentives for producers or green procurement and focus on circularity in the Ecodesign Directive. But the wording is often vague such as "promoting circular flows". There is therefore an extensive work to be done to make the measures concrete. Consequently, the EU package is neither sufficient nor concrete enough, because it is expected that the challenges will be fully resolved and flows influenced.

In scenario 3, a number of proposals on more far-reaching and specific measures have been formulated. In some cases, the project assesses that the challenge can be solved in scenario 3, as illustrated by green colour in the boxes in Fig. 13.4. This applies, for example, to mandatory legislation for the use of recycled materials as

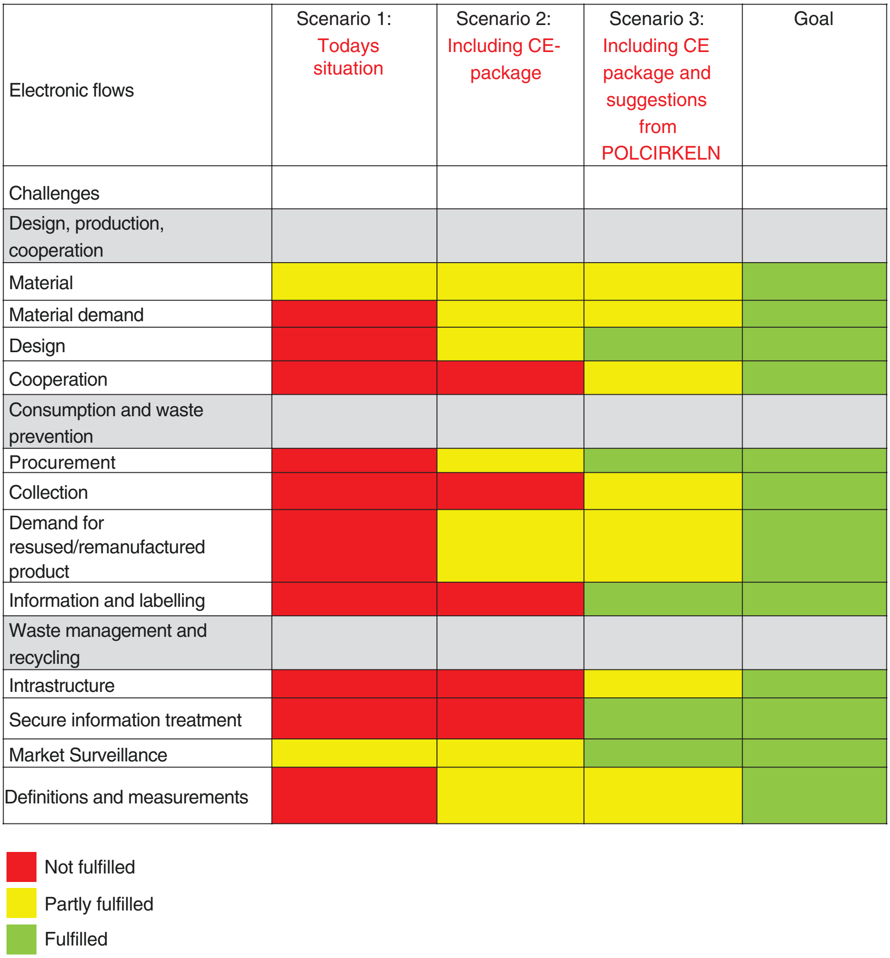

Fig. 13.4 A visualization of the outcome for electronic flows of the scenario analysis

well as requirements for prior approval of products. Such measures can solve the challenges, prevent waste and reach increased inner circle flows.

However, it should be noted that such new legislation, as suggested above, may have effects that potentially generate new challenges. In order to make sharp recommendations, measures should be defined and analysed in a more comprehensive context. Generally this is an indicative scenario analysis, conducted within the framework of this preliminary study. The result shows a first indication of the challenges that are addressed by different legislation and measures. For a more comprehensive analysis, detailed studies of each individual challenge are required, with a greater detail level.

Furthermore, the scenario analysis shows that policies can have an impact and lead to improved resource efficiency and improved competitiveness for companies starting early. For example, demands for design of products to make them better suitable for circular systems, such as reuse, remanufacturing, repair and recycling, will give an advantage for companies doing that and at the same time will improve the possibilities to change to a more circular system. Promoting products having a long life can be done through demands for longer warranty periods or similar. This will also promote companies providing "better" products from a circular point of view.

13.3.5 Discussion

The transition to a circular economy means, among other things, that companies, society and organizations highlight business opportunities based on circular flows, rather than linear processes. In order to minimize commodity withdrawals, maintain products and materials to their highest possible usefulness and value as long as possible and minimize the generation of waste, extensive change of design, production, use and waste management is required. New strategies and policies include environmental and economic aspects as well as social, which means that tools and incentives, as well as evaluations, must be based on a holistic view overall and a systems perspective.

Cooperation within companies, along the supply chain and with other organizations, is crucial when it comes to the implementation of a circular economy. In earlier research, e.g. related to ecodesign, done by Boks et al. [6], it is shown that the language and communication plays a crucial role and the under-researched link between ecodesign proponents and the executors (technical experts, decision makers and marketing experts). For a successful cooperation, the target image needs to be common and clear to the collaborating actors, which is not always the case. The findings in our study show the same challenges, and thus, we think that the need for further research and development of a common language and communication between different stakeholders is essential for a successful implementation of a circular economy.

Project participants demand clear, long-term rules and goals to strive towards. Powerful instruments such as prohibition and legislation provide clarity, and powerful efforts can be made here, compared with today's situation. However, knowledge, political courage and innovative thinking may be required on the side of the actors.

As a reflection after the project, it became apparent that participants in interviews and discussions neither lifted waste prevention activities nor the consumers preferences and lifestyle as major challenges for reaching more circular flows or resource management. Waste prevention is highly prioritized in the waste hierarchy, and the consumer should be an important player in this context. It is unclear why they did not receive more attention in the project's discussions. This could be due to the composition of actors, the project group's filtering or something else.

The project has a Swedish perspective, but several of the participating companies are working on a global market. National legislation must therefore be harmonized with international counterparts. How can the challenge of raising policy and regulation to an EU or even more international level be handled? There are extensive, ongoing international studies for policing and its impacts, where information can be exchanged. The current project Polcirkeln has exchanged experience with the European Commission, UN Environment Agency (UNEP) through its International Resource Panel, the World Trade Organization (WTO), as well as with several parties and organizations.

13.4 Conclusions and Recommendations

A holistic approach is needed.

To achieve a circular economy, changes are required which will have consequences for many actors and those can be enforced with the help of policies. So far, measures like prohibition of landfill and goals for recycling have moved us up the waste hierarchy. To get further, a pull from the top stairs is needed, e.g. by requiring a certain percentage of recycled materials in products, set goals in terms of life span of products or prohibit material that complicates recycling—a challenge for designers together with recyclers.

The results show that the EU package for a circular economy is ambitious but must be concretized and strengthened. Increased collaboration and a holistic approach are needed, between and within different organizations and companies, nationally and internationally, and also between authorities and political sectors. The global arena is a challenge for many companies, and policies should be raised to a sufficiently high level to have the desired effect.

Many companies have insufficient knowledge about existing and future policies and regulations for themselves and other actors in the value chain, and thus risk making mistakes.

13.4.1 Recommendations

In order to promote innovation and solutions with a holistic perspective we recommend:

13.4.1.1 Policymakers' Recommendations

1. Take a holistic approach and harmonize different policies along the value chain and on different levels.
2. Concretize measures and targets for the upper parts of the waste ladder.
3. Promote a material strategy that complements the waste hierarchy.
4. Eliminate barriers to circular economy while taking into account other environmental and sustainability goals.
5. Follow up the measures taken to speed up the transition to circular flows.
6. Promote collaboration, since it is easy to say, hard to do. Collaboration takes time: building trust, creating a common language and enabling knowledge transfer. Policymakers can push by, for example:
   (a) Promoting collaboration with a life cycle perspective, e.g., in public procurement.
   (b) Spreading good examples.

13.4.1.2 Company Recommendations

1. Create routines and networks to ensure adequate knowledge of policies and regulations.
2. Think long term and from a life cycle perspective.
3. Identify the company needs to achieve more circular flows.
   (a) Communicate these along the value chain, in order to ensure that other actors can do the right things.
4. Broaden perspectives to find new possible collaborations.

13.4.1.3 Recommendations for Further Research

There is a large need for further research in order to change the society and the industry to a circular economy. Some of it is mentioned here, based on our research findings.

1. Research about how to solve technical issues, such as:
   (a) How to design products that work in circular systems.
   (b) How to gather, save and share information needed from each part along the value chain in order to promote reuse, remanufacturing, recycling, etc.
      - For example, monitor the chemical content in order not to put something dangerous or even forbidden on the market.
   (c) Develop indicators which can help people along the value chain (including end customers) make smart choices.
   (d) Develop new and more sophisticated methods to take care of all the rare materials in electronics.

2. Research about other issues, such as:
    (a) How to handle economics along the value chain, in order to make every part in the chain happy, so the chain doesn't break.
    (b) How to develop law and ways to cooperate which work in a circular economy.
    (c) How to ensure that the circular solutions lead to "true" sustainability from a holistic point of view.
    (d) Language, definitions and communication in order to minimize barriers and promote a circular economy.
    (e) Statistics, in order to understand material flows, and possible consequences of suggested actions.

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Chapter 14
Circular Economy in Business Strategy of Manufacturing Company

Hidetaka Hayashi, Masatsugu Kitamura, Shin'ya Nagasawa, and Tadatomo Suga

14.1 Introduction

We have long enjoyed the outcome of industry spending a lot of resource and energy. Under the limited size of Earth, this industry mechanism will not sustainable in due course. The concepts of "inverse factory" and "circular production system" are proposed to reduce the impact of resource shortage by repeated use of recycled material [1]. Another impact on our lives is environmental destruction including global warming caused by increasing energy consumption and disposal of industrial products. It has been realized to be rectified in the industry system. As the circular industrial system could contribute to reduce resource consumption, it collected much expectation to be an effective way for rectifying environmental impact from industrial production. Up to now, we can reduce the speed of environmental destruction and resource shortage. These were critical issues in the last century and could foster common understanding against global warming assisted by the global legal Scheme [2, 3]. The material-saving design, the energy-saving technology, the alternative material for hazardous material, and the recycling technology have made big progress. The municipal solid emission and disposal amount per capita turned to reduction after the peak in 2000 and reduced about 24% in Japan in 2015 [4]. People had mutual understanding on the circular system that is effective to reduce both resource and environmental

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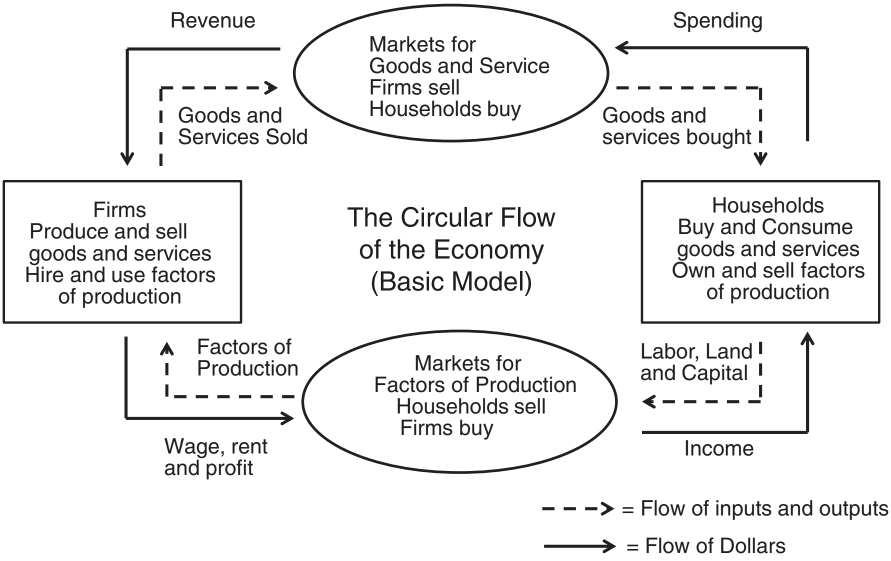


Fig. 14.1 Circular model of economy [13]

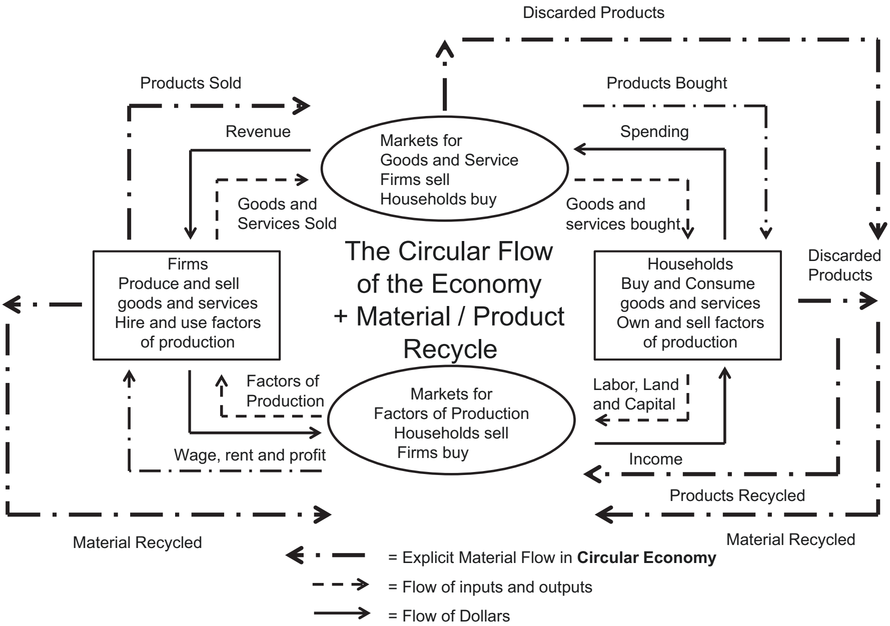


Fig. 14.2 Material/product flow in circular model of economy

impact by this evidence. The concept CE is an extended concept in economic system. The circular model in economics is just the cash or value system as shown in Fig. 14.1.

The material flow is not taken care in this flow model. But CE is projecting material flow together (Fig. 14.2). By this drawing economy is categorized into two. One is linear economy (LE) and the other is circular economy (CE). The concern of this research is whether the economic system can be transformed to CE without the help of legal enforcement. We must start our research by reviewing the value and company profit that are pointed out by our former research [5], but it has been rarely the subject of research on the circular system. This research is intended to find business strategy of manufacturing company that is the major player of supply side in the free-trading economy.

14.2 Circular Business Models

There are many closed circular supply and recycle business models carried by original manufacturers in copy machines [6], construction machines [7], medical electronic equipment, and more [8]. The featured characteristics of these models are the models operated by original manufacture's mixed production with new products recovering component values. The products taken back from the market are inspected and repaired, and the degraded components are replaced in the mixed production line, and they are finally put into the market as new products. There are similar circular models for the consumable goods. The business model of photograph film is a remarkable one [9]. In this system the reusable camera acts as package, and the manufacturer gets her profit from the amount of sold film. That is to say, it is the pioneering service providing business model. The common characteristic of those business models is that the original manufacture manages the recycling loop and the operating cost and profit are totally controlled by the manufacturer. Therefore the cost for partial operation could be covered by the profit of total business. For sales promotion, those products that use consuming supply material and service software set the price of products below the cost of production expecting future profit gained by selling consuming material and/or the service. Most IT equipments such as printer for PC [10], cell phone [11], and smartphone apply this profit plan. There are many business chances expected to refurbish products such as PC, cell phone, and smartphone and install new software to reuse. These products are exposed to rapid innovative technology; therefore, the first user will unwillingly or willingly quit using in a short time. Recycled components of big products such as home appliance and automotive are expanding market improving reliability assurance and refurbishing capabilities such as inspection repairing and refurbishing. Gas stations are providing sharing car service by their own long longevity car. Reusing business of books, CD, DVD, clothes, and furniture is an expanding business cooperating with delivery firms.

14.3 Competitiveness of Business Firm

To develop CE in the economy, the company in this business system must have relative competitiveness to the competitor out of this system. The competitiveness however is a not-so-simple measure because it is totally evaluated from assets, performance, and process of the company [12]. But apart from calculation, actual competitiveness is reflected in the profit or profitability of the company. That is to say, the profit is representing actual performance of accumulated competitiveness. Further, the competitiveness is not an absolute measure but relative measure, and it actually works through trading. Trading is a basic economic activity between two players in the market. One is supplier or maker, and the other is buyer or consumer [13]. The supplier supplies products to the market in accordance with the consumer's demands. The demand of the consumer is reflected on the value of products that is price. The key issue is the pricing of products. If the price can surpass or equal to supplier's value, the deal is made [14]. The price represents the value of products of consumer's demand. But it is not always for the supplier's expectation. The supplier expects the price could exceed the spending cost to make the products. The expected price or value of the products must exceed the cost with adding profit. The value of consumer's expectation is independent to the cost of supplier's, but the value of products for supplier is affected by the cost. There is always decoupling on the value for consumer and the value for supplier. The former is consumer's will, and the latter is supplier's expectation for recovery of spending. The will affected not only evaluation of the functionality but the emotional motivation. The spending includes not only the cost to make but the cost of distribution and follow-up service. Whether the supplier can expand her activity or not is depending on the decoupling mechanism. The market today is complicated. There are a lot of cascaded networks operated in the market. There are a lot of deals done at the every step of networks [15]. Each step forms supplier-consumer relations. That is to say, transactions in the mechanism of value, counter value, and cost relations are done. Figure 14.3 shows our CE model [16]. The products are made at the factory and delivered to the user

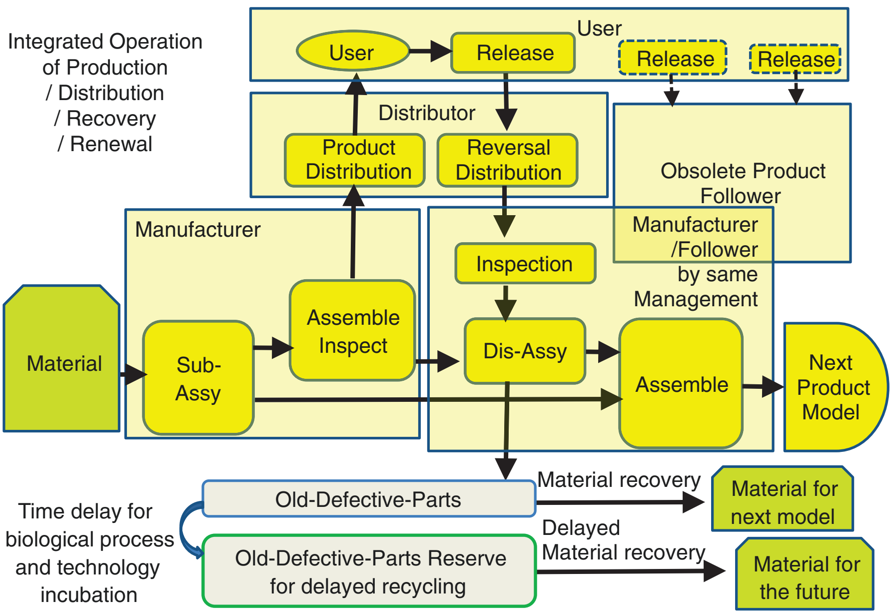


Fig. 14.3 IIDPS model

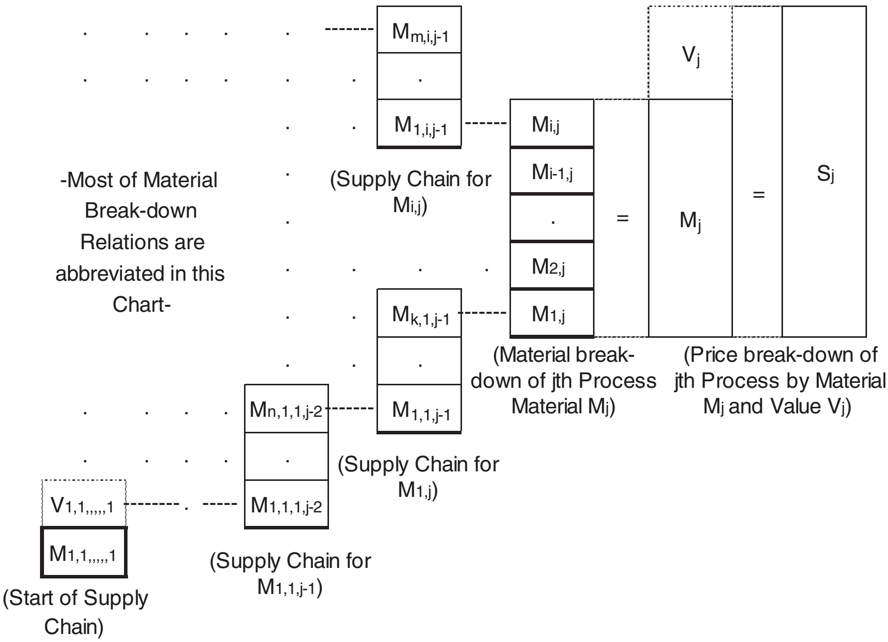


Fig. 14.4 Value chain in transactions

through distribution mechanism. This mechanism is similar both in CE and LE. The value chain in every transaction is shown in Fig. 14.4 [17].

14.4 Reducing Cost

If the cost is less than the intended price of products, the supplier can put them in the market. Therefore, cost reduction is a very important issue to get competitiveness in the market. The cost reduction for making distribution activity is the issue both for CE and LE including technical issue [18]. But CE is the business scheme to utilize the products after the end of use in any possible manner. This business scheme may limit the freedom of resource selection and distribution channel. This handicapped situation sometimes leads opinions to make legal framework that provides the same handicap to LE [19]. The possible limitation for LE includes material selection, process selection, and distribution channel.

14.5 Value-Add

The technologies of equipment functionalities, energy reduction, and reduction of consuming material are always advancing. New products are produced applying these outcomes of technology. In CE, products are expected for longtime usage. Therefore, it is not so easy to apply new outcomes in the products. An idea to mitigate the situation was proposed, including design of upgrading for the future [20]. This design concept is advanced, but it is not so easy to match user's preference because the forecast is made at the timing of production of products. The new product always has the advantage of new functionality and the visual appearance. Contrary to the novelty of new products, the difficulty to utilize it could be the disadvantage of the new product especially in the case of multifunctional and novel functionality introduced by thick guidance manual [21]. Therefore, the innovative change depends on the user's proficiency capacity. The EPR requirement to protect the user from risk could increase the volume of the user's manual. The owner of long-life product could reach well-experienced level during long usage.

14.6 Product Life Span and Value Change

The lifetime of products must be considered from two aspects. One is from the lifetime of equipment, while the other is from the length of user's intention to keep using it. The former is the healthy period of the equipment with no components (parts) damage by wearing or degradation. The latter is the period quitted by losing user's intention to own. The reason of quitting using is listed in the user survey [22] including malfunctioning, and limited functionality, compared to new model, or visual design is old. The repairing fee to repair and restore malfunctioning pulls back the first owner from repairing. If the fee is within the level of owner's expectation, the possibility to get repairing will increase and extend product ownership. The product quit using could be given over another user or thrown away. Whether the used product has value or not is the matter of the new product at that time. If there is no buyer in the market, the product is discarded.

14.6.1 Lifetime Discussion in Sustainability

In the sustainability discussion, the economic system that can reduce material input to the market is discussed. That is to say, even if the lifetime of equipment is long, and if the intention to keep the equipment of user is quitted, the equipment cannot fulfil its life. Moreover the equipment that cannot be accepted by the market cannot find its room in the market. The competing products at the timing of quitting using are not the competitive products at the timing of getting products but at the timing of quitting using. In CE, the product of quitting using is used by the succeeding user. A reused product has the same meaning as a new product for the succeeding user, because the succeeding user newly acquires the equipment. Then from the view of action, there is no difference from new acquisition of new product. The difference is only the historical situation of the equipment. There is a history of ownership of the equipment. Of course the equipment must not be disqualified in functionality including warranty.

14.6.2 Value Reduction During Long Ownership of Products

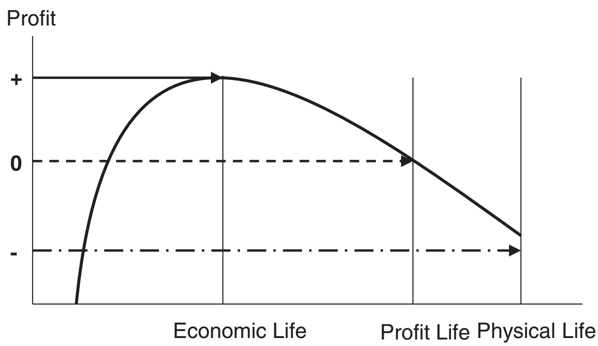
The value is reduced during the longtime ownership of the equipment. The causes of value reduction are mainly degrading of appearance and wearing components. To accommodate the situation, we do repairing. Especially for a big construction machine, the repairing cost is small compared with the cost of the machine. The life-cycle cost analysis (LCCA) gives us useful information on profitability of the business in longtime ownership of machines [23, 24]. There are three ways of lifetime: physical life, profit life, and economic life. Figure 14.5 shows that the owner can decide equipment lifetime considering expecting profit in terms of life span of ownership.

In LLCA the decision is based on the profit gained by the operation of the equipment. Therefore, the optimum ownership period is decided by calculating profit. In consumer equipment the decision is based on the expense of fixing and mixed with the feeling of satisfaction and dissatisfaction. The feeling of dissatisfaction is awarded by comparing competing products. The measure is more mental and psychological satisfaction, but improved functionality is compared by expense. The period of ownership reduces the feeling of expense as LLCA model. The new functionality added to competing products during the period of ownership also reduces the feeling of expense.

14.6.3 Acquiring Value During Long Ownership of Products

As abovementioned the longtime ownership reduces the value of products compared to competing products. Nevertheless it is not directly the motivation of replacing owing product by the competing products, because there is a barrier to

Fig. 14.5 Equipment life (LLCA) [23]



be cleared. The owner must pay for the cost of new ownership and spend time to master utilization. The level of maturity could be the acquired value during ownership. The appearance of product and operability of product are changed during long ownership. These changes reflect the way of owner and therefore cannot be given at the timing of production and the acquired value. The products inherited from the former owner can inherit the history of the former owner. This inheritance is not free but restricted by Private Information Protection Law. But the inheritance is done in the same family generation [25]; the situation is different. The scheme to keep and create value of product distinguishes the old product from new one. This value will be enhanced by the historical story of products like the luxury products [26].

14.7 Economic Effect by Cyclic Usage of Product

CE is the economic activity of cyclic use of product after quitting usage of first owner. The form of cyclic usage is versatile including from the whole product (the highest level) to material (the lowest level). The value recycled is distributed from less than 1% at the lowest level [27] of no effect on economic scale to comparative level of product (the highest level). In industry new energy and resources are introduced to make new product. In CE the discarded product by the first owner is followed by the new owner increasing penetration rate without resource consumption. Cyclic use of lower level has very limited effect on economic activity because the recovery of resource is very limited and the energy and human activity cannot be recovered at all. Therefore, the resource usage is mostly the same as in LE. Human activity includes production, design, and distribution.

14.8 Lifetime Design

The principal meaning of CE is enough product supply to reduce resource consumption and, at the same time, to keep economic activity of providing enough jobs. It must be mentioned that the low-level cyclic use cannot both keep value and save resource at the economic scale. Therefore, the major subject of CE is to put long life span product in the market. The life span of home appliance electric product is 4–12 years of age [28–30]. Therefore, at least 12-year lifetime design is necessary. It is desirable to supply long-life product to the market than recycled use of short-life product. Twelve years means about 1/3 of one generation and a little bit longer than the development period of innovative technology (10 years) [31] and the maximum period of user satisfaction. The design of standardized long-life component to make long-life product had been adopted in the integrated corporate strategy in a copy machine company [32].

14.9 Bolstering Strategy for the Competitive Strength Employing Marketing View

By the above discussion, it is hard to find competitive nature for a company in CE business model that binds free choice of the company. But this situation is very common in marketing environment. Every company is struggling in business with its limited strength. The strength of a company is not so consolidated but fluctuated reflecting floating consumer preference even if the management index of the company is stable. It is to say that unstable and handicapped market situation for every company is very natural. Moreover it is the market that allows a company to survive if the company changes its attitude by waking up sensitivity to the market. The definition of marketing is approved by the American Marketing Association in July 2013 as follows: "Marketing is the activity, set of institutions, and processes for creating, communicating, delivering, and exchanging offerings that have value for customers, clients, partners, and society at large" [33] after a lot of discussion. Still on the way of revising work [34, 35], it could be summarized as "the total activity to increase value (get customer satisfaction) of commodity in distribution and trading." That is to say, the activity is not included in manufacturing but included in distribution in the market. In modern marketing, the strength of company in the market is measured by market share [36]. Therefore, the business strategy starts planning to know market preference and find company strength and making a scenario to get market share step by step. The market preference is not clear in most cases, but we can draw a vague image from market survey. Using this kind of survey and making our own explanation combining additional information such as marketing location, year, customer layer, and so on, the effective strategy is completed. In this study we will show some hopeful scenario for company in home appliance electric products. The user's following opinions for acquiring products and reason for quitting using shows us are noteworthy. The past ownership of the brand, reliability, brand reputation, quality, price, cost for repair are the listed answers. Including brand reputation, the reliability issue can meet the user's preference.

14.10 A Business Strategy for Manufacturing Company in CE

As already mentioned, the business strategy is not the absolute and independent correct indication for business firm but a co-established product with market. We have to know the consumer choice that is not straightforward, and it is both rational and emotional in nature [37, 38]. It is time dependent and sensitive to the attitude of influential people and very fluctuating [39]. Therefore, the strategy must be supported by additional activity like war battle. But of course it is not free from business framework. The framework for CE is circular use of resource, and essence is minimal resource usage over the long term. The following are applicable strategies by a manufacturing company at the initial stage of business.

Key factors are long-designed lifetime, low defective rate in the market, repairing fee, and recovery of sold products.

1. Keep designed lifetime on the top of the manufacturers.
2. Keep lowest defective rate in the market on the top of the manufacturers.
3. Keep the repairing fee of user expectation within the designed lifetime.
4. Save the defective product for refurbishing from the user who wouldn't keep it during the designed lifetime.

14.11 Conclusion

In economics we should be aware of the two players, producer and buyer. They direct the economic deal, and the value is evaluated differently. In the value decoupling between producer and buyer, the strategy finds room for the company of less competitiveness. We hired high-reliability strategy. That is, we supply reliable and long-life products to the market. The feasibility of business success is very much relied on the defective rate of our product in the market. The more we improve the reliability of our product, the less we can make the repairing cost and our reputation higher. This is the very natural objective of industry. If the numbers of such company is increased, the less resource will be consumed. Again to reduce more, the cyclic loop in CE should be long. The longtime use of product is effective. Therefore, long-life economy (LLE) could replace CE for the industrial goal.

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Part III
Eco-Design, LCA and Footprinting

Chapter 15
Urban Factories: Identifying Products for Production in Cities

Christoph Herrmann, Max Juraschek, Sami Kara, and Sebastian Thiede

15.1 Introduction

Urban population rapidly grows all around the world. Today, more than half of the world's inhabitants already live in cities and urban areas [1]. As a consequence, a more sustainable development is linked to living and consumption patterns of people in urban areas. Densely populated spaces will be the main future driver for value creation offering a high density of knowledge, creativity, infrastructure, and customer vicinity. The 300 largest metropolitan areas accounted in the year 2014 for nearly half of the world's GDP with only a fifth of the world's population [2]. Propelled by diversity, cities will also be the main venues for innovation, as diversity leads to foster innovation [3]. Several studies highlight the economic potential and power of urban growth [4].

Historically, producing goods and living often took place in close proximity. Since the start of industrialization, production sites and factories were gradually pushed out of cities and located in industrial areas at the outskirts. This has led to a spatial separation of working and living areas with various negative impacts

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such as separating and unbalancing work and life of the citizens caused, e.g., by high commuting times. The trend of urbanization has accelerated and amplified the spatial and functional disconnection of cities and manufacturing. However, competitive manufacturing requires product and process innovation and therefore strongly depends on new product ideas and production technologies. (Re-) Integrating production into cities would allow manufacturing companies to benefit from the urban ecosystem and the proximity to potential customers. To rethink how we produce goods and how factories can be a positive neighbor in cities requires an interdisciplinary approach with a broad understanding of the city-factory nexus. Production in urban areas offers many potentials for companies such as, among others, a high density of knowledge and creativity, digital and physical infrastructure, as well as vicinity to consumers and prosumers [5]. Citizens may benefit from urban production as these sites offer jobs, (personalized) products and services in short distances, lower travel time and commuting stress.

Factories in urban areas are usually associated with negative impacts on their urban environments. However, latest production technology can produce fewer emissions and enables factories to fit in cities by being small and with low or zero emissions. At the same time, it can offer positive impacts to its surrounding and thus even foster new business models [6]. Urban factories can benefit from an innovative surrounding and new product-service-system possibilities. Cities can benefit from goods and services and positive working conditions offered by the urban factories as well. Thus, it is important to identify challenges and barriers that need to be overcome. The impacts of a production site located in the city need to be systematically analyzed with regard to their functional and spatial dimensions and their origin in product design and their impact on the product life cycle. Although manufacturing, urban areas, and supply chains have been studied for decades in their specific fields, the interdisciplinary nature of urban production poses questions that have not been looked at:

- Which products are most suitable to be produced in cities considering the impacts of urban factories?
- How can we systematically identify products to be produced in urban factories?
- What are the implications for product design if a product is produced close to the customer?

In order to identify the suitability of specific products or product types to be produced in urban surroundings, the impacts of urban production systems on their environment needs to be identified. Many of the impacts of urban factories are linked to the properties of the products and the production system which is determined during the product design phase. Therefore, products can be assessed regarding their suitability for urban production by investigating the links between product, production system, and urban environment. This knowledge can further be implemented in the design phase to create products and production systems in cities contributing to sustainability and in some cases even with a positive impact on their surroundings, moving from eco-efficiency to eco-effectivity [7].

15.2 The City-Factory-System Perspective

Looking into the city-factory-product nexus as illustrated in Fig. 15.1 means looking into the interdependencies between the city, people living there and factories including the workforce and products produced as well as consumed. An in-depth understanding of these interfaces supports the development of a more environmentally, economically, and socially beneficial value creation in urban areas. The city-factory-product nexus has similar features like ecosystems in nature. These are systems in a distinctly defined area, in that living organisms exist in communities in an abiotic environment [8]. Without external disturbances, ecosystems stay in a stable state. At the borders of ecosystems, transition zones exist in various shapes promoting biological diversity and concentrating primary and secondary productivity [9]. Cities are often described as urban ecosystems with humans as the predominant species shaping most of the environment to their needs. A positive approach is more and more taken in recent times to enhance functional diversity in urban ecosystems to improve the productivity and stability of the social, environmental, and economic dimension of city districts [10]. According to [11] the definition for an urban environment in the context of urban factories is linked to plurality of functions and utilization. The same definition is used in this work, specifically defining: "[…] urban space in the context of urban production is a multifunctional settlement area with complementary uses for production entities in close proximity to one another. Urban spaces inhabit multiple functions and utilization such as housing, social infrastructure or commerce."

The term urban factory describes a factory situated in an urban environment. Both city (district) and factory act as subsystems in the urban ecosystem exchanging energy, knowledge, information, and material flows across the system border. This perspective can be extended if the products produced in urban factories are included. For this exchange to happen, a technical infrastructure is required in which all subsystems influence each other in multiple ways. For example, an urban factory with a building of high architectural quality, selling personalized products with a high

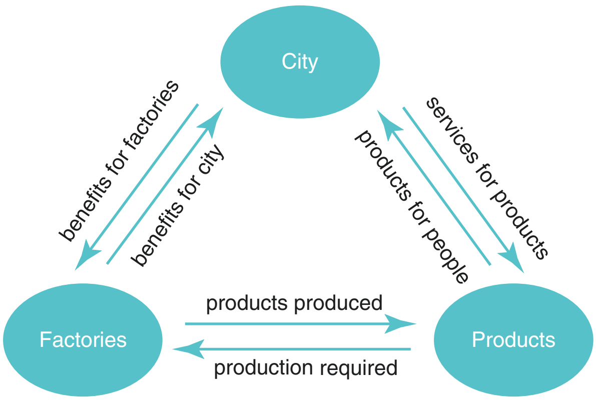

Fig. 15.1 The city-factory-product nexus

technological level, and offering social services for the surrounding citizens can become an integrated, functional part of the city district. In this example, the product influences the production (a high technological product level requires high technological production processes, which requires a highly qualified workforce) but also the surrounding city with the sales of a personalized product. The factory in this case influences the city positively by being open to the public and maybe even acting as a positive landmark for identification.

A production site in cities and close to customers can also foster product-service systems. In addition to that, as part of the factory-city nexus, the factory can offer services to the city forming a factory-service system. Based on the produced product or the urban production system, product-service systems and factory-service systems can be introduced by urban factories. The spatial and functional concentration of demand for goods and services in cities fostering the connection of both is one of the main reasons for the economic strength of urban regions.

The internet of things (IoT) nowadays allows physical products to be personalized with digital services. On a manufacturing system level, a production cloud linked to cloud manufacturing services as described in [12] could enable the implementation of factory-service systems. Among these services could be energy supply, sharing of production equipment or space, and various offerings of education and training (e.g., school labs at factories). Factories connected in a service network can offer services based on their free capacities and abilities enabling adaptable supply chains or distributed urban production systems.

Looking from the factory system outside across the factory border, several flows crossing the system boundary into the surrounding urban district can be identified. The most important flows influencing the city-factory-product nexus and offering potential for beneficial urban production are summarized in Fig. 15.2. The product is the outcome of a factory and its production system induces cross-system flows. These flows influence the surrounding urban quarter and can also be influenced by it. Research on urban factories is mainly undertaken due to one or both of the following two motivations:

- Minimizing the potential negative impacts of unintended urban factories originally located outside a city, but which have subsequently become part of the city due to city growth.
- Utilizing the potential of urban areas for manufacturing.

15.3 Identifying Products for Production in Cities

As highlighted in the introduction, the question arises, what kind of production fits most beneficially into cities? To evaluate this, a product perspective is potentially most promising, as products on the one hand are required to meet the needs of urban customers and/or benefit from the proximity to the urban ecosystem. On the other hand, their design greatly influences the associated production systems and the

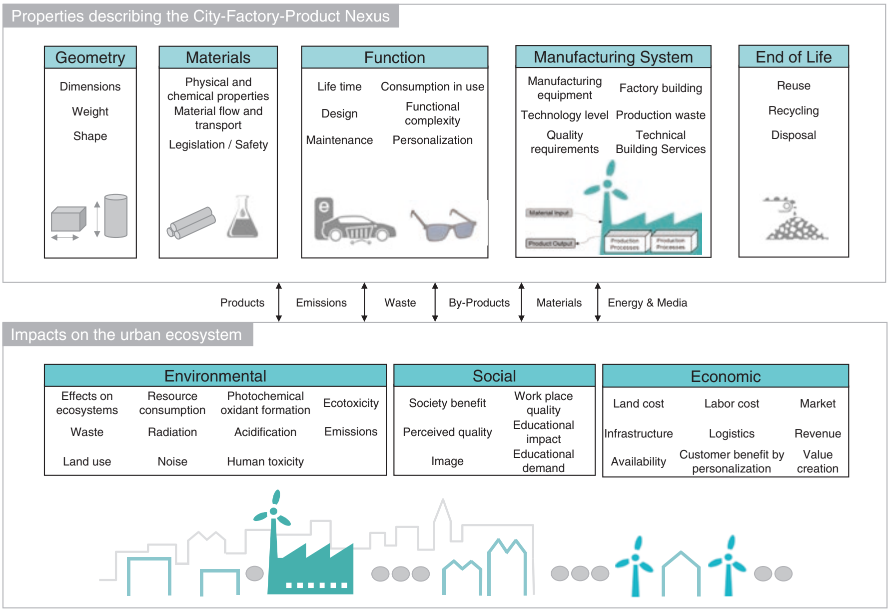

Fig. 15.2 Properties of the factory-product nexus linked to potential impacts on the urban ecosystem

flows across the border of the factory subsystem. The significant product properties are identified according to the physical and chemical properties divided into geometry and materials. As an extension to the physical properties, functional properties are also taken into account as well as the manufacturing system and the end-of-life phase. These identified properties are also referred to as the product and production system attributes and based on general product properties stated in [13, 14]. The most important properties of product and production system having a major influence on the cross-systems are explained in the following subsections.

15.3.1 Product Properties for Urban Production

15.3.1.1 Geometry

The dimensions and shape of a product are important physical properties. A smaller product requiring less space consuming production processes and auxiliary areas, e.g., for logistics and storage, can be more suitable for urban production than large products. The competition for space is one of the most enduring challenges in the city-factory nexus. In combination with the dimensions, the weight of a product is also a key indicator for the logistic demand created by a certain product. With the dimensions and the product mass correlating to the logistic effort, the necessary off-site infrastructure (e.g., roads, bridges, factory buildings) and on-site infrastructure (e.g., forklifts, HGV terminals, storage facilities) are determined. In addition, the energy consumption during processing is influenced by the product weight.

15.3.1.2 Materials

The material input and output of the urban factory is dependent on the materials used in a product and for its production. A great influence on the resource and energy flows induced by an urban production can be allocated to the materials of which the product is made of. Depending on their physical and chemical properties the flow of material, means of transport and storage facilities are defined. Legal requirements and safety issues are often linked to the materials especially in the urban areas due to the occupational health and safety rules. The materials used also greatly influence the type of production processes in the manufacturing system.

15.3.1.3 Function

The function describes the main purpose of a product. It is executed in the use phase creating a benefit for the user while in many cases consuming energy and resources. The use phase is also strongly characterized by the product life time. Design not only influences the perception and image of a product, it has also a decisive influence on the materials used and thus the manufacturing processes required. There are no guidelines to "urban-compatible product design" as such, taking the restrictions and potentials of cities into account, but certain aspects can be emphasized. The functional complexity of a product in most cases correlates with the technology level required for its production. Cities and their citizens are often early adopters when it comes to fashion trends and innovative technology. Personalized products can emphasize these trends and also foster personalized product-service systems. Maintenance and services required for a product can benefit from the vicinity of the manufacturing site and the place where the products are used.

15.3.2 Manufacturing System and End-of-Life Properties

The main impacts of urban factories on the city are in most cases induced by the manufacturing system, which is also designed during the product development as part of the manufacturing system design. Since the product and the required manufacturing system for its production are coupled, the product design also determines the required infrastructure and has implications at the end of the product lifetime.

15.3.2.1 Manufacturing System

At the core of the manufacturing system stands the manufacturing equipment. With the manufacturing system the inputs of materials and energy are transformed into products, by-products, waste, and emissions. These input and output flows of an urban factory are in most cases directly linked to the impacts on the urban surrounding. The manufacturing equipment is dependent on the technology level and the quality requirements. Both characteristics have an influence on the required workforce skills and the quality of the jobs in the factory. The operational practices and efficiency level further influence the amount of production waste generated. Technical building services (TBS), such as compressed air generation or HVAC facilities, support the operation of the manufacturing system demanding energy and are having a great influence on the emission characteristics of a factory. Around the manufacturing system, the factory building serves as insulation from external impacts to ensure sufficient conditions for all parts of the factory and to protect the surroundings from negative impacts, e.g., noise. The factory building determines many internal and external impacts and boundary conditions. For the outside, visual appearance is highly connected with the acceptance of a factory by the residents. A pleasant architecture can be a positive influence for an urban quarter and even act as a landmark for identification. The building shell further defines the emission patterns such as noise, light, or particle emissions to the surroundings. Innovative examples show that a factory building shell can even help cleaning the air in cities by absorbing and decomposing pollutants [15] or generate electricity with building-integrated photovoltaics. On the inside, the composition of the factory building limits the available space for the manufacturing system and the flexibility. Adaptive factory buildings are able to allow flexibility for changing production system requirements or even different utilization of the building space.

15.3.2.2 End of Life

At the end of its life cycle, a product can be reused, remanufactured, recycled, or sent to disposal. In cities, products accumulate according to the population density. At the end of life, products can be either treated within the city (e.g., in urban recycling factories) or transported out of the city boundaries requiring logistic effort. The impacts and potentials at the end of life are already defined in the design phase of a product. With the material concentration in cities, the concept of urban mining can be employed for urban factories sourcing the materials required for the manufacturing of new products from end-of-life products and infrastructure [16].

15.3.3 Impacts on the Urban Ecosystem

The described properties of products and manufacturing systems have in most cases a direct and/or indirect impact on the urban ecosystem. The impact can be on economic, environmental, and social dimensions. 26 attributes describing the potential positive or negative effects of a product and its production and consumption in urban areas compared with those made outside of cities were identified based on the three dimensions mentioned above. Impact categories that are similar in their effects for urban and non-urban production are not considered. The impacts on the urban ecosystem are described in the following sections.

15.3.3.1 Environmental

In the context of urban production, significant environmental impacts are related to the production stage, use, and end-of-life stages as these have a major impact on the city in which the product is potentially made. From [17] the impact categories which have a significant impact in the urban areas are taken into account. For example, urban land occupation or land use is more likely to have major impact on the sustainability of urban production, whereas the impact category agricultural land occupation is beyond the system boundary. Factories in cities can have effects on urban ecosystems and potentially act as sources of human toxicity, ecotoxicity, and acidification. Furthermore, particle and gaseous emissions, contribution to photochemical oxidant formation, noise, and radiation need to be taken into account, as these are impacts of major interest for densely populated cities. The abiotic and biotic resource consumption in cities by the production system and product is also an environmental impact linked to urban production. For suitable products, the vicinity to customers in cities can lower the environmental impact of the product distribution.

15.3.3.2 Social

Urban production has a certain positive and/or negative impact on its urban surroundings. For instance, social impacts can occur directly from product use or indirectly, resulting from the production system, due to a service connected to the product or to other effects. A product with a positive perceived quality can contribute to the positive image of the factory where it is produced and also to the surrounding area. This characteristic can also be influenced by marketing. One of the main social impacts of a factory are the jobs offered, allowing workers to generate an income. The impact of the workplaces in an urban production system depends on the workplace quality. A factory placed in the city in vicinity to the workforce can lower commuting times and distances. An urban factory can also have an educational impact on the urban society, either through the product or with services offered at the production site such as open learning factories or workshop areas. At the same time, an educational demand is generated by an urban factory for a qualified workforce. If the production system for a product requires a highly qualified workforce, it is usually favorable to locate the production in urban areas utilizing the vicinity to education and research facilities.

15.3.3.3 Economic

Value creation is the main purpose of a factory. This is achieved mainly through the production system producing functional goods. As described before, the production system is strongly influenced by the product properties. In return, product properties, directly and indirectly, influence the logistic effort, the land cost, and the labor cost as well as the required internal and external infrastructure. The vicinity to customers can be of economic advantage for companies as the urban market is spatially concentrated and might offer the possibility for a higher revenue. Producing near the customer can raise the availability in a spatial and temporal sense and possible degrees of personalization of products. In cities, it can also be more promising to implement product-service systems.

15.3.4 The Role of Life Cycle Engineering and Ecodesign

A current definition of life cycle engineering (LCE) by Hauschild et al. [18] addresses the importance of methods and tools in product development for the reduction of the environmental impact:

> *LCE is now defined as sustainability-oriented product development activities within the scope of one to several product life cycles. The methods and tools used in life cycle engineering must support reducing the total environmental impact associated with technology change and volume increase from one product generation to another, in order to ensure that new product technologies stay within their environmental space as derived from the planetary boundaries.*

With an increased understanding of the city-factory-product nexus, the role of ecodesigning products as part of life cycle engineering needs to be adjusted. Ecodesigning products for urban production and consumption becomes an interdisciplinary synthesis of designing products that can be manufactured in urban factories that have no negative impact or even a positive impact on the urban ecosystem. Furthermore, the ecodesign of products for cities should look into designing products and their properties that are not only of benefit for the individual customers but also of benefit for the city itself.

Figure 15.3 lists the properties describing the city-factory-product nexus and the potential impact on the urban ecosystem with qualitative evaluation. The goal of designing products suitable for production in cities can be reached by assessing the fulfillment of the desired manifestations for products and their production system. The desired manifestations are defined in Fig. 15.3 in such a way that a fulfillment leads in most cases to a less negative or more positive impact. In addition, co-dependency of these attributes also causes further challenges, which means a particular characteristic can be positive for an urban production in one case but also negative if the attributes of the surrounding city are different. The guidelines can be used to evaluate existing products and production systems regarding their suitability for urban production. Furthermore, it can be applied in the design or redesign during

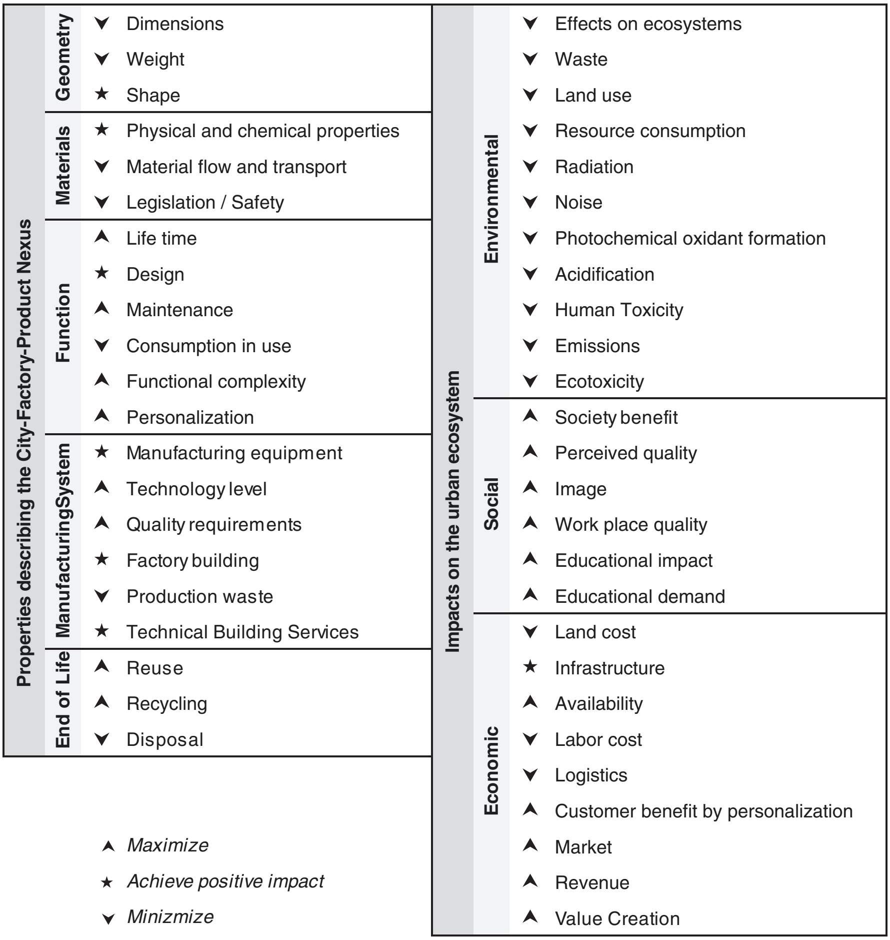

Fig. 15.3 Desired manifestation of product and production system properties and the impacts on urban environments by urban factories

the product development to lower negative impacts on sustainability and to utilize the potentials of production in cities.

15.3.5 Exemplary Application

In order to show the applicability of the methodology, four example products are assessed in the following based on real factories situated in urban environments. Being one of the world's favorite beverages, coffee is mostly consumed where people work or live. The product under evaluation is roasted coffee beans made from green coffee beans. Eye glasses are highly fashionable products that can benefit from personalization. A great emphasis is set to perceived quality of the product and its image. Bicycles are an emission-free mode of personal transport. Cities with high levels of congestion can benefit from more citizens riding bikes instead of cars. The assessment is done by considering also the production of the bicycle frame. Train cars as means for public transport can be found connecting cities and rural areas but also inside the city boundaries, e.g., trams.

The manifestations of the properties are evaluated qualitatively for a specific product or product type and the results are indicated by a color code.

- Green: The desired manifestation of the property is completely or mostly fulfilled.
- Yellow: The desired manifestation of the property is partly fulfilled.
- Red: The desired manifestation of the property is not or very poorly fulfilled.
- Gray: Evaluation of this property is not relevant or possible for urban production.

Different application scenarios of the methodology are possible to determine the feasibility for producing a specific or a generic product in urban areas. Three categories of products can be identified depending on their respective mean evaluation of manifestations: (1) suitable products for urban production with an expected benefit if produced in cities, (2) potentially suitable products that can be enabled to be suitable by the reduction of negative impacts, and (3) unsuitable products with severe negative impacts by their production and no or only minor benefits.

The framework presented can be used to evaluate existing products and production systems regarding their suitability for urban production. Furthermore, it can be applied in the design or redesign of the product to lower negative impacts on sustainability and to utilize the potentials of production in cities.

The evaluation results are shown in Fig. 15.4 for the generic manifestations of the example products. The overall (mean) assessment is indicated by the color in the top row of each example, which also names the product. The example products that can profit from customer vicinity and providing social benefits for the urban society are scored a medium to high suitability for urban production. Contrary, the train cars, which are large, heavy, and not for public consumption, perhaps score much lower and are thus not evaluated as positive products for urban production. It is important to note again that the assessment of the manifestations indicate the suitability for urban production. A yellow or red indication of a manifestation indicates that in this aspect the considered product does not profit or even suffers from being made in a city.

15.4 Conclusion and Outlook

Cities are the main area for value creation and will further rise in significance in the future. Manufacturing and urban production can be an important part of this urban value creation. In this paper, we look at the city-factory-product nexus and present

Example I- Roasted Coffee Beans

Properties describing the City-Factory-Product Nexus			
Geometry	▼	Dimensions
	▼	Weight
	★	Shape
Materials	★	Physical and chemical properties
	▼	Material flow and transport
	▼	Legislation / Safety
Function	▲	Life time
	★	Design
	▲	Maintenance
	▼	Consumption in use
	▲	Functional complexity
	▲	Personalization
Manufacturing System	★	Manufacturing equipment
	▲	Techonology level
	▲	Quality requirements
	★	Factory building
	▼	Production waste
	★	Technical Building Services
End of Life	▲	Reuse
	▲	Recycling
	▼	Disposal

Example II- Eye Glasses

Properties describing the City-Factory-Product Nexus		
Geometry	▼	Dimensions
	▼	Weight
	★	Shape
Materials	★	Phasical and chemical properties
	▼	Material flow and transport
	▼	Legislation / Safety
Function	▲	Life time
	★	Design
	▲	Maintenance
	▼	Consumption in use
	▲	Functional complexity
	▲	Personalization
Manufacturing System	★	Manufacturing equipment
	▲	Techonology level
	▲	Quality requirements
	★	Factory building
	▼	Production waste
	★	Technical Building Services
End of Life	▲	Reuse
	▲	Recycling
	▼	Disposal

Example III - Bicycles

Properties describing the City-Factory-Product Nexus		
Geometry	▼	Dimensions
	▼	Weight
	★	Shape
Materials	★	Physical and chemical properties
	▼	Material flow and transport
	▼	Legislation / Safety
Function	▲	Life time
	★	Design
	▲	Maintenance
	▼	Consumption in use
	▲	Functional complexity
	▲	Personalization
Manufacturing System	★	Manufacturing equipment
	▲	Technology level
	▲	Quality requirements
	★	Factory building
	▼	Production waste
	★	Technical Building Services
End of Life	▲	Reuse
	▲	Recycling
	▼	Disposal

Example IV - Train Cars

Properties describing the City-Factory-Product Nexus		
Geometry	▼	Dimensions
	▼	Weight
	★	Shape
Materials	★	Physical and chemical properties
	▼	Material flow and transport
	▼	Legislation / Safety
Function	▲	Life time
	★	Design
	▲	Maintenance
	▼	Consumption in use
	▲	Functional complexity
	▲	Personalization
Manufacturing System	★	Manufacturing equipment
	▲	Technology level
	▲	Quality requirements
	★	Factory building
	▼	Production waste
	★	Technical Building Services
End of Life	▲	Reuse
	▲	Recycling
	▼	Disposal

Fig. 15.4 Desired manifestation evaluated for exemplary products

a framework for determining which products are suitable for urban production. According to the properties of products and production systems, their influence and impacts on the urban environment are identified. For all attributes a desired manifestation is defined to rate their appearance. The resulting assessment allows the evaluation of the economic, environmental, and social suitability of a product for urban production and can be used at the product design stage.

As this work is a first attempt for a generic design and matching methodology of products, production, and cities, more research needs to be carried out in this field to foster sustainable urban production. Cities are areas where the current and future challenges of sustainability will concentrate. Urban production can offer benefits in the economic and social and even in the environmental development of cities. However, as cities are also very complex systems with many properties that influence each other in partly unknown ways, it is not possible yet to validate this approach comprehensively. In the course of the development of the framework, it became apparent that strong influences on the suitability of urban production are coming from the actual location and the actually implemented span of activities of the value creating steps. In the given example evaluations, different production steps were associated with the example products to be placed in the urban factory. To enable more applications of the methodology, this temporal dimension should be taken into account. The gained insights, possible measures and potential effects can foster the ecodesign of products for production in cities. An application is possible in either the product design phase, a running production system, or the strategic planning of a company.

Following research activities should aim at the extension of the framework by considering the attributes of the city, the span of activities placed in the urban boundaries, and the temporal application scenario. With an empirical study, the correlation of factual and perceived compatibility of urban factories should be more accurately determined. This will also lead to a large set of fields of actions that can be taken by councils and companies to promote urban value creation and the quality of life for the cities' inhabitants.

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Chapter 16
Environmental Impact Assessment of Functional and Visual Design Features of Smartphones

Tsubasa Naito and Nozomu Mishima

16.1 Introduction

Many studies regarding design methodologies have been carried out in order to enhance product functions. On the other hand, some case studies [1, 2] regarding quantitative evaluation of visual design features such as shape, color, texture, and so on have been studied but are still insufficient. However, visual design features are also important for users in determining which product to buy. Although enhancing product functions usually causes larger environmental impact, some visual design features can be modified without increasing environmental impact. Thus, focusing on visual design features might be a solution to design sustainable products. At least, favorite visual designs can be enough reasons for users to use the product for long.

In our previous study [3], we have proposed a method to quantify weights of functional and visual design features by using AHP [4]. The study focused on smartphone as a case study and extracted color, texture, thickness, and "customizability" as visual design features. Battery capacity was focused on to compare to the visual design features, applying pair comparison method. Then, the estimated weights of the features were integrated with the weights of functional design features including battery capacity, found in other studies. The previous study clarified that there is not a big difference between the weights of memory size and customizability. This result suggested that important visual design features are comparably important to functional design features. It is well-known that ICs contain metals with large environmental impact such as gold, silver, etc. And ICs are fabricated through compli-

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cated processes using large amounts of water and electricity. So, if "memory size" is not very important for users, it is not eco-efficient to focus on such function. Instead, it might be possible to design attractive and sustainable products by focusing on "customizability" which seems almost equally important for users as "memory size."

16.2 Approach of the Study Toward Eco-Efficient Design

"Customizability" can be a little strange visual design feature. It means that accessory parts such as Figs. 16.1, 16.2, 16.3, and 16.4 have large variations. It does not directly mean the product with or without optional parts. The product feature "customizability" means how much varieties of optional parts can be chosen.

To increase the memory size of a smartphone, NAND-type flash memory chip includes some amount of gold or silver that have large impact on environment. Since IC chips are produced through complicated fabrication process using water, electricity, reactive gas, and so on, it has been shown [5] that production stage of IC has a large environmental burden. One of the books [6] says 70–90% of the total environmental burden of electronics production is from ICs production. Therefore, if memory size is not really important for users, focusing on such function is not an eco-efficient way to produce the electronics. Instead, it can be possible to design a more attractive and sustainable product by focusing on "customizability" which seems equally important as "memory size."

Fig. 16.1 Rubber case for protection

Fig. 16.2 Hard plastic case

Fig. 16.3 Leather case

Fig. 16.4 Neon screen protection film

16.3 Analytical Method

16.3.1 Survey Method for Users' Wants

This study uses a pair comparison method used in AHP to know the weights of different design features. In the previous paper, weights of eight different design features of smartphones were investigated. Figure 16.5 shows the result of the survey which was carried out to 70 smartphone users. In this paper, we focus on "memory size" which is the least important functional design feature and "customizability" which is the most important visual design feature.

For the purpose, we made two different alternatives for each design feature that we focused on. As for "memory size," two different proposals 32 GB type and 128 GB type were provided. As for "customizability," two different proposals that are "number of available option parts is 1–10" and "number of available option parts is more than 10" were provided also. Figure 16.6 is the schematic view of the procedure to evaluate alternative proposals using AHP. Four alternative proposals were decided as the following:

A: Memory capacity 32 GB/customizability 1–10 types.
B: Memory capacity 32 GB/customizability more than 10 types.
C: Memory capacity 128 GB/customizability 1–10 types.
D: Memory capacity 128 GB/customizability more than 10 types.

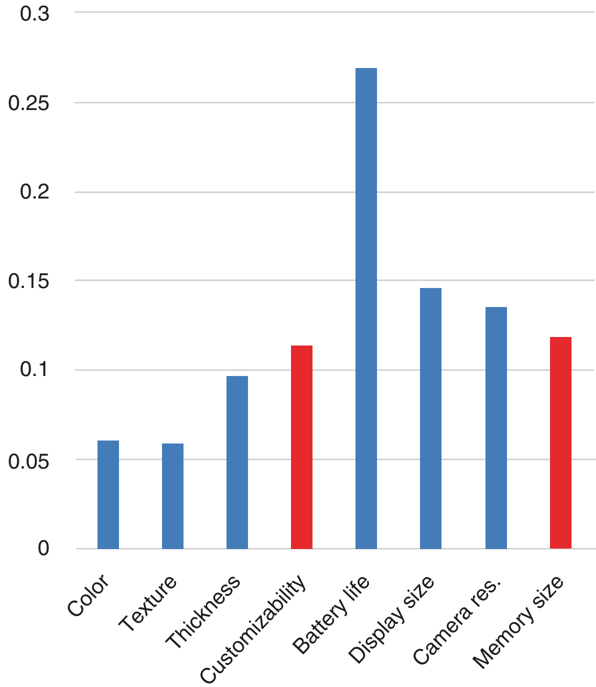

Fig. 16.5 Weights of eight design features including functional features and visual features

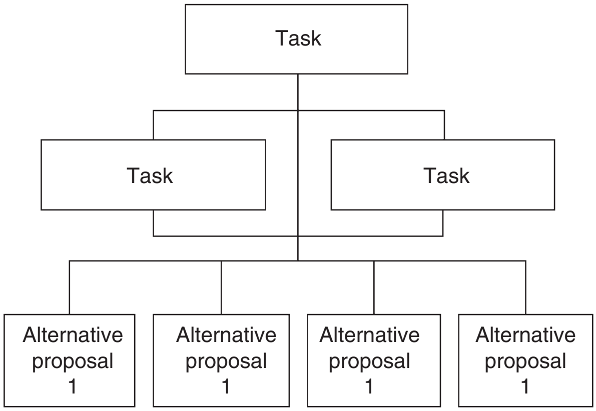

Fig. 16.6 Procedure of AHP

It was set that alternative proposals with 128 GB memory are 10 thousand JPY expensive than 32 GB type. Then, four alternative proposals were compared by pair comparison. The questionnaire was almost the same as the one used when the weights of four visual design features were decided.

Each respondent has to answer six questions like Fig. 16.7. When the respondent compares proposals A and B and he/she thinks proposal A is absolutely better than

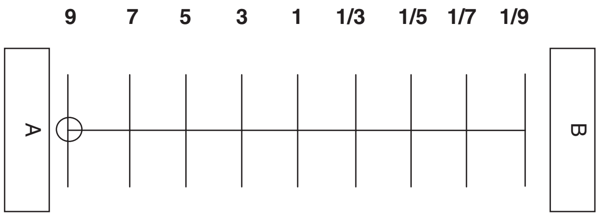

Fig. 16.7 Example of a question for pair comparison

Table 16.1 Sample matrix to calculate relative importance of four alternative proposals

	A	B	C	D
A	1	w_1/w_2	w_1/w_3	w_1/w_4
B	w_2/w_1	1	w_2/w_3	w_2/w_4
C	w_3/w_1	w_3/w_2	1	w_3/w_4
D	w_4/w_1	w_4/w_2	w_4/w_3	1

w_1–w_5: relative importance of four alternative proposals

B, he/she should mark 9. By answering to six questions, relational matrix like Table 16.1 will be obtained. By applying statistical analysis of Eqs. (16.1) and (16.2), weights of four alternative proposals evaluated by the respondent can be calculated.

- If A is absolutely important than B, 9 is marked.
- If A is rather important than B, 7 is marked.
- If A is important than B, 5 is marked.
- If A is somewhat important than B, 3 is marked.
- If A and B are equally important, 1 is marked.
- If B is somewhat important than A, 1/3 is marked.
- If B is important than A, 1/5 is marked.
- If B is rather important than A, 1/7 is marked.
- If B is absolutely important than A, 1/9 is marked.

$$W_i' = \frac{w_i^4}{w_1 w_2 w_3 w_4} \tag{16.1}$$

$$W_i = \frac{w_i}{\sqrt[4]{w_1 w_2 w_3 w_4}} \tag{16.2}$$

W_i: relative importance of spec *i*.
w_i: absolute weight of spec *i*.

16.3.2 Environmental Burden of Alternative Proposals

The paper also evaluated environmental burden of each alternative proposal by using LCA (life cycle assessment). Based on a previous case study regarding LCA of mobile phone production [7] and personal computers [8], it was assumed that

Table 16.2 Environmental burden of enhancing design features

Design change	Increase of environmental burden [kg-CO_2/unit]
Memory size; 32 GB–128 GB	1.9

environmental burden of memory chip production is much larger in 128 GB model than 32 GB model. As for customizability, it is unsure how much amount of environmental burden increases per one mobile phone. Since most of the plastic cases for mobile phone is fabricated by injection molding or die-casting, and such method produces as least 10,000 products per a mold, environmental burden of mold production should be divided by 10,000 at least, in considering that of a product. Thus, increase of environmental burden by increasing variations of mold is negligible. Although the burden of plastic material should be counted, in Japanese market, every user uses some kind of an optional part anyway. So, the variation is small or large whichever, and amount of plastic material is the same. As for memory size, it is known that IC chip of large memory is made by multiple layers. 128 GB chip has four layers, while 32 GB chip has single layer. Therefore, it was assumed that fabrication process of 128 GB chip is 4 times of that of 32 GB type. In a previous study [8], CO_2 emission of fabrication of an IC chip is assumed as 0.64 kg-CO_2. So, finally, Table 16.2 shows the calculation result of environmental burden of increasing memory size.

16.4 Result of the Analysis

16.4.1 Weight of the Proposals

The weights of four alternative proposals based on the survey are shown in Fig. 16.8.

16.4.2 Value Aspects of Alternative Proposals

In order to calculate eco-efficiency of alternative proposals, it is necessary to know not only environmental burden but also "value" of each proposal. In the previous paper, weights of eight design features were calculated as Fig. 16.3. Among the design features, sum of "customizability" and "memory size" was 0.2327. This weight is corresponding to the weight of alternative proposal A, since weight of basic specifications was surveyed through a questionnaire. In this study, it was assumed that the sum of values of two design features will linearly increase accordingly to the weight of the corresponding alternative proposal. Thus, values of four alternative proposals are values of two design features plus values of other six features. Total value of four alternative proposals can be calculated by Eq. (16.3):

$$V_m = \left(1 - 0.1143 - 0.1184\right) + \frac{S_m}{S_A} \times \left(0.1143 + 0.1184\right) \tag{16.3}$$

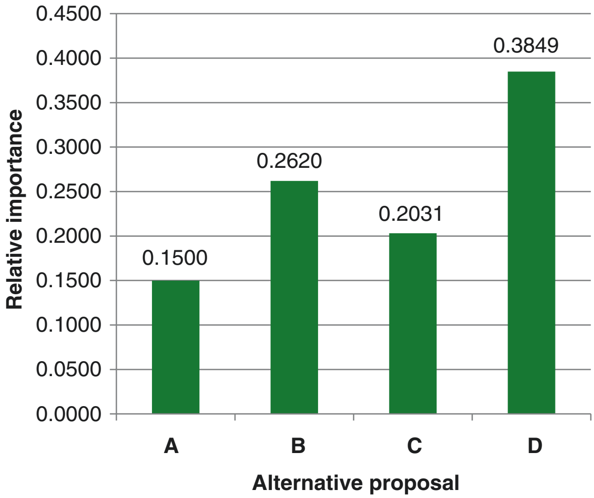

Fig. 16.8 Relative importance of alternative proposals

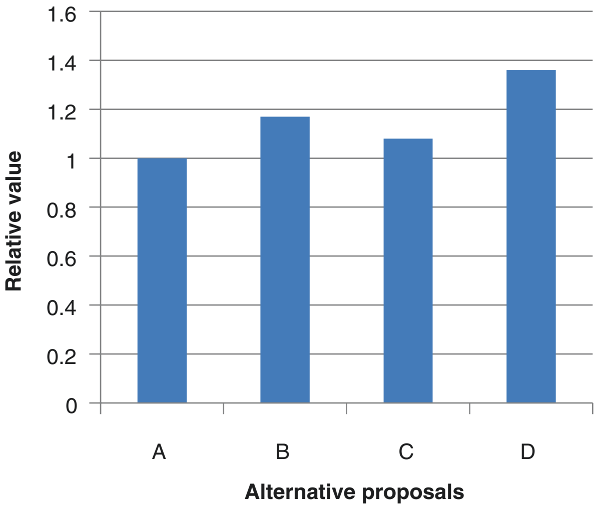

Fig. 16.9 Values of alternative proposals

V_m: Value of alternatives.
S_m: Relative importance of alternatives.
S_A: Relative importance of alternative A.

As the result, value of alternative proposals can be calculated as Fig. 16.9 by setting the value of the basic proposal "A" as 1. Alternative proposals and corresponding values of a mobile phone are shown in the figure.

Then, since the CO_2 emission of production of a whole mobile phone was also shown in the aforementioned paper [8], total CO_2 emission of four alternative proposals can be assumed as Table 16.3.

16.4.3 Eco-Efficiency Calculation

From the assumptions shown in Table 16.3 and the estimation shown in Fig. 16.9, eco-efficiency of each alternative proposal can be calculated, since product eco-efficiency is defined by product value divided by environmental burden. Since the relative values of the proposals were shown as Fig. 16.9, the relative eco-efficiency of the four alternative proposals can be expressed as Fig. 16.10, by assuming the eco-efficiency of the basic proposal A as 1.

16.4.4 Discussion

In our previous paper [5], it was shown that weight of memory size is a little larger than that of customizability. So, it can be said that "memory size" size is more important for users rather than "customizability." But, in this study, by comparing alternative proposals B and C, interesting discussion can be made. Even C has a higher function than B, the proposal has a lower eco-efficiency. This result means that, in the aspect of designing eco-efficient product, it is not really effective to

Table 16.3 Total CO_2 emissions of alternative proposals

Alternative proposals	Total emission of CO_2 [kg-CO_2/unit]
A	14.2
B	14.2
C	16.1
D	16.1

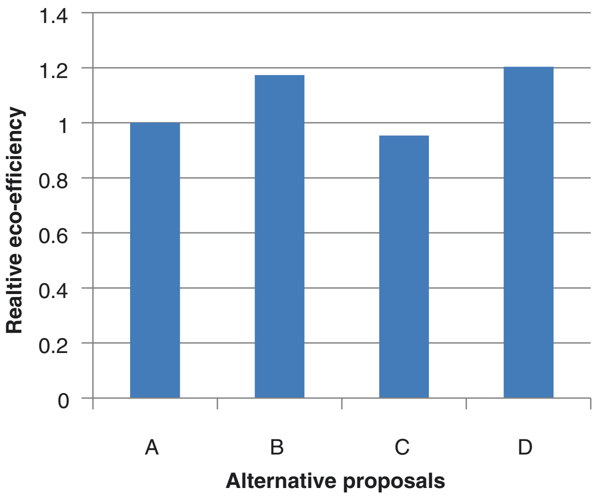

Fig. 16.10 Relative eco-efficiency of alternative proposals

increase the memory size. Although enhancing the function requires larger cost and environmental burden, users do not think such a design is attractive enough. Proposal D which has larger memory size and larger variations of optional parts has the highest eco-efficiency. However, the difference from B is not so large. And the design proposals with the highest specifications are assumed to be most expensive. In addition, it is important to remind proposal D has much higher environmental burden than proposal B. The fact reinforces that it is meaningful to focus on increasing customizability rather than increasing memory size in the aspect of designing eco-efficient, sustainable, and affordable product. The calculation of the paper suggests that if a design should choose one to enhance from the two design features, “customizability” should be chosen. This is a warning to designers who just think higher specifications are always better and also for users who seek for higher specifications even if they won’t use such function. Their preference should be re-examined.

16.5 Summary

In this study, discussions regarding guidelines to design eco-efficient product have been carried out. First, the study compared users’ preference regarding four alternative proposals, by changing “memory size” which has the lowest weight in all the functional design features and the most important visual design feature, “customizability.” Customizability means number of variations of optional parts such as case, cover, accessories, and so on. AHP was used in evaluating the user’s preference of the alternative proposals. It might be a special feature of Japanese market where most of the users use optional parts. But, the survey showed that such customizability is rather preferred by users and is rather important in designing eco-efficient product.

In addition, increase of environmental burden represented by CO2 emission by enhancing these two features has been examined through the aforementioned result. The values of four proposals have been also estimated based on the AHP results. Eco-efficiencies that are defined as the product value divided by the environmental burden were estimated. Then, the results led us to conclude that focusing on preferred visual design features might be a better strategy than focusing on functional design features too much, in the aspect of eco-efficiency.

Since the reliability of assumptions and estimations of environmental burden in improving the design features were not enough, it is necessary to examine these problems as future work. However, we think that this effort can be a significant approach in obtaining design guidelines of eco-efficient products by considering both functional and visual design features and focusing on the attractiveness of the various design features for users.

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Chapter 17
Integration of Sustainability Targets into the Product Creation Process of German Manufacturing Companies

Tom Buchert and Rainer Stark

17.1 Problem Statement

Fostering transition towards a sustainable society constitutes one of the major paradigms of the twenty-first century in politics and public debate. To implement the broad concept of sustainability, international agreements, such as the 2030 Agenda for Sustainable Development of the UN [1], aim for the definition of targets as a basis for national (or EU-wide) legislation.

To achieve these goals, significant efforts are necessary affecting all areas of human living. Value creation and the manufacturing sector in particular play a major role to increase sustainability since it contributes to a significant share of manmade emissions and consumption of limited resources. Manufacturing companies can contribute to sustainable development by creating safe and affordable products of high quality with low environmental impacts and resource consumption and without endangering financial stability of the company at the same time. Product development, therefore, has a key role and responsibility in this context. Research in the field of sustainable product development (SPD) and related branches, such as Ecodesign, aims at utilizing this potential.

However, while the majority of contributions in this field focusses on presenting new methods and tools for implementing SPD principles into the design process, industrial practice and actual needs of stakeholders are less often focused.

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There exist only a few examples, which provide a direct insight how sustainability aspects are addressed in companies. Warsen and Krinke published, for example, an article which elaborates the life cycle approach of Volkswagen from the perspective of the company [2]. In addition, some empirical studies were conducted which focus on adoption of design methods with a particular focus in the field of Ecodesign. First efforts in this context were made by Boks and Pascual [3]. In this study a gap was identified between available methods and actual application in industry. Furthermore, different barriers and success factors of Ecodesign method implementation were identified. More recent studies follow the same purpose but focus on different countries and industry branches [4–6]. One of the largest quantitative studies with 330 participants was conducted by Kara et al. [7]. The study presents an international comparison of Ecodesign diffusion in terms of tool utilization and management practices. Dekoninck et al. [8] presented the latest study for Ecodesign implementation in 2016 by analysis of 9 companies in case studies. Furthermore, they provide an overview on all conducted empirical studies on this topic.

As mentioned above, available studies are primarily focused on the environmental perspective of sustainability and aimed at identifying success factors for implementing Ecodesign methods into product development. Until now, less emphasis has been given on the actual relevance of factors concerning an integrated view on all three sustainability dimensions for design departments. Furthermore, the process comprising definition, implementation and validation of corresponding sustainability targets in the design process is still unclear.

This article presents an empirical study for identifying which targets are followed in the context of defined sustainability criteria and how these targets interfere in terms of trade-offs and individual company preferences. Furthermore, important stakeholders for target definition and means of target validation are identified. For this purpose, an expert workshop and nine expert interviews were conducted.

17.2 Framework for Sustainability Targets in the Design Process

As a starting point, this chapter aims at defining the term “sustainability target” in the scope of this study. While sustainability is a rather broad concept, it is necessary to define the term from the perspective of product development. Figure 17.1 gives an overview on selected criteria for that purpose. The criteria are based on the Product Sustainability Index (ProdSI) developed by [9]. The ProdSI considers all 3 sustainability dimensions and consists of 47 different measures reflecting all product life cycle phases. For this study the set of indicators was condensed to nine criteria to achieve a better overview about relevant sustainability factors (*see* Fig. 17.1). While emissions and cost rather reflect pure environmental/economic criteria, the social dimension is addressed by safety of the product and material origin. Material origin is here defined as the sourcing location of materials used within products. Targets on material origin could be, for example, restrictions imposed on product design

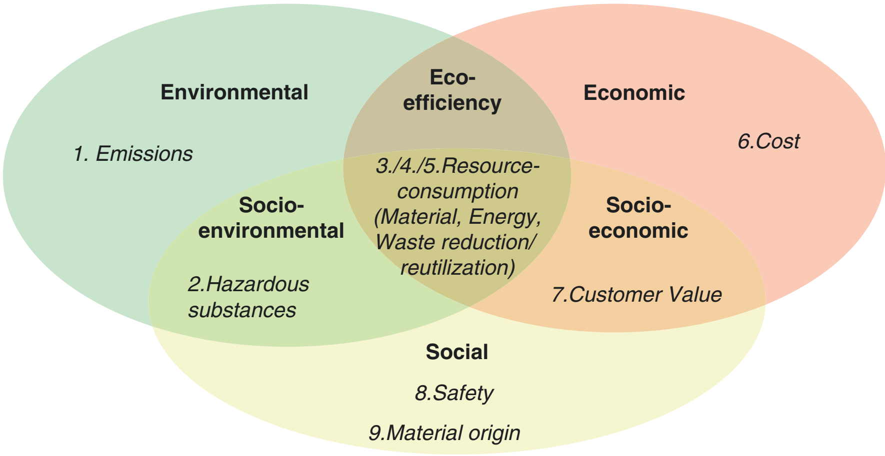

Fig. 17.1 Definition of considered sustainability criteria (based on [9])

concerning materials from countries with violations of human rights or low-paid workers. Other criteria, such as hazardous substances, reflect a mixture of two dimensions (in this case social aspects in terms of human health versus hazardous elements concerning environmental pollution). The customer value reflects functionality and quality of the product which satisfies a need/provides an added value for the customer.

Consumption of natural resources is located in the centre of Fig. 17.1 as it addresses aspects of all three sustainability dimensions (intergenerational resource equity, availability of materials for enabling value creation and long-term environmental stability in the context of resource extraction).

As considered sustainability criteria are now clarified, it needs to be evaluated how corresponding targets interfere with the product creation process. Figure 17.2 shows a framework, which was developed to highlight possible activities for considering sustainability targets in this context.

The framework is based on classical product development methodologies, in particular the V-model [10] and the approach of Pahl and Beitz [11]. In this study, respective steps of the framework are simplified to three steps: sustainability target definition (prioritization and decomposition of targets to decrease the solution space), implementation (solution generation and selection) and validation (prove of target achievement/comparison to initial target).

17.3 Study Design

To gather an enhanced understanding how sustainability targets are integrated into the design process of producing companies, an empirical study was conducted. The study comprised a combination of an initial expert workshop (conducted in

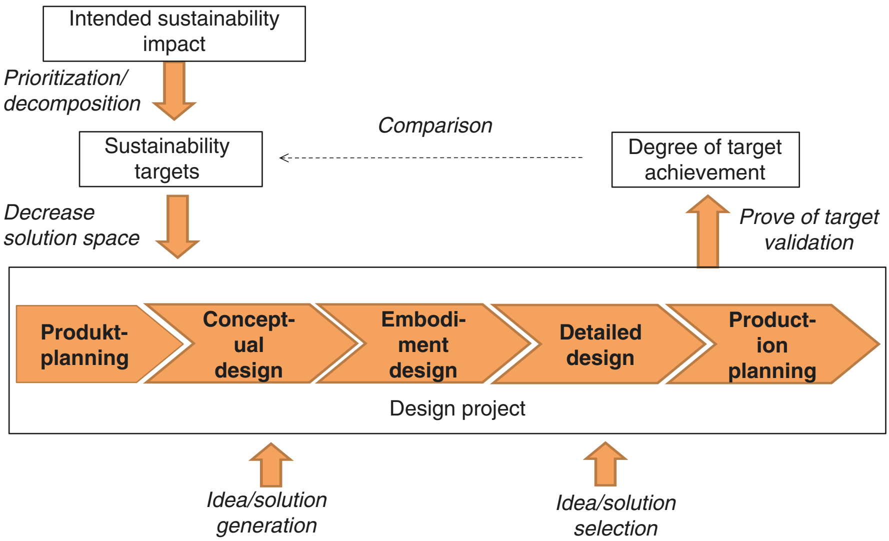

Fig. 17.2 Framework for definition, realization and validation of sustainability targets in product design

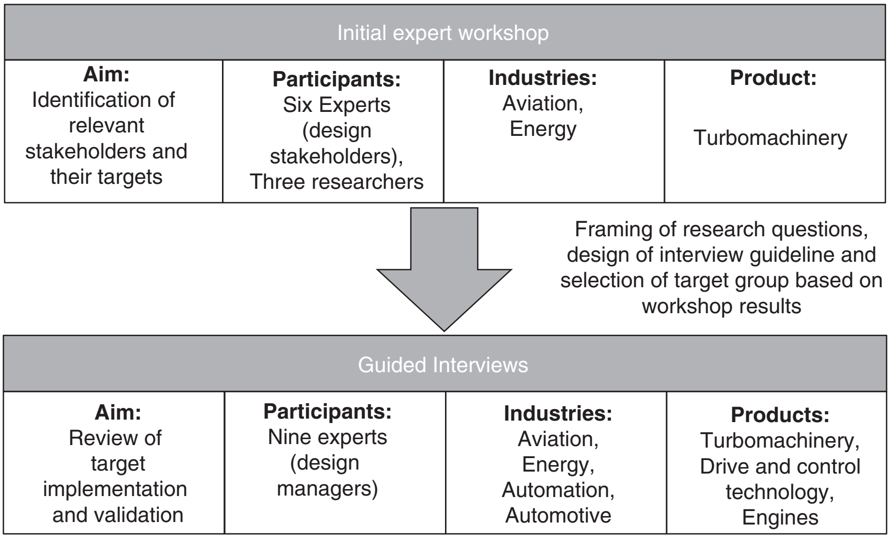

Fig. 17.3 Study approach

November 2014) and nine guided expert interviews (conducted in 2016 and 2017). The overall approach is shown in Fig. 17.3. The research format was selected to combine the advantages of two qualitative research methods. An expert workshop allows gathering a quick overview about a theoretical question by its generally more open setup which allows discussion between workshop participants. The produced output describes a consensus between the participants and should be regarded as a more objective source of information in comparison to individual statements. However, due to mostly strict time limits of workshop sessions, achievable results are on a rather high level of detail and can hence only provide a first basis for understanding a topic.

Guided expert interviews on the other hand provide an in-depth understanding of the interview partner's individual situation. Furthermore, comparisons of interviews with different persons allow identifying differences and similarities between their respective statements. As guided interviews are conducted with an interview guideline, it can also be ensured that all relevant points are addressed properly.

The qualitative expert approach was chosen for this study, as the topic of sustainability requires an in-depth understanding of the design process including different views on the product and corresponding stages of the product life cycle. Another reason for choosing a qualitative approach are ambiguities associated with the rather broad concept of sustainability. While the basic idea of sustainability is widely known, it can be interpreted in different ways (e.g. by only referring to economic sustainability). Predefined questionnaires with closed questions or rigorously standardized interviews without the possibility to reformulate questions or to give examples would have possibly lead to a bias in the study results.

To further reduce the wide area of interpretation associated with the term sustainability, the focus of the study was narrowed down to one product category. In this context power machines were selected as overarching category which comprises electrical drive and control technology, turbomachinery as well as combustion engines. Power machines are contributing to different types of emissions and consume precious natural resources. Furthermore, they are included in almost all technical products covering B2C and B2B goods and are relevant for almost all industries.

All in all 15 industry experts contributed to the study. Their respective affiliation to industries can be seen in Fig. 17.4.

Respective companies were selected regarding the following criteria:

Company size: The study focusses on larger companies as these organizations provide a sufficient capacity to build up systematic processes for considering sus-

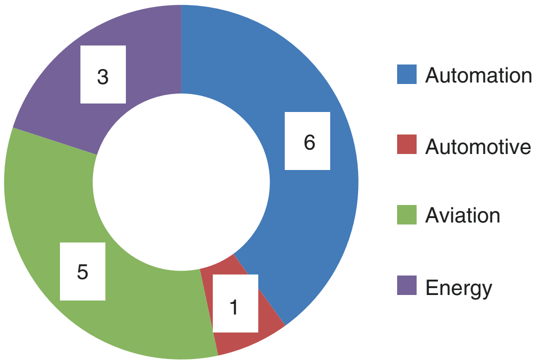

Fig. 17.4 Industry affiliation of experts

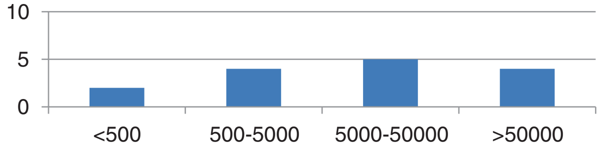

Fig. 17.5 Size of companies represented by study participants

tainability in product design. However, it was also seen as interesting how smaller companies cope with this issue. Hence, two SME with less than 500 employees were considered as well. The distribution of company size is shown in Fig. 17.5.

Company location: In order to reduce distortive effects of legislation in different countries, only companies which design and produce products in Germany were considered.

17.3.1 Expert Workshop

The initial expert workshop consisted of 11 people including six experts from industry (design of gas turbines for aviation and energy production), two moderators and three researchers with a focus on sustainability, design and life cycle engineering. The workshop focused on sustainability targets in the turbomachine industry. A major aim of the workshop was to gather a first understanding which sustainability targets are relevant for workshop participants. First, the authors deemed it advisable to identify key stakeholders which define sustainability targets in the design process. Hence, for being considered as an expert, participants needed specialist knowledge in a field with direct relation to product design (either designer itself or specific roles which are involved in design requirement specification or technology evaluation). As a formal requirement, a university degree and at least 5 years of working experience in the respective field were required. The gathered sample reflected a balanced mix of experts from different fields of product design (materials expert, sustainability expert, design manager, CEO, head of cost engineering department, test expert). The overall duration of the workshop was 6 h and was split in two sessions. In the second part, it was evaluated which targets are relevant for stakeholders along the product life cycle.

17.3.2 Expert Interviews

While the initial workshop focused on the identification of stakeholders and target definition along the product life cycle, the interview study was conducted to evaluate how targets were actually implemented in the design process and how these targets are validated.

For this purpose the target group was narrowed down to experienced design managers which are involved in operational decision-making in design projects. Focusing on persons with a good overview of the actual design process has been considered as the only way to gather real process data instead of idealized procedures described in sustainability reports or internal guidance documents. Since this group of persons has usually limited capacities to take part in surveys, the number of participants was relatively low. However, the experience of questioned managers as well as their respective position in the company was high. Only one of the study participants had a work experience of less than 20 years (13 years). Three participants worked between 20 and 25 years in design. Five participants were between 26 and 30 years employed in a design department. Seven persons had the explicit job title of chief designer. Two persons changed recently from the design department to the management board (CTO and CEO). As described above study participants worked in the field of power machines including electrical drives, automation equipment, turbomachinery and engines.

As a result of the initial workshop, clear structuring of interview with study participants was indispensable to achieve a common understanding of sustainability in design. Hence, the interview guideline was designed in adherence to both frameworks described in Chap. 2. The frameworks elements were synthesized to the following seven question clusters:

1. *Which sustainability targets are followed in the design process?* Examples for targets were given based on Fig. 17.1.
2. *How are these targets validated? At which stage of the product design process?* Given exemplary options were checklists/guidelines, qualitative comparison or quantitative assessment (utilization of models and IT support).
3. *What are common conflicts between sustainability targets? How are these trade-offs solved in practice?* A table was given which consisted of the criteria in Fig. 17.1 in rows and columns. Interview partners were asked to name the most important trade-offs based on this table.
4. *Which activities in product design are most challenging for considering sustainability targets?* This closed question provided the following answer possibilities: Target/requirements definition, conceptual design (idea generation and selection of alternatives), product architecture design/modularization, detailed design.
5. *What kind of support would you prefer for improved consideration of sustainability targets and for which task?* The question was formulated open but provided the same activities as in question six as a reference.
6. *Which elements of the sustainability definition are most relevant in the design process? Which elements will gain/lose importance or remain unchanged?* For answering these closed questions, a definition of elements characterizing the sustainability term was prepared for the interview partners. Considered elements were the social, economic and environmental dimension, life cycle thinking and interrelations between the sustainability dimensions.

The interviews lasted between 45 and 60 min. All interviews were recorded and transcribed. For analysis of results, qualitative content analysis was applied. For that purpose the approach of Mayring [12] for summarizing content was followed. For this purpose categories to analyse the transcripts were chosen in close relation to given example criteria in the interview guideline (deductive categorization approach). The transcripts were coded according to the developed categorization scheme. Furthermore, respective quotations were paraphrased to achieve a better overview on each category.

17.4 Results

In this chapter study results are presented comprising the initial expert workshop (*see* Sect. 17.4.1) and conducted interviews (*see* Sect. 17.4.2).

17.4.1 Expert Workshop

The results of the expert workshop are summarized in Table 17.1. The rows show the individual perspective of seven stakeholders which were identified as most important in the context of defining sustainability targets. The columns of Table 17.1 are representing the stages of the product life cycle including the design itself as well as the production, use and the end-of-life phase. Table entries reflect relevant sustainability targets for a product design from the perspective of all identified

Table 17.1 Stakeholders and associated sustainability targets for product life cycle stages

Stakeholder	Design	Production	Use	End-of-life
Shareholder	Time to market, low development cost, target costing	Low cost, capital intensity	Reliability, supply of exchange parts	Long product lifetime
Strategy, marketing, business development	Innovation, development of new markets, knowledge management	Supply chain availability, efficient energy consumption	Business model	
Manufacturing engineer	Design for manufacturing (DFM)	Manufacturability, certification of supply chain	Design for disassembly as a basis for MRO	
Test engineer	Early planning of testing with intelligent sensoring equipment			
System user			Reliability and availability, comfort, business model	
Legislation	REACH compliance		Country-specific emission regulation (CO_2, NO_x)	
Society			Noise reduction	

stakeholders. The table was filled through a moderated discussion by the experts. Points were only added to the table if it was agreed by all workshop participants. In a last step, identified targets were evaluated concerning challenges of target implementation by all workshop participants. The first two identified stakeholders represent the economic perspective of companies.

Shareholders are primarily interested in financial aspects and expect appropriate returns on investments. Hence, aspects such as low costs in design and production or fast time to market play a large role. Furthermore, turbomachines are often sold as a product-service system where customers only pay for machine operating hours. Hence, reliable machines with a long lifetime and low maintenance effort are beneficial.

From the perspective of *marketing/company strategy*, new product features are necessary to gain competitive advantages and open new markets and business models. Furthermore, effective knowledge management was identified as a target as it guarantees efficiency increase in design. For the production phase, it is also seen as relevant to decrease energy consumption by optimized designs.

Concerning the *manufacturing engineer* design for manufacturability is an important aspect. Furthermore, there are some significant restrictions on design through the supply chain as components/materials can only be sourced at certified suppliers. In addition, ease of disassembly for maintenance, repair and overhaul was seen as a relevant constraint for turbomachine usage.

Test engineers aim for validating the product functions regarding specifications. Hence, they directly influence quality and cost of the product through test costs (which are quite high in case of turbomachines). For decreasing test cost, early specification of test cases and virtualization of tests are considered as relevant.

System users exist in airlines for turbomachinery and as power plant operators. They consider reliability and availability of machines as the most important sustainability aspects. Furthermore, comfort of offered services associated with the product and the corresponding business model is important. *Legislation* imposes restrictions on turbomachine design by prohibition of substances (REACH) as well as by regulation of emissions (in particular CO_2 and NO_x).

Finally, noise of turbomachinery is identified as a *societal* pressure.

Validation of manufacturability of turbomachine parts and the achievement of CO_2 and NO_x emissions in the usage phase are rated as most uncritical targets from the perspective of workshop participants. Most challenging targets, however, remain reduced time to market and affordable target costing. Furthermore, ease of disassembly for efficient MRO was identified as an important barrier. A lack of knowledge management and missing targets for the turbomachine end-of-life phase were identified as further challenges for the future.

17.4.2 Expert Interviews

As specified in section three, qualitative content analysis was utilized to summarize and interpret the interview results. The categories were structured into three main categories (C1–C3) which are presented in the following paragraphs.

17.4.2.1 C1: Defined Sustainability Targets and Validation

Category one focusses on evaluating if sustainability criteria introduced in Fig. 17.1 are defined as targets and to which degree these targets are validated.

C1A: Emissions

From nine questioned experts, five claimed that no explicit targets for emissions were defined. These five persons worked on electrical drives and automation equipment. Indirect emissions from electricity consumption are also not considered. One interviewee even claimed that "our products are free from emissions in production and usage". The two participants involved in turbomachines development mentioned targets for CO_2, NO_x, particulate matter and hydrocarbons. Three people also referred to noise emissions. One interviewee from the automotive sector claimed that in addition to sound, also electromagnetic emissions and exhaust gas are strictly monitored. Concerning car exhaust gas emissions, it was also stated that the car power is increased until emissions are as high as allowed limits. If targets are defined, validation is done with CFD analysis, thermal models, empirical correlation and experiments on physical prototypes. In one case sound emissions were also simulated.

C1B: Hazardous Substances

Nearly all interview partners named targets for hazardous substances. One partner claimed that no explicit targets are defined but that it is tried to avoid these substances. Three participants mentioned RoHS, and two also referred to REACH regulation as a main driver for considering hazardous substances. Furthermore, exclusion of lead and PVC and regulations for adhesives, coatings and lubricants were mentioned. For validation, companies use checklists for forbidden substances which are often integrated into the list of requirements. Suppliers are also obliged to attach necessary material data for that purpose. Instead of checklists for forbidden materials, one company uses a catalogue of allowed materials instead. Only materials from this list can be used in design. In addition, one interview partner reported that the ratio of hazardous substances to the overall product weight is calculated.

C1C: Material Consumption

Seven of nine questioned experts claimed that material consumption is to be minimized in the design process. However, targets are only defined indirectly as material consumption is a cost driver (proved in six statements). In case of electric motors, the weight also influences energy efficiency which is considered more important. Measures for implementation are design guidelines (e.g. design of thin walls, adaption of forged parts to form design). For validation CAD volume calculation, FEM simulation of stability as well as process simulation to reduce manufacturing waste is conducted.

C1D: Energy Consumption

Six of nine interviewees follow defined targets for energy efficiency. In addition to targets induced by EU regulation, two experts stated that a new product needs to be more efficient than the previous one (by 10% in one case). Two experts referred to energy efficiency as primary driver for cost and emission of turbines and therefore see high efficiency as a key competitive advantage. Energy consumption in production is seen as less relevant as machines already exist. For validation a wide span of simulation models including thermodynamic and CFD models as well as weight optimization with FEM is used. Furthermore, two participants work with special design tools for efficiency analysis of electric motors. One expert also uses E-CAD libraries of components which also include efficiency data. Furthermore, checklists and measurements on physical prototypes are used.

C1E: Waste Reduction

Targets for waste reduction are seen as less critical by interview partners. Similar to results of the category material consumption, interviewees see waste as a cost issue primarily in production. Concerning the end-of-life phase, one expert claims to use 100% recyclable material (steel, aluminium). However, material selection was made primarily for limiting cost in production. Only two interviewees stated to follow targets for reparability, ease of disassembly and recyclability. One of the two argued in addition that remanufacturing is conducted as the value of components is very high. Furthermore, a long product lifetime is considered as a major measure to reduce waste. Another expert elaborated reduction of packaging waste as a target. An explanation for this low interest in the end-of-life phase is delivered by a statement given by an expert who referred to a missing obligation to take back outdated products in B2C markets.

C1F: Cost

Without surprise cost targets are defined by almost all study participants. Only one expert claimed that products should be designed "as cost efficient as possible" without concrete targets. Targeted product costs are defined based on market analysis, comparison to previous products or estimations based on experience. Monitored cost are production cost but also development cost and the total cost of ownership. Costs are evaluated at every milestone of the product creation process mostly with Excel-based calculation tools and with SAP.

C1G: Customer Value

Providing value for the customer is a central theme which constitutes the basic purpose of any development activity in the respective companies. The most important criteria in this context are basic functionality, quality, reliability, simple usage and low maintenance effort. Furthermore, durability and exchangeability of parts are rated as important. In two cases developments are completely customer-driven. One statement underlined the importance of a “unique selling point”. In product planning, companies collect statistical data on customer needs and competitor products. In the design process, the list of requirements constitutes the basic reference for capturing customer needs. In addition, balanced scorecard approaches and FMEA are used. Furthermore, the conventional engineering toolchain and specific software for quality management is used.

C1H: Safety

Product and production safety is strongly regulated and a large variety of guidelines and standards exist. Therefore, safety is relevant for all interview partners. Three experts even claimed that safety is the most important priority while developing products. One company is developing automation equipment in particular for safety applications in larger systems (e.g. wind turbines). Hence, safety can also constitute the basic function of the product. For validating safety, checklists and FEM simulation are used. Furthermore, two companies use dedicated tools for helping users to consider all relevant standards for their products. Other means of validation were IT-assisted FMEA as well as first efforts for anticipating assembly processes with VR.

C1I: Material Origin

Only three interviewed experts stated that the source of materials is carefully monitored. As reasons compliance to regulation with the American market (prohibition of “conflict minerals” by the Dodd-Frank Act) and strategical supply of rare earth metals was claimed by two persons. One expert working in an SME added that the source of used aluminium is known but that it is difficult to trace the origin of supply parts for their machines. Another interview partner working in a large company stated that all suppliers are certified and therefore information is available.

17.4.3 C2: Approach for Addressing Sustainability Targets

In category two, it is clarified how companies approach to implement sustainability targets with a particular focus on trade-offs and overall challenges of target implementation.

17.4.3.1 C2A: Dealing with Target Conflicts and Trade-Offs

Concerning trade-offs interviewed experts referred most often to the classic triangle of project management including time vs. cost vs. functionality/quality. Safety is also seen as a conflicting target but does not require trade-offs as safety concerns always rule other criteria out. Energy consumption and efficiency is seen as another important criterion, which is often conflicting with costs, customer value and material consumption. An example for the complexity of trade-off relations is given by one expert from the aviation industry. To increase efficiency of turbomachines, more compressor stages can be used. However, more stages increase cost and weight. Increased weight leads in turn to higher fuel consumption. Through measures for decreasing weight, durability of parts may be compromised (e.g. through design of thin walls). Increasing the pressure ratio of the compressor without additional stages may lead to compressor surge as a major safety issue. To deal with target conflicts, discussions with the customer and within the project team are seen as an important measure to identify all relevant constraints and preferences. Furthermore, risk assessments and IT-based testing of different product configuration were named.

17.4.3.2 C2B: Challenges of Target Implementation

Figure 17.6 shows major challenges experienced by interviewed experts concerning the integration of sustainability targets into product design. Most severe challenges are regarded concerning target definition and concept development/selection. The definition of product architecture and detailed design are also considered as challenges but remain less critical.

17.4.3.3 C2C: Support for Improved Target Implementation

In order to improve implementation of sustainability targets, six interview partners asked for enhanced transparency of relevant sustainability criteria and corresponding requirements definition.

In this context the economic value of following sustainability targets should be made visible. Furthermore, the conceptual design phase should be supported with knowledge management and improved means for anticipating sustainability factors

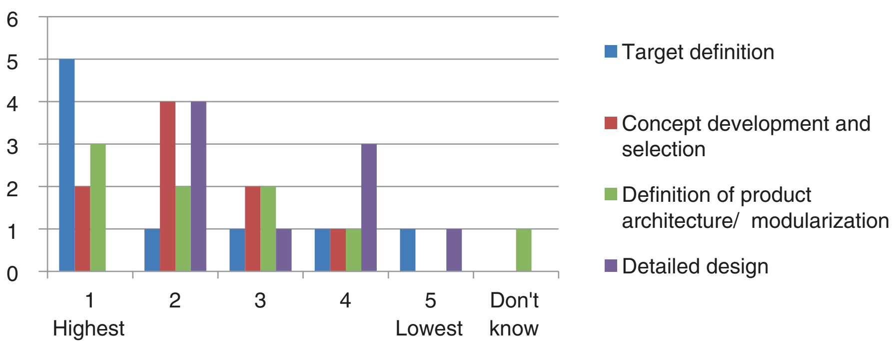

Fig. 17.6 Challenges for considering sustainability targets in the design process

with a focus on cost. Another expert formulated the demand of a database comprising all relevant requirements from legislation.

17.4.4 C3: General Perception of Sustainability in Design

Category three shows a more general view on sustainability in product design. In this context motivation for sustainability and most important elements of the sustainability definition are evaluated.

17.4.4.1 C3A: Motivation for Considering Sustainability

Three interview partners named explicit reasons for companies to care about sustainability. One aspect in this context was rising pressure induced by EU regulation. For example, the market for electric motors is driven by electrical efficiency. For turbomachines in aviation, customers even demand higher efficiency to anticipate future regulation as these products are used for a long time. Furthermore, cost advantages of efficiency improvements were assessed as a major driver in this context.

17.4.4.2 C3B: Relevance of Sustainability Elements

For this category participants were asked to evaluate which elements of sustainability are most relevant in the design process. Figure 17.6 shows the amount of interview partners who evaluated a sustainability element on a qualitative scale from 1 (very relevant) to 5 (less relevant). The chart shows that the economic aspect of sustainability and life cycle thinking are judged as most relevant. Environmental and social aspects and interrelations between dimensions are less often named as important.

While Fig. 17.7 shows the current situation, Fig. 17.8 gives an idea how interview partners are evaluating future developments.

The chart shows that the role of economic aspects will rather remain unchanged, while in particular social aspects as well as life cycle thinking could play a larger role in the future. For environmental aspects the image is less clear. Given examples for social implications were the question of job losses through increasing automation of factories, sourcing of materials of countries with harmful working conditions or political consequences for companies, which endanger other citizens (e.g. by utilizing heavy cars in residential areas). Importance of life cycle thinking will rise due to decreasing product life cycles, supply of many product variants in short time and increased effort for managing maintenance, repair and overhaul of outdated products with many variants.

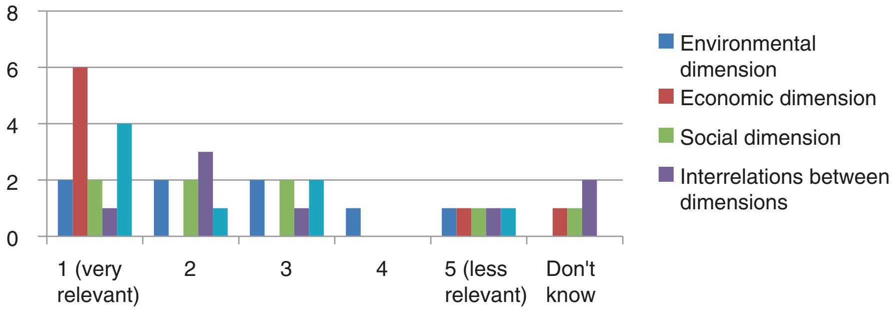

Fig. 17.7 Relevance of sustainability elements today

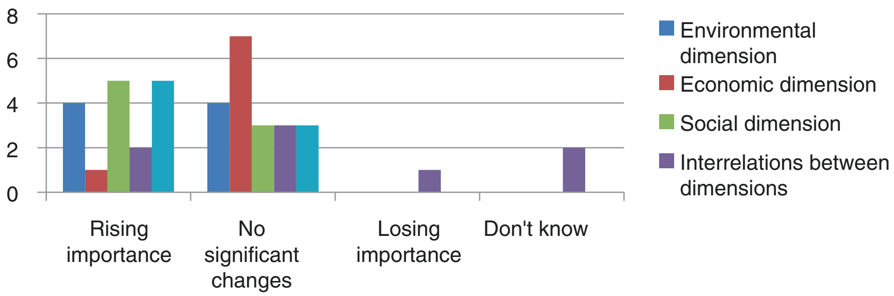

Fig. 17.8 Future relevance of sustainability elements

17.5 Discussion

In this chapter survey results are interpreted and study limitations are shown.

17.5.1 Interpretation of Results

The study results are now mirrored to the respective steps of the framework shown in Fig. 17.2.

17.5.1.1 Target Definition

Through the results of the initial workshop, it was shown that sustainability affects a large variety of stakeholders within and outside the company. Design engineers need to cope with the resulting set of diverse requirements and find a balance between conflicting targets as a “sustainability integrator”. As shown in the interview study, “conventional” design targets related to cost, functionality/

quality and safety are still predominant. However, legislation and cost also foster definition of targets for the remaining sustainability factors. Furthermore, life cycle thinking and social and to some degree also environmental aspects are seen of rising importance for future design projects. Concerning the product life cycle, both studies showed the low amount of targets concerning the product end-of-life phase.

17.5.1.2 Target Implementation

For implementing and validating sustainability targets, a large variety of qualitative and quantitative tools are used. Different checklists are utilized for reducing hazardous substances, cost and material consumption as well as for increasing safety. The lists are most often derived by standards and regulation documents. In some cases automated tools are used to simplify guideline selection and application. Furthermore, some quantitative tools for heuristic calculations are used already in early phases, e.g. for calculating energy efficiency and cost (mostly based on Excel). The classic CAx toolchain is used for estimating functionality parameters, material consumption and safety issues. However, as stated by the experts, there are still challenges for target implementation in particular concerning the conceptual design phase. Complex trade-off relations and comparison of many variants may be reasons for that purpose.

17.5.1.3 Target Validation

Many tests are already performed with engineering tools and other models which are used already in early phases and become more precise with increasing information about the product. However, physical prototypes are still widely used and also provide a basis to evaluate if emission values are met, for example. However, most sustainability-relevant criteria are decided beforehand (e.g. material consumption, origin of materials, hazardous substances). Not one of the interviewed experts referred to design methods for sustainable product development or Ecodesign (e.g. LCA) as a basis for their decision-making.

17.5.2 Study Limitations

The conducted study provided valuable insights about current practice in the design process concerning sustainability targets. However, these insights can only be understood exemplary as only one particular product category was considered. Furthermore, the qualitative expert approach does not intend to provide statistically representative results, as a low number of experts were considered. Furthermore, the considered sample of experts only represents German companies with a focus on

B2B products. In further studies there should be an enhanced consideration of B2C products as these also involve take-back obligations of products and a green image appreciated by customers.

17.6 Conclusions

As one of the main insights of the conducted study, knowledge of stakeholders and decision-makers in the design process on sustainability and its relevance for design activities is still limited. Currently, sustainability targets are still primarily driven by legislation and cost targets. However, many companies already follow a large variety of targets in the context of sustainability without explicitly relating them to that topic. With increasing company size, a broader spectrum of targets is considered, and a large variety of tools is already used. While existing theory on sustainable product development often refers to LCA and other Ecodesign methods, not one of the study participants referred to these means of decision support for target implementation or validation. To better utilize the potential influence of design engineers to define, implement and validate appropriate targets, three areas for improvement are identified:

- Guidance in formulating product-specific sustainability targets in a collaborative process involving the customer and other relevant stakeholders.
- Appropriate knowledge management to train engineers how to implement sustainability targets with a focus on conceptual design.
- Consolidation of available product models and validation tools to enable analytic consideration of target conflicts between sustainability targets.

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Chapter 18
Challenges When Including Sustainability Aspects in Product Development at Two Large Manufacturing Companies in Sweden

Fredrik Paulson and Erik Sundin

18.1 Introduction

This research is about the challenges manufacturing companies may face when developing more sustainable products. Prior studies have explored and described these challenges (*see*, e.g. [1, 3–10, 12, 13]); however the reasons for these challenges are not thoroughly described. Dekoninck et al. [1] have made a compilation of this type of challenge into a comprehensive framework; however, experience from speaking with manufacturing companies and from studying literature indicates that there are more challenges to be added to that framework. Moreover, in order to achieve a better understanding of reasons behind the industrial challenges, further investigations are needed.

The aim of this paper is to expand current knowledge about challenges faced by manufacturing companies when including sustainability aspects in product development. The study is mainly explorative and descriptive. The aim is broken down into three parts: firstly, to give examples of challenges that manufacturing companies face when including sustainability aspects in product development; secondly, to explore reasons *why* the companies face such challenges; and thirdly, to test the hypothesis that there exist challenges to be added to the framework of Dekoninck et al. [1].

18.2 Terms Used Within This Research

Within this research many terms have been used, which is described in this section.

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18.2.1 The Product Development Process and Functions

The product development process can be described as a "sequence of steps or activities which an enterprise employs to conceive, design, and commercialize a product" [2]. Several functions in a company perform activities during the development of a product, e.g. marketing, general management, design and finance [2]. A function in this study is defined as a group of employees that work with similar tasks and belong to the same department, e.g. environmental management, purchasing and engineering.

18.2.2 Sustainability Requirements and Aspects

Requirements which are inherited from a purpose of reducing the negative environmental impact are in this study called environmental requirements. If social aspects are included too, then the term *sustainability requirements* is used. An *aspect* is in this study a requirement that has not yet been set.

18.2.3 Challenges When Including Sustainability Aspects in Product Development

Challenges are in this case, for instance, optimizing environmental and social aspects from a life cycle perspective in combination with being competitive [3] and to address the "short-term economic thinking" [4].

Several researchers study *barriers* to the inclusion of sustainability aspects in product development. Three examples of such barriers are time constraints [5], "finding environmental impact information" [6], and that such inclusion is not found profitable enough [7].

In addition to *challenges*, there are several other terms used when studying the inclusion of sustainability aspects in product development, such as *hinders* and *hurdles* [8], *problems* [9, 4] and *obstacles* [10]. An example of a hinder is "No apparent requirement from market or customers" [8]. Some authors treat some of these terms as synonyms with challenges, e.g [1, 4]., while some do not [5]. These terms are in this research collectively interpreted and called challenges. It is acknowledged, however, that the meaning of them can be interpreted differently.

In this paper, *manpower* is used as a synonym with *a number of employees* or *several employees*. Lack of *relevant competence* is interpreted as synonymous with lack of *knowledge*. *Cause* and *reason* are used as synonyms.

18.3 Methodology

A multiple case study approach was used for this research. Data was collected from semi-structured interviews with employees at two large manufacturing companies, between May and August 2016. Additional data was gathered from the companies' sustainability reports. All interviews were held at the companies' principal product development site, which prior to the interviews were located in Sweden. The companies got a brief description of what the interview would deal with, and they were asked to select which employee/employees would be suitable to interview. All interviewees are presented in Table 18.1. The interviews lasted about 40 min and mainly dealt with challenges that the company face when including sustainability aspects in product development. The principal interview question relevant for this paper was: *Which challenges does your company face today when including sustainability aspects in product development?* Questions related the meaning of sustainability for each company, and drivers for the inclusion of sustainability aspects in product development, were asked too, in order to get a context of the challenges described. The interviews were recorded and transcribed. At a later stage, follow-up questions were asked in order to get more information about the cause of the challenges and who face them. Finally, the respondents read, adjusted and approved the authors' compilation and interpretation of their answers.

The selection of companies built on the assumption that respondents who understand the research questions well will deliver a comprehensive amount of relevant data. Therefore, companies with some experience of including sustainability aspects in product development were searched for. The selected companies (A and B) explicitly informed on their websites that they include environmental or other sustainability aspects in product development. Additionally, both companies use a structured product development process, which is an important factor for successful integration of sustainability aspects in product development [11].

Table 18.1 Characteristics of the respondents of Company A and B. RXY stands for Respondent Y in Company X

Respondent's role	Experience of respondent
RA1: head of environmental management	20 years of experience working with environmental issues in different positions at Company A
RA2: project environmental coordinator	3 years of working experience as project environmental coordinator at Company A
RB1: coordinator of environment, safety and health	29 years of experience of working with environment and work environment. 8 years working with sustainable development. 15 years at Company B
RB2: manager of the main product development department	2 years in current position. 18 years of experience from working as a designer and project manager in product development at Company B

Each challenge described by the companies was divided into the claimed challenge and the reasons for it. The reasons were classified as internal or external, inspired by van Hemel and Cramer [12], where internal means that the reason originates within the company and external means that the reason originates outside the company. The identified challenges were compared to each other. The reasons for the challenges were also compared to each other. The challenges, and the reasons for the challenges, were thereafter compared to the challenges described in the framework of Dekoninck et al. [1] and four additional selected empirical prior studies [3, 4, 7, 12]. The purpose of the comparison was to find similarities.

The study by Dekoninck et al. [1] focuses on the products of the company and includes a review of the type of challenge relevant for this research and a consolidating framework, which makes it suitable to compare with and suggest improvements to.

The multiple case study by Jönbrink et al. [7] was selected for comparison due to that it is comprehensive and the challenges are well explained. The case study by Hallstedt and Thompson [3] was selected because it is informative and the lifetime of the products of the studied company is long, which is similar to the products of both companies studied in this research. The study by Schulte and Hallstedt [4] was selected due to that it seems to include both environmental and social aspects, which this research also do. The challenges described by van Hemel and Cramer [12] seem to have more of a designer's perspective than the other studies, which makes it interesting to compare with.

When the challenges were compared, the interpretation whether two challenges are the *same*, are *similar*, or *have similarities*, (shown in the results in Table 18.2) was based on the descriptions of the challenges. The following was compared: (1) how many words of the description of the challenge that have the same meaning; (2) if the challenges are considered to mean the same thing; (3) if they describe things in the same level of detail; and (4) how easily one of the challenges can be interpreted as meaning something else. *Reasons* for challenges were compared to challenges in the same way.

Challenges faced by two large manufacturing companies are presented in the next two sections.

18.4 Challenges at Company A (Case A)

Company A develops and manufactures complex products that include both mechanical and electronic equipment. It is an international business-to-business (B2B) company with more than 12,000 employees.

18.4.1 Sustainability According to Company A

Both respondents and the sustainability report give several and different descriptions of what sustainability mean for Company A. The sustainability report describes a number of social, environmental and economic aspects, e.g. no tolerance for corruption, reduce climate impact and engage in society for promoting education.

Table 18.2 Comparison of challenges and causes between Company A, B and prior studies. Explanation of symbols used when comparing two challenges, here presented in declining order of how similar they are: same = ●, similar = ▲, have similarities = ■. When comparing the reasons for the challenges at Company A and B with challenges in prior studies, hollow variants (○, Δ, □) are used. Numbers in brackets refer to a specific challenge in the framework of Dekoninck et al. [1]

Case A	Case B	[1]	[3]	[4]	[12]	[7]
CA1	–	● (3.2.4)	–	■	–	–
CA2	–	□ (3.2.1)	–	Δ/□	□	Δ
CA3	–	□ (4.3.2/5.1.3)	–	□	□	□
CA4	● (CB3)	■ (3.2.2)	–	▲	–	–
CA5	–	□ (4.3.1/ 4.3.2)	–	–	□	Δ
CA6	■ (CB3)	■ (4.2.2)	–	■	–	–
CA7	–	■ (4.2.2)/Δ(4.3.1/4.3.2/ 5.1.2)	–	□	□	Δ
CA8	▲(CB1)	■ (4.2.2)/Δ(4.3.1/ 4.3.2/5.1.2)	–	▲	□	Δ
CA9	–	▲(5.2.1)/□(4.3.2)	–	■	□	□
CA10	–	▲(4.2.2)/Δ(4.3.1/4.3.2/5.1.2)	–	■	□	Δ
CA11	–	▲(4.2.1/5.2.2)	■	□	●	□
CA12	–	Δ(5.1.3)	–	□	–	Δ
CA13	–	–	□	–	□	–
CA14	■(CB3)	▲(3.2.3)	–	Δ	–	–
▲(CA8)	CB1	Δ(4.3.1/4.3.2)	–	■	□	Δ
–	CB2	●(4.3.1/4.3.2)Δ(5.1.3)/(3.1.4)	–	□	■	▲
●(CA4)	CB3	□ (5.1.3)	–	▲/□	□	□
–	CB4	●(4.1.5)/ ■(4.2.2)/ Δ(5.1.3)	–	□	–	Δ
–	CB5	□(4.2.1)	□	■ / Δ	–	□
–	CB6	●(4.2.1)/Δ(1.1.1)	●	○	Δ	Δ
–	CB7	–	–	–	–	●

However, phasing out hazardous chemical substances (HCS) from products and the product system is an aspect described by all three sources. The three sources describe several and various reasons for Company A to work with sustainability. However, two reasons described by all three sources are economic motives and to comply with legislation like REACH (registration, evaluation, authorisation and restriction of chemicals) and RoHS (restriction of the use of certain hazardous substances in electrical and electronic equipment).

18.4.2 Main Drivers to Include Sustainability Aspects in Product Development

Company A includes sustainability aspects in product development. Several different reasons are described by all three sources, e.g. minimize the risk of losing the supply of critical chemicals due to legislation (e.g. REACH) and scarcity of resources, to be competitive, to be an attractive employer for engineers, fulfil demands from customers in order to earn money, enable making service on their products in a way that comply with legislation and technical requirements, fulfil internal goals, fulfil the internal environmental policy and fulfil legislation.

18.4.3 Challenges Currently Faced When Including Sustainability Aspects in Product Development

CA1 (challenge, company A, challenge number 1): *Getting sustainability-related information from suppliers about chemicals and substances they use in their products.* In those cases where this challenge occurs, the reason can be that the supplier does not want to give that information to Company A, caused by a lack of legislative requirements on giving such information to customers. Add to that the added cost for the supplier to collect and send that information. Another reason is that the supplier does not have the information readily available. This challenge is mainly faced by purchasers; however, the environmental function faces it too, since that function supports the purchasers in this type of issues [RA1].

CA2: *Buying components that include chemicals or substances, for which permission to use must be applied for, from companies in countries that do not have to follow the same legislations as Company A does,* e.g. *REACH*. The cause of the challenge is that the company that has to get the permission to use a certain chemical or substance has to include the use of it in the whole supply chain; otherwise, the supply chain break and the supply of components to Company A vanish. This is a complex challenge to address, since it requires relevant competence, is time-consuming and may require the work of several employees. There is a lack of knowledge in both Company A and in companies in their supply chain of how to manage this challenge. The whole company is affected by the challenge [RA1].

CA3: *Finding out how to efficiently solve the problem that occurs when two pieces of legislation (*e.g. *environmental legislation), which have to be complied with, contradict each other.* The problem has to be solved for the development of the product to proceed. The reason for the challenge is that the problem is complex, and solving it requires relevant competence and significant time. A similar problem is when a piece of legislation becomes updated and a formerly nonrestricted chemical or substance becomes restricted [RA1].

CA4: *Making the suppliers of Company A fulfil the sustainability requirements that Company A puts on them*. This is not always a challenge. However, when it is, the reason for the challenge is often that the supplier finds the expected income from doing business with Company A too small, in relation to the efforts the supplier has to make in order to comply with Company A's requirements. The challenge is faced by the function that manages environmental legislation [RA1].

CA5: *Finding new suppliers or redesign components in order to maintain satisfactory delivery reliability in situations when components or substances the company uses vanish from the market*. The reason is that legislation, like REACH, makes suppliers move their operations away from Europe or shut their operations down. REACH is the major external reason for this challenge. Finding new suppliers or redesign components are complex and time-consuming tasks, which may require several employees to work with. The whole company is affected [RA1].

CA6: *Following up and ensure that their list of restricted substances is complied with.* The list is Company A's compilation of own, legislative and customers' requirements, which have to be considered. The reason for the challenge is that it is a complex task. The challenge is faced by the person that is responsible for making the product comply with the requirements on the product. That person is usually the same as the person responsible for the design of the product [RA1].

CA7: *Having a good understanding within Company A of all relevant legislation/directives in all countries Company A sells products to.* The reason is that achieving and maintaining that understanding are a large and complex task, which is time-consuming, require relevant competence and may require several employees to work with. The challenge is faced by the function that manages environmental legislation [RA1].

CA8: *Understanding how the environmentally related goals (*e.g. *climate goals) that the UN, the EU, various nations* etc. *have agreed upon can be concretized into relevant key performance indicators (KPIs) and goals applicable at Company A.* Relevant KPIs and goals help Company A to reduce both the environmental impacts from its products and make a profit. To be called relevant, the investments needed to fulfil the goals require a payoff time and profit that can compete with other investments suggested to management at Company A. The reason for the challenge is that the creation of relevant KPIs requires relevant knowledge, a system's perspective and resources (time, money and manpower), which are not easily acquired. The challenge is faced by the environmental management function [RA1].

CA9: *Investigating if Company A has conflict minerals in its products.* The reason for the challenge is that the materials in which conflict minerals may occur are used in almost all electronic equipment in the world today. The smelting plant, which is close to the source and from which it is a better possibility to investigate the origins of the material, may be 30 supply chain links away. Company A has not yet faced this challenge; however, they will on the day a customer requires that Company A's product shall not include conflict minerals. For Company A, that investigation would be a complex task that would require much time and other resources, if answers can be found at all [RA1].

CA10: *Managing and working with Company A's comprehensive list of regulated chemicals and substances.* One reason for the challenge is that there is country-specific legislation and customer-specific requirements that affect their products, and Company A has to manage and consider all of them. Moreover, the applicability of legislative and customer requirements on Company A's products is difficult to analyse. Managing and working with the list are a complex task that requires relevant knowledge, time and money. Legislation regarding the phasing out of HCS, especially REACH, is a major cause of this challenge. The challenge is faced by the environmental function. See CA6 regarding the list [RA1, RA2].

CA11: *Making the actual substitution of HCS within Company A's own factories and at its suppliers while still fulfilling all technical requirements for the product.* The reason is that there is not as much knowledge about the consequences (e.g. functional) if changing to the alternatives, as for the currently used chemicals and substances. Legislation aimed at the phasing out of HCS is a major cause of this challenge, especially REACH. This challenge is faced by the engineers when stipulating and managing requirements on products in the procurement process. The engineers are responsible for finding a solution, which complies with applicable environmental legislation while fulfilling technical requirements [RA2].

CA12: *Helping in-house engineers understand the environmental requirements well, in order to give them the ability to see which of the environmental requirements allow for some play and which do not.* One cause of the challenge is that different pieces of legislation sometimes dictate different things. The company's engineers, in general, do not have the knowledge required regarding environmental requirements and therefore find it difficult to decide whether they shall use, or not use, a specific chemical or substance. The challenge is caused mainly by legislation relating to phasing out HCS. A misunderstanding of these requirements might lead engineers to spend too much effort on solving a less prioritized requirement, which may cause the solution to be unnecessary costly. This challenge is faced by engineers as well as RA2, who helps them when they ask for help [RA2].

CA13: *Including environmental aspects when evaluating suppliers for purchasing components.* One reason is that Company A would like several suppliers of, e.g. each chemical, substance or device to be able to minimize economic risk. However, having several suppliers is not always possible because there might exist only one supplier that fulfils more prioritized requirements. Moreover, several suppliers hesitate fulfilling Company A's environmental requirements since Company A is by them considered too small of a customer, i.e. the suppliers have more important customers. This challenge is faced by purchasers [RA2].

CA14: *Making suppliers aware that they have to take responsibility of rising their own knowledge of environmental requirements and to make them rise that knowledge.* Without that knowledge they cannot fulfil Company A's requirements. One cause of the challenge is that the employees of suppliers in some cases think they have sufficient knowledge of environmental requirements for being a supplier of Company A, but they do not. In some cases (a second reason), there are employees of the supplier that have the required knowledge, but they are of some reason not involved in the discussions regarding the environmental requirements. A third reason is that the suppliers may prioritize other activities. Currently there is a mix between helping suppliers to get rid of regulated chemicals and substances and getting permission for using the regulated components. Purchasers face the challenge [RA2].

18.5 Challenges at Company B (Case B)

Company B develops and manufactures products that include both mechanical and electronic equipment. It is an international B2B company with more than 10,000 employees.

18.5.1 Sustainability According to Company B

Both respondents and the sustainability report give similar descriptions of what sustainability mean for the company. Several environmental, social and economic aspects are described by the sources, e.g. reduce water and energy consumption and greenhouse gas emissions from own operations; voluntary social activities, e.g. providing water that is safe to drink to people living in areas where that type of water is lacking; and no tolerance of child or forced labour in the supply chain. However, improved energy efficiency during the use phase of the principal products they develop is described by all sources as a description of what sustainability means for Company B. The respondents give slightly different reasons for why the company works with sustainability. However, one reason that both respondents describe is that it is good for the economy of their business.

18.5.2 Main Drivers to Include Sustainability Aspects in Product Development

Company B includes sustainability aspects in product development. Several and different reasons for that are described, mainly by the two respondents. Some examples are:

1. Efforts to reduce the environmental impact from their principal products' life cycle (mainly the use phase) are justified by a high correlation with economic savings for the customers.
2. It is good for the economy of their business.
3. To reduce the environmental impact from Company B's products.
4. To help customers achieve goals and implement strategies to reduce their environmental impact.
5. To help customers comply with legislation on CO_2 emissions.
6. Company B's mission and main technical development strategies and goals are seen by Company B as a contribution to sustainable development, which makes inclusion of sustainability aspects in product development easily justified.

18.5.3 Challenges Currently Faced When Including Sustainability Aspects in Product Development

CB1: *To efficiently and as soon as possible have found relevant, measurable KPIs that can be followed up for the products in their portfolio that are not yet affected by the latest version of Company B's formal product development process.* The latest version of the process is their only version that includes sustainability aspects by using product-type-specific KPIs, inherited from a number of LCAs done for their principal product. The use of such KPIs is considered best practice by Company

B. The reason for the challenge is that addressing it requires more time and money than currently available. For instance, new product category rules might have to be developed, which requires significant time and money. This challenge is faced by the environmental, health and safety function and RB1 [RB1].

CB2: *Get time and money to develop their product development engineers and managers in a way that they have a sustainability mindset when they solve problems and invent new products in general.* They already have such a mindset for economic and quality aspects, but not for sustainability aspects. Having this mindset is more important than only thinking of sustainability aspects when the formal process asks them to, for instance, by the use of a checklist. The reason is that it takes great effort to complete such an initiative, and RB1 has not been able to prioritize it yet. If, for instance, designers and managers had a wider awareness of the need to develop this mindset and asked for it, then it would be easier for RB1 to prioritize it. The challenge is faced by RB1 [RB1].

CB3: *Making sure the social requirements that are put on the suppliers are complied with and that there is a follow-up on those requirements.* It is a complex task to do in practice, and one reason for the challenge is that there is a lack of employees, especially purchasers, with the competence of doing audits that include social aspects. The formal process is there already, but not the practical routines and organization. A reason for the latter may be that the economic and medial risks of not prioritizing the work are considered low by the management of Company B. A comment to the challenge is that RB1 wants the practical routines and organization to be implemented more quickly than is taking place and therefore thinks the perceived slow rate of implementation is a challenge in itself. Mainly purchasers face the challenge, but the environment, health and safety function faces it too [RB1].

CB4: *Including sustainability aspects already in the planning phase of the product development projects, in a better way than is currently done.* Currently, there are formal questions that must be answered in the beginning of the product development project; e.g. "Are there any customer requirements on sustainability aspects?" The answer from the project is often "no". Identifying more "yes" might require more proactive work than is currently done. One reason for this situation is that this is not how employees at Company B currently are working and formerly have worked. Moreover, improving the energy efficiency of the product is highly relevant in reducing the environmental impact, and that activity already gets many resources. Employees may wonder: "What is wrong with that?" A reason for the challenge seems to be that employees do not have the awareness that a proactive approach is needed if other important sustainability aspects are to be gathered from the customer. The challenge is faced by the environment, health and safety function [RB1].

CB5: *Explaining and internally marketing Company B's sales activities in business segments, which by some of Company B's employees is considered not contributing to sustainable development.* The main reason for the challenge is that it is important for some of Company B's employees to work at a company that contributes to sustainable development, and they find sustainable development not correlating with sales activities to customers in those business segments, especially since Company B externally and internally market themselves as contributing to sustainable development. The values and beliefs of these employees affect what activities they think contribute to sustainable development, and what is not. An additional reason for the challenge is that the company has to fulfil economic goals and such business segments can be lucrative. It is mainly RB2 and other managers that face the challenge [RB2].

CB6: *Keeping up the work of improving their products from a sustainable point of view in some situations where Company B is pressed by competitors.* In such a situation, management can decide that a product with older and less energy efficient technology shall be developed, which has happened. Such a product is not in line with the most prevalent opinion at Company B regarding what types of products are needed when striving for sustainable development. The main reason for the challenge is that Company B has economic goals, there are customers interested in such a product and the opportunity to sell it is great. Product development can argue for using more energy-efficient techniques in the product and that customers should be educated instead, which should make them prefer a more energy-efficient product. However, the latter is often more complex and requires more time and other resources. This challenge is faced by the product development function itself, RB2 and other employees that strive for reducing the environmental impact of every new product developed [RB2].

CB7: *Educating and convincing some of their customers to invest in smarter, smaller and more energy-efficient products that can save them money, reduce maintenance and are as dependable as former products.* One reason is that some customers still, to a large extent, ask for high maximum performance, caused by a preconception of high maximum performance being of high importance for the principal function of the product. They do so despite the existence of alternatives, which can cut life cycle costs in half while still fulfil all requirements. Another reason for the challenge is that the dependability of the product is, in general, the most important customer value. Changing from an old but dependable product that the customer is familiar with to a new, less proven product may be perceived as a large risk by the customer. The economic consequences for the customer of a sudden unplanned stop are huge and can have a serious economic and physical effect on a large number of people. It is not worth taking the risk. Mainly sales and marketing personnel face the challenge, but design engineers face it to some extent as well [RB2].

18.6 Comparison of Challenges

The comparisons in this section are pictured in Table 18.2.

18.6.1 Comparison of Challenges and Reasons in Case A and B

Only two challenges described by Company A and B are considered to be the *same*, that is, CA4 and CB3. The others are unique. At first glance, other such pairs may seem to be the same, but when looking at the details, differences appear, which rather make them *similar* or *having similarities*. One example of this is the case of CA8 and CB1. In CA8 there is a need to *understand how* to address the challenge expressed. That need is not expressed in CB1.

The three most common *internal reasons* mentioned by both companies are presented here, in order of the most frequently mentioned: (1) lack of resources (mainly time, money and manpower), (2) lack of knowledge within the company and (3) other initiatives than the more sustainable ones are considered most efficiently contributing to the economic goals of the company. Regarding reason (1), sometimes one type of resource is mentioned, e.g. time in CA3, and sometimes several types are mentioned, e.g. time, money and manpower in CA8. The lack of knowledge in reason (2) is about the specific knowledge required to address the related challenge, which is unique for each challenge. For instance, the lack of knowledge in CA2 is about requirement management in the supply chain, while it is about how to efficiently elicit sustainability-related customer needs in CB4. Examples of reason (3) are described in CB6 and CA8 and point out that products and KPIs have to competitively contribute to the economic goals of the companies, if they are to be selected.

The three most common *external reasons* of the challenges are environmental legislation (mainly REACH), suppliers who do not think that complying with the sustainability requirements of their customer is an activity that gives sufficient return on investment and suppliers' lack of knowledge about environmental requirements.

18.6.2 Comparison of Challenges and Reasons in Case A and B with Prior Studies

As seen in Table 18.2, more than half of all challenges faced by Company A and/or B share at least similarities with challenges described by Dekoninck et al. [1].

CA4 and CB3, here summarized as *making suppliers fulfil the sustainability requirements that are put on them*, are not clearly included in the framework of Dekoninck et al. [1]. However, both "Changing the type of interaction in the value chain from transactions to collaborations" [1] and "Supply change management", described by Schulte and Hallstedt [4], have similarities with CA4 and CB3.

CA8, here rephrased as *how to transform sustainability aspects, or general goals, into measurable requirements that contribute to reduced environmental impact from products and in the same time competitive profit*, is not clearly included in the framework of Dekoninck et al. [1] either. The challenge "Difficult to manage customers' requirements for ecodesign", identified by Dekoninck et al. [1], is considered to have similarities with CA8. A challenge similar to CA8 is "translating these future requirements into […] actions in the present", identified by Schulte and Hallstedt [4].

Many of the challenges described in the selected prior studies are similar to, or have similarities with, the internal reasons for the challenges of Company A and B. For instance, *lack of time* [1, 7, 12], *lack of knowledge* [1, 4, 7] and *lack of profit in order to fulfil economic goals* (at least in short term) [3, 4, 7].

Three of the nine case companies investigated by Dekoninck et al. mentioned that cost-efficiency of a product is still more important than reducing the environmental impact of it ([1], p. 418). This statement is considered being similar to reason (3), described earlier in this section. Similar challenges are identified in three of the prior studies [4, 7, 12]. Despite this similarity, a clear corresponding challenge in the framework of Dekoninck et al. [1] is lacking, and the challenge is suggested to be described as *identify how to gain competitive profit out of a more sustainable initiative or solution.*

Only two of all challenges described in the prior studies (in Table 18.2) are considered to have any similarities with the external reasons described in case A or B. Those are "The company does not feel responsible for realizing the option" [12] and "The option only becomes relevant if supported by market demands" [12].

18.7 Discussion

Stewart et al. [13] identified the challenges "Lack of goal translation to functional/department basis" and "Difficulty to define relevant sustainability performance metrics […]". Both share similarities with *how to transform sustainability aspects, or general goals...*, identified in this research. The same authors describe the challenge "Difficulty to elaborate business case, […] manage trade-offs", which is similar to *identify how to gain competitive profit…*, identified in this research.

None of the challenges faced by the companies, in combination with the causes of the challenges, are exactly the same. This fact implies that it is important to have a thorough understanding of each challenge and what is causing it, in order to be able to efficiently address the challenge.

The analysis indicates that what one person describes as a challenge, a second person can describe as a reason for another challenge. The implication is that the whole chain of reasons to a certain challenge can be called challenges. It all depends on how the persons describing the challenges denominates them.

Despite many reasons for the challenges have been identified, the ultimate root causes to them may not have been found. That would most probably require a more focused scope of the research.

Worth noting is that several of the challenges are faced by the function the respondents belong to, some by the respondents themselves. That indicates that the result may be biased towards them. What challenges would have been described if designers were interviewed? However, the respondents were selected by the companies. All challenges are described by the respondents, none in the sustainability reports.

18.8 Conclusions

Within this paper current knowledge about challenges faced by manufacturing companies when including sustainability aspects in product development has been expanded. The research has been conducted in three parts:

Firstly, novel descriptions of 20 challenges faced by two large manufacturing companies when including sustainability aspects in product development are presented.

Secondly, reasons why the companies face such challenges have been explored in the analysis of the two companies. Here it is indicated that lack of resources (mainly time, money and manpower) is perceived as the major internal reason for challenges of including sustainability aspects in product development. Other important internal reasons are lack of knowledge (the type of knowledge vary) and that a more sustainable initiative or solution is not always the most efficient choice when it comes to fulfil the economic goals of the company. The most common external reasons for the challenges at both companies are environmental legislation (mainly REACH); the supplier that finds the return on investment, from complying with the customer's sustainability requirements, too small; and lack of knowledge about environmental requirements at the suppliers.

Thirdly, to test the hypothesis that there exist challenges to be added to the framework of Dekoninck et al. [1], the following three challenges are suggested to be added to their framework: (1) *making suppliers fulfil the sustainability requirements that are put on them*; (2) *how to transform sustainability aspects, or general goals, into measurable requirements that contribute to reduced environmental impact from products and in the same time competitive profit*; and (3) *identify how to gain competitive profit out of a more sustainable initiative or solution.* They are suggested to be included in the themes of their framework that describe external collaborations, integration with new product development and building the business case, respectively.

Prior studies of challenges related to the inclusion of sustainability aspects in product development are mainly explorative and descriptive. That opens for more explanatory research in this area.

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Chapter 19
Integrating Sustainable Development and Design-Thinking-Based Product Design

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19.1 Introduction

'We can't solve problems by using the same kind of thinking we used when we created them' is a quote often attributed to Einstein. In this study, we explore a relatively new way of thinking—design thinking—to address the problem of unsustainable product life cycles.

19.1.1 Motivation

19.1.1.1 Why Product Design?

Product life cycle impacts are a major contributor to many of society's environmental and social challenges [1–3] and thus a problem worthy of our attention. Sustainable product development is also a means for companies to become and remain competitive [4, 5].

19.1.1.2 Why Integrate?

Integrating sustainable development with existing product design processes and practices is critical for successful implementation of sustainable product design [6, 7]. Even the international standard ISO14006:2011 describes sustainable product design as involving the integration of sustainability considerations into product

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design. We therefore describe 'sustainable product design' as the *integration* of (1) sustainable development and (2) design processes and practices—such that the product design helps society to transition to a sustainable future.

19.1.1.3 Why Project Teams Need Help?

Project teams need help with the integration of sustainable development and product design. The nature of sustainability is complex; it relates to social and ecological systems [8] and includes considering not only current global issues but also potential future issues. Unsustainability can also be experienced as distant in time and in space [9]. Wrestling with the complexity of sustainability is relatively new for product developers, compared to what they usually include in their decision-making. This novelty and complexity makes for tough decision-making conditions [10]. In particular, bringing a sustainability perspective to new product development 'complicates an already complex process' [11] (p. 106).

19.1.1.4 Why Customise?

Since product development processes are unique to each company (even if they have similarities), the integration with sustainable development needs to be customised [12]. According to European ecodesign practitioners, a challenge with existing suggestions is that they are often not tailored to the business needs [12, 13]. One-size-fits-all approaches for modelling the product design process ignore important aspects of reality [14]. Salerno et al. [14] identified six types of innovation process, and Gericke and Blessing [15] identified multiple significant ways to differentiate between processes. Several other authors have demonstrated their disillusionment with one-size-fits-all approaches to product design [14] (e.g [16, 17]). Even if we were to try to integrate sustainable development with a generic, discipline-independent design model, generic models are too abstract to provide effective support for project teams [15], and thus, our contribution would unlikely be effective. We therefore focused on a specific product design process.

19.1.1.5 Why Design Thinking?

One popular type of process is 'design-thinking'-based product design. Design thinking prioritises grounding design decisions in a thorough understanding of user needs, uses iterative prototyping and problem-solving to explore wicked problems, and employs divergent-convergent thinking [18]. Since design thinking was created to design in complexity, with an optimistic solution-expecting nature and diversity in project teams, it is a relevant process to explore from a sustainable development perspective [19]. Design thinking is optimised for breakthrough innovation (rather than incremental innovation) [18], which means that project teams are not locked into a particular (physical) solution, and so the potential for impact is large. In fact, design thinking focuses on the needs of the user and delivers a functional result that addresses these needs, which is critical when designing *sustainable* solutions (with some mix of physical artefact and intangible service) [20].

19.1.1.6 Research Question

Based on the above, we joined with an innovation consultant to define the following research question, aiming to be relevant for both academia and practitioners:

RQ: How might project teams that use a design-thinking-based product design process start to integrate sustainable development into their work?

19.1.2 Previous Studies and the Gap

During our study, the Ellen MacArthur Foundation and IDEO[1] jointly launched the 'circular design guide'. This is a design guide where circular design has been integrated with (a simplified version of) IDEO's design thinking process. There are currently no academic studies behind this guide nor on its implementation. It will be interesting to follow its development and compare with our findings.

19.2 Participatory Action Research

The research question is grounded in a desire to enhance practice, which is in line with the purpose of sustainability science to be solutions-oriented [21, 22]. We therefore chose (together with some research participants from the company) to engage in *action research* due to its inherent intention to improve *practice*. In particular, we chose the type of action research that is *participative* knowledge construction. This combines action research with collaborative methods for constructing knowledge together with those immediately affected (participatory research), in line with what Bergold and Thomas [23] call participatory action research and Greenwood and Levin [24] call pragmatic action research. The people who are immediately affected are knowing subjects and participants, rather than objects of the research. In our case, the participants are employees of a product innovation consultancy that uses a design-thinking-based product innovation process.

Our action research consisted of iteratively completing the cycle shown in Fig. 19.1. The cycle comprises three not-wholly-distinct phases, and we com-

[1] A design consultancy. See ideo.org

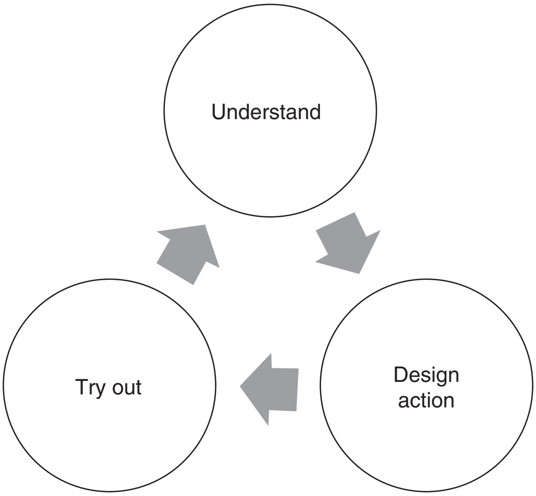

Fig. 19.1 Action research cycle of three not-wholly-distinct phases

pleted three iterations. The description here is a simplification in order to aid communication of what was a very iterative and alive process, complicated with the messiness of reality.

19.2.1 Understanding

The purpose of the *understand* phase was to increase collective understanding of relevant academic fields and of the current industrial practices and associated challenges. In addition, the purpose of this phase in the second and third iterations was to also incorporate understanding of the results of previous 'try out action' phases.

In order to meet the above purposes, the academic researchers reviewed literature on sustainable product design, product development, decision-making for sustainability, and organisational learning and change, as well as the intersections between these areas. In order to increase understanding of the processes and practices of the project teams that use the design-thinking-based product process, we used the following data collection methods: briefings by both sides—preparatory work that helps set the scene for greater levels of participation (in line with Bergold & Thomas [23]), interviews with practitioners on their practices and perspectives, collection of process and methods documents, observations during interactions, survey of employees, participants describing their own needs in meetings and emails, and a focus group-style workshop for exploring needs, which is 'one of the key instruments for the creation of a "communicative space"' ([23], Sect. 4.4). In order to increase understanding of the challenges that employees perceive in the integration with sustainable development, we used the following data collection methods: interviews; observations during meetings, workshop, and evening course; and employee survey.

The outcome of this phase was understanding the needs (for action) described in Sections 19.3.1 and 19.3.3. With each iteration, our understanding became more comprehensive.

19.2.2 Designing Action

The purpose of the second phase was to use the understanding from the previous phase to *co-design actions* (enhancements to process and practice). We have thus far completed this phase three times, resulting in three versions (v1, v2, and v3). The first version was at the overview level, for which we actually designed two prototypes to be compared. Generating and comparing alternatives can help reduce the effects of confirmation bias [25, 26] and evaluability bias [10] and lead to better designs [27], higher success rates in decision-making [28, 29], and even quicker decision-making [30].

In order to design the enhanced process, we generated ideas on how to address the identified needs. We fuelled our ideation by reading literature on how others have solved similar problems, for example, literature on supporting decision-making for sustainability in other contexts.

19.2.3 Trying Out Action

The purpose of the third phase was to *try out the designed actions* and gather data on how it went and what could be improved. In the first iteration, we compared the pros and cons of the two alternatives in joint academics-practitioners meetings and via email. Data was collected through observations during meetings and emails.

In the second iteration, we collected observations during a teaching session with product developers. In this iteration, the academic researchers also went outside of the partner company and tested the suggestions with product development students. Data was collected through observations during class when they were using the suggestion, students' reflections after using the suggestion, and the outcomes from them using the suggestion.

In the third iteration, we discussed the workability of the suggestion—the adequacy of the suggestion according to how well it works in the local context [24]. In line with pragmatic action research (see [23, 24]), we adopted the view that different participants may have different perspectives on what is adequate/good, and so the academic researchers first asked the practitioners to think about their views on what it means for them for the suggestion to work well, before commenting on the suggestion itself.

19.2.4 Ethical Considerations

Key principles of action research are that democracy is a prerequisite and that a safe space where participants can be open and show dissent needs to be developed [23, 24]. Although building trust can take time, we believe that we have been fairly successful in creating this space and a power equality between academic- and practice-based knowledge since participants have been open with both positive and negative comments and even emotional sharing of frustrations.

All survey and interview data were handled anonymously. This paper was reviewed by a company representative before being submitted.

19.2.5 Credibility of the Research Design

The selection of action research as an approach and the top-level design were made jointly by researchers and company participants. In action research, it is not a matter of standardising methods but rather choosing methods appropriate to the participants [23]. Many of the methods that we started out with are not especially participatory, for example, interviews. However, the interviews and surveys were research techniques that were familiar to the participants and therefore served both as a knowledge building step (for all involved) and for constructing the safe space and trust necessary for the later use of more participatory methods.

The iterative nature of our research and the multiple data collection methods and sources give us confidence in our results. In future research, we intend to extend this further to include many more participants. In particular, the lack of testing at the partner company on a real, live project is a weakness that we will address as soon as possible.

19.3 Results

In this section, we describe the needs at a high level before giving an overview of our suggestion. Then we dive into more detail, first on the needs and then on the suggested process enhancements.

19.3.1 High-Level Description of Needs

We identified the following needs:

(A) Target the early phases of product development. These phases are a leverage point for integrating sustainability since the early-phase decision-making influences

the sustainability impacts of manufacturing as well as other life cycle phases [31]. Decisions in the early phases also determine, to a large extent, the success of a project [32] and significantly impact development costs [33].

(B) Follow a value-focused approach. One empirical insight of the study was the difficulty in navigating the complexity of the decision-making context. Emphasising values and value trade-offs helps decision-makers to navigate this and focuses on the sustainability considerations that matter for the project [34]. This can be achieved by fully investigating what is valued before exploring alternatives [35].

Considering how sustainability performance is valued and wanted would help project teams to make decisions that would likely deliver both business and societal benefits. This is in line with strategic sustainable development thinking (see [8]) as well as the shift in sustainable design research from trying to propose detailed and exhaustive support to proposing strategies that consider the opportunities and limitations of the business world [36] and have a more explicit focus on the strategic implementation of sustainable product design [37]. A value-focused approach may help in avoiding one of the main critiques of earlier sustainable product design suggestions – critique that there was not a strong enough link between strategic intent and content of the suggestion [6]—and also avoid the implementation barriers that arise from scepticism for return on investment of sustainability initiatives [38].

(C) Focus on supporting the decision-making process and not only on supporting analysis. The quality of the decision-making process (including exploiting analysis and reaching a decision) can be six times as important as the quantity and detail of analysis performed [39]. A good process also helps avoid poor analysis [39].

(D) Vary according to type of decision-making activity and use specific techniques to mitigate for cognitive illusions. Cognitive illusions lead to a perception, judgement, or memory that deviate from 'reality' [40]. Cognitive illusions can also be known as biases [41]. Cognitive illusions likely occur in the tricky decision-making environment of starting to include sustainability considerations in product design. In order to mitigate for cognitive illusions, suggestions should vary with the type of activity [10], such as diverging and converging, including product development decision-making [42].

(E) Be simple enough to be practically usable by product design teams. Research participants frequently emphasised the need for the tools to be highly usable by sustainable design novices. In fact, one barrier to uptake of sustainable product design is that many tools are complicated and time-consuming [43] and, according to European ecodesign practitioners, overly complex [13]).

(F) Assist project teams to learn about sustainable development and develop tacit knowledge on doing sustainable design. The human side, or 'soft side', of sustainable design is important [44], and insights from other disciplines (such as organisational learning [7]) are needed to understand this side [45, 46]. Knowledge and skills in sustainable design within the organisation is one of the two categories of internal company barriers to sustainable product development (for small-to-medium enterprises) [47]. Capability of the designers and engineers, in terms of knowledge, skills, and decision-making power, is a success factor in sustainable design implementation [38, 43, 47].

19.3.2 Overview of Suggested Enhancements

The existing product design process at the partner company is based on design thinking similar to that used by IDEO (ideo.org). The IDEO process comprises three phases: investigating the challenge and the needs of the people involved (inspiration phase), generating ideas, identifying opportunities and prototyping (ideation phase), and bringing the concept to life and selling it (implementation phase). This process involves many iterations between convergent and divergent thinking. The ideation phase of the partner company's process comprises three subphases—strategy, ideas, and concept. (Their concept subphase includes a little more convergence than is apparent in IDEO's model.)

In order to meet the needs identified in the previous subsection, we suggest that the company enhances the ideation subphases with the activities shown in Fig. 19.2. The key principle behind the suggestion is that the project team *chooses* between different ways to work with sustainability during the ideation phase, according to what is *relevant* for their project. These enhancements will be specified in more detail in later subsections.

In the strategy subphase, project teams use their knowledge from the inspiration phase to choose sustainable product design strategies that are relevant to their project. These strategies offer ways to ideate for sustainability, with each strategy doing so from a different perspective. Example strategies include design for remanufacture and design for the base of the pyramid. Through deciding what is relevant to their current project, project teams are identifying leverage points, as recommended by Shapira et al. [19], and can work with sustainability in a way that matches the project goals, including business goals. Choosing between ways to work with sustainability is also appropriate because different projects have different possibilities for sustainable product design. For example, designing electrical equipment (with slower innovation cycles, common materials, and well-known use scenarios) is a very different context with different possibilities for sustainable design than designing electronic equipment (with shorter innovation time, specialised materials, and evolving usage) [48]. In addition, the team chooses sustainable product design strategies at the same time as choosing other strategies, such as the overall marketing strategy. This is in line with how companies seem to prefer to complement existing operations strategies, rather than creating sustainability-specific ones [49]. A sentiment shared by the partner company.

19.3.3 Detailed Needs: Required Functions

Given the overall suggestion shown in Fig. 19.2, we now explain some of the detailed needs that we uncovered. Expanding on need (D)—when project teams are choosing strategies and selecting concepts—the suggested process enhancements should help project teams to mitigate for cognitive illusions by facilitating them to [42]:

Fig. 19.2 Overview of suggested sustainability enhancements

(Di) *Emphasise values and value trade-offs (related to need (B).*

(Dii) *Check that the alternatives are credible*.

(Diii) *Use ends objectives* instead of means objectives.

(Div) *Compare alternatives rather than considering each option in isolation*.

(Dv) *Make it as easy to evaluate with respect to sustainability as for other aspects*.

(Dvi) *Prioritise searching for key knowledge*.

(Dvii) *Use a diagnostic strategy* to mitigate for confirmation bias.

(Dviii) *Scrutinise where information came from*.

(Dix) *Search for evidence of the unexpected*.

(Dx) *Frame analysis results in multiple ways*.

(Dxi) A*sk themselves if they are being overly cautious*.

Also expanding on need (D)—when project teams are employing the strategies to generate ideas—the suggested process enhancements should help project teams to mitigate for cognitive illusions by [42]:

(Dxii) *Employing passive decision-support techniques.*

and facilitating project teams to [42]:

(Dxiii) *Generate alternatives that are meaningfully different from each other.*

(Dxiv) *Include stakeholder perspectives.*

(Dxv) *Use a diagnostic strategy.*

(Dxiv) was also a strong desire from those responsible for the design process in the partner company, probably because of the central role that understanding stakeholder perspectives plays in design thinking.

Research on the human side has started to converge on some general principles, including (1) the transformative nature of sustainable product design and (2) the need to include both organisational and individual dimensions [50]. Using Lam's [51] model for organisational learning and need (F) can be expanded in two dimensions—individual/collective and explicit/tacit—as follows. In order for the organisation to learn and develop (in terms of sustainable design knowledge), individual project team members need to learn:

(Fi) *Embrained (formal, abstract) knowledge*, through formal instruction.

(Fii) *Embodied (context-specific bodily) knowledge*, through direct interaction and mutual adjustment during practical experience in a relevant context.

Similarly, teams need to learn:

(Fiii) *Encoded knowledge (selected, simplified knowledge coded into rules and procedures*).

(Fiv) *Embedded knowledge (norms and shared beliefs that can support complex interaction patterns)*, through multifunctional team practical experience in a relevant context.

Learning may lead to attitude changes, which is important because one of the key challenges for ecodesign implementation in companies is people's attitudes [52]. It is not so surprising that attitudes are not always conducive to sustainable design implementation since unsustainability can be experienced as distant, in time and in space, and the communicating climate disruption (see [9]), in order to avoid emotive and political nature of sustainable development, can even lead to individuals experiencing discomforting dissonance [9]. Taking tips from the science of psychological barriers in sustainability communication and to encourage action, instructions, and support should:

(Fv) Use the power of the social nature of humans.

(Fvi) Be framed positively (showing opportunities, rather than just what to avoid).

(Fvii) Be easy and convenient to employ.

(Fvi) and (Fvii) were also strongly supported by our empirical studies. The above detailed needs are of course in addition to the high-level needs (A), (B), (C), and (E).

19.3.4 Details of Suggested Enhancements

19.3.4.1 Choosing Strategies

In the strategy subphase, when project teams are answering other questions about strategy, we suggest that they also ask themselves the following: *Which sustainable design strategies shall we employ? Which will likely deliver value for this project?* To aid with this, we have prepared the instructions shown on the left-hand side of Fig. 19.3.

The *strategy comparison table* is a decision-support prototype designed to help project teams to choose between strategies. It provides information on both potential business value that can be achieved by applying the strategy and potential sustainability value, in line with the prioritisation guidelines used in the framework for strategic sustainable development (see [8]). This prototype was developed as part of our project since a high number of strategies exist, and it is difficult to select the most appropriate one(s) [36]. When using the prototype, project teams will hopefully learn about sustainability, as defined in the framework for strategic sustainable

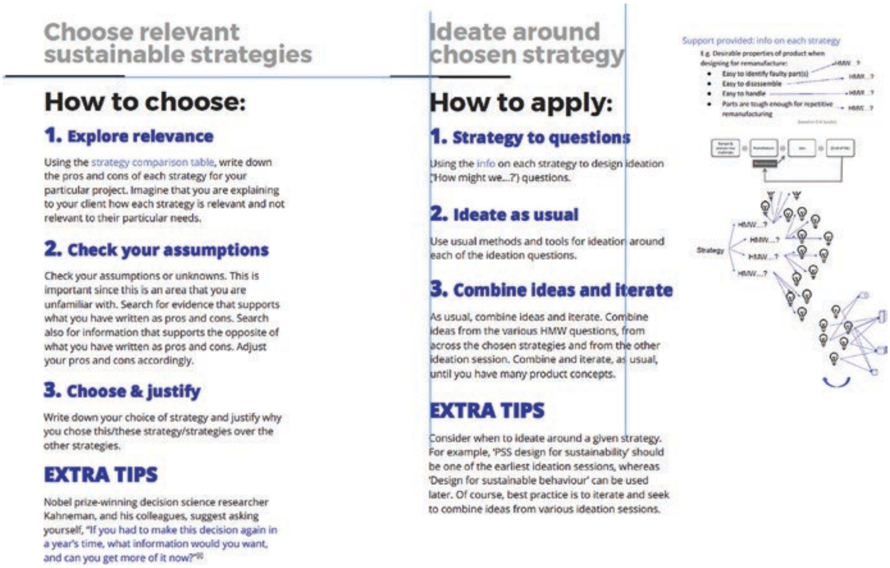

Fig. 19.3 Suggested enhancements to the strategy and ideas subphases—instructions to project teams

development and make a choice while understanding what aspects of sustainability and which life cycle stages they are not yet addressing. See [53] for details of the prototype.

19.3.4.2 Applying Strategies

In the ideas subphase, when project teams are ideating, we suggest that they ideate also around the chosen sustainable product design strategy(ies). See the right-hand side of Fig. 19.3 for the instructions for project teams.

19.3.4.3 Comparing Concepts with Respect to Sustainability

We have not focused on support for comparing and selecting concepts since there is much existing support, even support based on the same definition of sustainability.

19.3.5 Evaluation and Results from Trying Out

Looking at the identified needs, our overall suggestion is value-focused (B✓) and addresses the early phases (A✓). We suggest process-centric enhancements (C✓), such as how to gather information. As is evident from Fig. 19.3, the suggestions do vary with type of decision-making activity (selection/ideation) (D✓), and most of the detailed needs have been addressed. Future work should investigate how to encourage teams to involve sustainability stakeholders in their ideation (Dxiv).

The suggested enhancements are knowledge encoded in process format (Fii✓), and they encourage the project teams themselves to learn tacit knowledge by taking practical step-by-step action (Fiii✓). The suggestions also provide positive framing (Fvi✓) by taking an opportunity-based perspective of sustainable design (which also aligns with design thinking). Although some formal instruction (Fi✓) on sustainability and sustainable design is included in the suggestion (not shown in this paper), there is an opportunity for more. In fact, the partner company has asked for more.

During the first iteration, we learnt that it is better to integrate sustainable development in the methods used for generating ideas to address the customer needs (and choosing between ideas), rather than merely adding 'sustainability' as an additional need. The chosen approach received a positive and energetic response in the teaching session with product developers (second iteration). Reflecting on the suggestion, one (heavily involved) research participant wrote 'I realise that we are completely right with this… [it is] something that I definitely think that we should work with'. These responses give indications of the workability of the suggestion. During the second iteration, we learnt much about gaps in the usability (E and Fvii) of our suggestion when students struggled to understand parts of the instructions or used them in unexpected ways. These enhancements are included in the instructions shown in Fig. 19.3, which is our prototype v3.

19.4 Summary

We have outlined the needs of project teams that use a design-thinking-based product design process and who want to start to integrate sustainable development into their work. To address these needs, we have suggested *enhancements to a design-thinking-based product design process that project teams can use to start to integrate sustainable development their work*. Through our action research project, we learnt that:

It is better to integrate sustainable development with the process used for generating ideas to address customer needs (and choosing between ideas), rather than merely adding 'sustainability' as an additional need.

Sustainable development should be integrated into the process such that teams are facilitated to work with sustainable design in a way that is relevant to their particular project (industry, market, customer needs) while also better understanding the advantages and limitations of that chosen way. This is in line with the purpose of design thinking to address complex problems and also support stronger competence development in the project team.

The suggested enhancements can now be tested by others using a design-thinking-based product design process as well as by the partner company on a real project.

19.4.1 Contribution

Our contribution to research is not just another tool, which is a problem with research in the field that was identified already in 2002 [6], but enhancements to a design process that help project teams to make sense of and choose between *existing* strategies for sustainable product design. Our contribution to practice is suggested enhancements that are designed to be, not just academically credible but also practically relevant through integration in an existing process and customizability. Our suggestions address a gap in support for those working with design thinking. We found no equivalent studies and thus argue originality.

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Chapter 20
Constructed Wetlands as an Environmental Friendly System for Wastewater Treatment in Al Akhawayn University

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20.1 Introduction

The treatment of wastewater has become a priority given the growing awareness of the danger of the discharge of untreated water. Wastewater is very rich of harmful bacteria like salmonella and many others that can cause serious allergic reactions or severe diseases. In addition, it contains high concentrations of some toxins and heavy metals. Unfortunately, 1.8 billion of the world population uses the contaminated water daily which results in approximately 842,000 deaths each year. In 2017, there is over 80% of the total wastewater generated around the world that is dumped directly to nature with no prior treatment [1]. The main approach when it comes to wastewater treatment is the conventional method used by the municipal treatment which includes primary and secondary and can be extended to include tertiary and quaternary treatments. The quality of wastewater depends on the income of the country. For instance, in developed countries 70% of the generated wastewater is treated; however, in countries with low income, only 8% of the wastewater is treated [2]. Nevertheless, the last years, there has been a particular interest in experimenting with some non-conventional methods to treat wastewater. The main advantage of these techniques is that of being environmental friendly unlike the conventional method. Constructed wetlands (CW) are a widely used eco-friendly method of wastewater treatment in developed countries. It demonstrated and granted a high efficiency of wastewater treatment. Its efficiency is due to the fact that it only relies on naturally occurring processes and reactions. In other words, constructed wetlands mimic the mechanism that can be found in a natural wetland. The objective of this project is to provide an environmental friendly system through constructed wetlands to treat wastewater from two residential buildings in Al Akhawayn University's campus. The analysis will include a design from scratch taking into consideration

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all the specifications that could interfere with the good functioning of the project. This report will start off with a general evaluation of wastewater and its treatment in Morocco, followed by a steeple analysis of the project. The second part will be a literature review that will enclose the conventional wastewater treatment methods and detailed description of the different processes. This part will also contain the unconventional methods that have been used for wastewater treatment including constructed wetlands. The third part is the general methodology which involves the treatment in constructed wetlands, the design specifications, and the modeling using SubWet software. The fourth part will include the results and stimulations, as well as a discussion of the results. Finally a detailed financial analysis will be conducted to determine the feasibility of the study as well as the payback period.

20.2 Methodology

The choice of the type of constructed wetland is extremely important since it will take into consideration several factors:

- The climate: The project will be implemented in Ifrane which is located in the Atlas region of Morocco at an elevation of 1665 m. This part of the country is characterized by a cold climate during winter and warm climate during summer. Ifrane also experiences heavy snowfalls between the month of October and March.
- Location: The constructed wetland will be located near the residential area in Al Akhawayn University campus. The terrain available for this project is not restricted.
- The size of the population: The total number of residents of buildings 38 and 39 is 500. It's considered as a small-sized population with an average production of wastewater.

With all the previous factors in mind, the appropriate form of constructed wetlands is a subsurface flow horizontal CW. The use of this type of design will be suitable for the climate since the treatment will be below the surface. Therefore, it will prevent the water to be exposed to the snow providing a thermal protection, and the treatment will not be as slow as if it was exposed to the cold. In addition, with regard to the proximity of the stations to the residential area, SSF wetlands are perfect to avoid insects and mosquitos that can be attracted by untreated water, and it reduces any undesired human contact with the influent sewage. Given that there's no restriction in the area dedicated to this project, the SSF horizontal CW can be implemented even if it usually requires an important terrain's area. However, the overall surface will not be extreme either since the population is small or consequently the volume of the influent is limited. Last, but not least, SSF horizontal CW provides a pleasant and bio-diversified view as well as an educational ground for students and researchers.

20.3 The Treatment Process in Subsurface Horizontal Flow Constructed Wetlands

The treatment of wastewater consists of removing nutrients, organic matter, heavy metals, and suspended solids. There are several processes that take place in the constructed wetlands and contribute directly or indirectly to the treatment of wastewater. These processes can be branched to three focal types: biological (nitrification, denitrification, etc.), chemical (precipitation, etc.), and finally physical (sedimentation, filtration, etc.).

20.4 The Design

20.4.1 The Dimensions of the Constructed Wetlands

According to previous studies, the area of a constructed wetland is defined in accordance with the number of people generating the wastewater within a household. Typically this number is set to be between 2 and 8 m^2 per person for regions with cold climates like Ifrane [3]. The two residential buildings in Al Akhawayn University contain a total of 500 habitants. From the range mentioned before, taking the value 4 to be the area needed per person, the total area will be as follows:

$$\text{Total area} = 500 \times 4 = 2000\,\text{m}^2 \tag{20.1}$$

However, in order for the process to be more efficient and more importantly to achieve optimal results after the treatment, it is wiser to opt for multiple CWs with smaller surface areas. Therefore, the total number of CWs will be 5, each with an area of 400 m^2 (40 × 10 m) which will sum up to the total area of 2000 m^2. The choice of the width and the length is not arbitrary. According to previous work conducted on constructed wetlands, it was suggested that the ideal ratio (L:W) is of (4:1) [4]. The height of the wetlands will depend of the type of vegetation chosen, because we have to take into consideration the space needed for the roots of the plants to grow. We will discuss in the sections to come the type of plants that will be used.

20.4.2 The Volume of the Effluent

According to an article published by the ministry of energy, mines, water, and environment in Morocco, the average production of wastewater per person in a day is 45 l [5]. The total number of residents in the two buildings 38 and 39 constitute a total of 500 students as mentioned in the previous section. Therefore the total wastewater generated from the two buildings is 22,500 l per day.

20.4.3 The Type of Lining

Determining the type of liner that should be used is an imperative part of the design. In some cases, the liner is not an obligation but only if the soil is of a clayey nature. These textures prevent any seepage to underground waters [4]. In our case it's better to use a liner since any of the characteristics that were mentioned before are available. The typical materials used are polyvinyl chloride (PVC), polypropylene (PPE), and HDPE (high-density polyethylene) [4]. Therefore, we will be using one of these three materials as a liner. The dimensions will be the same as the ones of the wetlands adding the height plus 10 cm in each side for the design purposes.

20.4.4 The Type of Media

The choice of the type of media is also critical in the design and the overall functioning of the wetlands. There are several factors to take into considerations when choosing the media, namely, the hydraulic conductivity, the shape, the size, and the porosity. These specifications can influence directly the flow within the system. The commonly used media for this type of application is coarse sand, gravel, or small rocks. The media used should be uniform and of small size in order not to contradict the assumption of laminar flow used by Darcy's law, which is an important equation that is useful in the many calculations, for instance, the hydraulic retention time in the system. The table below shows the different types of media possible to use and also their relevant characteristics for the project [6] (Table 20.1).

Even though uniformity of the media is a requirement of the design of constructed wetlands, it is recommended to use bigger-sized media next to the inlet and outlet in order to decrease the possibility of clogging [6]. It is also essential to thoroughly clean the gravel before using it. Moreover, it should have specific characteristics like being hard and most importantly durable to be able to keep its initial shape through time [4].

The type of media we will be using is fine gravel giving that it has a low hydraulic conductivity and porosity.

Table 20.1 Types of media and their properties

Type of media	Size (mm)	Effective porosity %	Hydraulic conductivity (m/day)
Rock	128	45	3048
Fine gravel	16	38	2286
Medium gravel	32	40	10,000

Table 20.2 Types of vegetation and their root depth

Type of vegetation	Root depth (m)
Bulrush	0.6
Reeds	0.3
Cattails	0.2

20.4.5 The Type of Vegetation

There are several types of vegetation that can be ultimately used for these kinds of treatment stations, namely, cattails, reeds, and bulrush. However, the choice should not be done arbitrarily since it mainly depends on the climate and type of species existent in the area. For instance, in the presence of animals like nutria which depends on plants like cattails, this animal can eat and destroy the plants. Taking the biodiversity and the climate of the region, reeds are the most appropriate for the constructed wetlands. These plants don't need any harvesting or care since the fallen leaves serve as a thermal insulation on top of the gravel during winter times. Each wetland will contain a total of 1600 plants as an average of 4 plants per m^2. The table below shows all types of vegetation taken into consideration when choosing the vegetation as well as some of their root depth as it's a major factor when determining the height of the wetland [4] (Table 20.2).

20.4.6 The Type of Pumps

To assure that the water gets into the constructed wetlands from the septic tank and from the residences to the septic tank as well, it's crucial to install a pump. However, the pump that will help with getting the water from the septic tank to the treatment should be indeed a timed water pump that will be timed according to the hydraulic retention time (HRT) of the system. This installation will help monitoring the amount of water entering the constructed wetlands in order to assure efficiency of treatment within the system.

20.4.7 The Type of Inlets and Outlets

Inlets and outlets should also have a customized design to support the whole system. In addition to the fact that the gravel near the outlets should be larger than the media to prevent clogging, there are many others to take into consideration.

- The inlet should be slightly above the media to allow better aeration of the influent before it enters the wetland. The oxygen will help with the chemical reactions that rely on oxygen such as nitrification. In this project we will take the inlet to be approximately 5 cm above the media surface. Moreover, the inlet pipe should be designed and placed in such way to grant even distribution of the water at the inlet.

- The outlet is preferable of the perforated manifold type and has an easy access in order to be able to control the level of effluent. The adjustable standpipe needed for this purpose can be replaced by a weir box, since it provides much more ease during the control process. The weir box will include a pipe that will directly convey to the treated water collector.

20.4.8 Operations and Maintenance

The operations and management of subsurface flow horizontal constructed wetlands are minimal and of relatively low cost. This kind of treatment stations usually operates by itself and requires maintenance only few times along many years of operations. The main work that should be performed to assure good functioning of the plant is the pumping of the septic tank to remove the accumulated sludge, the removal of overgrown plants that can be sold later on. An inspection of the quality of water is also necessary from time to time along with an occasional cleaning of the inlets and outlets. Last but not least, there is a low chance that some mechanical problems concerning either pumps, pipes, or the timer that will require an immediate intervention.

20.5 Software Simulation of the CW

20.5.1 Software Introduction

SubWet is the software that will be use; it was designed by the United Nations Environment Programme and more specifically the Division of Technology, Industry and Economics. At first SubWet was developed to be used for the modeling of horizontal subsurface flow constructed wetlands only in regions with warm climates, so it has a limited applicability. However, it was recently upgraded to also involve sites of cold climates despite the limiting conditions it represents. The latest modifications have been done as part of research project between UNEP and Fleming College in Canada that calibrated the software using the data model in a constructed land in the region of Nunavut, Canada. SubWet 2.0 is a tool that assists the experts and individuals in designing and implementing subsurface flow constructed wetlands. It allows the user to simulate the removal efficiency of the main contaminants that exists in wastewater, namely, phosphorous and nitrogen. In addition, it can estimate the biochemical oxygen demand for 5 days during the treatment period. In addition, SubWet also grants the user the possibility to experiment with different sets by modifying the values of the variables as well as the initial concentrations of some data in order to obtain the optimum results.

20.5.1.1 Input Variables

The first step in the software is to determine the primary factors that control the general design. The input consists of the width, length, depth, precipitation factor (PF), slope, the percentage average particulate matter, the hydraulic conductivity, and the selected flow.

- *Width, length, and depth*: We already defined these parameters in the previous sections. Each of the five constructed wetlands will be 10 m wide, 40 m long, and 0.6 wide.
- *Precipitation factor*: The precipitation factor takes into consideration the precipitation and the evapotranspiration. It's calculated as the volume of water obtained from precipitation after deducting the volume evaporated over the initial volume in the wetland [7]. In the case of similar precipitation and evapotranspiration, the precipitation factor yields to 1 which is also the case of this project since the average precipitation and evapotranspiration are approximately 30 mm per day [8]. The calculation are expressed below:

$$\text{Avg precip} - \text{Avg evap} = 30 - 30 = 0 \tag{20.2}$$

$$\text{Initial volume} = 400\,\text{m}^3 \tag{20.3}$$

Then

$$\text{PF} = \frac{400 + 0}{400} = 1 \tag{20.4}$$

- *The % average of particulate matter (AP):* The average particulate matter is calculated using the following empirical equation [7]:

$$\%\text{Avg AP} = \frac{(25 - \text{SF})}{8} = \frac{25 - 45}{8} = 2.5 \tag{20.5}$$

- *Slope*: In order to facilitate the flow of water from the system to the outlet, it is necessary to have a slight slope within the wetland, but not to exceed 1% to keep the uniformity of treatment [6]. Therefore, the value that will be used for the simulations is 0.5.
- *Hydraulic conductivity:* In this context, hydraulic conductivity represents the ability of water to go through the media in the constructed wetland. As mentioned before, fine gravel will be used as the media for the constructed wetlands. Therefore, the hydraulic conductivity is around 2286 m/24 h.
- *Selected flow:* The selected flow is the total flow that will be flowing through the system per day. Given that the total flow for the five wetlands is 22,500 l per day, so each one of them will have a flow of 4.5 l/day.
  After imputing all the previous parameters, the software generates the values of the area, volume, hydraulic loading, recommended hydraulic flow, the recommended flow, flow width and flow length, and finally the number of paths.

- *Hydraulic loading*: According to the ecology dictionary, the hydraulic loading is the volume of water applied to a certain filtering medium [9].
  The second step in the software is to determine the forcing factors which include the porosity of the media, the length of the simulation, the average oxygen, and the temperature. In addition, it is necessary to include the initial concentration of contaminants like nitrate, ammonium, and phosphorous.
- *Average oxygen*: The software requires five values for the average oxygen, because it divide the wetland into five separate cells and tracks the concentration of the wastewater in each of the cells.
- *Temperature*: The temperature required is the one of the water, it is normally calculated experimentally. However, a research done about the seasonal variation in physic-chemical parameters in Ifrane provides the temperature of water in each season and the average yields to 12.98 °C [10].
- *Porosity*: The porosity was taken to be 0.03 (as a fraction of the percentage), which is the porosity of the fine gravel used as the media.
  The forcing factors input allow to get the water volume in m^3, as well as the hydraulic retention time per cell in days.
  The next window prompts the user to inter initial values; however this time, it requires an estimation of the value of BOD5, nitrate, ammonium, total phosphorous, and organic nitrate in each of the five cells that constitutes the wetlands. An array of parameters also requires an entry by the user. These parameters are essential in defining the final model and they include values parameters like the maximum denitrification rate and the temperature coefficient of nitrification. The value of these parameters is defined in the software manual according to the climate type.
- *The hydraulic retention time*: The hydraulic retention time is the time needed for the wastewater going through the wetland to be treated completely. This value is calculated by the software, and it is 3.75 days per wetland. It can also be calculated using the following formula, and it gives a similar result:

$$\text{HRT} = \left(n \times L \times W \times D\right) / Q \qquad (20.6)$$

where:

n: Effective porosity of the media %
L: Length of the wetland
D: Depth
Q: The average flow
W: The width of the wetland

20.6 Results

The last step is to simulate the efficiency of removal of the contaminants and the total amount that was removed after treatment in milligram per liters. The results are represented in graphs in terms of the number of days chosen before as the length of the stimulation (30 days). In addition, the software has the option to compare the results collected from the actual wetlands to the one generated. Furthermore, SubWet enables the user to get data sheets of the results of the concentration of all of the contaminants in each of the cells: A, B, C, D, and E any day.

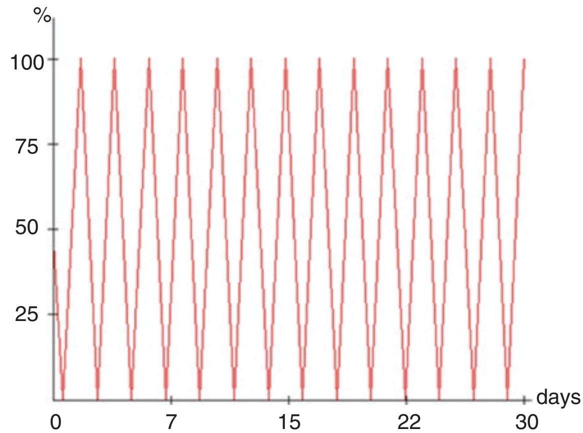
The table below displays the initial concentrations in the influent and the targeted concentrations of the contaminants in the effluent (Table 20.3).

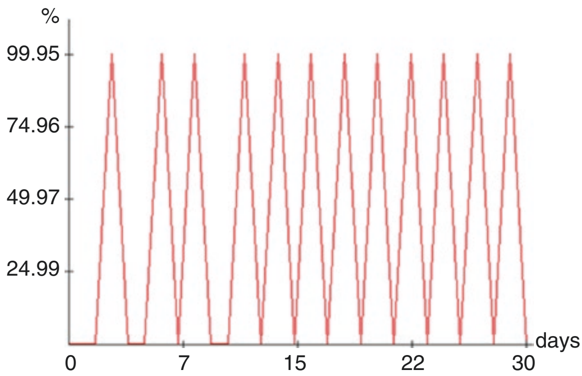
According to these concentrations, the software generates graphs to show the efficiency of treatment in the wetland. In other words, it measures the extent to which the target concentrations were achieved. The following are the graphs generated (Figs. 20.1, 20.2, 20.3, 20.4, 20.5).

Table 20.3 Influent and effluent concentrations

Constituent	Influent concentration (mg/l)	Effluent concentration (mg/l)
BOD_5	201	11
Nitrate	30	4
Ammonium	29	1
Total P	5	1
Organic nitrogen	10	2

Fig. 20.1 Removal efficiency of BOD5





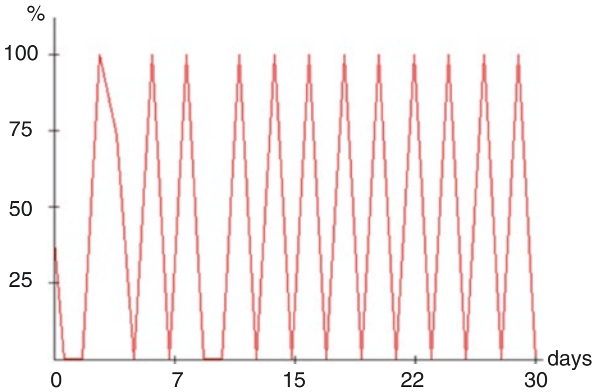


Fig. 20.2 Removal efficiency of nitrate

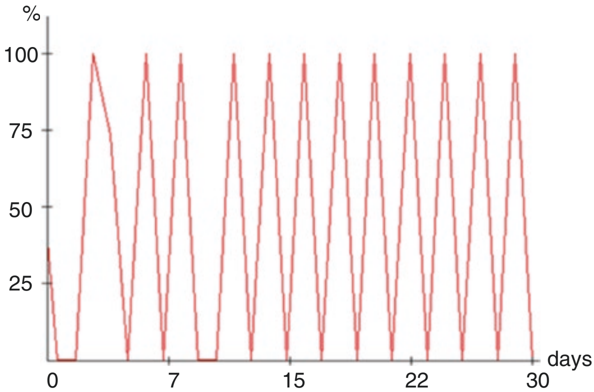


Fig. 20.3 Removal efficiency of ammonium

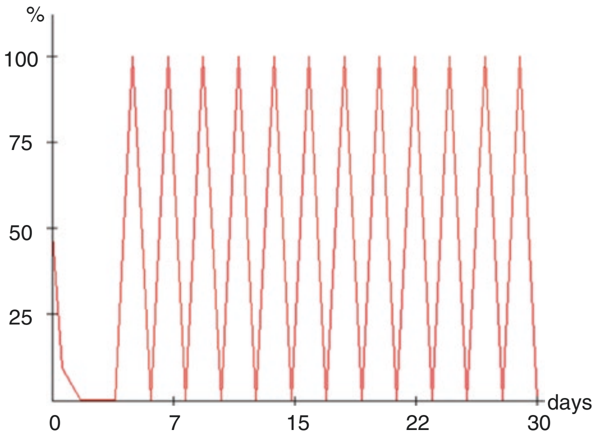


Fig. 20.4 Removal efficiency of phosphorous

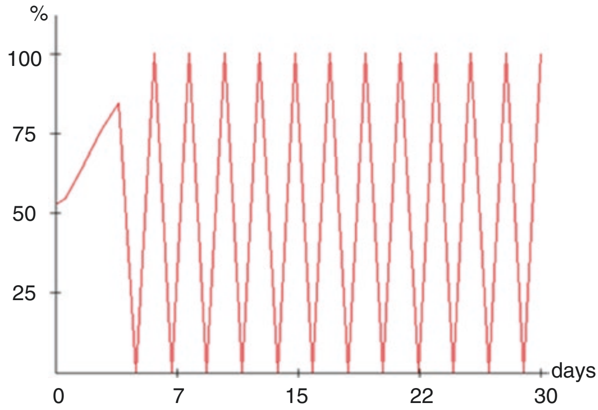


Fig. 20.5 Removal efficiency of organic nitrogen

20.7 Discussion

The results generated by the software indicate that the design and all parameters set for the constructed wetlands are efficient. In general, all the graphs display a removal efficiency of 100% which confirms the fact that the designed constructed wetlands are capable of reaching the targeted concentrations in the effluent. In addition, all the graphs display sharp oscillation between the value of 0 and almost 100% which is due to the hydraulic retention time (time needed for treatment). The hydraulic time is found to be 3.75 day which we can observe from the graph, and that's what creates the ups and downs. Moreover, the graphs also show that during the first days there is an inconsistency which can be explained by the fact that the constructed wetlands usually need few days to start working efficiently.

20.8 Financial Analysis

The final part of this project is the financial analysis. This step is extremely crucial before implementation in order to measure the feasibility of the study performed. It also allows an approximation of the return on the investment over the long term in addition to the payback period. In this financial analysis, there will be also a comparison between the cost of treatment following the conventional method of treatment and the constructed wetland treatment.

The Excel table below summarizes all the costs and expenses related to the implementation of the project (Table 20.4).

Table 20.4 Cost and expenses

Item	Cost (MAD)
Land	–
Site cleaning	42,500
Earthwork	60,000
Liner (polyolefin)	825,512
Media (G1,G2)	72,000
Plants	12,000
Pumps	20,000
Pipes (400,PVC)	62,500
Total capital cost	1,094,512.55

Table 20.5 O&M cost and profit

Cost item	Cost (MAD)
Capital cost	1,094,512.55
Operation and maintenance/year	2000
Reeds sale revenue/year	24,000
Total present worth costs	86,144.55
Cost per m^3 treated via CW	0.41
Cost per m^3 treated via conventional method	2.54

The system will require maintenance as mentioned in previous sections which is estimated to be 2000 MAD per year. There will also be a generation of profit yearly through selling harvested reeds. The profit is estimated to be 24,000 MAD per year given that there is a total of 8000 reeds and the selling cost is 3 MAD.

- *Comparison between the conventional and constructed wetlands cost for wastewater treatment*:

  The local rate for wastewater treatment is defined as 2.54 MAD per m^3. In the other hand, taking into consideration the total cost, operation and maintenance, and profit generated, the cost yields to 0.41 MAD per m^3. That is to say, the cost will sum up to 3367.12 MAD per year if using the constructed wetland system. However, if using the conventional way of treatment, the cost will be 20,859.75 MAD per year which denotes a great difference (Table 20.5).

- *Payback period*:

  The payback period is amount of time needed for the recovery of the initial investment. Taking into consideration all the previously mentioned costs and profit generated. The payback period will yield to *6.165 years* following the general formula for payback period and allowing a *5%* increase in the operation and maintenance cost each year.

20.9 Conclusion

Wastewater treatment has become a necessity for the protection of the environment. The conventional methods used for wastewater despite their efficiency can be indirectly harmful to the environment because of the high energy consumption and the risky use of toxic chemicals. On the other hand, constructed wetlands provide an alternative that assure the treatment of water naturally and efficiently. All the solids and contaminants such as nitrate, ammonium, and phosphorous can be eliminated after going through the system that consists of a septic tank and the constructed wetland. The removal efficiency is granted since all the treatment relies only on biological and chemical processes that naturally occur when the appropriate conditions are available. As a matter of fact, the system could have some limitation, namely, the cold climate, however, if the necessary measures are taken into consideration. The resulting effluent can have different uses. It can mainly be used for irrigation; also the sludge collected during the primary treatment can be used to generate biogas. In this project, a complete design and analysis were conducted in order to implement a treatment system relying on constructed wetlands to provide treatment for wastewater from two residential buildings in Al Akhawayn University's campus. The efficiency of the wetlands was represented using a modeling and design software developed for this kind of applications. Last but not least, a financial analysis was conducted to determine the payback period which yielded to approximately 6 years.

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Chapter 21
Proposal of the Index of Environmental Burden and Health Information

Yasuko Watanabe, Yuna Seo, and Kiyoshi Dowaki

21.1 Introduction

In recent years, the global food supply system has developed rapidly. With the expansion of global food trade, the establishment of international standards and agreements is important for ensuring traceability of production processes involving food safety, nutrients, and environmental impacts at each stage of the supply chain. In Europe, the Product Category Regulation (PCR) clearly states how to assess environmental impacts across the entire manufacturing process using the life cycle assessment (LCA) method. It is being positioned as an important international standard, supported by ISO 14045 and ISO/WD 14067 [1]. For example, one Italian food company uses an indicator based on environmental evaluation of its chopped tomatoes available from Valfrutta daily [2]. Other companies have also conducted research on organic soybeans and apples and so on, but there are no evaluations made to correlate with nutrients and quality only by environmental assessment [3, 4].

In addition to packaged foods, the environmental impacts of vegetables cannot be neglected if we are to achieve a sustainable society. The agriculture sector accounts for 13.5% of global greenhouse gas emissions [5]. Thus, it is necessary to consider ways to reduce agricultural emissions in the long term. As the world population increases and economic and social development progresses, destruction of natural capital in rural and world continues, farmland and water resources are decreasing, and the climate is changing. And that will lead to a rapid increase in demand for environmentally friendly products.

To strengthen the global agriculture sector, it is important to evaluate global standards such as PCR and to introduce value-added foods by providing nutrient, safety,

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and taste information on labels. Across the world, life spans are increasing, and elderly populations continue to grow, placing a larger burden on social security. The government of Japan recognizes that to prevent the deterioration of an individual's quality of life and to increase the sustainability of the social security system, it is important to lengthen the "healthy life span" through the promotion of each citizen's health [6]. Moreover, we are faced with problems such as the increase of chronic diseases, including obesity and heart disease, due to the consumption of unbalanced meals and changing dietary habits. In Japan, illness due to lifestyle habits accounts for about 30% of medical expenses and about 60% of deaths [6].

From such a viewpoint of protecting consumers, with regard to the health and nutrition claims of foods, nutritional labels on packaged foods are mandatory in many countries [7]. In Japan, nutrition composition including specific vitamins and minerals is labeled on food products [8]. However, such labels appear on only "products" and are not required for raw foods. Extending labeling to raw foods would be helpful to raise awareness of eating a balanced variety of fruits and vegetables [9], as well as to prevent possible health risks. In recent years, safety concerns regarding raw foods also have arisen. For example, the overfertilization of crops leaves excessive nitrate-nitrogen in soil, and the interaction of nitrite-nitrogen with saliva hinders the action of hemoglobin, which carries oxygen in the blood [10, 11].

Here, we propose a composite index of environmental and nutritional qualities of vegetables that satisfy the global environmental standards and customer needs. This index includes five indicators: CO_2 emissions, food miles, nutritional quality, food safety, and taste. It is compiled as a star mark, with the five points corresponding to the five indicators (Fig. 21.1). Each indicator is rated into five ranks. A large fully shaped star

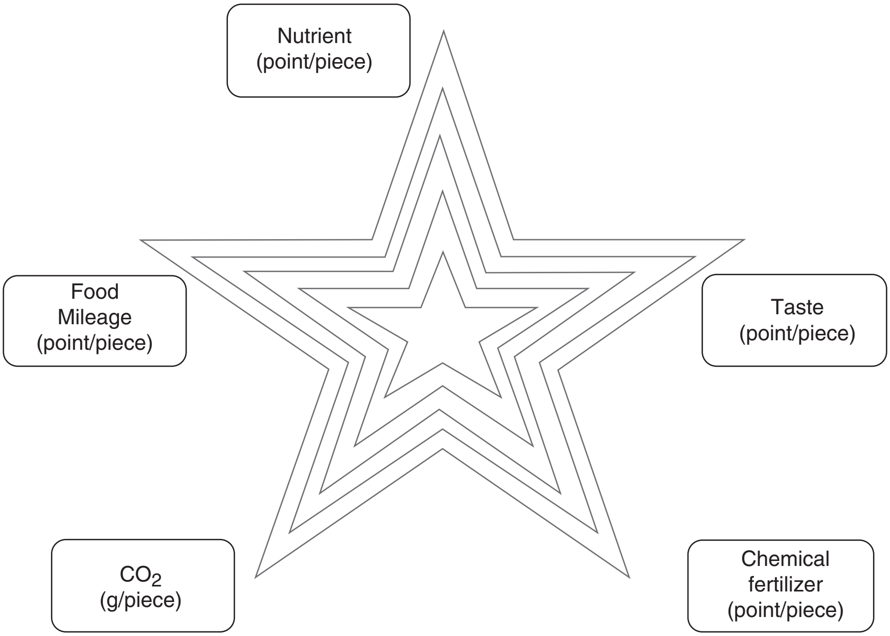

Fig. 21.1 Star mark of environmental and health index of vegetables

indicates an environmentally friendly, nutritionally qualified, safe, and tasty vegetable. To illustrate the practical application of this index, we applied it to two leaf lettuce crops, which differed in cultivation method (hydroponic vs. field-grown) and farm location.

21.2 Methods: Process of Calculating the Requirements for Indicators

To compare and label star marks, we assessed leaf lettuce from two different farms (Table 21.1). The evaluation unit used throughout the evaluations was set as the sales unit of leaf lettuce (1 piece), that is, 50 g for hydroponic lettuce and 300 g for field lettuce (Fig. 21.2).

21.2.1 CO_2 Equivalent Emissions

We calculated CO_2 equivalent emissions of leaf lettuce on both farms based on LCA.

The system boundary is shown in Fig. 21.3. Because the hydroponic cultivation's lettuce was not commercialized, so the system boundary was defined only as the production phase. The functional unit is taken as one sales unit of leaf lettuce as described above. In addition, no restrictions were imposed on fertilizers. The CO_2 equivalent emission during the disposal phase of leaf lettuce and the production phase of seeds was not considered because it is difficult to collect data.

Inventory data were collected using a bottom-up approach by interviewing farmers (Table 21.2). Inputs were mineral fertilizer (N, P, K), organic fertilizer (N, P, K),

Table 21.1 Farm description

	Farm A	Farm B
Location	Hokkaido	Saga
Area [m^2]	0.32	1
Method	hydroponic	Field-grown
Crop	Green leaf	

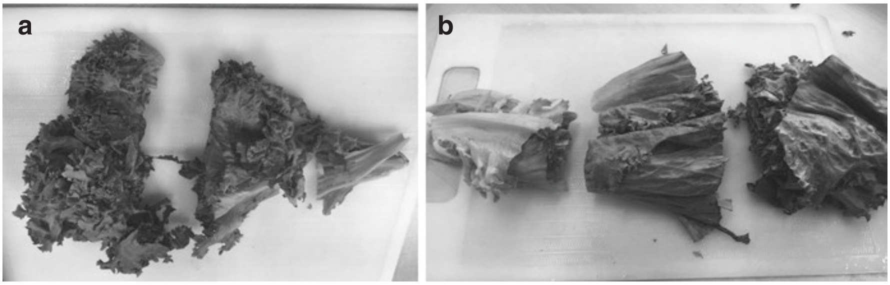

Fig. 21.2 Leaf lettuce grown by (**a**) hydroponic cultivation and (**b**) field-grown cultivation

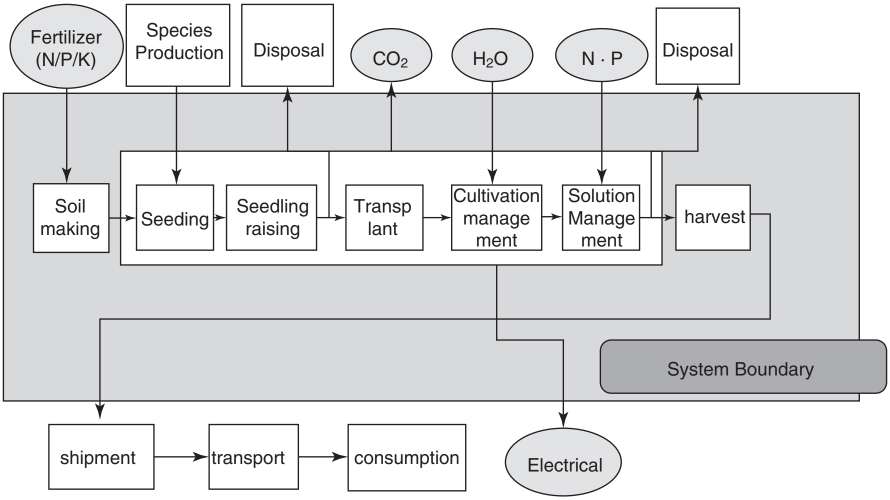

Fig. 21.3 System boundary

Table 21.2 Inventory data

Input	Farm A	Farm B	Unit
Mineral fertilizer (N)	12.5	5.80	kg/m^2
Mineral fertilizer (P)	2.67	4.40	kg/m^2
Mineral fertilizer (K)	15.2	6.20	kg/m^2
Water	3.01e + 3	5.57e + 3	m^3/m^2
Organic fertilizer (N)	0.00	0.02	kg/m^2
Organic fertilizer (P)	0.00	0.00	kg/m^2
Organic fertilizer (P)	0.00	0.00	kg/m^2
Limestone	0.00	7.93	kg/m^2
Electric power	1.06e + 4	0.00	kWh/m^2
Lamp oil	1.25e + 3	0.00	L/m^2
Mineral fertilizer	0.12	0.02	kg N/m^2
Crop residue	0.60	0.00	kg N/m^2

water, limestone, electric power, and lamp oil. For direct N_2O discharge, mineral fertilizer and crop residue were calculated. Fertilizers were used at a much higher rate in hydroponic cultivation, more than double that of field cultivation, but more water was used in field-grown cultivation. Electric power for illumination was used only for hydroponic cultivation. CO_2 intensity units are given in Table 21.3.

The hydroponic farmers used the boiler for the period from November to April each year and the use of 400 L of water on every 20th (Table 21.2). That is, in hydroponic cultivation, there is a work that constantly runs nutrient solution and replaces all of the nutrient solution after a certain period of time. Therefore, we assumed that this was averaged over a year. Because of the regional nature, electricity is listed in Table 21.3 for each location as a comparison.

Table 21.3 CO_2 intensity units

Input	Unit consumption	Unit
Oil	2.8	kg-CO_2 eq/L
Electric power (Hokkaido)	0.68	kg-CO_2 eq/kWh
Electric power (Saga)	0.58	kg-CO_2 eq/kWh
Mineral fertilizer (N)	3.27	kg-CO_2 eq/kg
Mineral fertilizer (P)	2.44	kg-CO_2 eq/kg
Mineral fertilizer (K)	0.44	kg-CO_2 eq/kg
Organic fertilizer (N)	1.15	kg-CO_2 eq/kg
Organic fertilizer (P)	0.86	kg-CO_2 eq/kg
Organic fertilizer (P)	0.15	kg-CO_2 eq/kg
Limestone	0.44	kg-CO_2 eq/kg
Water	0.36	kg-CO_2 eq/m^3
Direct discharge of N_2O	298	kg-CO_2 eq/kg

Table 21.4 Fertilizer composition of hydroponic cultivation (g)

Fertilizer	1	2	Note
Magnesium sulfate	190	–	
Potassium nitrate	120	260	
Calcium nitrate tetrahydrate	–	480	
Monoammonium phosphate	100	–	
Otsuka House No. 5	50		[12]

Table 21.5 Fertilizers used in field-grown cultivation

	N	P	K	Note
Altitude 444	14.0%	14.0%	14.0%	
Marinex	1.12%	–	–	[13]
Neocar	–	0.0001	0.0001	[14]
OKF1	15.0%	8.00%	17.0%	[15]

The composition ratios of fertilizer production are shown in Tables 21.4 and 21.5, respectively. In hydroponic cultivation, each was mixed in 1 and 2 in Table 21.4, and then work to dissolve in water was carried out and used. Among them is Otsuka House No. 5 fertilizer [12]. The proportion of these N, P, and K was used as inventory data. In open-field cultivation, liquid nutrient solution by foliar application was evaluated in addition to fertilizer of high precision No. 444. In this case, the content of N, P, K, and lime may not be able to ignore, so inventory data was used. The CO_2 emission coefficient was obtained by Eq. (21.1) from the carbon content per unit limestone weight of 0.12 [t C/t] and the carbon content per unit dolomite joule of 0.13 [t C/t].

$$C\_Ca = T\_C \times \frac{44}{12} \tag{21.1}$$

C_Ca: CO_2 emission intensity [g-CO_2/g-C].
T_C: carbon content [g-C].

Because large amounts of water are used by hydroponic farmers and for liquid fertilizer dilution by field-grown farmers, this use is reflected in the LCA result.

Finally, because nitrogen has a large global warming potential that cannot be ignored, its emission is calculated from Eqs. (21.2) and (21.3).

$$N_2O \text{ emission} = \text{Fertilizer} \times \text{coefficient} \times \left(\frac{44}{28}\right) \quad (21.2)$$

$$N_2O \text{ emission} = \sum \text{Fertilizer} \times \left(1 - 0.47 - 0.07 \times 0.008\right) \times \left(\frac{44}{28}\right) \quad (21.3)$$

N_2O emission: direct N_2O emission [g-CO_2eq].
Fertilizer: amount of nitrogen in fertilizer [g-N].
Coefficient: emission factor of mineral fertilizer [g].

To calculate CO_2 emissions per functional unit [kg CO_2eq] at the production stage, we first calculated those per unit area [m^2] by multiplying the inventory data (I_i) of input i by the CO_2 emission intensity unit (U_i) (Tables 21.2 and 21.3). Then we estimated those per functional unit by considering the annual lettuce yield per 1 m^2 [kg/m^2]. Note that the moisture change of lettuce was not considered. CO2 emissions were calculated using Eq. (21.4).

$$X_i = \sum_i \left(I_i \times U_i\right) \times k_i \quad (21.4)$$

X_i: CO_2 equivalent emission intensity [g-CO_2eq/piece].
i: Each step.
k_i: Conversion factor to functional unit [1, 50 g; 2, 300 g].

21.2.2 Food Miles

The use of food miles is a way of measuring how far food has traveled before it reaches the consumer and shows the environmental impact of foods and their ingredients [16]. We took food miles to be the environmental load equivalent to the transport distance. The environmental load was calculated when carrying the product with 2-t trucks from each farm to the nearest central wholesale market. We used literature values for CO_2 intensities of trucks [312 gCO_2/t/km] [17]. We used the free Google Map Application Programming Interface (API) to calculate distances. And, CO_2 emissions from transportation were calculated by the Eq. (21.5).

$$D = 2 \times L \times 312 \quad (21.5)$$

D: Food miles evaluation [g-CO_2].
L: Transport distance [km].

21.2.3 Nutritional Quality

We analyzed the contents of dietary fiber, iron, vitamin A, vitamin K, vitamin E, and folic acid in the lettuces. To reflect customer preferences, we surveyed consumers by using an online questionnaire that presented information on these nutrients, and asked “When nutrients are displayed at the time of purchasing lettuce, which nutrient is preferred?” Most of the 200 participants were concerned mostly about dietary fiber when buying leaf lettuce (72 [%] dietary fiber, 8.5 [%] iron, 6.5 [%] vitamin A, 5.5 [%] vitamin E, 5 [%] folic acid, and 2.5 [%] vitamin K). We weighted the results using Eqs. (21.6) and (21.7). We calculated the value factor, using the Japanese meal intake standard (R_i) and Japan food standard value (S_i) of each nutrient i. Then we evaluated the nutritional quality value (LRik) of each type of lettuce k.

$$V_i = \frac{\left(\frac{R_i}{S_i}\right)}{\sum_i \left(\frac{R_i}{S_i}\right)} \tag{21.6}$$

V_i: value factor [−].
R_i: Japanese meal intake standard [−].
S_i: Japan food standard value [−].
i: nutrients [1, dietary fiber; 2, iron; 3, vitamin A; 4, vitamin E; 5, vitamin K; 6, folic acid].

$$LR_{jk} = \sum_i^6 \left(\frac{L_{ik} \times {C_i}/{V_i}}{R_i} \right) \tag{21.7}$$

LR_{jk}: nutritional quality value of each lettuce [−].
L_{ik}: nutrient amount of each lettuce [−].
C_i: consumer preference survey result [%].
k: lettuce by cultivation method [1, hydroponic; 2, field-grown].

21.2.4 Food Safety

To evaluate food safety, we assumed mineral fertilizer [18]. We summed the total quantity of N fertilizer used during production on each farm [kg/m^2] and compared the values. Nitrate-N turns into nitrite by reduction reaction. Nitrite reacts with aliphatic amine to form nitrosamine. It also produces methemoglobin, which decreases oxygen transport by hemoglobin, and may cause methemoglobinemia (blue baby syndrome). In addition, some nitroso compounds are thought to cause cancer, hepatic disorders, and reproductive disorders [19]. There are concerns about how much nitrate-N in vegetables is converted to nitrous acid or nitrosamine and how much these substances contribute to the onset of disease. Although the EU and the USA regulate the concentration of nitrate-N in spinach and owing to the possible health harms [19], no regulation has been established in Japan.

21.2.5 Taste

To evaluate the taste of lettuce, we measured nitrate concentrations. Tastes of vegetables are correlated with "bitterness" and "astringency" [19]. Because the content of nitrate ions differs among portions, it was measured in three equal parts, and the average value was used. Nitrate was measured a nitrate ion meter (Horiba Seisakusho). The actual measured value was divided by the average value (1100 [ppm NO_3^-]) and evaluated by using Eq. (21.8).

$$T = \frac{\sum_{i}^{3} \mathrm{Cal}_i}{1100\left[\mathrm{ppm}\ \ NO_3^-\right]} \tag{21.8}$$

T: taste evaluation [−].
Cal: the actual measured value [−].
i: measured in three equal parts [1, upper parts; 2, central parts; 3, lower parts].

21.2.6 Building the Star Mark Indicator

Finally, we compiled the data of the five indicators. Data were scored at five levels, and the score was plotted on a star mark, ranked from the inside to the outside.

Measured values in each category are shown in Table 21.6, and the delimiter values of the five stages are given in Table 21.7. However, we note that this delimiter value is based on this research, and it can vary depending on the type of vegetables and research method.

For the environmental evaluation, the value was calculated with [g CO_2eq/piece] as a delimiter. Food miles evaluation assumed that each farm's lettuce was delivered

Table 21.6 Evaluation values in each category

		Cultivation	
Indicator	Unit	Hydroponic	Field
Environmental	g CO_2 eq/piece	784	295
Food miles	g CO_2/piece	88,608	30,950
Nutrients	point/piece	3	12
Food safety	g/piece	3	1
Taste	ppm NO_3^-/piece	4019	9500

Table 21.7 Delimiter values of the five stages

Stage	CO_2	Food miles	Nutrient	Food safety	Taste
1	≥8	<10	<4	≥8	≥8
2	<8	<8	<6	<8	<8
3	<6	<6	<8	<6	<6
4	<4	<4	<10	<4	<4
5	<2	<2	<12	<2	<2

to the Tokyo Metropolitan Central Wholesale Market, and we evaluated the environmental load (6.24e + 5 [g CO_2/piece]) at that time as the maximum value. Nutritional quality was based on the delimiter value (1.97 [−]) divided into five equal intervals between the health component value and the normal (1 [time]) obtained by doubling the nutrient value of the Japanese Food Standards [20]. For food safety evaluation, the *N* content [g/piece] was used as it was. For the taste evaluation, the values were calculated as described in Sect. 21.2.5.

21.3 Result and Discussion

We evaluated leaf lettuce grown on each farm according to CO_2 equivalent emissions, food miles, nutritional quality, food safety, and taste. Each of indicators was scored at five levels and plotted on a star mark (Fig. 21.4).

From the viewpoint of environmental burden, hydroponic lettuce (7.84e + 2 [g CO_2/piece]) resulted in about 2.7 times the CO_2 equivalent emission of field lettuce (2.95e + 2 [g CO_2/piece]). Hydroponic lettuce was scored as 1, and that of field lettuce was 4. Air conditioning and lighting in hydroponic cultivation result in a large environmental burden. Hydroponic cultivation also needed excessive fertilizer, making the environmental burden due to direct discharge of N_2O large. The use of solar and geothermal heat could reduce CO_2 equivalent emissions. An optimized fertilizer composition could reduce both fertilizer use and CO_2 equivalent emissions.

For food mile, we calculated by using the distance to the nearest central wholesale place of each cultivation area. Hydroponic lettuce showed a score of 8.86e + 4 [g-CO_2/piece] and 5 point; field-grown lettuce showed a score of 3.10e + 4 [g-CO_2/piece] and 1 point. This result indicates that eating locally grown produce would improve the food miles score. Hence, food miles could also indicate freshness and thus help to reduce food loss. In 2012, the Japanese government instituted a policy to “buy local,” promoting the use of local produce [21].

In the evaluation of nutritional quality, 72[%] of respondents considered dietary fiber the most important nutrient when buying lettuce, but the fiber content of lettuce is far below daily requirement. This preference was consistent across generations. Nutritional quality was evaluated by weighting the actual nutrient contents (iron, vitamin A and E, and folic acid) by the preference survey results. It was higher

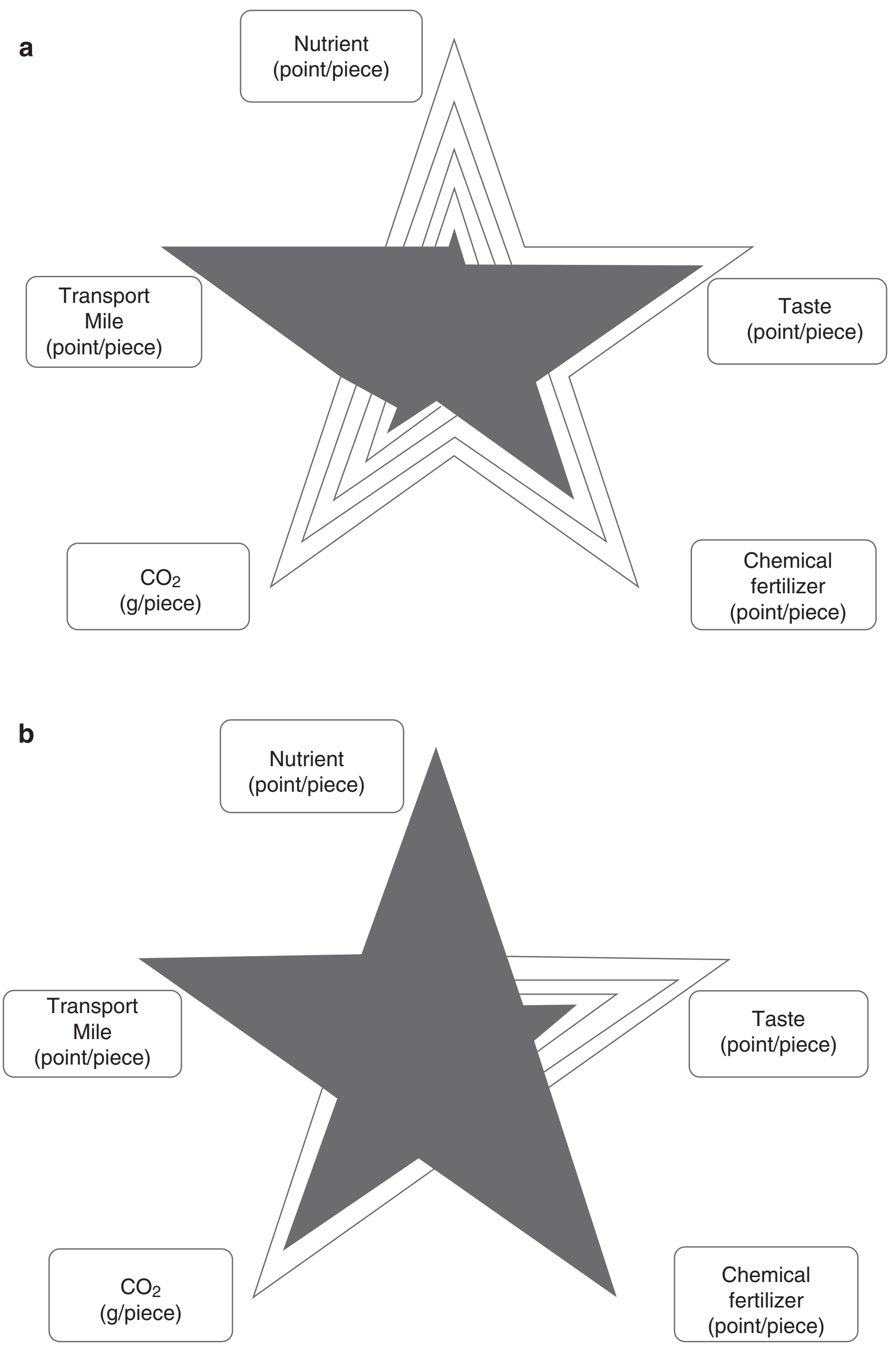

Fig. 21.4 Star mark quality indicators of (**a**) hydroponic lettuce and (**b**) field lettuce

in field lettuce than in hydroponic lettuce. The nutritional quality of hydroponic lettuce was 2.66 [points/piece] (scored 1), and that of field lettuce was 12.0 [points/piece] (scored 5).

Hydroponic lettuce had 2.54 [g N/piece] (scored 3), and field lettuce had 0.84 [g-N/piece] (scored 5). Although the influence of nitrate-N on the human body has been studied for more than 50 years, it is very difficult to clarify its metabolism in the body, and the presence or absence of harms to health by nitrate-N is not clearly understood. However, it is clear that N fertilizer poses risks to human health, and it is necessary to reduce its use on farms.

For the taste component, the content of nitrate was scored 4 for hydroponic lettuce, with 4.13e + 3 [ppm NO_3^-/piece], and 1 for field lettuce, with 9.50e + 3 [ppm NO_3^-]. Unfortunately, fertilizer might influence this measurement. On the basis of these environmental and nutritional indicators, we were able to label two leaf lettuce products (Fig. 21.4a, b). Star marks showed good taste and intense use of mineral fertilizer in hydroponic cultivation and high nutritional quality, low CO_2 equivalent emissions, and low mineral fertilizer use in field-grown cultivation.

21.4 Conclusions and Recommendations

In this research, we proposed index considering the global environment and consumer needs. In this index, we investigated in leaf lettuce with different cultivation methods, evaluated in five items of greenhouse gas emissions, food mile, nutritional quality, vegetable safety, and taste. As a result, it became possible to distinguish products by cultivation method.

Thus, by devising a simple visual tool, it will be possible to approach consumers in any age, and this index can contribute to the development of sustainable agriculture by seeing it more people. As a future task, the important part is to approach this index directly to consumers and reflect opinions. In addition, it is necessary to consider how differentiation among various kinds of vegetables is possible, not evaluation by one kind of vegetables like this time, and how seasonal change affects.

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Chapter 22
How to Create a Business-Relevant LCA

Xiaobo Chen and Jacquette Lee

22.1 Introduction

The combination of legislation, company values and consumer pressure is making sustainability increasingly important criteria for product design. Given that 80% environmental impact is determined in the formative design stages [1, 2], it is especially important to include these aspects early on. From business point of view, sustainable development means adopting business strategies and activities that meet the current economic needs of the companies while maintaining and protecting the natural and human resources that will be used in the future [3]. On one side, the public require environmentally friendly products and services without negative impacts in the current and future world. On the other side, companies need to consider environmental impacts of their products as a competitive and innovative factor, as well as a social and legislative responsibility. Despite a great awareness of sustainability, companies struggle to cost-effectively incorporate all three aspects (economy, environment and society) into their business management that traditionally focuses mainly on an economic perspective.

Environmental aspects of products and services are normally covered by undertaking a life cycle assessment (LCA), evaluating the environmental impacts through the entire product life cycle [4]. Critical environmental impacts can result from any of the stages of the life cycle, from extraction, through manufacture and product use phase, transportation and storage, to final disposal of product (from cradle to grave). Therefore, LCA provides for the managers of companies a wider vision of product innovation opportunities through a close cooperation with different stakeholders. Although many companies have interest in using LCA for knowledge acquisition and marketing purpose, it currently cannot be used directly for marketing decisions. Firstly LCAs, especially detailed LCA which requires amounts of measured data or

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refined reviews from literatures, are time consuming and expensive and produce a wealth of environmental information that rarely provide an absolutely definitive answer, if the indicators have contradicting impact results (with all LCA studies, the answer normally starts with ‘it depends’). Considering the cost and difficulty in capturing data, companies may not have motivation to carry out detailed LCA as one of the primary activities for business management. Secondly, the biggest complicating factor in using LCA during early product design is that much of the required information is not known, and thus many assumptions are made which increase the uncertainty of the results and decrease confidence [5, 6]. Thirdly, although life cycle cost assessment and social LCA have been development with more and more attention [7, 8], the traditional LCA methods only consider environmental impacts, but neither economic nor social impacts are too narrow to be used independently to determine sustainable perspective of a product/service [9, 10]. Hence the benefit of LCA for early design decisions is limited. The alternative to full an LCA is eco-design approach (also known as design for environment or design for X). This is a streamlined assessment requiring less effort for data acquisition and evaluation and utilising a wide range of indicators that are not commonly used in a traditional LCA. The process does, however, still employ the concept of life cycle thinking (LCT) [11, 12].

An eco-design approach considers systematically product performance with respect to environmental, health and safety and social objectives throughout the entire product life cycle [13, 14]. A successful eco-design process should combine environmental performance with stakeholder requirements, so that the environmental issues become the drivers for product innovation, as well as marketing strategy, cost and competition. In contrast to traditional LCA, the choice of indicators and assessment for eco-design is performed in a way that is relevant to business topics, so that managers can readily monitor concerns and make improvements regarding their business purpose. In this paper, we demonstrate this business-relevant life cycle approach and show its application in collecting eco-data according to industrial requirements. Section 22.2 states the industry engagement to identify their business requirements. Section 22.3 introduces environmental indicators according to stakeholder requirements, and Sect. 22.4 describes a matrix-based tool to collect information used to evaluate environmental impacts that are mostly concerned by the industry. Finally, we discuss and conclude our study in Sect. 22.5.

22.2 Industry Engagement

A previous study [15] has engaged with business to determine what data are required by companies in the electronic sector at the early design stage. The aim of that study was to understand what the key factors are that affect the decisions made by industrial companies relevant to their business strategies. Through the questionnaires and interviews with industry stakeholders, it was found that product performance and consumer demands were considered as the top factors that determine product decision making. With regard to environmental aspects, three categories were identified: climate change, energy consumption and water use. Human health and environmental toxicity were also assessed but were normally effectively dealt with via risk management, rather than through a LCA-type process.

Based on this feedback from industry stakeholders, it suggested that the future LCA to product evaluation should change from such traditional environmental assessment to one that should consider both product performance and customers' demands, with a limited but more focused set of environmental impact categories.

22.3 Business-Relevant Indicators

In this paper, we define indicators used to evaluate the properties of materials and compare the performance of alternative materials in aerospace industry from environmental point of view. These indicators (plus an additional category—reduction in greenhouse gases) were developed by the ADS (Aerospace, Defence, Security and Space) Design for Environment working group [16]:

1. Easy access to resources—material criticality.
2. Reducing energy consumption.
3. Reducing waste generation.
4. Efficient water use.
5. Recyclability and reusability.
6. Reducing greenhouse gases (GHG).

22.3.1 Easy Access to Resources: Material Criticality

A reliable, sustainable and undistorted access to certain key raw materials is of growing concern across the world [17]. It is thus important to identify the materials within the value chains where there are significant risks arising from two main dimensions: economic variance due to price volatility (temporal and spatial) and potential interruptions in supply chain [18], and a material is considered critical for businesses when it has high economic importance and high supply risk.

Apart from business risk, access to resources also relates to environmental issues, such as depletion of natural resources and irreversible damage to ecosystem through extraction activities. In addition, the extraction and processing activities are energy intensive and produce significant amounts of emissions, which can pollute air, soil and water.

Therefore, consistent data fed into criticality assessment is needed to manage material risks effectively and support the development of effective policies and strategies for the benefit of economy and environment.

22.3.2 Reducing Energy Consumption

Energy consumption is defined as the amount of energy consumed during the life cycle of products. Increasing demand for energy requires energy efficiency at each life cycle stage. There is a need to safeguard business continuity from risks such as potential increasing energy costs, energy dependencies and interruptions in supply. In terms of environment, the emissions during energy use have both direct and indirect environmental impacts, such as climate change, resource depletion and damage to ecosystem.

Therefore, reducing energy consumption and promoting efficient use of energy are considered as key factors to achieve a sustainable business.

22.3.3 Reducing Waste Generation

Waste is defined as the amount of solid, liquid and gaseous residues, which are not retained as part of the final products, generated during the life cycle of products and services. Higher environmental standards and requirements for green products enforce business to develop cost-effective management of waste [19]. The generation of wastes represents both business and security risks due to significant cost and heavy regulations for waste management and disposal. So the more wastes are generated, the more companies have to pay for materials to use. Additionally, the companies have to pay to deal with wastes, and that cost will be higher if wastes are hazardous to natural environment or human health. So in terms of environment, hazardous waste emissions contribute to ecosystem damage and human health issues. Over-release of wastes into the environment may lead to the degradation of natural environment and loss of resource for the future generation.

Therefore, reducing wastes enables to save production costs and decease the environmental impacts as well as improve the efficiency of resources use. Moreover, the development of innovative transition from wastes to useful by-products has potential to create additional value to production system.

22.3.4 Efficient Water Use

Water use is defined as the abstraction, supply and consumption of water throughout the life cycle of product. Water is a vital resource to support industrial manufacture and human health. Increasing industry demand and growing population could affect the availability and supply cost of water for both current and future circumstances, which leads to a risk to business continuity. Water has local environmental impacts that are influenced by various factors, such as the sources of water, the rate of abstraction (overabstraction of water can result in shortage of water and local environmental degradation, which may lead to social conflict) and the treatment of water.

Therefore, companies have interest in developing an effective approach to manage water risk and account for water use towards resource-efficient economy.

22.3.5 Recyclability and Reusability

Recyclable and reusable materials or product components can be recovered at the end of life and re-enter into industrial flow to become parts of new product chains. Increasing demands for materials and large pressure on reducing the environmental impacts of raw material extraction have a long-term influence that can affect the stability of material supply, a key aspect of business continuity. Recovering materials and product components can help business to prevent loss of materials, reduce supply risks and minimise costs for production and disposal. In environmental terms, recycling and reusing materials can (in appropriate circumstances) reduce the environmental impacts associated with raw material extraction and waste treatment at the end of life.

Therefore, business needs to understand the recyclability and reusability potential of their currently used materials and components.

22.3.6 Reducing Greenhouse Gases

The GHG are the primary cause of global warming. Concern over climate change has promoted the development of policies to reduce GHG and encourage the creation of a low-carbon economy [20, 21]. At a company level, declaration of companies' GHG emissions at the product level is no commonplace and indeed expected.

22.4 Business-Relevant LCA

To achieve an environment-friendly product or service, business should aim to provide an innovative product with that meets the required performance, as well as minimum negative impact on the environment over the entire product life cycle. To support this, a matrix-based tool to identify necessary key information for typical life cycle stages of manufactured product, in order to meet these six aspects above, is used. This approach aims to support business strategy with more relevant environmental information based on the perspective of LCT. Meanwhile, data collection will be more time- and cost-effective, since the effort only focuses on a limited set of categories in which the business has more interest. The categories used in this paper are derived for the specific case of the aerospace sector. It is likely that other industry sectors will define different key indicators.

This matrix has been generated by linking and cross-checking the identified business-relevant indicators with the five life cycle stages (Table 22.1). For each stage, general information has been included to describe the characteristics of materials extracted or used, such as mass or volume. The following sub-sections explicit how to use checklist to identify the key information for each life cycle stage.

22.4.1 Extraction of Raw Materials

In the first stage of product life cycle, information is most closely related to criticality of materials because of its direct effect on business continuity.

- Supply risk: as one of the important indicators to evaluate material criticality, the European Commission applies a method using four metrics to evaluate supply risk. Substitutability index measures the flexibility to change materials, recycling input rate indicates the recycle potential of materials which is also as key information for recyclability and reusability, world governance indicator considers political risk from the suppliers of unstable countries, and factor of concentration relates to the availability of natural sources [17, 18].
- Economic importance: the economic variance (price volatility) of raw materials has significant influence to the material criticality. Combined with supply risk, the European Commission defines a list of critical materials at EU level [17].
- Efficiency of material extraction is considered as key information. It links to the quantity of resources needed to meet manufacture demand. Therefore, improving extraction efficiency can reduce loss of natural resources extracted from the ores to save costs for materials used.
- As the three important environmental indicators, embodied energy consumption, GHG emissions and water usage cover the extraction process and its associated waste generation.
- Waste generation includes the type and quantity of wastes generated during the extraction, while its environmental information is already accounted previously.
- Legislative information: apart from the risk due to the criticality, other environmental or toxicity risks should be noticed according to local or global legislations and regulations. For example, the EU REACH regulation identified substances of very high concern (SVHC) and put on the 'candidate list for authorization' [22]. The manufacturing companies should ask and record this information from their suppliers.

Table 22.1 Example of information checklist for business-relevant LCA

Life cycle stage	Information requirement	Access to resource	Energy consumption	Water use	Recyclability/ reusability	Waste management	Climate change
Extraction of raw materials	Supply risk	X			X		
• Material extracted	Economic importance	X					
• Wastes generated	Extraction efficiency	X	X				
	Embodied energy		X				
	GHG emissions						X
	Water usage			X			
	Waste generation					X	
	Legislative requirements	X					
Manufacture	Efficiency of materials used		X	X		X	
• Materials used	Embodied energy		X				
• Production process	GHG emissions						X
• Consumable materials	Water usage			X			
• Wastes generated	Waste generation					X	
Product use phase	Embodied energy		X				
• Usability of product	GHG emissions						X
• Wastes generated	Water usage			X			
• Repair and maintenance	Waste generation					X	

(continued)

Table 22.1 (continued)

Life cycle stage	Information requirement	Access to resource	Energy consumption	Water use	Recyclability/ reusability	Waste management	Climate change
	Lifetime of use	X			X		
	Components for repair service	X			X		
End of life	Embodied energy and recovery		X				
• Recycle/reuse	GHG emissions						X
• Landfill	Water usage			X			
• Remanufacture	Recycling/reuse rate				X		
• Combustion							
Distribution	Transport characteristics		X				X
• Transport	Packaging mode		X		X	X	X
• Packaging	Packaging materials	X			X	X	

22.4.2 Manufacturing Process

The materials extracted are used through different production processes at this stage. Consumable materials are defined as materials used in production processes, but do not form any part of the final product. Additionally, wastes are generated.

- Efficiency of materials used: an effective use of materials can reduce the natural resource demand (e.g. materials, water) and waste generation and save energy consumption.
- The information of embodied energy consumption, GHG emissions, water usage and waste generation are collected and identified for each process of this stage.

22.4.3 Product Use Phase

The product use phase includes usability of the product, waste generation and processes or components used to repair and maintain the function of product during its use. The information of embodied energy consumption, GHG emissions, water usage and waste generation are collected and allocated to each part of the stage. Lifetime of use refers to the durability and recyclability of materials. The information of components used for repair service can also be linked to natural resource demand (access to resource) and reusability potential of product.

22.4.4 End of Life

The disposal of product at the end of its life has diverse destinations. Some parts of product can be recycled, remanufactured and reused back to the industrial flow. Otherwise, some parts of product can be treated in landfill or incinerated for energy recovery. According to different ways of treatment, the environmental data is collected, such as energy consumption and recovery, GHG emissions and water usage. The recycling/reuse rate is a key factor to evaluate the efficiency of recyclability or reusability. As mentioned in Sect.22.4.1, the more materials are recycled for remanufacture, the less raw materials are needed from the extraction.

22.4.5 Distribution

This stage contains the transportation and packaging of both materials to manufacture and assembly facility and products to customers. The transport characteristics, including transport mode, distance and frequency, offer an opportunity to minimise environmental impacts and prevent hazardous risk. The mode and materials used for both product and transport packaging should be collected, which help the designers to reduce the packaging stages and minimise environmental impacts and risks due to the use of hazardous materials.

Once the checklist is completed and validated, a targeted investment in capturing data will be more efficient and inform further quantitative assessment when data is available. In addition, the checklist identifies the data gaps that will trigger uncertainty and sensitivity analysis to estimate their influences to final results.

22.5 Discussion and Conclusion

The eco-design approach based on LCT integrates environmental consideration into the existing product design process. It corresponds to the expectation of business, which needs to develop useful and effective environmental indicators to support their business strategy. A systematic eco-design approach offers opportunity to optimise product performance over the entire product life cycle, as well as any specific stage or aspect. For example, designers can focus on energy efficiency during the manufacture (i.e. design for energy efficiency) or using recycling materials to lower the raw material requirement (i.e. design for recycling). Our matrix-based tool offers flexibility to fit different eco-design strategies; the required information can be defined for different life cycle stages according to diverse business objectives.

Business expects to use some form of environmental assessment to improve product performance, with the aim of increasing market share. Although the interpretation of different environmental indicators of LCA can help business to learn more about their product or system at the environmental viewpoint, it is hard to draw an overall conclusion when several indicators give conflicting information. By contrast, the information provided by eco-design approach do relate well to business management that meets the needs of different stakeholders. Thus, business is encouraged to collect such information within and outside of an institution, which enhances the cooperation among the stakeholders. However, given that it is highly likely that the result is a multicriteria comparison between the products, designers should set priority orders of criteria including cost, social and environmental factors. When comparing products, the smaller set of indicators defined by the eco-design approach are much more specific and practical (may be less informative than detailed LCA) for preceding a new product design comparing with the older product.

Today, the companies are seeking for an effective way to integrate LCA into their business management, while the large cost for data acquisition and strict requirement of data reliability limit the adoption of LCA in business strategy. It seems that companies prefer to implement more simplified assessment based on LCT that can reduce costs and efforts for capturing data [9, 23–25]. Therefore, refining the data capture process is of critical importance in product innovation for sustainability, especially at the early design stage of industry where there are limits of data availability, transparency and reliability. This qualitative eco-design approach is much more readily used than a quantitative LCA and enables the designers to focus on more targeted information associated with business strategy of the company. The identification of key environmental information will trigger a detailed LCA, when it becomes necessary to quantify the environmental impacts.

This matrix-based tool is a preliminary framework for data capture, and an improved version should combine with data quality evaluation tools to carry out uncertainty analysis. This is because uncertainty about the quality of the information is useful for decision makers as well as information itself. Confidence in data can be defined and assigned quality scores associated with collected information. Such a scoring approach evaluates data quality (generally, but not exclusively) based on expert judgement and will be determined differently in the different business areas and industry sectors. Therefore, this matrix-based approach offers a possibility to develop a mixed data capture and evaluation tool in the future, which will help the managers to manage environmental data and its associated uncertainty.

In conclusion, we demonstrate the role of eco-design approach in business strategy and how to integrate environmental information within other business-related aspects (e.g. cost and benefits, product performance and environmental risks). The matrix-based tool provides a cost-effective way to gather targeted information over the product life cycle, so that the communication among various stakeholders can be more appropriately involved in product development and business management. It is a practical and proactive approach for product innovation used at the early stage of product development where few data are available to carry out quantitative environmental assessment, such as detailed LCA. Moreover, data gaps can be identified through information capture process, and new methods for filling data gaps should be developed.

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Chapter 23
An Approach for Establishing Eco-Product Value Indicators

Chen-Fu Chen

23.1 Introduction

As the concept of product value is often intuitive and emotional, measuring the value of a product has always been a challenging issue. The term "eco-value" is mainly defined from the perspectives of technical evaluation on the market and environment. However, other factors related to the creation of eco-products should not be overlooked, such as product aesthetics, functionality, and the consumer's expectations/perceptions. Whether a product is environmental or not is largely dependent on consumers' perception or feeling. However, little studies have been specifically focused on consumers' perception of eco-product design in terms of aesthetics, function, and environmental considerations, all at once. To fill in this gap, this study develops a new model for evaluating the value of eco-products as perceived by consumers, especially in the circular economy.

A review of various environmental analysis methods and tool application shows that potential approaches and the functional/technical aspects of the product have gained considerable progress in terms of reducing environmental impacts. These methods have shown their advantages mainly from the perspectives of engineering and management. In addition, very often in eco-product design, one has to make a selection between design alternatives, such as product aesthetics and environmental consideration. Although some sound environmental products are available in the market, there is still a lack of environmental information perceived by the consumer in terms of product life cycle as well as product-specific indicators, such as energy consumption and saving, carbon dioxide (CO_2) emission, disassembling, and material recycling.

In this study, aesthetics, function, and environment from the consumer-oriented design perspective are to be integrated by their associated indicators to represent the

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value of eco-products. The sustainable development of eco-products aims at reaching a compromise among these three distinctive dimensions, on which their value should be based. For example, the value of an office chair with environmental labels may be manufactured using recycled material. Especially, the appearance of eco-products may not be good-looking compared to regular ones. Indeed, it is necessary to develop promising methods for measuring consumers' perception in quantitative terms, which can be used to justify design decisions under trade-off situations in the new eco-product development. However, there may be a need for establishing an eco-product value indicator which can help consumers perceive the value of eco-products in the circular economy.

23.2 Literature Review

23.2.1 Sustainability and Eco-Products

Manufacturer responsibility or product stewardship is taking the manufacturing industry into a new era where manufacturers are considering the environmental impacts of the product at every stage of its life cycle from the extraction of raw materials to the end-of-life disposal. For example, office furniture manufacturers are making products from renewable and recycled materials and reducing toxins in chair frames, upholstery, carpet, flooring, and adhesives through the manufacturing process.

Figure 23.1 shows some claimed eco-product examples produced by office chair manufacturers, such as recycled resin table, office chair, desk, partition, and lighting. Using recycled material has been emphasized commonly through the product development process, while CO_2 emission is more focused in recent years. For example, consumers may find the quantitative information of CO_2 emission in the recent eco-product market. Typical environmental indicators are listed on various consumer guides, recyclability, recycled content, fuel efficiency, toxic content reduction, carbon emission, and others. Many eco-products come with environmental labels that state product features to inform and appeal to consumers.

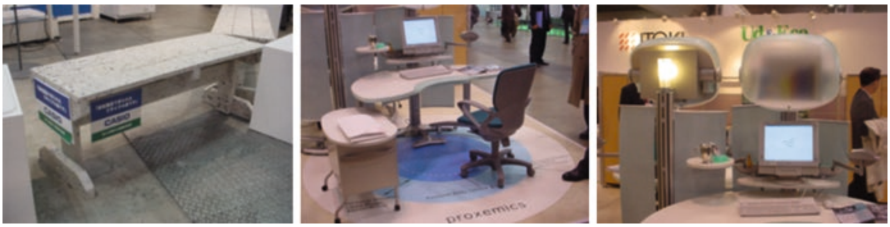

Fig. 23.1 Office furniture as eco-products in an international eco-product exhibition

23.2.2 Eco-Product Value Indicators

Value is more complex in business markets due to various consumer segments. In other words, consumers' perception of value reflects how they perceive and evaluate the beneficial indicators for product.

Furthermore, Stevels [1] indicates the role of eco-design is to maximize the value for consumers, while value here is defined as the price paid by consumers. He mentions that traditionally value has two functionality dimensions: physical functionality and economic functionality (cost of ownership). Two other types of functionality are more emphasized for influencing consumers' buying decisions, which include intangible functionality (health and safety, convenience, fun) and emotional functionality (quality, feel good, nice design, recyclable). However, an increasing group of consumers have intangibles and positive emotions as their priority. Eco-value defined in this study is the ratio between life cycle cost and environmental load.

Masuda [2] claims that we have other measures of value in our culture and aesthetic sense. For example, the pleasure we take in using natural materials, the quality we find in glass and ceramics despite the fragility of these products, and the value we see in items in which history is engraved or inscribed are all different measures of value than what we find in modern industrial civilization. Because this concept of value is often intuitive and emotional and hard to quantify, it has purposely been neglected in the design of products, which should be emphasized as seeking sustainable design of products that provide "eco-value."

Yim and Herrmann [3] have introduced the eco-means-end chain which has four levels: indicators, functional sequence, psychosocial consequences, and values. This methodology tries to link tangible product indicators to functional and psychosocial consequences and in turn to more abstract and personal values and goals. In a sense, the original function should be primarily well fulfilled; otherwise, consumers may think negative about the product no matter how good the environmental benefit is. Yim and Herrmann propose that the concept of "value" suggests a higher level of human needs such as self-esteem, fashion, and happiness fulfilled by eco-products.

The concept of "eco-value" has been used increasingly for eco-products and services in terms of technical and financial evaluation. The environmental awareness has been emphasized increasingly to eco-products for pursuing the lower environmental impact than traditional products, while eco-products have been criticized for being less attractive in terms of aesthetic awareness and functional quality to consumers.

This study has proposed a conceptual framework of "eco-product value (EPV)" which consists of three evaluation dimensions obtained from the literature review and expert interview. An EPV is a combined value of product aesthetic, functional, and environmental dimensions, which will be regarded as the factors for evaluating the value of eco-products. The concept of EPV can be a holistic view integrating different perspectives such as design, engineering, and environment, which can be evaluated by consumers in terms of EPV indicators. However, not all of EPV indicators may be perceived directly by consumers due to the unknown information, such as the manufacturing technology and process, technical quality, cost, and energy consumption. The price and quality can be measured objectively, whereas the aesthetic, functional, and environmental dimensions are to be assessed subjectively by consumers and experts. That is, both price and quality have been embedded explicitly in the consumer perception. Hence, price and quality dimensions are not considered in this research.

Each evaluation dimension may provide a way for increasing value perceptions, such as reducing environmental loads, decreasing consumption, increasing functional quality, and evoking perceptions of relevant aesthetics to signal value. These indicators may delineate several design strategies for adding value in eco-products. Moreover, the correlation between aesthetic, functional, and environmental indicators of eco-products is still not well established, which can be analyzed through both qualitative and quantitative methods.

This research focuses on consumer-perceived EPV indicators into the mainstream eco-product development process. In this view, an effective eco-design method should improve both the product's environmental performance and the resulting product's performance perceived by consumers in terms of EPV indicators. Thus, eco-product value indicators are emphasized to the systematic indicator analysis approach.

23.3 Methodology

23.3.1 Expert Interview for Extracting EPV Indicators

For extracting EPV indicators and from which they can be perceived visually, expert interviews were conducted by providing a semi-structured questionnaire and Internet phone Skype. Seven male and three female professional product designers with more than 10 years of professional office chair design experience were interviewed. The participated expert was asked to review the listed indicators and ticked these indicators which can represent for each dimension. Then, the participated experts tried to tick indicators which can be perceived visually from the ticked indicators.

To extract EPV indicators for describing the consumer's perception of the office chair image, the following steps were carried out:

Step 1: Collect a set of EPV indicators from the literature and designer interviews.

Step 2: Evaluate the collected EPV indicators using the semi-structured questionnaire.

Step 3: Apply the percentage (50%) rule to the result of semi-structured questionnaire survey obtained at Step 2. Table 23.1 shows all of the proposed EPV indicators and their selection frequency in parentheses based on ten subjects who are professional product designers.

Table 23.1 Fifteen EPV indicators perceived visually by grayscale image, with the selection frequency enclosed in parentheses (based on 10)

		EPV indicator
Aesthetics	Y_1	Harmonious form proportion (8)
	Y_2	Consistent form elements (8)
	Y_3	Fashionable (6)
	Y_4	Timeless style (5)
	Y_5	High cultural reference or identity (8)
	Y_6	Elegant (7)
	Y_7	Form simplicity (9)
Function	Y_8	Comfortable (6)
	Y_9	Stable (5)
	Y_0	Ease of mobility (6)
Environment	Y_{11}	Upgradability and modularity (5) (ease of maintenance, ease of replaceability, and extending product life)
	Y_{12}	Space adaptability (8) (suitable for various office spaces, e.g., large- or small-size spaces, visitor room, or other public areas)
	Y_{13}	Simplicity and minimalism of mechanism (6) (reducing numbers of components and material)
	Y_{14}	Ease of disassembly (5) (shorter process and using simple tools)
	Y_{15}	Harmony with environment (7) (harmonious relationship between the consumer, product, and environment)

Step 4: Determine the representative EPV indicator image and its concise description of the EPV indicators based on design experts' opinions and the visual perception performed at Step 3.

Originally, 8 and 4 indicators are from the aesthetic and functional perspectives, respectively, while 21 indicators are from the environmental perspective. These indicators are all designated to analyze the value of eco-products. For selecting representative EPV indicators from three perspectives, all aesthetic and functional indicators are selected, while 20 environmental indicators are selected with more than or equal a 50% selection rate. Furthermore, the perceivable EPV indicators among all selected EPV indicators are surveyed by these product designers simultaneously, and the results are shown in Table 23.1.

In the dimension of product aesthetics, all eight aesthetic indicators are selected with more than a 50% selection rate. However, the indicator "coincident style of form elements" is not considered for avoiding the similarity with the indicator "harmonious form elements," while the rest seven indicators are chosen from product aesthetics.

Most indicators in the dimension of product function are perceived visually having a lower value; especially the indicator "ease of adjustability" has a value of "1," which can be hardly perceived through visual elements or image. The indicator "stable" is perceived as having a value of "5," which is slightly lower than "comfortable" and "ease of mobility." Thus, the "comfortable," "stable," and "ease of mobility" indicators are chosen for the questionnaire survey.

Interestingly, only 6 out of 20 previous selected environmental indicators are chosen for being perceived visually having a value equal to or above "5." Among these six indicators, both "space adaptability" and "natural material" have the highest value of "8," while "recyclability" is perceived lowest with a value of "1." Other four chosen indicators include "upgradability and modularity," "simplicity and minimum," "ease of disassembly," and "harmony with environment." Due to the fact that real materials used in product samples are all artificial, the indicator "natural material" is removed from the questionnaire survey questions. Totally, five environmental indicators are selected in the dimension of environmental performance. In addition, some environmental indicators are more recessive and would be better provided with details for participants to understand. As such, the indicator description is amended in this dimension as shown in Table 23.1.

We finally selected 15 representative EPV indicators, as shown in Table 23.1, for describing the product EPV indicator images of office chairs. These 15 EPV indicators can be visually assessed for evaluating the consumer's perception of the 27 representative office chair samples. A five-point Likert scale was applied to obtain the assessment value for each EPV indicator image of a given office chair.

Office chairs consist of design elements such as back, seat, armrest, and base that are essential to the functional quality of office chairs and affect consumers' perceptions. In this study, we have presented an experimental study on office chairs to address the issue of different armrest types combined with other design elements of office chairs for achieving the desirable consumers' feeling, applying morphological analysis, Kansei engineering, and neural network (NN) techniques. The experimental result has demonstrated that the NN model is an approach for modeling consumers' feelings of office chairs.

This study has shown the advantages of using these techniques for examining how the armrest type of an office chair will affect consumers' feelings of the office chair. For example, office chair designers should consider using the "none" armrest type on office chairs in order to best match the consumers' feelings of very "aesthetic," "functional," and "environmental" value indicators. The result of this study provides useful insights in helping office chair designers design eco-products that meet consumers' preferable perceptions.

The NN model links consumers' perception of EPV indicator images with eco-product form elements, which can be used to build a design support database for supporting product form design decisions. In actual design settings, eco-product indicators may be given different weights by designers, since there may be different degrees of importance in meeting specific design objectives. In this regard, a multi-criteria decision-making (MCDM) approach can be used for determining the optimal value of eco-product form element combination with given weights of eco-product EPV indicators.

23.3.2 Experimental Samples

The office chair is a general consumer product and exhibits wide variety in product form with various visual structures. In this study, a set of office chairs is selected as eco-product (environment-friendly product) sample, from which part of them may apply environment-friendly technology and be entitled environmental labels. However, consumers can hardly distinguish general products from eco-products due to complex criteria, such as recycled material, reuse, assembly and disassembly, and waste management. Environmental indicators in a product seem to be a positive addition in products, but it should not conflict with primary functionality and aesthetics. Thus, this study assumes all product samples are eco-products with varying levels of technical and environmental consciousness.

To identify the commonly used form elements of office chairs in the market, we first selected 100 office chairs of various makers and models. The pictures of product samples are all treated in grayscale for avoiding interruption from color and texture. Twenty subjects were invited to classify these 100 office chairs based on their similarity degree, using the KJ method. The KJ method classifies ideas, concepts, or objects into several groups by their similarity degree. It has been successfully applied to a variety of classification problems. We then performed the multidimensional scaling analysis and the cluster analysis based on the classification result obtained from the 20 subjects. This result was then used to extract the 27 representative office chair samples as shown in Fig. 23.2 from hierarchical cluster analysis.

Fig. 23.2 27 extracted product samples

23.3.3 Measuring Relative Importance of Eco-Product Value Indicators

In a product design process, designers often rely on intuition and/or past design experiences due to lack of the conceptual tools for problem-solving. The few that theorize how product design affects/reflects our values and sense of product often focus on our sensual experiences of products.

For the support of establishing business strategy and management decision-making, some product design evaluation methods have been applied to establish product design elements through quantitative numerical analysis. By the way, design support models have been developed. They have been applied successfully in the product design field. For example, some studies have developed approaches for translating the consumer's perceptions of product image into product design form elements through using gray relational analysis model, Kansei engineering, morphological analysis, fuzzy logic, and neural network (NN) models.

This study focuses on the integration of consumer-perceived EPV indicators into the product development process for all eco-products. Based on this view, an effective eco-design method should improve both the product's environmental performance and the resulting product's performance perceived by consumers in terms of EPV indicators.

23.3.4 Questionnaire Design for Consumer Perception of EPV Attributes

The result of expert interview with semi-structured questionnaire survey indicates 15 EPV attributes which can be visually perceived and assessed for evaluating the consumer's perception of the 27 representative office chair samples. A five-point Likert scale ("1" as strongly disagree and "5" as strongly agree) is applied in an online questionnaire to obtain the assessment value for each EPV indicator of a given office chair. Then, the formal questionnaire is developed and put on a questionnaire survey website "my3q." Considering the load for answering 15 questions with 27 office chair samples, 3 groups of experimental product samples are constructed with 9 samples for each group. The order of the samples is randomly arranged for considering the reliability of answering questionnaire by 40 subjects. However, a total office chair sample picture is provided in the beginning of the questionnaire for the participants to perceive and compare as possible before answering the questionnaire with nine samples each group.

23.3.5 Evaluating Eco-Product Value Indicators with Multi-Criteria Decision-Making

Eco-product design planning and decision-making is often based on vaguely structured information. Decision problems within eco-product design are often less-structured because of the technical and natural attributes as well as the often conflicting objectives to be considered. In this context, decision analysis is strongly recommended to assist eco-product designers (as decision-makers) in problem-solving. For exploring the comparative relationship between the EPV indicators perceived by consumers, this study combines multi-criteria decision-making (MCDM) and other research analysis methods for evaluating EPV indicators in supporting design decisions in a new eco-product development process.

MCDM is a methodology that aids the decision-maker in making preference decisions (e.g., assessment, ranking, selection) over a finite set of available alternatives characterized by multiple, potentially conflicting attributes. It provides a formal framework for modeling multi-criteria decision problems, in particular when the nature of the problem demands a systematic analysis, such as the complexity of the decision, the regularity of the decision, and the significant consequences.

23.3.6 EPV Ranking with MCDM

In this study, subjective weights of both EPV dimension and indicator importance are obtained by the average weight given by product designers.

The EPV ranking problem involves a set of m alternatives (office chair design alternatives) A_i ($i = 1, 2, \ldots, m$). These alternatives are to be assessed by a cardinal scale with respect to a set of EPV n indicators C_j ($j = 1, 2, \ldots, n$), via consumer-oriented experiments. The result of the evaluation forms a decision matrix, where rows and columns indicate m design alternatives and n EPV indicators, respectively, given as

$$X = \begin{bmatrix} x11 & x12 & \ldots & x1n \\ x21 & x21 & \ldots & x2n \\ \ldots & \ldots & \ldots & \ldots \\ xm1 & xm2 & \ldots & xmn \end{bmatrix} \tag{23.1}$$

where x_{ij} are the performance ratings of design alternative A_i ($i = 1, 2, \ldots, m$) with respect to EPV indicators C_j ($j = 1, 2, \ldots, n$). A weighting vector representing the indicator weights is to be given by a cardinal scale as

$$w_j = \left(w_1,,,w_2,,,\ldots,,,w_n\right) \quad (23.2)$$

where w_j is the weight of the EPV indicators C_j ($j = 1, 2, \ldots, n$).

Cardinal weights are usually normalized to sum to 1, in order to allow the weight value to be interpreted as the percentage of the total importance weight. The cardinal values given in the decision matrix and the weighting vector represent the absolute preferences of the decision-maker. The objective of the EPV ranking problem is to rank all the design alternatives in terms of their overall EPV preference value.

Based on the concept of the degree of optimality, the overall preference value of a design alternative is determined by its distance to the positive ideal solution and to the negative ideal solution. This concept has been implemented by a widely used MCDM method called the technique for order preference by similarity to ideal solution (TOPSIS) [4] and has been applied widely under different decision contexts [5].

The advantages of using this concept have been highlighted by (a) its intuitively appealing logic, (b) its simplicity and comprehensibility, (c) its computational efficiency, and (d) its ability to measure the relative performance of the alternatives with respect to individual or all evaluation criteria in a simple mathematical form. Hence, all design alternatives are compared with the positive and negative ideal solutions rather than directly among themselves.

23.3.7 Expert Interview for Extracting Weights of EPV Indicators

After the NN model is developed, this research conducts sensitivity analysis to investigate the robustness of the NN model. As such, this study conducts expert interview for extracting weights of the office chair EPV indicators. The following steps were carried out:

Step 1. Seven office chair designers, each one with more than 10 years of experience, are invited to participate in this study task. The email and Skype are used for communicating and providing data.

Step 2. Develop an EPV weight table with no default weights for 3 categories and their 15 attributes. Office chair design experts are provided with an EPV table with dimensions and their indicators. Product design experts are asked to give weights to three dimensions (z_k) and their 15 indicators (c_j), which are scaled from 1 to 9 based on the importance of each dimension and attribute.

Step 3: Calculate the final normalized weight $w_j^{'}$ for each attribute by multiplying the average weight (w_j) of each attribute (c_j) and its respective average dimension weight (z_k). The weights for all EPV indicators collected from the office chair design experts.

Some experts have made qualitative comments to the weight for dimensions and indicators which can be taken into consideration in the design process. For example, in office chair business, functional attributes especially "comfortable (c_8)" can be the top priority; thus, the weight for the dimension of "function (z_2)" can be increased compared to "aesthetics (z_1)" and "environment (z_3)" dimensions. "Environmental" indicators may be additive criteria and reinforced, while functional and aesthetic indicators are the key priorities when designing eco-products for the global market.

23.3.8 TOPSIS Method for Design Decision-Making Based on Combination of Design Elements

In this study, 960 design alternatives ($i = 1, 2, \ldots, 960$) are generated from the NN model (generating design alternatives based on samples automatically through NN software), while 15 EPV indicators C_j ($j = 1, 2, \ldots, 15$) are categorized into aesthetic, functional, and environmental dimensions.

In the context of this study, the procedure of the TOPSIS technique can be described in the following six steps:

Step 1: Obtain normalized attribute weights of EPV attributes.

We interview 7 office chair design experts for giving weights to 3 dimensions (z_k) and their 15 attributes (C_j), which is scaled from 1 to 9. The average weight for each attribute is generated and multiplied with its respective average dimension weight. The value can be calculated by

$$Ykj = zk \times wj$$

where if $k = 1$, then $j \in \{1,2,3,4,5,6,7\}$;
$k = 2$, then $j \in \{8,9,10\}$; and.
$k = 3$, then $j \in \{11,12,13,14,15\}$.

$$X = \sum_{j=1}^{7} Y_{1j} + \sum_{j=8}^{10} Y_{2j} + \sum_{j=11}^{15} Y_{3j}$$
$$w_j^{'} = \sum_{j=1}^{7}\left(\frac{Y1j}{X}\right) + \sum_{j=8}^{10}\left(\frac{Y2j}{X}\right) + \sum_{j=11}^{15}\left(\frac{Y3j}{X}\right) \quad (23.3)$$

where $w_j^{'}$ is the normalized weight of the jth attribute and $\sum_{j=1}^{15} w_j^{'} = 1$.

Part of the result shows the average weight ($w1$) for "harmonious form proportion" (Y_1) is 7.29 and "aesthetics" dimension (z_1) is 7.57. The normalized weight ($w_1^{'}$) is 7.29 × 7.57/738.45 (X) = 0.07. Normalized weights for Y_2 to Y_{15} are 0.07, 0.07, 0.06, 0.05, 0.06, 0.05, 0.08, 0.08, 0.05, 0.08, 0.06, 0.09, 0.07, and 0.07, respectively.

Step 2: Calculate the weighted normalized ratings.

In this study, each attribute is measured on the same scale, and the predicted rating value is directly used. The weighted normalized value of r_{ij},v_{ij}, can be calculated by

$$v_{ij} = w_j^{'} r_{ij}, i = 1,2,\ldots,960; j = 1,2,\ldots,15 \tag{23.4}$$

A decision-making matrix is established by multiplying weights by ratings.

Step 3: Determine the positive and negative ideal alternatives.

The ideal alternative is a hypothetical alternative in which all attribute values correspond to the best level. On the contrary, the negative ideal solution is also a hypothetical alternative in which all attribute values correspond to the worst level. The ideal alternative, A^*, and the negative alternative, A^-, are denoted as

$$\begin{aligned} A^* &= \left\{v_1^*, v_2^*, \ldots v_j^*, \ldots, v_n^*\right\} \\ &= \left\{\left(\max v_{ij} \,|\, j \in J_1\right), \left(\max v_{ij} \,|\, j \in J_2\right) | i = 1,2,\ldots,960\right\} \end{aligned} \tag{23.5}$$

and

$$\begin{aligned} A^- &= \left\{v_1^-, v_2^-, \ldots, v_j^-, \ldots, v_n^-\right\} \\ &= \{\left(\min v_{ij} \,|\, J \in J_1\right), (\max v_{ij} \,|\, J \in J_2) | i = 1,2,\ldots,960\} \end{aligned} \tag{23.6}$$

where J_1 is a set of benefit attributes and J_2 is a set of cost attributes.

Since all the chosen attributes are of benefit (the higher, the more preference), the positive ideal alternative consists of the largest value of each attribute. In this research, A^*= (0.286, 0.252, 0.306, 0.241, 0.185, 0.234, 0.202, 0.338, 0.337, 0.207, 0.285, 0.242, 0.395, 0.309, 0.255).

The smallest values of each attribute make the negative ideal alternative. That is,

A^- = (0.116, 0.111, 0.108, 0.107, 0.095, 0.106, 0.105, 0.125, 0.126, 0.103, 0.181, 0.105, 0.179, 0.135, 0.155)

Step 4: Calculate the separation measures.

The separation (distance) between design alternatives can be measured by the n-dimensional Euclidean distance. The separation of each design alternative from the ideal alternative, S_i^*, is given as

$$S_i^* = \sqrt{\sum_{j=1}^{15}\left(v_{ij} - v_j^*\right)^2}, i = 1,2,\ldots,960 \tag{23.7}$$

Similarly, the separation from the negative alternative, S_i^-, is given as

$$S_i^- = \sqrt{\sum_{j=1}^{15}\left(v_{ij} - v_j^-\right)^2}, i = 1,2,\ldots,960 \tag{23.8}$$

Step 5: Calculate EPV value for each design alternative.

$$\mathrm{EPV}_i^* = S_i^- / \left(S_i^* + S_i^-\right), i = 1, 2, \ldots, 960 \quad (23.9)$$

Clearly $\mathrm{EPV}_i^* \in [0, 1]$, as $S_i^* \geq 0$ and $S_i^- \geq 0$.

Step 6: Rank design alternatives by their EPV_i^* value for EPV attributes.

The result shows the design alternative number 559 is ranked highest as an optimal combination of office chair for elements with EPV_i^* value of 0.8009 followed by 0.7901 (No. 719) and 0.7660 (No. 539). Then, the form of the design alternative with highest score can be identified.

23.4 Conclusion

To address the eco-product design decision problem, this study has developed a new approach applying several methods especially NN and TOPSIS. Hopefully, EPV indicators can be illustrated by an eco-friendly label or index with scales for consumers in the market, which is just like energy consumption (e.g., water, electricity, gas) grading to home electronics. The result of this study shows EPV indicators can be identified and calculated through a more objective and scientific process.

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Correction to: Component Recoverability Analysis in Product Design Using System Dynamic Modelling

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Dr. Nur Shafieza Riwayat's name had been misspelt in the original version of the book in chapter 10. The author's name has now been corrected.

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