Smart Innovation, Systems and Technologies 155

Peter Ball
Luisa Huaccho Huatuco
Robert J. Howlett
Rossi Setchi *Editors*

Sustainable Design and Manufacturing 2019

Proceedings of the 6th International Conference on Sustainable Design and Manufacturing (KES-SDM 19)

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Foreword

For over a decade, the mission of KES International has been to provide a professional community, networking and publication opportunities for all those who work in knowledge-intensive subjects. At KES, we are passionate about the dissemination, transfer, sharing and brokerage of knowledge. The KES community consists of several thousand experts, scientists, academics, engineers, students and practitioners who participate in KES activities.

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About KES International

Formed in 2001, KES is an independent worldwide knowledge academy involving about 5000 professionals, engineers, academics, students and managers, operated on a not-for-profit basis, from a base in UK. A number of universities around the world contribute to its organisation, operation and academic activities.

Robert J. Howlett

Preface

Sustainability is the current big challenge of this generation and of (hopefully) future generations to come. As academics, we can contribute something to improving our survival chances in this world. Whatever we do will have an impact on our environment, being positive or negative, we would like to think that the impact of organising and carrying out this conference will be outweighed by the positives of its legacy.

We would like to welcome you to this volume, which forms the proceedings of the Sixth KES International Conference on Sustainable Design and Manufacturing (SDM-19), organised by KES International in collaboration with the University of York, York, UK, and held on 4th–5th July 2019 at the Danubius Health Spa Resort Margitsziget, Budapest, Hungary.

While many authors have contributed in past SDM conferences, for which we are grateful, we are also pleased to see so many new contributors to this conference, and we welcome you all and hope that you can be part of the growing body of academics pursuing sustainability research and would like to contribute to the organisation of future conferences. We hope that you will build on the relationships that you forged during the conference and collaborate in future academic and professional endeavours.

This conference provided excellent opportunities for the presentation of interesting new research results and discussion about the theory and applications in the field of sustainable design and manufacturing, leading to knowledge exchange and generation of new ideas. This field includes both sustainable design and advanced manufacturing of sustainable products. The application areas included all the activities during the product life cycle and other activities such as modelling and simulation, decision support, production planning and control, logistics and supply chain management.

This conference builds on the successes of the previous five conferences held so far led by Cardiff University, Wales, UK (2014); University of Seville, Spain (2015); University of Crete, Greece (2016); University of Bologna, Italy (2017); and Griffith University, Gold Coast, Australia (2018).

The conference featured general tracks chaired by experts in the field, including sustainable design, innovation and services; sustainable manufacturing processes and technology; sustainable manufacturing systems and enterprises and decision support for sustainability. Topics in this theme of sustainability keep evolving at a fast pace, so the papers presented here show that trend, and you will find a good combination of technical and management papers which is the aim of the conference to bring those disciplines together.

We are grateful to our distinguished keynote speakers: Prof. Kai Cheng, Theme Leader for Micro-Nano Manufacturing/Head of AMEE, Brunel University London, UK, and Prof. Fazleena Badurdeen, Mechanical Engineering, University of Kentucky, USA. They have provided inspiration for our delegates, specially our Early Career Researchers who can see in them a role model to follow.

We also thank our Programme Committee members, chairs of general tracks or special invited sessions, authors and reviewers for their unwavering commitment to ensure the quality of the work submitted, revised and accepted to SDM-19 was of the high standard required by Springer Nature proceedings.

As in previous SDM conferences, SDM-19 attracted high-quality paper submissions from around the world. Submissions for the Full Paper Tracks followed a two-stage single-blind peer review process, whereas submissions for the Short Paper Track followed a ‘lighter-touch’ review and published in an online medium, but not the Springer Nature proceedings.

We are indebted to the many people, who in whatever capacity, have given their time and goodwill freely to make SDM-19 a success. Finally yet importantly, we would like to extend our thanks to the city of Budapest for welcoming our delegates.

York, UK

Prof. Peter Ball
Dr. Luisa Huaccho Huatuco
General Co-chairs

Contents

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Peter Ball is a Professor of Operations Management at The York Management School, UK. His research focuses on how operations can be designed and improved. Application areas span manufacturing, supply chain and service. Responsible business, environmental sustainability and resource efficiency feature strongly in his work. Peter has published his work in numerous papers globally in journals, conferences and practitioner publications. He is a Chartered Engineer (IET) and Senior Fellow of the UK's Higher Education Academy.

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Part I
Sustainable Design, Innovation and Services

Chapter 1
An Exploratory Study to Identify the Barriers and Enablers for Plastic Reduction in Packaging

Xuezi Ma, Curie Park, James Moultrie and Min Hua

Abstract How do we reduce plastic content in packaging? To answer this question, this paper did three case studies with packaging supply companies. It investigated the barriers and enablers of plastic reduction in packaging by using a grid. Factors have been summarised, categorised, and discussed. It is clear that there are certain enablers who can surely help companies to reduce plastic usage. Because of the size of the company, some barriers in one company can be enablers in others. The research findings can help companies take as a reference when they make strategies specifically for plastic reduction.

1.1 Introduction

The use of plastics in packaging is becoming an increasingly hot topic, with growing awareness of the significant damage that plastic waste causes to marine and land environments. As a result, there is an unprecedented level of the consumer pressure demanding that firms reduce or eliminate unnecessary plastic. Governments are beginning to place pressure on producers and retailers to reduce or eliminate "avoidable" plastic and especially "single-use plastic" in their business practice (e.g. UK Government declares to eliminate all avoidable plastic by 2024). In spite of the heightened, widespread awareness of the need to reduce plastics in packaging, industry response has so far been insufficient [1–3].

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Companies are increasingly receiving criticism for their usage of plastics in packaging. Furthermore, although many companies that are involved in researching this area have recognised the potential benefits in reducing plastics in their packaging, little knowledge has been shared how to achieve this.

Whilst there is much known about sustainable packaging design and development, including procurement, lifecycle analysis (LCA), and waste management [4–8], little is known about why firms are not changing their packaging practices more rapidly. There is genuine reticence on behalf of goods providers to change, and the reasons underpinning this reticence are still not fully understood [4–6]. Indeed, most of the existing work has been retrospective or conducted for assessments that involve later stages of the packaging development process [7–10].

In this study, we are seeking to understand the different barriers and enablers that both inhibit and encourage the transition away from plastic packaging to answer the question: *What inhibits the transition towards zero plastic packaging and how might these barriers be overcome and how can we define and measure them?*

1.2 Method

Data was collected from three companies through semi-structured interviews with key employees, onsite observations, and document analysis. During the interviews, a graphical means of capturing data were used, in which participants identified, mapped and explored the relationship between different factors. This graphical approach to data collection provided a structured means of engaging with the topic as well as producing comparable outputs. Whilst working with the map of factors, interviewees described their thinking and this was recorded and later transcribed. As a result, we had a rich set of visual as well as textual data to analyse.

Before conducting the interviewees, the graphical approach to engaging with the topic was developed. The underpinning rationale for this approach is described in more detail in a previous paper [11]. This study also aimed at trailing this method of collecting the data relevant to this topic.

Interviewees were identified by attending conferences and sustainable packaging events (e.g. Packaging Innovations 2018 and Open Innovation Forum 2018) to make contact with participating firms. In addition, the researcher used sustainable packaging reports published by non-governmental organisations (NGOs), including ThePackHub, Worldwide Responsible Accredited Production (WRAP), the British Antarctic Survey and the Ellen MacArthur Foundation to find potentially interested firms. Table 1.1 provides an overview of all the interviewees and their organisations.

All interviews followed the procedure described below:

1. At the beginning of each interview, the interviewees were asked to share general information including their job responsibilities, experiences in plastic issues, and relevant projects they had encountered.

Table 1.1 Interviewees and their organisations

Company	Company type	Location	Market Size	Occupations of the interviewee
Company A	Packaging supplier	UK	Local	CEO and Founder
Company B	Packaging machine supplier	Germany	International	Packaging technician
Company C	Secondary packaging supplier	UK	European	Marketing representation

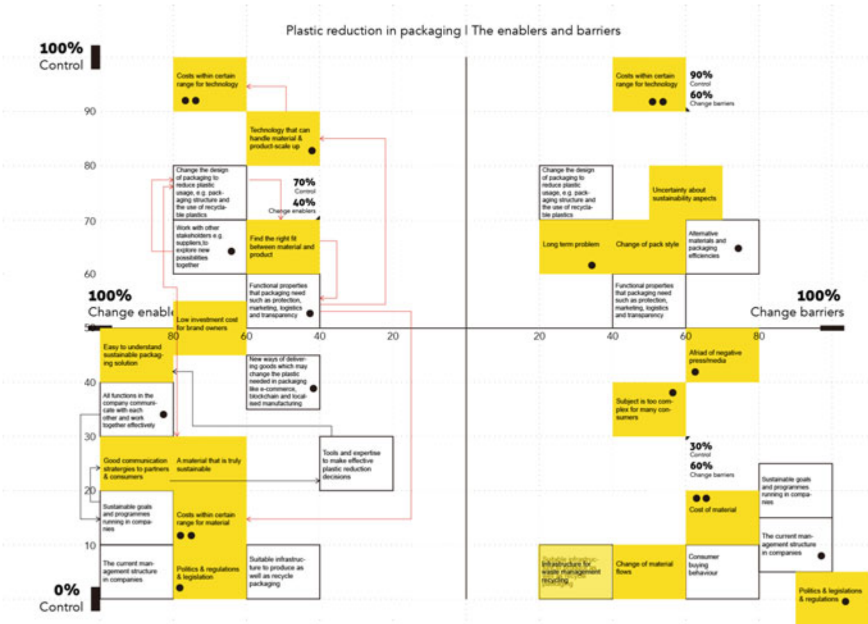

Fig. 1.1 An example of the finished grid

2. They were then asked to brainstorm the enablers of barriers that they have experienced to being able to reduce the plastics in their packaging.
3. Subsequently, they were provided with cards that included factors identified from practitioners and literature in a previous phase of this research. Interviewees were asked them to place both their own factors and the provided factors on the grid (see Fig. 1.1). The grid has a y-axis for the level of control companies have over each of the factors, and an x-axis for the level of influence of the factor as an enabler or as a barrier.
4. The interviewees were then asked to rate the importance of each of the factors. There were 10 dots for enablers and another 10 for barriers. The interviewees

used these dots to vote for factors they believed to be important. They were allowed to use more than one dot for each factor.

5. Finally, the interviewees were asked to consider whether there is any logical sequence of activity in order to progress towards zero plastics. This aimed to provide insight into factors which are of immediate importance and those which depend upon other actions before becoming relevant.

The interviewers took audio recordings during the interviews, and these were then transcribed. The results of the interviews were divided into three parts: the transcripts, the interviewees' explanations regarding their understanding for some factors on the grid, and pictures of factors they placed in the grid. The transcripts were analysed using the software MAXQDA 2018. In addition, the researcher took pictures of each grid after the interview, and these were made into digital versions using Adobe Illustrator CC 2018.

The most frequently mentioned factors in the interviews were identified as they represent multiple views. Employing the thematic coding method [12], we coded the transcripts and attached the segments to the relevant factors. We then categorised the factors under the coded themes and their segments. All coding was verified by an independent researcher.

Finally, based on the responses from all interviewees, a new grid was synthesised which aimed to represent all of the factors discussed.

1.3 Results and Discussion

From the suppliers' perspectives, what are the current enablers of and barriers to reducing the use of plastics in packaging? The results for each company are presented first, followed by the categorisations of the factors. Then, we present the cross-comparison between categories.

1.3.1 Company A

Company A is a British SME that provides a non-plastic packaging solution for end consumers in the food sector. Company A's product can be reused and is biodegradable. The interviewee is the company's founding CEO.

As a start-up, the biggest barrier for Company A was ***Cost***, including costs for the material itself and the costs of developing the new technology itself.

> Plastic is cheap, very cheap and it's very durable and it's disposable, which is the biggest problem.

The low cost of plastic can be a major barrier for companies to adopt the product Company A provides. In addition, most plastic packaging in food products is not reused. This helps to keep the food from contamination. This interviewee believes that for alternatives to plastic to be adopted, the physical properties of these alternatives need to be improved. To do this requires further R&D and the firm has limited budgets for this. Therefore, the products that Company A can offer are currently perceived by potential customers as having lower functionality than plastic at a higher price.

In Company A, the most significant enabler of plastic use reduction will be the ***Consumer*** or end-user, placing demand upon suppliers. In addition, the interviewee believes that having sustainability as a core goal is essential in order to ensure that this is an issue taken seriously at a senior level. This is seen through the existence of different business ***Goals and Programmes*** which seek to translate this core goal into actionable results. Whilst the company is not in control of the attitudes of end-users, they do have control over their business core values.

1.3.2 Company B

As a subsidiary of an international corporation, Company B provides packaging machines for many fast-moving consumer goods (FMCG) companies across the globe. The interviewee from Company B is a senior packaging technician for this company, which supplies packaging machines.

The ***Cost*** of both product development and raw materials are perceived to be the most significant barrier to reducing plastic usage in Company B. To adopt new materials, Company B's clients also need to make changes to their production lines, which can introduce significant expenditure, including investment in new machinery.

The interviewee in Company B also noted that cost has the potential to be an enabler as well as a barrier to plastic reduction. However, this requires the company to ensure that the processing of new materials can be scaled-up cost effectively. They noted that their clients are often eager to use new materials to satisfy pressure from their customers, providing that costs do not increase.

1.3.3 Company C

Company C is a national distributor of packaging solutions in the UK. The interviewee representing this company is from the marketing team. Their clients are mainly retailers who are in charge of transferring the products from their warehouses to local stores or end consumers. The packaging they handle is mainly secondary.

Company C sees ***Cost*** as the most significant concern. Substitute materials might not only increase these costs, but also make it difficult to meet the requirements for secondary packaging. For this type of packaging, efficiency is the critical deciding factor for material selection and Company C is currently exploring whether new materials could provide the packing speed needed for secondary packaging.

This interviewee noted that capabilities in the ***Design and product development*** of new packaging are a critical enabler if we are to change the status quo and make our future plastic-free. She also identified that ***Working with other stakeholders to explore different possibilities*** is essential if this is to happen. Finally, she noted that both ***New ways of delivering goods in the future*** and gradually shifting ***Consumer behaviour*** are also important enablers.

1.3.4 Discussion

Responses from all interviewees have been collated and are represented in a new, synthesised grid (Fig. 1.2). This seeks to present a comprehensive overview of the critical factors, their relative importance and any major sequencing observations. The most significant of these will be discussed in more detail below.

Barriers to transitioning towards zero plastic in packaging

The categories of ***Materials***, ***Cost*** and ***Functionality*** were the most frequently cited as barriers towards transitioning towards zero plastic in packaging. ***Cost*** received the highest rating of importance (7 dots), *Functionality* was the second most important (4 dots), and ***Materials*** (3 dots) was third. Other factors including ***Infrastructure*** and ***Design*** were also noted as barriers.

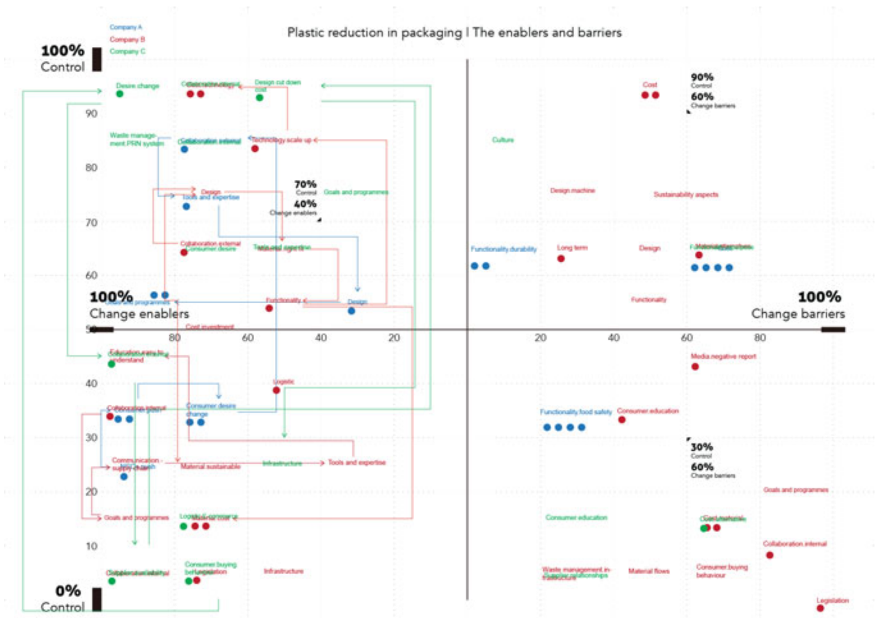

Fig. 1.2 Illustration of the results by categories

Materials refer mainly to the availability of alternatives to and substitutes for plastics. Whilst this could be seen as an "enabler", it is noted as a barrier as all interviewees mentioned that they are somewhat dubious about the current environmental and functional properties of alternative materials. Respondents were concerned that if these materials consume more energy to produce and potentially cause more pollution than plastics, then it is hard to justify their adopted as alternatives to plastics. Interviewees also mentioned ***Functionality*** as a critical barrier as alternative materials are not perceived to provide the durability, food safety and water resistance required. In addition, many of the alternatives to plastic are currently significantly more expensive to produce and so increase the ***Cost*** of packaging for consumers. For all interviewees, further R&D is needed to reduce production costs and increase functionality, and this comes as a different form of ***Cost*** which is also a significant barrier.

Enablers to transitioning towards zero plastic in packaging

Seven factors emerged from all interviewees as essential enablers in transitioning towards zero plastic in packaging. These factors are: ***Functionality***; ***Collaboration; Consumer; Cost; Goals and programs; NGO****; and* ***Design and Product Development****.*

Although ***Functionality*** can be a barrier to plastic reduction, interviewees also feel that there is also great potential for new materials to increase the functionality offered in packaging. This might then compensate for any increases in raw material or processing costs.

Collaboration refers to both internal and external collaborations. To achieve efficient internal collaboration with respect to plastic reduction, employees need to believe in sustainability "*from the bottom of their hearts (Company B)*" and all departments should have good communication and support, both mentally and financially, from the higher levels of the company. Thus, effective internal ***Goals and Programmes*** are essential. External ***Collaboration*** can help companies to obtain new resources and support. For example, collaborating with NGOs and academics can help companies to gain access to external expertise to solve their technical problems. Collaborations with their partners along the supply chain can help them get everyone on board regarding sustainability topics and to understand the needs of each other. Communication is as important for external partners as it is between internal employees. All respondents acknowledged the importance of investment in ***Design and Product Development*** and noted that collaboration is critical to this activity.

Pressure from ***Consumers*** is a strong enabler of change, and currently, this is growing due to the increased media exposure to which plastics pollution is subjected. The interviewee from Company A notes that his company would not have been as successful if they had launched their products five years ago. The shift in consumers' opinions towards plastic packaging has had a substantial effect on the supply chain and made companies more willing to consider plastic-free alternatives. But this still does not seem to be sufficient to overcome the perceived cost and functionality barriers described above. As suppliers, the interviewees from all the companies can educate their clients and steer them to change their choices for packaging material.

Through marketing and enhancing functions that address alternative solutions to plastics, companies could make their plastic-free packaging more attractive.

It is interesting to note that after interviewing people from different levels in companies, the researcher found that people from either the higher or the lower levels were very excited about sustainability ideas and enthusiastic about making changes. Those from the higher level want to make this change because they know it is the right direction for the future, while those from the lower level want to make changes because they are involved in the production process and know that things must change. However, people in the middle levels were not always eager for change because they are the ones who will be challenged by implementing new solutions.

Perhaps surprisingly, ***Government legislation*** was not noted as a significant enabler of change for these three interviewees. However, ***NGOs*** were perceived to be enablers by bringing different stakeholders together and as a result of lobbying and influencing policy-makers.

In control or not?

We captured data regarding the level of 'control' the firm feels it has over these different enablers and barriers.

Goals and programmes are mentioned to be controllable for Company A and Company C. However, this is not the case for Company B who emphasised that as a division of an international cooperation, they have to compromise most of the time and are not always in control of initiatives from head office.

This is similar to ***Collaboration***. Companies A and C both feel in control of their different collaborations while Company B felt that external collaborations are often easier to broker than internal ones.

All companies rated ***Consumer*** on the lower half of the grid, i.e. out of their control. However, they put ***Desire*** from their clients and consumers on the upper half of the grid. So, they all feel it is possible to influence consumers' desire (e.g. through promotion) which can change their buying behaviour. But, they do not think they have control over *Consumer* purchasing behaviours.

All interviewees believe they have control over the ***Design*** of their packaging and feel that with better design, and packaging could increase packaging functionality, even if there is a marginal cost increase.

In prioritising and sequencing the factors which need to be addressed in order for change to happen, companies typically begin with the factors where they have less control. Company A sees ***NGOs*** as a strong enabler that has the potential to kick-start the whole change of plastic reduction in packaging industry. Company B thinks ***Internal collaboration*** can help set the ***Goals and programs*** in companies and move plastic reduction in packaging forward. Company C believes ***Consumer buying behaviour*** is the starting point for the reduction of plastic usage in packaging. Thus, in two of these firms, the first thing that needs to happen is not in their control.

1.4 Conclusions and Future Work

Through examining the cases of three companies, this research tries to understand how packaging suppliers could reduce the plastic content in their packaging. By analysing the transcripts, combined with the results on the gird, we found some common enablers and barriers.

Lewin's force field analysis [13] was used to illustrate the barriers and enablers in reducing plastic usage in packaging (see Fig. 1.3). Enablers can be viewed as "forces for change" (left-hand side) while barriers are "forces against change" (right side). We have added to this notation by indicating whether the firm feels in control of each barrier or enabler (by line type). In addition, the order in which these are presented (top to bottom) represents the sequence in which the firm feels these must be addressed.

It is clear that externals such as ***NGOs*** and ***Consumers*** are considered the first step for initiating reducing plastic by the interviewees. But, companies have little control over these external stakeholders. This is followed by companies' competence in ***Design*** to stimulate the creation of cost-effective new materials and processes as alternatives to plastics. Each force for change has its force against change, and most of them are out of companies' control.

Future work

This is an exploratory study, reporting on a small sample of interviewees from a specific point in the packaging supply chain. This has demonstrated the efficacy of a highly visual approach to capturing and representing different barriers and enablers. Future work will use this method to sample a larger number of companies to verify and expand the results from this research. This is part of the ongoing research into reducing the plastics in packaging, in the Design Management Group, at the Univer-

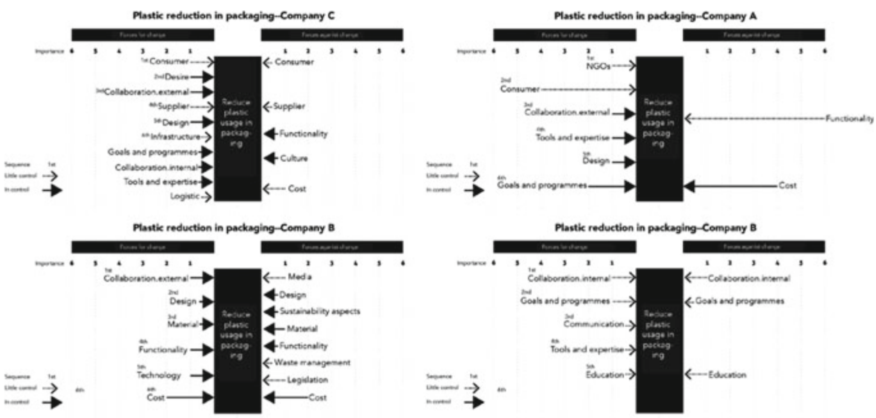

Fig. 1.3 Force field analysis in plastic reduction in packaging

sity of Cambridge. Further research should involve companies that include not only the suppliers but also other stakeholders in the supply chain.

Author Contributions Xuezi Ma designed this study, conducted the interviews, analysed the data, and produced the first draft of this paper. Curie Park independently verified all of the data coding and provided proof reading for the paper. James Moultrie helped steer the direction of the research, also verified the coding and provided a significant contribution to the writing of the paper. Min Hua independently verified all of the data coding.

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Chapter 2
Design Merged X for Eco-product Development

Jing Shen, Lichao Peng, Yilun Zhang and Zhinan Zhang

Abstract Design for X (DFX) issue in product design and development is generally considered in the late design process, e.g., detailed design phase. DFX issue plays a crucial role in determining cost, time and quality of product design. Due to the current DFX, research pays little attention to incorporate the industrial design, and the industrial design is rarely taken into account in the early design phase; design iteration is unavoidable. This paper identifies the new X issues requires in development of product life cycle design methodology, and then proposes a Design Merged X (DMX) framework to combine industrial design and product design with existing DFX methods. A process model of how to apply the DMX framework is also presented. An illustrative case is presented to show how the proposed DMX framework can be used to fulfill the new design process with considering the industrial design in the early design phase. Results of this study contribute new knowledge to DFX field.

2.1 Introduction

The efficiency of product innovation is strongly supported by efficient design and manufacturing methods. With the maturity of management methods such as lean production system and Six Sigma quality control system, the efficiency of manufacturing has been extremely improved. However, in contrast, the "Gerdios knot" of improving design efficiency still keeps untied. Design is still an uncontrollable

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nonlinear process, i.e., unstable initial design inputs, unstable "5M" (man, machine, material, method and money) during design, and the quality of design's delivery is certainly unstable. Design process management can only improve the running efficiency of design activities in multi-functional team, not the quality of the design itself.

In order to improve the efficiency of design, many theories and approaches have been proposed, e.g., TRIZ, QFD and DFX. Among them, DFX (i.e., DFA, DFM, DFC, etc.) approaches now have been widely promoted in the industry. As a design method considering "core product-feature modeling" (CPM) and "product-feature-driven design" (PDD) [1], the meaning of "X" in the DFX includes cost, assembly and manufacturing. On the basis of this concept, concurrent product development by multi-department can be realized, and the amount of design rework can be reduced to a certain extent.

Nowadays, DFX theory has evolved from early focusing on only "A" and "M" into today's multi-dimensional decision-making. Raymond Holt and Catherine Barnes have emphasized the importance of linking DFX technology to the overall function of the product (not only other DFX) and looked forward to the possibility of making a decision through DFX technology [2]. In addition, many scholars from different industries have extended the connotation of DFX. Andrew N Arnette proposed the concept of design for sustainability (DFS). Remanufacture, reuse and recycling were used as decision basis to conduct DFX comprehensive decision-making in his paper [3]. Christoph Klahn proposed the concept of design for additive manufacturing (DFAM). In this paper, Christoph Klahn pointed out two different design strategies which took advantage of additive manufacturing benefits in product development [4]. These extensions and researches of DFX technology have greatly enriched the connotation of DFX. Since the late 1990s, hundreds of papers about DFX's application in the manufacturing industry have been published, most of which are widely distributed in many different disciplines and publications. However, in general, DFX's main focus is still placed on environmental design, recyclability design, manufacturing feasibility design, etc. [5]. The application of DFX technology in mechanical structure design has now become a trend. When engineers are working on a specific product structure design, in addition to considering the realization of product's functions (operation, waterproof, thermal design, wearing, driving, power generation, etc.), assembly (DFA) [6], parts manufacturing (DFM) and cost (DFC) [7] should also be systematically considered at the same time to make the results (drawings, BOM, FA process, etc.) in mechanical structure design stage fully satisfy the cost efficiency and technical requirements of mass production. Based on this, the research mentioned above also proposed methods and formed tools, and some were integrated into software [8, 9] to help engineers conduct standardized and systematic quantitative analysis to make accurate judgment and control.

In summary, the current intervention timing of DFX technology is in the stage of specific mechanical structure design, on the base of the higher-completeness 3D design data, and then the automation calculation (like DFMA, aPriori, DFMPro) would be conducted to provide timely "manufacturing feasibility assessment." However, insufficient attention has been paid to the early stage of design for function

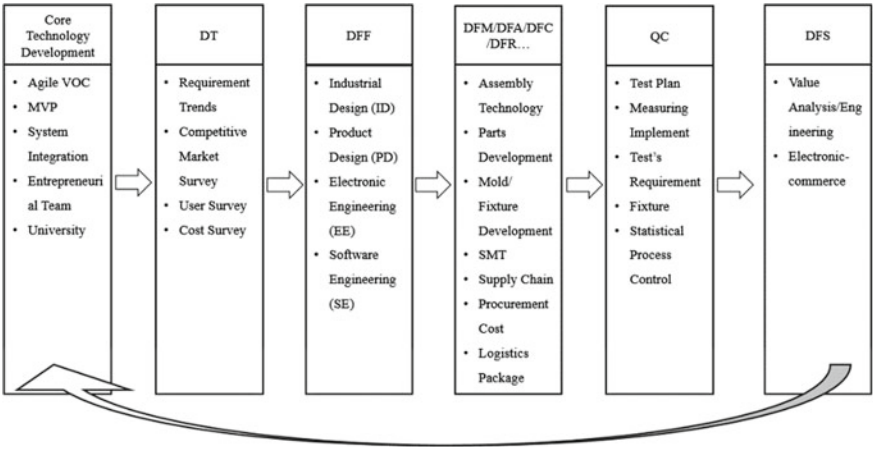

Fig. 2.1 Process of product development

(DFF), especially industrial design (ID, part of DFF). ID and DFX are still two independent and incoherent links, which often lead to the appearance of the lack of manufacturing feasibility in the DFX stage and therefore overturn the work of ID and DFF. Therefore, the connotation of DFX should be extended to the early stage of the industrial design phase.

Generally, the entire process of product development includes the following steps: core technology research and development, design thinking (DT), design for function (DFF), design for X (DFX), quality control (QC), design for serviceability (DFS) (see Fig. 2.1). Among them, DT and DFF are two of the most crucial links.

Although DT\DFF only accounts for about 5% of the total cost of a product, they have a direct impact on 75% of the total cost.

1. The overall cost of product is determined by the stage of ID/DFF.
2. The small batch trial production problems' cause in new product introduction (NPI) is planted in the ID/DFF stage.
3. Most of the problems mentioned in the second are recurring.

In the ID stage, the target is VOC: User requirement is the input, and the outputs are the product function definition, the appearance design scheme, the structural design scheme, etc., that can realize user's requirement. At this stage, the designers, especially ID designers, are very lack of effective knowledge supply means, especially for the knowledge of mass production's manufacturing feasibility that DFX has.

Similarly, DFX engineers are often unable to provide mass productivity assessment opinions according to ID designers' expression of "design language" (lines, shapes, color proportion, tones, textures, etc.).

With the wave of innovation, "personalized mass customization" has already become a trend, and manufacturing feasibility assessment of mass production in the

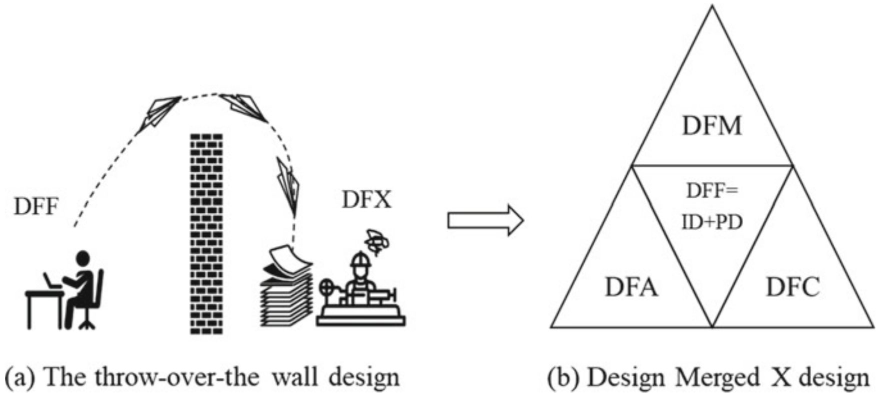

Fig. 2.2 Design merged X method

ID stage is now playing an increasingly crucial role. Most innovative products today have very attractive ID scheme. Unfortunately, once it comes to the DFX part, there often occur a large number of mass production feasibility problems that lead to hasty design change, or even completely overturn the ID scheme. Such a circumstance is called "fake design" (see Fig. 2.2a). In conclusion, there still "throw-over-the-wall design" exists between ID and DFX.

2.2 Design Merged X

Considering that DFX theory has many shortages in the VOC → VOT (DFF: ID + PD) stage, the author integrates the phase of ID into DFF and considers DFF as the core of DFX for comprehensive evaluation to complete early merging in more dimensions, and therefore the design merged X (DMX) methodology can be built as shown in Fig. 2.2b.

The current synergy between the ID and DFX is basically regarded as "the mode of the mutual harm" or, in other words, "sitting together and fighting together."

On the other hand, there are only sketches (including ID and PD sketches) in the early stages of product design which means there are not enough objects to evaluate. How to start convenient, systematic and quantitative assessment of usability and cost efficiency requirements of the following aspects—design route/direction and mass production (traditional standardization and newly emerging customization)—remains to be a major difficulty.

The significance of the earliest assessment of the product is obvious: reducing the time cost of the common back-and-forth solution correction between design and mass production design; further, avoiding the excessive gap between the design and the final product; and furthermore, through the integration of various databases, designers can obtain cross-industry and systematic input of CMF more easily and effectively, extend the effective degree of freedom of design, promote the combination between design services and manufacturing industry and improve the efficiency of innovation and creativity.

Under the precondition of fully satisfying the "function" or "user experience," in the early stage of design, the various elements X (A, M, C, $S\ldots$) of mass production would be taken into consideration to carry out "comprehensive weighing." When it comes to user experience, "creative" and "design" are two crucial factors that cannot be ignored. The fields that traditional DFX faces have extended from mechanical design to the range of "market demand" and "user experience," and further to the "demand research" and "product creativity." Since it is a "comprehensive weighing" process, an equation would be used to express this:

$$D = C + \sum_{i=1}^{n} K_i * X_i \tag{2.1}$$

D The result of the comprehensive weighing and the reference value used to assist decision-making for design.

C Creativity degree, which is an uncontrollable factor in conceptual design.

X_i The objective scores of product design elements, including but not limited to experience, creativity, requirement, function, assembly, parts, cost and reliability.

K_i Elements' weight for the comprehensive weighing.

The internal logic of DMX (Fig. 2.3):

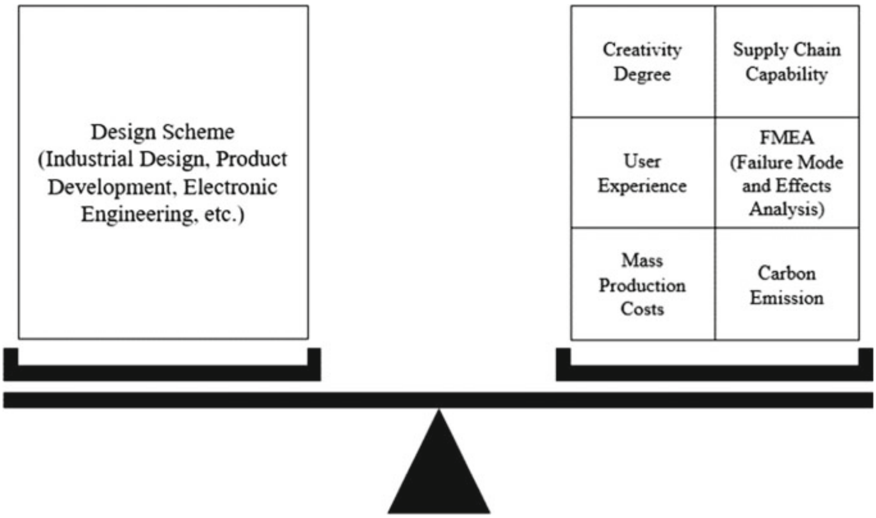

Fig. 2.3 "DMX" evaluation system

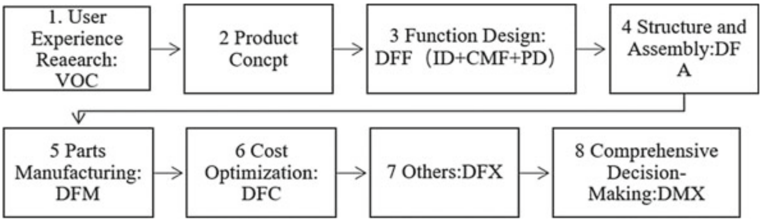

Fig. 2.4 Common flow of traditional design

1. Extend to the idea generation stage, improve the manufacturing feasibility of the ID scheme in the early design stage, and evaluate user experience comprehensively, creativity degree and other dimensions.
2. The evaluation objects should be extended from 3D data to the geometric features of ID scheme's plane hand-drawn sketch.

Figure 2.4 shows the common flow and eight links that a traditional design should go through. Among these links:

1. User Experience Research-VOC: The user experience research refers to the investigation on users' entire feeling process and requirements before, during and after using a product. Such an investigation is also called voice of customer (VOC) which can be regarded as a crucial reference to the following product concept construction and product improvement.
2. Product Concept: Based on VOC, the proposal of product concept can also be regarded as a form to satisfy customer requirement. Generally, the total product concept includes three layers: core (main function), shape (product's appearance, quality, wrapping, etc.) and extension (after-sales service, supporting service, etc.).
3. Function Design-DFF (ID + CMF + PD): The function design can also be regarded as a combination of the industrial design, color, material and finishing and product development. Such a design is conducted on the basis of user requirement analysis and realizes the product concept.
4. Structure and Assembly-DFA: DFA refers to ensure the assembly feasibility of product during the product design stage. During the process of DFA, designers realize the cost reduction and avoid the overturn in the practical assembly process by the means of modular design, multi-function part design, etc.
5. Parts Manufacturing-DFM: Different from DFA, DFM focuses on lower costs and improves the efficiency through improving the manufacturing feasibility.
6. Cost Optimization-DFC: DFC is another crucial link which places more concentration on the aspect of cost. Under the condition of satisfying customer requirements, the aim of DFC is to optimize the cost of product's full life cycle through modification or replacement of the high-cost parts.

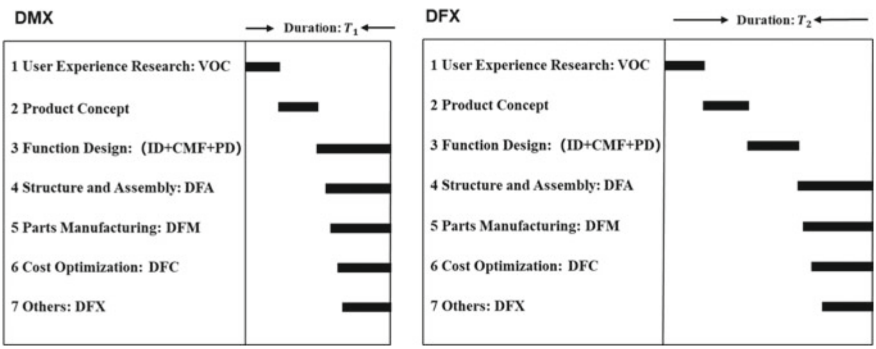

Fig. 2.5 Simplified Gantt chart of DMX and DFX processes

7. Others-DFX: The full name of DFX is design for X, where "X" indicates any competitive factor or link exists in a product's life cycle such as manufacturing, environment, cost and procurement.
8. Comprehensive Decision-Making DMX: Decision-making for design with a comprehensive consideration of various factors, including but not limited to experience, creativity, requirement, function, assembly, parts, cost and reliability.

Figure 2.5 shows the simplified Gantt charts of two same projects completed by DMX and DFX methods. The left side of the chart lists the common steps of the design, and the right side shows the rough time bar of each link. As shown in Fig. 2.5, the concurrent link in DMX process starts in the function design (DFF) sub-process and goes throughout the entire DMX process. This means the comprehensive weighing starts at the DFF stage and exists in each following links.

In the entire design process of DMX, each design step from the function design turns to be concurrent but not independent so that product's later production feasibility can be fulfilled. However, it is hard to conduct concurrent cost/manufacturing/assembly assessment at the early stage of design (industrial design/function design) due to the lack of complete parameters and 2D drawings. At present, these assessments still rely on the experience of engineers, while such experience judgments also have limitations and subjectivity. Under such circumstances, graphics recognition and searching technology could be a good solution. Based on the establishment of database, graphic recognition and search technology can rapidly provide production feasibility information like cost, assembling and manufacturing parameters through similar products.

Distinguished from DMX, the function design is independent to the subsequent link in DFX process. This means production feasibility assessments including cost, manufacturing and structure would not be taken into consideration at this stage. From Fig. 2.5, although the single function design link's time cost of DFX is much lower than DMX, the overall time cost of DFX has a high probability more than DMX because it may contain potential rework time cost.

2.3 The Application Scenarios of Design Merged X

In the early stage of product concept, ID designers always design on the basis of their own prediction of the user experience, and they prefer to use their individual experience and knowledge to stimulate design ideas. However, when such a design flows to the subsequent links, structural and mold engineers often raised questions about its manufacturing feasibility and cause design changes, which can directly lead to reworks.

Figure 2.6 shows the different evolutions of a product in the traditional and DMX design process. The design product in the figure is a plastic case used for medical equipment. In the traditional design process on the left, the ID designer equips the product with a scientific appearance including antiskid area on both sides and elegant curve at the front end. However, after the DFA and DFM stages, the original scientific design has been replaced by a more practical design to ensure product's manufacturing and assembling feasibility. The modified design only retains the basic ID intent. During the modification process, a lot of unnecessary communication and reworks may occur between manufacturing design (MD) and ID designers. Further, when design flows to the subsequent links like design for assembly or design for cost, the similar problem may rise again. The entire case project lasted for nine months, and after gone through three major design changes, the overall project costs have finally reached 5 million RMB, which had significantly exceeded the original budgets of 2 million RMB. Most of the overspent budgets were used for making additional prototypes (500,000 RMB average set) and extra labor costs in the reworks. In addition, due to the lack of adequate mass production assessment in the early ID stage, nearly half of the time was wasted on the rework.

One of the cores of DMX design process is to bring the ID into the evaluation scope. In the DMX design process on the right, DMX's scheme decision-making method would go throughout the entire process. In the design process, DMX evaluation system can be used by ID designers to consider the subsequent problems of mass production to obtain a more feasible design. Similarly, MD designer can consider the structure design of mass production with less design changes. As shown in Fig. 2.6, since the mass production feasibility assessment was involved in the ID

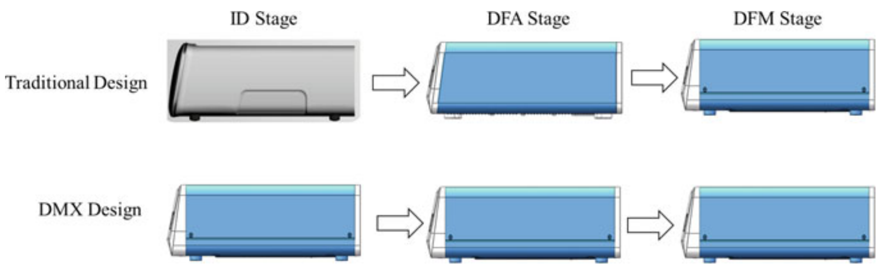

Fig. 2.6 Difference between traditional design and DMX design

stage in advance, the initial design does not change a lot throughout the entire design process and therefore the potential risks of rework can be effectively avoided, which reflects the sustainability of DMX design.

2.4 Conclusion

This paper proposes a new DMX evaluation framework to overcome the lack of DFX considering decision-making at the initial design stage. The DMX method focuses on the integration of the sub-modules of DFX to support quantitative design parameter-based decision-making. This method can be extended in various new dimensions, such as multi-dimensional feature evaluation by using graphic recognition, sensory adjective modeling by using fuzzy clustering, and drawing crucial value from descriptive analysis of design scheme by using semantic analysis. With the support of these emerging technologies, DMX can effectively reduce the costs of various aspects in the traditional design process under the conditions of meeting the requirements and thus achieve a sustainable design.

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Chapter 3
Sustainable Biodesign Innovation: Integrating Designers, Engineers, and Bioscientists

Christina Cogdell

Abstract After first clarifying the concept of sustainable biodesign innovation, this paper uses a case study of rapid, short-term interdisciplinary collaboration involving designers, engineers, and bioscientists to explore why this method is so energizing, stimulating, effective, and efficient. Using as its example a two-quarter Honors course at the University of California at Davis that prepared teams to compete at the international Biodesign Challenge in New York City in June 2018, it briefly explains the process of the course and the project of the team that competed and won two of six prizes at the competition. It then discusses and argues that the process of sustainable biodesign innovation is enhanced by interdisciplinary collaboration between designers, engineers, and bioscientists, owing to their complimentary theoretical knowledge, technical training, approaches, foci, and skills, and that this process can be utilized in industry for sustainable biodesign innovation.

3.1 Introduction

This paper is from the standpoint of the discipline of design—meaning architecture, interiors, products, fashion, graphics—where it is still rare for design students, professional designers, and design firms to work directly with biology, including familiarity with laboratory processes. This distinguishes the paper's framework at the outset from that of different biotech fields, where scientists and engineers may describe their work as "design" but are producing innovations for agriculture or healing the human body (pharmaceuticals, health and beauty products, etc.).

"Biodesign" is a new subfield or approach in design that integrates biology into the design process; the term has become popular after William Myers published *Bio Design: Nature, Science, Creativity* in 2011 [1]. Since then, a number of exhibitions on this topic have been staged, including those associated with the international Biodesign Challenge competition held at the Museum of Modern Art in New York,

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beginning in 2016 [2–7]. Myers's book includes examples of using plants for architectural structures, surface design or energy; new materials for design produced by bacteria or other living organisms; biomimetic designs; speculative design for debate; and designs relying on synthetic biology [1]. Biodesign differs from eco-design or green technologies through its dependence in some way upon living organisms in the design ideation or production process—criteria not necessary for eco-design or green technology—and it may or may not involve biotechnology or synthetic biology.

Despite how it may appear, within the design sub-disciplines not all approaches that are referenced as "biodesign" are sustainable, when sustainability is defined by minimal environmental and energetic impact with generational longevity. For example, although biomimetic designs that apply to product design a solution for a particular problem—where the solution is inspired by the form or function of a living organism—are modeled upon natural processes, the life-cycle analysis of that product or technology may still reveal high environmental and energetic impacts. I therefore define "sustainable biodesign" using the lens and tools of life-cycle assessment with an important goal of achieving closed-loop design, which is also referred to as "design for the circular economy" [8, 9].

This paper argues that the process of sustainable biodesign innovation is enhanced by interdisciplinary collaboration between designers, engineers, and bioscientists, owing to their complimentary theoretical knowledge, technical training, approaches, foci, and skills. My personal experience with this process is not in industry but academic—twice now leading teams of interdisciplinary students to create sustainable biodesign innovations for the international Biodesign Challenge student competition. I believe this experience is relevant to industry because many environmentally minded companies are discovering the value of interdisciplinary collaboration made possible with the teams of diverse professionals. This paper thus extrapolates my interdisciplinary team-based classroom experiences to broadly reflect upon why this type of collaboration is so energizing, stimulating, effective, and efficient for sustainable biodesign innovation.

3.2 Background

In January 2018, biomedical engineering professor Marc Facciotti and I teamed up to co-teach a two-quarter Honors Program course at UC Davis that would prepare interdisciplinary teams of students to compete to enter the international Biodesign Challenge competition in June 2018. The goal of the competition is to introduce art and design students to new approaches using biology, biotechnology, and synthetic biology as important strategies for considering and achieving a sustainable design. While the field of design has strongly emphasized sustainability for the last decade, few art and design students have access to or familiarity with working with living organisms and materials, a process that usually involves working in a laboratory. The competition encourages art and design students to seek out collaborating scientists and laboratories or DIY spaces to break through the discomfort of unfamiliarity to inspire new modes of design thought and production.

Because UC Davis is a comprehensive university, students entering our course were fortunate to have access to interdisciplinary undergraduate and graduate student collaborators, a laboratory, and mentors from different disciplines. Marc Facciotti directs the student-research-focused TEAM Molecular Prototyping and BioInnovation Laboratory, so we were well prepared to offer students both foundational knowledge in biodesign and access to the tools that teams would need to be able to innovate new solutions. We sought a balance of students from the biosciences, engineering, and design, which we basically achieved in the enrollment along with students from a few other majors on campus. Our class combined students from design, economics, biophysics, biology, cell biology, neurobiology-physiology-behavior, cognitive science, genetics and genomics, animal science, sustainable environmental design, chemical engineering, biomedical engineering, and material science and engineering.

For practical reasons of cost limitation and laboratory facilitation, and because we hoped to advance knowledge about a particular material, Facciotti and I chose to limit all teams to innovating with bacterial cellulose (BC). Most commonly in the last few years, BC has been grown as a textile for fashion design using the health drink kombucha as its growth media [10–12]. Bacterial cellulose produces a purer form of cellulose than that available through cotton, which also has lignin in the fibers; BC can also be grown in sheets rather than needing to be made into thread first. However, it is challenging as a textile because it is very hydrophilic, manifests with various textures—more or less brittle, soft or durable—and has proven difficult thus far for scaling up in production cost-effectively [13].

General questions that we posed to the students at the outset of the course ranged from ideas about the life cycle of bacterial cellulose and the potential of creating "healthy fashion," to ways to alter BC's material properties, understand or shift consumer distrust of a material made by bacteria, and discover ways to scale up cost-effectively. Specifically, we asked them to consider:

(1) If kombucha is a probiotic healthy drink, and our microbiome covers our body inside and out, could wearing clothing made by kombucha bacteria and yeast affect our skin health? For example, could biodesign fashion help dermatitis or other painful skin conditions?
(2) Given that BC is hydrophilic, what products might make use of this capacity? Are there biodegradable additions that could make it hydrophobic to increase its versatility? How can we address the smell, which bothers many people?
(3) Despite growing knowledge of the human microbiome, many consumers are still afraid of bacteria. What will consumers think about bacterial cellulose as a material for clothing, products or interiors, and how can we overcome this hurdle?
(4) Using the production of the dessert nata de coco as precedent, can we address the challenges in scaling up in production, making BC production more economically viable? What if BC is grown not with tea and sugar but with local

agricultural waste, such as grape bagasse, milk whey, or the juice from the abundant citrus that falls from trees here?

To help us consider answers to these questions, we invited research professors from other departments on campus to speak to us about how BC is used in their profession. We learned from Dr. Rivkah Isseroff how BC is being used for wound dressings, moreso in Europe than in the USA, and how it aids skin healing [14–17]. Dr. Daniela Barile in Food Science and Technology explained the differences between prebiotic and probiotic and considered how the drink kombucha and BC functioned nutritionally. She cautioned us against misusing the word "probiotic" in the marketing of our student innovations. Dr. Stephanie Maroney (then ABD) explored aspects of the microbiome and the sheer complexity of ascertaining which species of bacteria make up the biome, much less how they interact with each other and the human body. Dr. You-Lo Hsieh, a chemist who works in Textiles Science, explained the molecular structure of cellulose, the reasons for its hydrophilicity, and how natural and synthetic dyes interact with this molecular structure. These professors became mentors later on during the course for different teams whose project designs required more insight from their specialties.

We spent the first ten weeks in the classroom gaining foundational knowledge about bacterial cellulose and then brainstorming ideas for product innovation. We formed eight teams, of three to four students per team, based upon their common interest in a particular problem or product and interdisciplinary diversity and balance. We strove to have every student on a team come from a different major, so as to impart greater diversity of skills and knowledge to the team. Ideally, we aimed also to balance teams by having one bioscientist, one engineer, and one designer, owing to the different methodological approaches and frameworks that these disciplines generally tend to foster.

Teams proposed to use bacterial cellulose to create: biodegradable packaging; feminine hygiene products (tampons and sanitary pads); diapers; air filtration panels for health-giving interior decoration; water filters for purifying arsenic-contaminated water; a shopping bag that also functioned as a backpack; an armband with embedded sensor that could monitor health function, readable through an app; and fast-fashion sandals with mycelium soles that were easily biodegradable.

Over the second ten weeks in the TEAM laboratory and design prototyping laboratories, students experimented with the material and created prototypes of their ideas for the competition. They learned how to waterproof BC using a corn zein protein [18], different ways of layering and drying the sheets to strengthen it and make it more durable, and the effects that different types of dyes had on the material in terms of softness and suppleness. Two teams grew BC using waste citrus juice rather than tea in the primary media, which resulted in softer and more pliable cellulose sheets [19]. One team designed a DNA plasmid with the ArsR gene to chelate arsenic, which they inserted into the cellulose-producing bacteria *Komagataeibacter rhaeticus iGEM* to use as a water filter; they imagined also that the cellulose would be engineered to change colors in the presence of various contaminants. Another tried to infuse BC with the bacteria *Xanthobacter autotrophicus*, which has the capacity to degrade the chemical 1,2 dichloroethane (DCE) that offgases from PVC and vinyl, thereby purifying the air in interior spaces, especially that of a PVC factory [20]. Finally, two teams successfully created BC aerogels that are exceptionally lightweight and absorbent for use in their packaging material and diaper designs [21].

Because the Biodesign Challenge generally only allows one team from a participating university to compete in New York, we invited a panel of judges to decide which of our teams would have that honor. They unanimously selected the team that created the biodegradable diaper, branded as Sorbit, short for Ab-sorb It. This team consisted of biomedical engineering freshman Jolee Nieberding-Swanberg, material science and engineering sophomore Annie Wang, design and economics double-major sophomore Julie Xu, and genetics and genomics senior Sergio Gonzalez.

Team Sorbit tackled the huge problem of the 3.4 million tons of landfill waste each year in the USA alone that come from conventional diapers [22, 23]. These take approximately 450 years to biodegrade in the open air (even longer in a landfill), and the energy and carbon footprint of eco-diapers or cloth diapers is still very high, with CO_2 equivalents close to driving 1400 miles [24, 25]. Their solution to the problem, the Sorbit diaper, is an almost fully closed-loop design made of bacterial cellulose grown from inexpensive local waste citrus juice, sugar, ethanol, and acetic acid, seeded with kombucha. The outer layers are treated with the corn zein protein for hydrophobicity to prevent the diaper from leaking. It is lighter weight than conventional diapers owing to its aerogel absorbent core, which was shown to be 32% more absorbent to point of saturation than the sodium polyacrylate used for the absorbent core in conventional diapers. This lighter diaper weight results in a lower overall CO_2 footprint for transportation to retailers. The team focused only upon urinated diapers, owing to the public health issues in the USA about human feces disposal. The urinated Sorbit diapers are fully compostable, and the team imagines seeding the external BC layer of the diaper with mushroom spores for faster biodegradability. The resulting compost can be used to grow more citrus or other crops, as it replenishes soil with nutrients.

In its overall life-cycle analysis, the primary material inputs are low-processed and food-grade quality, apart from the fuels used in transportation. The primary energy involved comes from the process of material acquisition and energy for freezing, freeze-drying, and transportation. The only wastes are the acidic liquid media after the growth of the BC (which, with further experimentation, can likely be reused) and the pollution caused by transportation and the generation of electricity. Eight-eight and one-half percent of the parents they interviewed said Yes or Maybe, they would try BC diapers, with their primary concerns being the baby's comfort, absorbency, and material of the diaper [26].

Team Sorbit won two of the six prizes at the 2018 Biodesign Challenge competition, Runner-Up overall, and Outstanding Science. Although Sergio has graduated, the team is still collaborating, recently submitting their product design to Proctor and Gamble's Receptor Incubator Challenge.

3.3 Discussion

Apart from being the most rewarding teaching experience that I have ever had, with many students in the course saying the same thing about their learning experiences, what does this interdisciplinary process of competing for the Biodesign Challenge demonstrate that is relevant for sustainable biodesign innovation?

This process is like a low-stakes, mini-version start-up innovation, and entrepreneurship experience. In other words, just as start-ups (that already have a good idea) are encouraged to create inexpensive prototypes at the outset in order to learn the most the fastest with the least cost outlay, this interdisciplinary classroom experience (which had minimal laboratory costs and travel costs for the team) serves as an inexpensive prototype in answer to the question: How can industry innovate for sustainable biodesign? Having students or employees from different disciplinary backgrounds work closely and rapidly together on innovation is efficient, effective, engaging, and energizing for a number of reasons. To expand upon this with an eye toward teams containing bioscientists, engineers, and designers, consider the complementarity of the general core theoretical knowledge, technical training, approaches, foci, and skills of individuals trained in each of these three areas.

Biodesign uses living materials, most commonly plants, animal cells, bacteria and yeasts, as part of its process or outcome. This means that knowledge of the functioning of plants and eukaryotic and prokaryotic cells is important for understanding not only the needs of these living entities but also how any changes introduced might have effects. Cells, much less multicellular organisms, are complex biological systems consisting of a permeable membrane, organelles, cytoplasm, and genetic information system. They have metabolism and capacity to reproduce, and they interact with their environment not just for food and to deposit waste but also in other chemical ways, health-giving, or disease-inducing. They respond to physical forces as tensegrity structures, and within the structure of tissues, they have filaments that extend from the nucleus through the cell membrane beyond to the extracellular matrix [27–31].

Because of their complexity and environmental interactions, cells and organisms behave uniquely, even if patterns are predictable, and they produce variable outputs in different contexts. For this reason, bioscientists are trained to work in laboratories with standard equipment, processes, and software, use the scientific method including controls in their experiments, and aim for reproducibility in experimentation, such that results of experiments can attain the status of knowledge upon which others can build. Often, biological research pursues knowledge in and of itself in pursuit of the understanding of life, although depending upon which field of bioscience in which one specializes, this knowledge frequently leads to applications in agriculture, medicine, biomedical engineering, biotechnology, etc.

This focus upon application inheres to training in the engineering disciplines, where control and predictability function as core values for successful design. Engineers have foundational knowledge of physics, chemistry, and perhaps biology, and they work to improve and develop new technologies for useful ends. They possess knowledge of the physical properties of different materials and the effects of forces on materials, which they use to develop tools, techniques, or products with improved functionality. In their methodology, engineers have traditionally followed what is called the "design waterfall" or "design cascade," which is similar to "design thinking" in its steps. These steps entail conception, initiation, analysis, design, construction, testing, and deployment; in the past, these generally were treated in linear fashion, with each prior stage completed before the subsequent stage begins. This rigid structure is made much more flexible and iterative by the "agile model," where portions of the design process proceed in team-based "sprints" which involve the user throughout the design process rather than just at the beginning [32]. Engineers are trained to use a variety of software and visualization tools, finite element analysis, and 3D printing and machining, etc., so they bring these useful prototyping skills to collaborative design efforts.

Even more than engineers, designers are skilled in user experience research and user interfacing, for in general, they have functioned professionally as the intermediaries between engineers or companies and consumers. This is often described in the field as being "human-centered," a value that is deeply important alongside social and environmental responsibility. Designers work to understand social, political, and economic contexts and to factor this knowledge into their design processes and outcomes. They are taught formal aesthetic principles for strong visual and information design, which can be applied from 2D to 3D to time-based formal structures, and many are introduced to effective branding and marketing strategies. More recently, design educators are introducing life-cycle assessments and closed-loop design, in order to help designers take material, energetic, and pollution considerations into their choices of which materials they use, which tools these require, and how to design for disassembly and recycling.

"Design thinking" is one prominent design methodology that, owing to its effectiveness for innovation, has been applied in many other disciplines, particularly in business management. Its core steps are to empathize, define, ideate, prototype, and test; these steps are used linearly, circularly, and iteratively to arrive at a successful outcome [33–35]. The empathy step not only reflects the human-centered nature of design but also entails significant user research, with the need for open-minded understanding and listening on the part of the designer. The ideation step famously is captured by images of multitudes of post-it notes with scribbled ideas on them covering a wall; it is best performed standing up and moving and thinking quickly. The goal in the prototyping phase is to inexpensively and creatively gain the most information possible in the last amount of time [35]. Designers work both by hand and digitally, using drawing implements and shop tools for different materials, as well as software for design and visualization, 2D graphics, web, and information design, 2D laser cutting, and 3D printing and CNC milling.

When individuals collaborate from these three disciplines or others, they are forced to communicate their different assumptions and approaches in order to work together. For example, how will they proceed through and merge the "design waterfall," "agile design," and "design thinking" processes? What fits their specific research and product design needs? Even if each participant does not grasp the full explanation of various ideas or processes shared by others as they discuss how to achieve their goals, they are exposed to new ideas, considerations, methods, and possible outcomes simply by listening to and trusting their teammates. They all learn from each other by doing and watching, broadening their conception of what they thought was possible in the design process and, potentially, raising their standards about what counts as a successful sustainable biodesign innovation.

The projects that our teams tackled and the laboratory experiments and prototyping that were part of their development would never have been possible in 12 weeks if only designers were working together, or only bioscientists, or only engineers. Designers are not trained in designing DNA plasmids or trying to hybridize bacterial cultures to introduce a new bacteria for particular chemical effect in the overall functioning. Yet on a more basic level, even, designers generally are not laboratory-safety trained and do not know when to use a vent hood, centrifuge or incubator. They also do not read scientific articles that give them the idea to turn BC into an aerogel so as to attain new material properties that offer increased functionality.

Similarly, bioscientists do not usually conduct user interviews or consider, say, the wall panel forms—shape, color, size—in which the new bacterial colony will be grown and shaped. They are not trained in software that lets them mock-up how the panels will be arranged and function in a virtual interior space. Engineers may be satisfied with attaining predictable functionality—for example, UC Davis's winning iGEM olive oil rancidity detector (2014)—but leave the human interface of the casing material, ergonomics, and aesthetics for a designer to add on later [36]. This sequence extends the timeframe of the overall process of design to production, especially if the technical portions could be arranged differently early on to better final user success and the engineer receives this feedback then.

In the workload distribution during the experimentation and prototyping phase, we observed a complementarity of effort both in terms of skills and action and in sequence. Those more comfortable with laboratory experimentation took the lead early in the quarter as teams tried to discover how they could attain the material functionality they sought. Ten weeks go by very quickly, and often the experiments continued up to the deadline of the day of our local competition. The designers participated in formulating the desired functionalities and in hands-on experimentation, thus gaining very useful laboratory skills. With teammates, they interviewed potential users, conducted surveys, and even talked with innovators at other biomanufacturing start-ups. (This has, in fact, led to an ongoing internship and potential job for one design student after she graduates). One spent weeks learning how to use Arduino circuits so as to integrate them into a BC armband. The designers spent the bulk of their time, however, on collaboratively creating the name and brand, doing photograph documentation, designing the poster, Web site, video, and the finished form of the physical prototype.

This ten-week interdisciplinary blitz can be a strategy used by companies to spur innovation. The architectural firm The Living, headed by David Benjamin, does something very similar to this in their "Flash Research" projects. These projects entail the quick and inexpensive exploration of new ideas, in three months or less, for $1000 or less, through the making of full-scale functional prototypes. Some of the projects involve collaborations with artists, musicians, engineers, and scientists. "We are not scientists," Benjamin writes, "but we have developed methods for collaborating with these experts to explore new questions and uncover results that would not be possible either by us alone or scientists alone" [37]. "We use some of the protocols of science—including reviewing existing literature, developing hypotheses, testing multiple conditions, aiming for verifiable and reproducible results, and publishing our findings," but he adds that their form of research is more "open-ended" and seeks applied rather than "pure knowledge" [37].

3.4 Conclusion

When teams of bioscientists, engineers, and designers (as well as other specialists) come together to tackle a problem, aiming for a sustainable biodesign innovation as the result, the process becomes a catalyst for new modes of thought, process, and production. This process stretches each individual beyond her comfort zone and sparks curiosity and joy from learning something new and accomplishing something not possible by oneself or within one's own discipline. Perhaps this is why both the instructors and students involved in the Biodesign Challenge two-quarter course at UC Davis found the learning process so energizing, invigorating, and effective. We pushed beyond past practices of having engineers first design a functional product followed by designers then coming into "touch up" its exterior surfaces or complete the human-centered requirements or branding adjustments. By putting designers into to mix from the outset, their creativity and insights shape the design all the way through, so that each successive iteration has the possibility of being further along or more thoroughly considered at each stage. Similarly, because biodesign entails biology, bioscientists offer crucial insights about the needs and infrastructures of living systems and potentialities or lack thereof of standardized outcomes at the end. Biodesigns are often unique, variable, perhaps even short-lived, although usually death enters somewhere in the production process owing to the need for stable end products to result.

To return to the framework of the field of design, few designers working in the field today have had experience in biology. Introducing them to biodesign and having them learn fundamental biological considerations that come with working with living materials gives them a much deeper understanding of and questioning about what counts for sustainability, and it often shifts their expectations from perfect predictability to the beauty of natural variability. Designers still serve as the intermediaries between industry and consumers, so even in biodesign production, in order to shift the consumer mindset toward greater consciousness of the importance of life-cycle assessment and variability, first we need to accomplish this with designers. The process of interdisciplinary sustainable biodesign innovation is a fantastic way to cultivate this, whether in academia or in industry.

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Chapter 4
Needs-Based Workshops for Sustainable Consumption and Production in Vietnam

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Abstract This paper focuses on the fulfillment of fundamental human needs in the achievement of sustainable consumption and production (SCP). Here, we focus on the Human-scale development (HSD) theory proposed by Chilean economist Max-Neef, in which the following nine fundamental needs are introduced: subsistence, protection, affection, understanding, participation, idleness, creation, identity, and freedom. In HSD, an important role is played by satisfiers, which are ways of fulfilling the above-mentioned fundamental needs in a particular context, such as climate and culture. From the standpoint of a producer, satisfiers are regarded as the starting points of product development for SCP. This paper introduces the opposite concept, referred to as a barrier—a factor that interferes with fulfilling fundamental needs. The purpose of this paper is to determine the satisfiers and barriers for younger people in Vietnam based on the results of needs-based workshops. Around 1200 satisfiers and barriers were extracted; however, barriers were largely equivalent to satisfiers. We found that the concept of satisfiers is useful to achieve SCP, because it is comprehensive, realistic, and provides an opportunity for social practice.

4.1 Introduction

Humanity is currently facing many severe global crises, such as biosphere integrity loss, climate change, non-fulfillment of basic human needs, inequality, and social exclusion [1–3]. All of these issues are intricately linked with one another. In order to solve these problems, we must recognize them in a comprehensive manner. Along these lines, the United Nations formulated the Sustainable Development Goals (SDGs) in 2015 as a comprehensive framework for solving the most pressing social and environmental challenges facing humanity. Sustainable consumption and

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production (SCP) of industrial products was set as one of the SDGs to be achieved in all regions. Here, SCP is defined as the use of services and related products which respond to fundamental needs and contribute to a better quality of life while minimizing the use of natural resources and toxic materials as well as the emission of waste and pollutants over the life cycle of the service or product so as not to jeopardize the needs of future generations [4]. This paper focuses on basic human needs because SCP is necessary for all people.

In the real world, many approaches have been applied and implemented in the name of sustainable production, such as eco-product development and cleaner production. On the other hand, sufficiency of basic needs has not been understood precisely. A producer should recognize that it is increasingly necessary to develop essential products for everyday life. Here, "sufficiency" is the concept of an alternative economic model of consumerism and an important component of a sustainable lifestyle [4]. In terms of material flows, we tend to see over-consumption in developed countries and under-consumption in developing countries. However, as increases in population and economic growth in developing countries continue, then the consumption patterns of lesser-developed countries may become similar to those of developed countries. We assume that not only resource-efficient production but also "basic needs-sufficient production" are both important for achieving SCP around the world. In this paper, "basic needs-sufficient production" implies that appropriate products satisfying a consumer's basic needs are produced for each region or country. Over-production and over-consumption of industrial products are to be avoided.

In order to achieve production that maximizes consumer's sufficiency, we focus on the concept of "satisfiers" as proposed by Chilean economist Max-Neef, which are factors associated with the realization of fundamental needs [5]. In other words, satisfiers can be regarded as enablers for SCP. Furthermore, the opposite concept of "barriers" which interfere with the fulfillment of fundamental needs has recently been introduced. Barriers are regarded as hurdles to fostering SCP. The purpose of this study is to determine satisfiers and barriers for younger people in Vietnam using a needs-based workshop method.

4.2 Related Works

4.2.1 Human-Scale Development

Human-scale development (HSD), which was proposed by Max-Neef, is an approach to support endogenous development processes proposed [5]. HSD consists of three interdependent elements: self-reliance, balanced relationships, and human needs satisfaction. In HSD, fundamental or basic human needs are categorized from two perspectives, the axiological and the existential. Based on the axiological perspective, the following nine needs are introduced: subsistence, protection, affection, understanding, participation, idleness, creation, identity, and freedom. From the existential perspective, the fundamental needs are categorized into being, having, doing, and interacting. On a matrix of the axiological and existential needs, satisfiers are identified. Satisfiers express the ways of being, having, doing, and interacting associated with the realization of needs. For instance, examples of the satisfiers for subsistence extracted at the workshop held in Spain included being empathetic (being); education that stresses values, equality, and freedom (having); valuing time over money, thereby redefining fundamental needs (doing); and refraining from speculation, and having a natural environment that lies at the center of municipal decision making (interacting) [6]. Max-Neef's need matrix has been applied in various contexts, such as requirements engineering [7] and conflict analysis [8]. Max-Neef proposed a workshop method using the matrix to extract satisfiers [5]. He also suggested utilizing a negative matrix to extract things necessary to overcome for social change to occur. Guillen-Royo et al. have also organized and facilitated needs-based workshops for extracting satisfiers using negative and utopian matrices [6, 9]. Their workshop methods [6, 9], however, seem to bring about some confusion because elements in both the negative and utopian matrices are called "satisfiers." Indeed, Max-Neef classified satisfiers into five types, namely (a) violators or destroyers, (b) pseudo-satisfiers, (c) inhibiting satisfiers, (d) singular satisfiers, and (e) synergetic satisfiers [5]. In this study, we introduce the concept of "barriers" to avoid confusion about definition of satisfiers, which interfere with the fulfillment of fundamental needs, to facilitate the construction of a negative matrix.

4.2.2 Living-Sphere Approach for Locally Oriented Sustainable Design

Here, we show the research agenda for a producer contributing to SCP [10]. Although some approaches can be enhanced to take into account locality, more and more market-specific and highly reproducible design methodologies are being developed. In traditional eco-design approaches, the universal requirements of environmental issues related to the product life cycle process, such as disassembly and parts reuse, have been discussed and eco-design methods to solve them have been developed. From the standpoint of SCP, the sufficiency of consumers' basic needs should be more explicitly reflected in product design.

One of the approaches for this requirement that has been proposed is referred to as "the living-sphere" [11]. This approach has been used to model and design products that completely satisfy fundamental needs in daily life. Here, it is assumed that fundamental needs are fulfilled by activating the satisfiers proposed by Max-Neef [5]. Multi-products are connected to satisfiers in a framework of the living-sphere approach (Fig. 4.1). Therefore, extracting adequate satisfiers is a key task for the living-sphere approach.

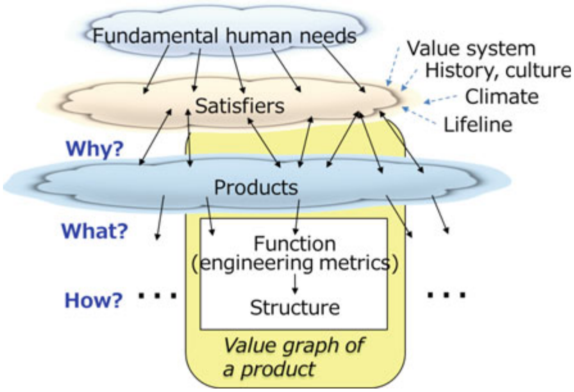

Fig. 4.1 Schematic of the living-sphere approach framework [11]

4.3 Method

In this paper, satisfiers and barriers in Hanoi, Vietnam, were extracted using a needs-based workshop method proposed by Max-Neef [5, 6]. Characteristics of the participants are shown in Table 4.1. Twelve participants were university students and ten were younger workers, while all were under forty years old, because satisfiers are to be used to develop the future SCP after 10 to 20 years. They were chosen by VASS having full knowledge about their local condition. Participants were divided into four groups: six students for extracting satisfiers, six students for extracting barriers, five employees for extracting satisfiers, and five employees for extracting barriers.

The procedure of the workshop was as follows.

Step 1: Introduction.

- Introducing the purpose of the workshop.
- Dividing the participants into four groups as mentioned above.
- Explaining how to identify satisfiers or barriers.

Step 2: Identifying satisfiers or barriers by group.

- Each participant considers satisfiers or barriers for each element of the matrix shown in Table 4.1 and writes them on a sticky note (1 min).
- Participants share the satisfiers or barriers they thought of with their group (2 min). Other satisfiers or barriers can be added during group discussion.

Table 4.1 Characteristics of participants in the workshops

	Sex		Social identification		Total
	Men	Women	Students	Employee	
Number of participants	11	11	12	10	22

- A facilitator counts the number of participants who agree with satisfiers or barriers (1 min).
- A facilitator selects the satisfiers or barriers agreed upon by more than half of the participants in each group.

Step 3: Synthesizing a matrix of satisfiers or barriers made by students and employees.

4.4 Results and Discussion

During the workshop to extract satisfiers, we found there were also some advantages for realizing SCP as well:

1. It creates opportunities to relativize a capitalist market in which societies are embedded into the economy and commodities are connected directly to consumers' needs as a collective of individual needs. This gives us insight into alternative social systems for SCP.
2. It creates opportunities to relativize the mode of "having," mainly having commodities as a result of commodity fetishism, with other existential modes, including "being" as self-reflection, "doing" as changing, and "interacting" as relationships with other human beings as well as nature. It is important to recognize that a commodity is not a final purpose but a means of satisfying a need and to think about alternative forms of ownership such as sharing. "Having" appropriately designed commodities could facilitate appropriate social practices. This could embody satisfiers for the participants themselves and the sharing of others' satisfiers as they recognize the capability of individuals and society.
3. It enables the visualization of the relationship between satisfiers: satisfiers that satisfy one particular need and in turn inhibit the satisfaction of other needs (inhibiting satisfiers), satisfiers that satisfy one particular need only and are neutral in regard to the satisfaction of other needs (singular satisfier), and satisfiers that satisfy a given need while simultaneously contributing to the satisfaction of other needs [5]. Although Max-Neef did not state as much, it could also be used to visualize the relationship of satisfiers with others in the same society. This is important as we seek to make SCP effective and comprehensive.

Here, we discuss the concrete results from the workshop. The one-day workshops were conducted in Hanoi, Vietnam, in September 2018. A total of 715 satisfiers and 501 barriers were extracted. In Appendix Tables 4.2 and 4.3, only satisfiers receiving the approval of three or more participants are shown. As most "having" frames for barriers were answered in the style of "don't have," most of the answers can be considered as satisfiers rather than barriers. The number of common satisfiers between the students and the employees was 107.

There are some important findings on the rapid changes in Vietnamese society. For example, before rapid modernization in the twenty-first century, family was seen as a "cell" in Vietnam. It is the satisfier at the base of almost all needs, particularly "subsistence." Now, however, its function seems to be limited or altered. On the other hand, "games" has become a very popular and basic satisfier for young urban adults in Vietnam as shown in Appendix Tables 4.2 and 4.3. In the case of working adults, it emerged in many frames of needs, even in those of "creativity need," where it appeared as game programming. We can surmise that workers play games individualistically. On the other hand, when students were asked, it emerged only in the frames of "leisure need" even though they play game both individualistically and collectively. These respondents usually organize networks to play games apart from their family and local communities. It is therefore important to reconsider how we think about the living sphere.

We focused on the results of "having" a commodity to further explore SCP. Based on a structural comparison between students and young working adults, we found that satisfiers for "having" a commodity in the case of the students were more diverse, ranging from very abstract concepts to very concrete needs that are closely related to social change. In addition to "money," "food," "clothing," and "shelter," young working adults mentioned only "self-defense tools," "insurance," "books," "facilities" (Internet access and a personal computer), "games," "novels," "cars," and "personal assets." On the other hand, students mentioned "materials," "assets," "water in general," "self-defense tools," "sanitary space," "arms," "fire extinguishers," "a good health care system," "presents," "movies," "books," and "games." A distinctive feature of the satisfiers of the students is that money emerged in 7 of the 9 frames of basic needs, in contrast with 3 of the 9 in the case of young working adults. We can see how money is rapidly subsuming most of the basic needs as a satisfier of a specific commodity in the case of students.

Moreover, most student satisfiers are meaningful in their capacity for social change. For example, "water in general" as distinct from "water to drink" is an important satisfier in Vietnam. In 2016, the country had its worst ocean pollution ever. This may have caused the students to gain a wider perspective and help them recognize this satisfier as a basic societal need, which is different from "water to drink" as an already well-recognized satisfier of individuals. Another interesting satisfier is the fire extinguisher. In this case, a situation caused by a changing society arouses the satisfier. In recent years, apartment housing has become more prevalent due to urbanization. In 2018, Vietnam's worst-ever high-rise apartment fire occurred. Many of the affected apartments were found to have poor fire protection systems. It is interesting that for the same need of protection, students selected the same satisfier, the fire extinguisher, but in a different mode. A subsequent public safety awareness campaign included fire safety tips.

Social practice theory provides some means to understand this case [12]. Usually, a practice emerges as a visible individual performance. According to Shove, a holistic social practice exists behind an individual practice. This is a combination of three components: materials (objects, tools, and infrastructures), competence (knowledge and embodied skills), and meaning (cultural conventions, expectations, and socially shared meaning) [12]. As this is also routine, the complex will be reproduced in daily life. The example of "fire protection" as a satisfier for students in Vietnam shows that asset satisfiers of Max-Neef's method could help show the capacity for new social practices to emerge. Moreover, such workshops as ours could be used to recruit new practitioners while exchanging ideas. In the case of "fire protection," we see an expectation of safety within society.

As expected, only a few commodities for conspicuous consumption emerged as satisfiers for basic needs. No electrical home appliances or even smartphones are listed, but the results do include cars and computers. The perspective of the workshop in Vietnam was very wide and vague. Because Shove emphasized the role of materials in the complex of social practice [10], we may reconsider their roles and design products oriented around a living-sphere approach framework.

4.5 Summary

In this paper, around 1200 satisfiers and barriers for young people in Vietnam were chosen based on needs-based workshops, but many barriers could not be analyzed because they were equivalent to satisfiers. Based on the comparison of satisfiers between students and employees, we found few commodities of conspicuous consumption as satisfiers for basic needs. We conclude that the satisfier is a useful concept for achieving SCP. Extracting and comparing satisfiers between different countries will be future topics of research. A facilitation method to extract barriers is to be developed, too.

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Appendix

See Appendix Tables 4.2 and 4.3.

Table 4.2 A matrix of satisfiers extracted from students

	Being	Having	Doing	Interacting
Subsistence	Joyful, clean, endeared, healthy, sufficient, not sick, able to work, peaceful, satisfied, active, adorable, communicable	Good spirit, food, things, healthy body, money, property, clothes, water, drinking water, knowledge, good virtue, good house, good affection	Enjoying leisure time, resting, eating, communicating, breathing, playing sports, expressing emotions, exchanging, drinking, observing, act, taking care of family, exchanging visits, doing collective activities, selling products legally, learning	Thoughtful relationship, communication, talking with each other, market mutual aid, sexual relationship, mutual concern
Protection	United, protected, educated on safety (fire prevention), cooperative, wearing a condom, paying attention to health, cooperating for crisis response, concern for others, talking, concern for community	Life skills, insurance, knowledge, protective tools, clean space, weapons, fire extinguisher, good security and environment, a house, good quality, health care system	Protecting, keeping good health, keeping peace, taking care of, assuring, feeling peace, trusting	Regular medical examination, flood prevention, creating a good environment, living rationally (scientifically), knowing ways of self-defense, living carefully, exchanging skills, migrating from dangerous places, wearing protective equipment, keeping address confidential, self-defense, maintaining one's health, enhancing community awareness, examine and treat diseases, doing well in a good situation, learning martial arts, playing sports, planning life and work
Affection	Joyful, happy, having concern, lovely, taken care, favorite, to love, familiar, mild, to respect, to trust	Real thought, a family, trust, partner, a precious person, respect, a heart, delicacy, affection, a present, emotion, money	Taking care of each other, protecting, listening and understanding, being filial to parents, being calm, traveling, concerning, sharing time, loving, cooking, going out together, sharing emotions, communicating, kissing, respecting, hugging, confessing, giving a present	Communication, holding hands, taking care of someone, hug, sharing one's true intentions, kiss, sexual relationship, looking back on an emotion, sharing an emotion, being protected, holding someone in one's arms

(continued)

Table 4.2 (continued)

	Being	Having	Doing	Interacting
Understanding	Experienced, smart, skilled, profound, intellectual, to know much about universe, having lucid knowledge, abstruse	Knowledge, quick thinking, movie or document, books, transportation, cultural understanding, seriousness, perseverance, intelligence, ability to learn, skills, life skills, experience, money, a good brain	Getting information through books and the Internet, searching for information, watching movies and reading books/magazines, learning to study, doing social activities, having experience, exchanging ideas with experts, teaching, doing a good job, traveling, talking and exchanging ideas, becoming positive	Exchanging learning, communicating knowledge, discussing in a group, learning in groups, gathering opinions, learning, participating in social activities, joining workshops, having question always
Participation	Prepared, enthusiastic, active, excited, aggressive, favorite, in a good environment, joyful, sociable, matched, charming, comfortable	Enthusiasm, authority, longing, available time, responsibility, sociability, aggressiveness, delicacy, bullishness, young power, concordance, self-consciousness, money, comfortableness of interaction	Expressing an opinion, having fun, interacting, exchanging opinions, working, reserving, participating in social activities, creating, learning, moving	Talking, playing games, playing mini-games, having opinions, going out together, working and playing together, discussing in a group, sharing emotions
Idleness	Aggressive, having enough, fresh, joyful, relaxed, active, favorite, comfortable, satisfied, matched, interested	Toys, ideas for recreation, a telephone, money, transportation, infrastructure, Internet access, a personal computer, game devices, skills, relaxing space, comfortableness, a spirit of entertainment	Calling out, visiting each other, listening to music, play, playing games, watching a movie, inviting guests over, hosting a game, telling a joke, participating in social activities, reading books, playing healthy and non-addictive games, making plans to go out as a group	Group participation, talking with each other, playing sports games, exchanging ways to play better, speaking one's mind to each other, hosting and exchanging in games, communication

(continued)

Table 4.2 (continued)

	Being	Having	Doing	Interacting
Creation	Concentrated, wise, having a theme, acceptable, confident, excited, comfortable, having new ideas, thoughtful, free-thinking, free, smart, clear	Insight, ideas, money, understandings, good thinking, dexterity, private time, fun, sharp thinking, seriousness, colleagues with same idea	Drawing a picture, deciding, studying, trying, challenging to think and do, investing, thinking, doing unordinary things, understanding, listening to feedback, working to exchange ideas, playing	Participating in group activities, considering the opinions of others, approaching information, collecting feedback, having workshops, playing in groups
Identity	Official, active, responsible, strong, free, cultural, familiar, sociable, with family, earnest, enthusiastic, traditional, aggressive	Good health, talent, own culture, name, self-consciousness, one's own hairstyle, a spirit of freedom, sensitivity, traditional clothing, good-looking, a slim body	Maintaining ethnic characteristics, maintaining and developing, having and participating in ceremonies, understanding characteristics of ethnic groups, understanding the party's political agenda, wearing glasses, getting a tattoo, haircut, extra-curricular activities, private life, teaching each other life skills, considering, making a revolution, dyeing hair	Participating in a ceremony, cultural enlightenment activities, playing games, gathering opinions, exchanging, workshop, group dating, eating together, fashion contests, living with brothers and close friends, drinking alcohol cooking class, bullfighting
Freedom	Relaxed, comfortable, joyful, tipsy, to harmonize with the natural environment, to sympathize, to make a leap forward, calm	Own living space, money, private space, spirit, rights and interests, personal hobby, oneself, conformity, personal belongings, favorites, bachelorhood	Dancing, reading books, doing as one pleases, expressing emotions, spending money, traveling, singing, talking, singing the national anthem, flying, running and jumping, listening to music, exercising one's rights	Going out and traveling together, going out with my best friend, exchanging, learning, theater, workshop, cooking, one's own room, listening to music, dancing, sleeping, watching a movie, singing in front of a lot of people

Table 4.3 A matrix of satisfiers extracted from young employees

	Being	Having	Doing	Interacting
Subsistence	Joyful, happy, healthy, sufficient, optimistic	House, food, money, drinking water, clothes	Maintaining personal hygiene, enjoying leisure time, working, breathing, eating, drinking, resting, exercising	Exchange, environmental protection, loving, conversation, shopping (exchange), interaction
Protection	At home, helping a loved one, healthy, in a safe place, sufficient, helping children, protected, economically independent	Money, a job, a house, a family, protective tools, insurance	Regularly getting a checkup, having interests, helping, sharing, doing yoga	Following traffic rules, environmental protection, tree planting, enlightenment to prevent bad acts
Affection	Loving, happy, familiar, bustling, laughing, joyful, crying	Being treated well, care, sharing, love, loved	Loving, sharing, giving presents, kissing, hugging, taking care of someone, holding hands, having interests, consulting someone, trusting	Playing happily with friends, playing with children, loving, gathering as a family, traveling, taking care of one's family, reading, interaction, enjoying leisure time
Understanding	Studying hard, erudite, studying, higher education, knowledgeable (versatile), language	Books, teachers, knowledge, schools, wisdom, equipment (ex. Internet access, computer), qualification	Studying, reading a book, creating, inventing, observing, teaching, following the law, writing	Group learning, no smoking, maintaining environmental sanitation, following the law, courtesy, standing in line at a store, following company regulations, following traffic rules, petting animals, helping a friend or colleague, devotion to parents

(continued)

Table 4.3 (continued)

	Being	Having	Doing	Interacting
Participation	Enthusiastic, excited, joyful, passionate, sociable, joyful, enthusiastic, familiar	Work procedures, work sharing, responsibility	Expressing an opinion, participating in social activities, participating in charity activities, going to work, going out, getting ready, selling, going to school	School, charity group, friends and social group, community, group, organization, NPO, WHO, church, art, organization for maternal and child health, neighborhood association
Idleness	Fresh, listening to music, sleeping, comfortable, quiet, reading a book, playing a game	Books, games, novels, having a car	Taking a walk, sleeping, playing a game, traveling, reading a book, laughing, playing, having a rest, visiting a temple, participating in social activities, sightseeing, tree planting, shopping	At home with one's family, gathering as a family, place for amusement, gathering with friends, ocean, park, climbing, homecoming visit, talking, supermarket
Creation	Imaginative, bustling, studying, thinking, demanding learning, active, inventive, conscious	Wisdom, patent, imagination, sensibility	Drawing a picture, programming, designing, inventing, stage acting	New employee, film school, stage, theater, classroom, debate, resort, practical game program
Identity	Aggressive, calm, enthusiastic, lively, sociable, mild, delicate, diligent	Charm, beauty, preparation, friendliness	Laughing often, traveling, always having fun, loving to see my friends, visiting a temple, going out often, liking swimming, liking taking pictures, exchanging often, playing games often	Loving charity activities, loving traveling abroad
Freedom	Sleeping, meditating, going out, having independence, listening to music, being single, doing yoga	Gender equality, self-reliance, economic independence, freedom of speech, having money, ownership of personal assets	Writing, voting, talking, playing, traveling to one's favorite place, selecting, playing games, shopping, drinking and eating, going to a café, traveling, listening to music	Amusement facilities, airport, game center

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Chapter 5
Development of an Additively Manufactured Adaptive Wing Using Digital Materials

Stefan Junk, Philipp Gawron and Werner Schröder

Abstract The ability to change aerodynamic parameters of airfoils during flying can potentially save energy as well as reducing the noise made by the unmanned aerial vehicles (UAV) because of sharp edges of the airfoil and its rudders. In this paper, an approach for the design of an adaptive wing using a multi-material 3D printer is shown. In multi-material 3D printing, up to six different materials can be combined in one component. Thus, the user can determine the mixture and the spatial arrangement of this "digital material" in advance in the pre-processing software. First, the theoretical benefits of adaptive wings are shown, and already existing adaptive wings and concepts are explicated within a literature review. Then the additive manufacturing process using photopolymer jetting and its capabilities to print multiple materials in one part are demonstrated. Within the scope of a case study, an adaptive wing is developed and the necessary steps for the product development and their implementation in CAD are presented. This contribution covers the requirements for different components and sections of an adaptive wing designed for additive manufacturing using multiple materials as well as the single steps of development with its different approaches until the final design of the adaptive wing. The developed wing section is simulated, and qualitative tests in a wind tunnel are carried out with the wing segment. Finally, the additively manufactured wing segment is evaluated under technical and economic aspects.

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5.1 Introduction

Adaptive wings can change their shape during the flight and thus adapt to different flight conditions, for example, at takeoff, landing, on the cruise and high or low airspeeds. Conventional rudder pads have many sharp edges and transitions that increase drag and noise emissions. In many adaptive wings, the actuators are completely inside and it creates a continuous surface without interruptions for example rudder. This reduces drag and noise emissions while increasing efficiency.

Early in the manned flight, the Wright brothers used adaptive wings. They developed a kite, which consisted of a wooden frame covered with French satin fabric. Together, this resulted in a stable, light and flexible construct. Due to cable pulls, the fabric could be deformed specifically. The steel-wire-reinforced double-decker construction was rigid enough to return to its original shape after deformation [1]. However, with the development of faster and more powerful aircrafts, solid and rigid structures have been needed to withstand the increased pressures. Thereupon, the actuators necessary for adaptability were dispensed with in favor of weight and installation space. Using the technical progress in terms of miniaturization and lightweight construction, the adaptability came back into focus of aircraft engineers for a better maneuverability or higher ranges. Furthermore, additive manufacturing enables the fast and efficient implementation of adaptability.

5.2 Literature Review

Many adaptive wing concepts aim to be able to vary the buoyancy generated and thus adapt to the flight conditions. For example, a higher profile airfoil will create more lift, thereby providing more lift either at the same airspeed (e.g., higher payloads possible) or, for the same buoyancy, correspondingly reducing airspeed and saving energy. Thus, research on reducing fuel consumption in transport aircraft shows that using adaptive wings a remarkable increment of lift coefficient slope and an overall aerodynamic efficiency enhancement can be achieved [2]. The reduction of noise is also an important motivation for the development of adaptive wings [3].

The change in shape of the wing can be done in many different ways [4]. These have been subdivided into three categories: planform alternation, airfoil profile adjustment and out-of-plane shape transformation. Below are examples of corresponding approaches or systems implemented. The focus is on younger systems, preferably unmanned aerial vehicles (UAVs).

5.2.1 Planform Alternation

An adjustment of the span allows the control of the generated lift. An increase in the flow area means more buoyancy and vice versa. The "Variable AirSpeed Telescoping Additive Unmanned Air Vehicle" (VAST UAV) features telescopic wings, allowing it to change its wingspan during the flight. Fuselage and wing are manufactured by additive manufacturing. The extendable segments are reinforced with carbon rods and allow the wing to adapt to different speeds [5].

At the University of Maryland, an airfoil has been developed that can double its span from 61 to 122 cm, without relying on interleaved, extendable wing segments. The wing consists of a rib structure, which is each connected to V-shaped links. These intermediate links allow an elongation of the structure in the transverse direction of the wing with simultaneous transverse contraction number of zero, that is, while maintaining the profile thickness. The structure was generated with an acrylic-based photopolymer by stereolithography on a 3D printer [6].

Changing the sweep changes the profile that flows from the front, which affects lift. In the development of the "iMorph," Blue Bear Systems modeled the flight behavior of birds with regard to the extension and attraction of the wings. The UAV has a mechanism that allows it to adapt the wings. The extended wing is beneficial for takeoff, landing and slow flight speeds. The attracted wing, however, allows for better maneuverability and is more efficient at high speeds and windy weather. For flight searches, the "iMorph" has shown great benefits in terms of efficiency. This adaptive wing was manufactured by additive layer manufacturing [7].

5.2.2 Out-of-Plane Transformation

By a variable curvature of the generated buoyancy of a wing can be influenced, in general, a stronger curvature means more buoyancy. As part of an Air Force research program, "FlexSys" developed a variable-crown rudder with a seamless transition between wing and rudder. Due to the adaptability, the curvature can be adapted to the respective load conditions (e.g., weight reduction due to fuel consumption). For long-haul aircraft, fuel can be up to 50% of the total mass. Depending on the flight distance, an average fuel reduction of 3–5% would be possible for an average transport aircraft. In addition, the flow resistance due to the continuous surface as well as the susceptibility to icing and dirt deposits decreases due to the elimination of the joints and gouging of conventional rudders [8].

In 2012, a prototype adaptive wing with a fishbone structure was developed by Woods and Friswell. The rear area of the wing has the fishbone-like structure, which allows a change in the curvature. The prototype used fused deposition modeling (FDM) as 3D printer and ABS as material. The deflection of the rear edge is via tendons made of braided polyethylene cord, which are wound on a coil in the front spar or unwound. The outer skin of the prototype support surface is made of silicone and was created without additional fiber reinforcement [9].

Due to the distortion of the wing, the rudder flaps can be omitted and the control is done by the targeted twisting of the wing ends. In the demonstration model of a wing flyer without rudder of the West Virginia University (WVU), the aircraft is controlled in each case over the outer third of the wing. Both adaptive wing tips allow the aircraft to be controlled along its vertical, longitudinal and transverse axes [10].

The Massachusetts Institute of Technology, in collaboration with NASA, developed an adaptive wing made up of lattice structures (cellular solids). The 2D lattice building blocks were made from a carbon fiber-reinforced polymer and cut out by water jet. The use of such a grid type allows to specify the component stiffness for individual areas and thus to influence the behavior of the overall structure under load. The torsion of a wing half takes place via a CFK-spar, which is connected to a seated in the fuselage servo motor [11].

5.3 Restrictions for Design and Additive Manufacturing

The adaptive wing will consist of several components: the core profile, the outer skin, the actuators and the transmission elements. The necessary change in shape of the adaptive wing results in different requirements for the respective components. The core structure must be able to vary the curvature and should have a minimum possible mass. The profile thickness must remain the same under curvature. The skin should have a high elasticity and at the same time be as thin as possible. This is to achieve a low mass and low force necessary for the deformation. The skin is designed for a temperature range of 10–80 °C and should have high UV resistance. In addition, a gluing on plastic must be possible. The actuators require very little space within the airfoils (compact design of the actuators necessary). In addition, they must enable a backlash-free deformation of the core structure.

To implement the adaptive wing, the polyjet modeling (PJM) method based on photopolymerization is used. In the photopolymerization, viscous, non-cross-linked or low-cross-linked monomers (single molecules) are used, which are interspersed with photo-inhibitors. The photo-inhibitors prevent or delay an unwanted polymerization, but as soon as an irradiation by means of ultraviolet light takes place, the polymerization begins. The exposure triggers an exothermic reaction of several liquid monomers that chain to a solid polymer (macromolecule). During polymerization, densification of the material and thus shrinkage occurs.

In the PJM process, droplet-wise liquid monomer is applied to the build platform by means of multi-nozzle print heads and then polymerized by the UV lamps located on both sides of the print head. Model and support material are applied simultaneously. After each layer, the build platform lowers and a new layer is applied. The Stratasys J750 multi-material printer used in this article has the ability to print six different materials at the same time, for example, mixing different colors, solid or flexible materials and several materials. This results in a wide range of possible combinations as well as the depiction of a large color palette. For example, “Digital ABS” is produced from two different materials through targeted placement and combination of the individual drops. This material has similar mechanical properties to ABS to produce rigid parts. In contrast, for the flexible parts like joints a “Tango mix” with the Shore A hardness of 60 and for the intermediate links with the Shore A hardness of 50 is selected.

5.4 Design Concepts for Additively Manufactured Adaptive Wings

At the beginning, various concepts were examined to determine the deformation of the profile and thus to allow the curvature. The first version had a 2 mm thick outer skin made of digital ABS. The upper side was provided with a wave structure, which should allow improved deformability under force. To retain the profile thickness, 1 mm thick ribs were integrated, which were connected to the outer skin via small joints of flexible material at the ends. The joints should prevent the ribs from breaking off and allow a degree of flexibility. The printed segment proved too rigid and did not allow much deformation.

5.4.1 V-Shaped Structure

The structure of Vocke et al. [6], with V-shaped pontics that allow for a stretchable wing along the transverse axis, is rotated 90° to allow the profile curvature to be adjusted. The printed segment allows in the rear of an exceptionally good adaptation of the curvature of the profile in both directions while maintaining the profile thickness (see Fig. 5.1a). The front edge could be deformed a little worse, since there are only a few rows of V-members for adaptation and a short lever arm.

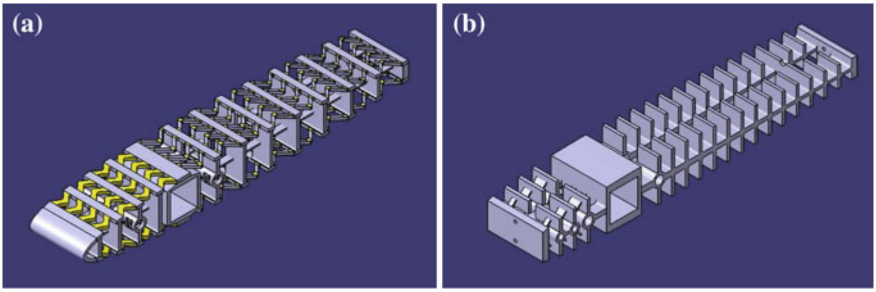

Fig. 5.1 Comparison of design concepts: **a** V-shaped structure (flexible material in yellow) and **b** Fishbone-shaped structure

5.4.2 Fishbone-Shaped Structure

As a geometrically less complex alternative for the V-limb segments, a segment is designed using the fishbone structure used by Woods and Friswell [9]. Actually, this structure is a one-sided clamped bending beam (see Fig. 5.1b). As a combined solution based on the previous prototypes, a hybrid with outboard (out of segment, not outboard) linkage with servo adapter and steel strand was created. This structure allows scaling to multiple segments using a servomotor and prevented uneven deformation of the segments since no ribs had to be recessed on one side for the servomotor. This design concept allows a very good deflection. To decouple the two ends of the power train, the vortex of a steel leader is used. Thus, the beam could be brought to tension with the thread of the soldering sleeve.

5.4.3 Actuators Concept

To control the curvature of the wing actuators are needed, which can be mounted within the core structure. Servos consist of a small electric motor, a gearbox and a control electronics. The receiver transmits a PWM signal (pulse width modulation) to the controller. This detects via the potentiometer, when the electric motor has reached the target position, and then holds this position until the signal changes. The advantages of using commercially available servos are the wide distribution and the availability in many different variants in terms of design, torque and size. Furthermore, no additional medium would be needed (e.g., compressed air). In addition, the servos can rotate in both directions, thus deforming the wing both down and up.

Figure 5.2 shows a main rib segment with a built-in servo and steel strand. The installation of the steel strand was quite complicated due to the tight installation space. The steel strand is connected to the servo horn by means of a soldering sleeve and clevis. At the trailing edge, an eyelet is formed with the steel strand and pressed by wire end ferrule. The eyelet is connected by shackle with an eyebolt. To decouple the two ends of the power train, the vortex of a steel leader is used. Thus, the strand could be brought to tension with the thread of the soldering sleeve.

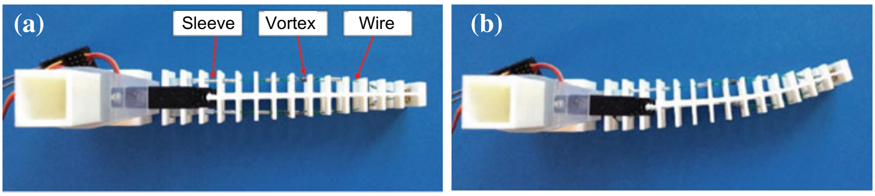

Fig. 5.2 Segment with fishbone structure: **a** zero position and **b** full deflection

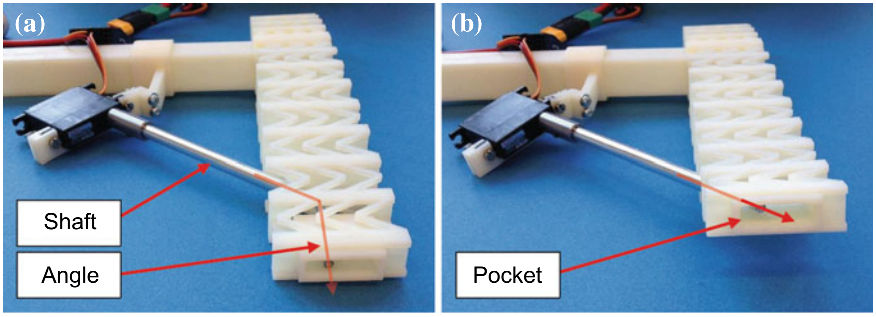

Fig. 5.3 Segment with Rotary Driver System (RDS): **a** zero position and **b** maximum deflection

As an alternative, an RDS variant (Rotary Driver System) is created. In this case, a shaft attached to the RDS adapter is rotated with an angled end. The angle is in a pocket and forces a deflection of the segment when the shaft is rotated, see Fig. 5.3. The installation of this variant is very easy, but the shaft was not in position and required additional stability for stability. The stiffness of the mount for the servo is also insufficient.

5.4.4 Selection of Design Concept

First, a qualitative consideration of the advantages and disadvantages of both variants is made (see Table 5.1). Various criteria from the fields of geometry (e.g., complexity of shape, robustness and surface) as well as assembly of actuators and deflection are taken into account. Finally, the requirements for the additive manufacturing are also observed. These include the use of the flexible material, the possibility of heat treatment and the resolution of the deposition of layers.

Due to the simpler geometry, the better-functioning slat deformation and the not tightly bound tango material (if the tango material on a V-member fails, the entire segment would be affected because the V-members are not interchangeable), it was decided to continue working with the fishbone structure.

5.5 Wind Tunnel Tests

For the test in the wind tunnel, a part of an adaptive wing with internal actuators and a length of 500 mm was additively manufactured and then assembled (see Fig. 5.4a). The wind tunnel used in these experiments is one of the Göttinger type with an open measuring section. In this design, the air circulates within the ring-shaped wind

Table 5.1 Criteria and evaluation of the two developed designs concepts

Criteria	V-shaped structure	Fishbone structure
Geometry		
Shape	Complex	Simple
Robustness	Medium	Good
Surface	Continuous	Interrupted
Assembly		
Assembly actuators	Simple	Simple
Assembly deflection	Complex	Simple
Additive manufacturing		
Flexible material	Yes	No
Heat treatment	No	Optional
Resolution	Medium	High

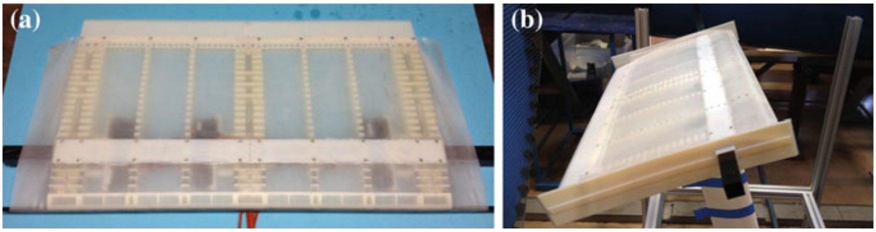

Fig. 5.4 Wind tunnel test: **a** assembled and silicone covered part of an adaptive wing (500 mm long), **b** adaptive wing in the wind tunnel at approx. 25 m/s

tunnel. An existing measuring stand was used to fix the wing [12]. The adaptive wing was connected to the measuring stand with an adapter (see Fig. 5.4b).

The qualitative investigations were carried out up to a wind speed of 25 m/s and angles of attack from 0° until 20°, using the silicon outer skin. As might be expected, at higher angles of attack and wind speeds, the outer skin on the top of the nose began to buckle due to the suction effect. The larger the angle of attack, the sooner bulging of the outer skin occurred. One measure, to prevent this, the outer skin would be stronger to bias or use a stiffer material, e.g., a higher modulus of elasticity or a thicker foil. Gluing the outer skin to the ribs would prevent buckling directly over the ribs, but in the areas between the ribs (without glue), this would not bring any improvement.

Due to the detachment of the film from the ribs, the test series was carried out with the latex outer skin only with an angle of attack of 5°. During the experiment, the film slowly began to peel off laterally on the back bars. To prevent the detachment from progressing, no further angles were investigated. With regard to the bulging of the outer skin from latex above certain wind speeds, nothing could be detected with the naked eye. This would be explained by a higher modulus of elasticity of the latex film.

To evaluate the results from the wind tunnel, the software XFOIL was additionally used, which i.a. used to calculate airfoil profiles. A systematical wing profile (NACA 10) was compared with the curved, adapted profile (NACA 3310). Based on the output values, it can be seen that the curved profile has a higher lift coefficient and a later stall (14° to 12°) compared to the symmetrical profile. The resistance coefficient of the curved profile increases less with increasing angle of attack than that of the symmetrical profile. The polar diagram also illustrates that the drag coefficient of the curved profile increases less rapidly than the symmetrical profile.

5.6 Technical and Economic Evaluation

The realization of an adaptive curvature is a very complex task. The two largest fields are the core structure and the outer skin. The core structure comprises the wing (3D printed structures and purchased parts) without the elements of the outer skin. The rear area of the wing with the bending beam is geometrically less complex and provides sufficient space for the placement of the actuators and the linkage. The servo adapters have no visible wear even after prolonged use. Depending on the gear wheel geometry (not too flat flanks of the gear), 3D printed attachments are therefore a cheap, flexible and in their design completely free alternative to expensive original adapters.

The nose of the wing is significantly more complex compared to the rear area, which is another very limited space in combination with the short lever arm. As a result, compact actuators are needed, which, however, entail losses in the available power. The solution used for this, the subdivision of the nose into several areas that are connected by axes and held in place by flexible spring elements, proved to be very flexible. With the spring elements used, which can be influenced by their assigned hardness in their rigidity, it is possible to control the achievable deflection of the nose to a certain extent too precise. The modularized design of the spring elements also allows easy replacement, since these elements use the sometimes very short-lived "Tango mix" material.

The separation of the outer skin from the core structure to provide quick access to the interior has proven to be extremely useful. The adaptation of the hardness of the spring elements or the change of the servo adapter would not be readily possible with glued outer skin. In addition, both silicone and latex can be tested easily as a material for the outer skin. The construction has a fairly high mass when covered with silicone with approx. 912 g and thus with a surface load of 61.6 kg/dm^3. The core structure and the purchased parts are to be regarded as fixed, the mass of the outer skin varies depending on the material used and the type and amount of adhesive used. By using a fabric with latex, the surface load can be reduced by 5.9% to 58.0 kg/dm^3.

The two components of the "Digital ABS" material and the support material represent the largest expenditures and therefore cost positions of the material. For example, the costs for the printing material for covering with silicone are approx. 210 EUR. For purchased parts, there are additional costs of about 295 EUR. Most parts are printed in a way, which enables to use as little support material as possible. Nevertheless, the consumption of support material with a share of approx. 20% of the total material costs is quite high. A further reduction in the consumption of support material would have been possible, for example, in the case of the main rib segments, in that the profiling bones would have been constructed continuously. Due to the missing recesses, however, this would have led to a higher mass of the finished main ribs, which is why the variant with recesses was preferred at the expense of supporting material consumption.

5.7 Conclusion and Outlook

The successful implementation of a wing concept with adaptive curvature lays the foundation for creating a complete adaptive wing for a UAV. Furthermore, the wind tunnel model allows the demountable outer skin, the testing of various elastomeric films in terms of their suitability for covering a wing. There is no need to build additional core structure models for other skin materials. The findings gained through the qualitative wind tunnel tests allow a more targeted selection or search for suitable materials.

The multi-material capability of the used polyjet 3D printer with the flexible tango material could not be used completely due to the short life of the tango material under high loads. However, the tango material proved to be extremely useful due to the modular handling and the targeted use in problematic areas. The “Digital ABS” in conjunction with the fine resolution of the 3D printer also allowed the production of precisely fitting tooth structures for power transmission. The multi-material capability in general is likely to lead to very interesting approaches and constructions in upcoming investigations.

The experiments in the wind tunnel and their evaluation with the aid of a software show that the curved, adaptive wing profile has higher lift coefficients and lower resistance coefficients. Thus, better flight characteristics and lower fuel consumption can be achieved here, which can contribute to improved sustainable aviation.

Optimization potential for actuators and lightweight construction still demands future investigations. A disadvantage of the servos is that they consume energy permanently when the deformation is activated. For long periods with active deformation would thus result in high energy consumption, which could possibly destroy the energy savings from the stronger buoyancy again. An alternative to using servos would be to use a worm gear because it is self-locking at rest, i. no energy is consumed. Another advantage would be that the servos would no longer be in the wing. By using a coil concept similar to Woods and Friswell 2012 [7], a thinner surface profile can be used. This would allow material savings, which could result in a lower minimum flight speed. For the purpose of lightweight construction, the increased use of lattice structures offers new opportunities. High mass components should first be investigated for potential savings. These include in particular the adhesive strips and the various ribs.

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Chapter 6
The Bottom-Up Side of Eco-innovation: Mapping the Dynamics of Sustainable Grassroots Innovations

Yannis Mouzakitis and Emmanuel D. Adamides

Abstract In this paper, we adopt a sociotechnical systems perspective and relying on six published cases of sustainable grassroots innovation (SGI) implementations worldwide, we develop a conceptual framework for analysing the dynamics (in both micro- and macro-level settings) of individual SGI initiatives. From the framework, indicatively, we select the attribute of *(origin of) technological innovation*, and we present trends in SGI trajectories with respect to the *adoption* of an established environmental technology, the *development* of an eco-innovation 'in-situ', and the *infusion* of novel technologies developed externally in order to fulfil specific SGI needs.

6.1 Introduction

Over the last two decades, an increasing number of a wide spectrum of bottom-up initiatives towards sustainability has been reported in the literature. Described as 'community-based', 'local', 'grassroots', 'user-led', 'citizen-driven', 'outsider', these initiatives concern sustainability-oriented innovations situated in the civic society [1–4]. They are responses to local issues of sustainability which frequently rise to a global scale as far as appropriability of solutions/innovations is concerned. In general, grassroots innovations refer to "networks of activists, development workers, community groups and neighbours, who generate bottom-up solutions for sustainable development, responding to the local situation and the interests and values of the communities involved" [5]. Smith and Seyfang [6] stress that a grassroots innovation includes ideas and innovations whose origins may have begun outside a grassroots setting, but whose appropriation and adaptation to local communities and their

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socioeconomic situations is carried out with local groups in control over the process and the resulting benefits. Grassroots innovations differ from conventional market-based innovations in that they are driven by ideological commitment rather than profit, actors and resources are aligned and protected by values and culture rather by regulation and organisational rules and norms, involve communal ownership structures and usually operate in the social economy, where voluntary contribution is the norm.

Sustainable grassroots innovations (SGI) is a form of *eco-innovation*, which concerns the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organisation (developing or adopting it), and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives [7]. Such innovative activities may go beyond the conventional organisational boundaries of the innovating organisation and "involve broader social arrangements which trigger changes in existing sociocultural norms and institutional structures" [8].

SGIs have been mainly considered at a meso-level of analysis as sociotechnical niches in the context of the Multi-level Perspective (MLP) of (sociotechnical) system innovation [9]. This model, by adopting a quasi-evolutionary perspective, assumes that large-scale innovations are initially nurtured in protected spaces (niches)—through experimentation and learning across cases—before they diffuse and achieve regime status by the selection forces of the wider context/landscape (political, social, technological, etc.). The MLP has been particularly useful for studying SGI projects of the same, or similar, type (e.g. community currency niches [10], or initiatives based on food waste [11]), but in order to form a wider picture of the dynamics of the entire field of SGI, an approach not restricted to MLP is required, since neither all SGI projects achieve niche status, nor all cases of SGI diffusion (if they diffuse) fit to this model (as well as other forms of system innovation) [12].

Towards this end, based on six diverse case studies of SGI projects worldwide, and adopting a contingency perspective, we develop a conceptual framework that can form the basis for studying the dynamics of sustainable grassroots innovations through the dynamics of individual concepts and interactions of concepts of the framework. Following, in the paper, we first place SGI in the context of eco-innovation with respect to other participative innovation models, we then, in Sect. 6.3, briefly present six cases whose qualitative analysis gave birth to a conceptual framework of Sect. 6.4 and the related evolution trajectories. We finally draw brief conclusions of the research (Sect. 6.5).

6.2 Literature Review

The literature includes a diversity of typologies for sustainable transitions, with different interpretations and perspectives. In the frame of Scoones et al. [13], one may find four broad narratives of green transformations, each one with different

Table 6.1 Grassroots versus conventional innovations [1, 2, 5]

	Grassroots innovations	Conventional innovations
Who	Local community (activists, cooperatives, volunteers, etc.)	Individual firms, research centres, universities
Why	Alternative way to do things, respond to local problem,	Profit, Schumpeterian rent
Where	Neighbourhoods, villages	Laboratories, boardrooms
Resources	Social capital, cooperation, local knowledge	Venture/public capital, scientific expertise
Appropriability	Common good, not individualistic	Intellectual property, patents
Sectors	Small scale RES, reuse, repair, co-housing, agro-ecology	ICT, biotechnology, nanotechnology, geoengineering

diagnoses and solutions: first, they identify *technocentric* transformations, where technologies are considered as global public goods to tackle with environmental crisis, and they continue with *marketized* transformations, where ecopreneurs and green consumers through economic investments and market incentives will lead to a green and sustainable economy. In addition, they refer to *state-led* transformation, which emphasises the role of state involvement through green policies, and finally, they mention *citizen-led* transformations, where change comes from below, involving connected social movements from local communities. The authors stress on the fact that their typology is porous, as the four narratives are not mutually exclusive.

In this vein, we see grassroots innovations as citizen-led transformations, which are combined (in different extent with respect to each individual context) with a technocentric (use and development of technologies), state (when public agencies provide financial and/or institutional support), or even marketised (in cases of 'partnerships' with individual firms) flavour.

Kemp and Pearson [7] classify eco-innovations into four broad categories: *environmental technologies* (pollution control, cleaner process, etc.), *organizational* innovations (auditing schemes, cooperation in chain management, etc.), *product and service* innovation, and finally, *green system* innovation (alternative and environmental benign production and consumption systems). Under this perspective, and as we will demonstrate in the next section, sustainable grassroots initiatives can be seen as potential green system innovations (as they challenge existing social practices), which are based primary on organisational innovations (stemming from various forms of social participation), but they are also 'blended' with and supported by the two other types of eco-innovations (environmental technologies and products/services).

Finally, we consider grassroots initiatives as *social innovations*, namely as activities which are motivated by the goal of meeting a social need in different ways than existing approaches, while they are predominantly developed and diffused through social processes (civil society, volunteering, activism, etc.) [14]. In this vein, Table 6.1 presents a synopsis of the differences between grassroots and conventional innovations.

Table 6.2 Grassroots innovations in action

Case (references)	Societal need (mission)	Means (technical & organisational)	Outcomes
Anti-Gaspi, France [11, 16–18]	Food consumption (reduce food waste)	IT applications; campaigns, petitions, activism, food banks,	Anti-food waste legislation (France, EU)
Car-sharing Switzerland [19–22]	Mobility (reduce car use)	Cooperatives; IT applications; customised vehicles	>130,000 members 3000 vehicles 1500 locations
Co-housing international [3, 23–25]	Housing (decreased footprint)	Shared space & equipment, use of green technologies; cooperatives	>1000 cases (Denmark, USA, UK, Netherlands, Germany)
Fab Labs international [1, 26–28]	Manufacturing (local & distributed production)	Flexible equipment (CNC machines, rapid prototyper, 3-D printers, etc.); DIY, free & open source movement	>1300 Labs in 30 countries
Repair Cafés international [29–32]	Reuse & repair (circular economy)	A basic toolkit (sometimes a 3-D printer for replicating broken parts); (expert) volunteers	1500 Labs in 33 countries
Wind power Denmark [33–36]	Energy production (renewable sources)	Pilot plants & prototypes; cooperatives	>3000 units (run by cooperatives)

6.3 Sustainable Grassroots Innovation in Action

In the following paragraphs, we provide a short description of six existing grassroots innovations, which form the basis for the development and discussion of our conceptual model which follows in the next section. The cases studies, which are products of secondary level research, are presented in alphabetical order, and they are summarised in Table 6.2. The case studies were developed from websites and other publicly available documentation [15]. The information was classified and indexed, and six case study dossiers were compiled. Before, standard qualitative analysis of the data was carried out to extract concepts and relationships between concepts. Below, a short description of the six cases is depicted providing references to comprehensive information about each one.

The first case is from France, where *Anti-Gaspi* (gaspi means waste in French) emerged in a commune located 8 km from the centre of Paris, as a local anti-food waste initiative [11]. In short, Anti-Gaspi was initiated in 2014 by a local councillor and volunteers, with actions such as distribution of unsold supermarket food to needy people, and after an effective campaign and a successful petition resulted to the adoption of the first anti-food-waste law (December 2015). In other words, in less than 12 months, France has become the first country in the world to ban specific retail shops from throwing away unsold food, forcing them to donations to charities or food banks [16, 17]. In 2017, The European Parliament has voted for a 50% cut in food waste by 2030, while grassroots campaigners now hope to persuade other member states to adopt similar legislation. In addition, The Anti-Gaspi movement resulted in the creation of new supply chains where food banks and charities collect and stock the food in properly hygienic conditions and distribute it with dignity [18]. In addition, a number of smartphone applications have/are been developed in order to support the related initiatives.

One of the first European initiatives in *car-sharing* can be found in Switzerland (Zurich, 1948) where a cooperative initiated a related initiative which was mainly motivated by economics [19]. In its current form, the car-sharing rental scheme initiates in 1987, by two cooperatives which were founded independently from each other by environmentally concerned citizens. After an exponential growth rate, the two cooperatives merged in 1997, and currently, the new cooperative serves 13,000 members, offering 3000 vehicles in 1500 stations run by companies, municipalities and resident complexes [20, 21]. Today, car-sharing services which decouple ownership and use of cars (resulting in positive environmental effects stemming from the higher degree of utilisation of existing vehicles) are available in over 1000/30 cities/countries, with an estimation of over 1.7 million members [22].

The roots of *co-housing* as a community development model can be traced back in the 1960s in Denmark. This approach was introduced in North America in 1988, with the publication of a seminal book by two architects who observed the co-housing movement in Europe, and introduced the related term in English [3] Co-housing builds on clustering of private residencies around common facilities and open spaces and emphasises the non-hierarchical consensus process in decision-making. Besides enhanced social interaction between participants, co-housing initiatives involve the use of green technologies in shared infrastructures, a fact that renders them as significant grassroots niches towards sustainable development [23, 24]. Currently, there are more than 1000 co-housing initiatives worldwide, and many of them are organised under the umbrella of national associations [25].

The first *Fab Lab* emerged in 2001 as an initiative of the MIT Media Lab (funded by the US National Science Foundation) aiming to democratising access to the tools for manufacture and technical invention [1, 26]. *Fab Labs* (Fabrication Laboratories) can be defined as community-based digital fabrication workshops where people come together to learn about, use and develop digital tools, technologies and science projects [27]. Today, the Fab Lab network (site) includes over 1200 digital fabrication facilities (from community-based labs to advanced research centres) in 100 countries, which act as bottom-up facilitators of sustainable design and manufacture [28].

Repair Cafés are free community-centred workshops, where one may bring consumer products in need of repair, maintenance or modification, and work with volunteer fixers [29]. The first Repair Café opened in Amsterdam in 2009, and the Repair Café Foundation was established in 2011, and till this day, it has provided support to 1500 initiatives in 33 countries [30]. Expanding the product life cycle, the Repair Cafés contribute to circular economy, and they constitute another example of remarkable citizen-led sustainable innovation [31, 32].

Social movements have a significant contribution in the development of renewable energy sources [33]. In the context of wind energy in *Denmark*, the emergence of modern wind turbines which started in the early 1970s, initiated from a social movement against nuclear power and built on strong capabilities stemming from traditional windmills [34]. More specifically, activists were organised into local groups throughout the country, discussing techno-economic issues of wind technologies. The government provided the necessary support, and in the next few years, a significant number of grassroots pilot plants were built. While the majority of them are mainly small-sized, many large-scale constructions were set-up as low-budget bottom-up initiatives [35]. By 2001, over 100,000 families belonged to wind turbine cooperatives, which had installed 86% of all the wind turbines in Denmark. Today, more than 3000 units are operated by local cooperatives [36].

6.4 Grassroots Innovations: Towards a Conceptual Model

In this section, we first present our conceptual model (see Fig. 6.1), where we put together the influential factors of a grassroots initiative as they were extracted from the cases above, and then we demonstrate how it can be employed in order to map the dynamics of sustainable bottom-up initiatives.

6.4.1 Connecting the Attributes

Clearly, SGI is responses to locally expressed societal functions/needs (housing, mobility, energy generation and use, etc.) that have a sustainability impact. So far, as the above cases indicate, SGI may have varying influence to incumbent practices and technologies according to their dynamics. Individual SGI initiatives/projects are characterised by the actors participating (individuals, organisations, movements, etc., with varying roles, such as technicians, scientists, delivery workers), the purpose and mission they have (e.g. response to state initiatives, provide cheap community services, etc.), the technologies developed, adapted or used (e.g. wind power generators) and the benefits achieved in terms of sustainability (e.g. reduced food waste, thus reduced food production). Some initiatives stick to their altruistic, community-centred mission, whereas others, after the initial success of the project, aim at commercial gains. This may be the result of the inherent dynamics of the project. Grassroots technological innovations are more likely to turn commercial than organisational ones that are tight to the communal nature of the projects. As far as participating actors are concerned, some projects and initiatives remain grassroots with communal ownership and alternative to mainstream institutions, whereas others

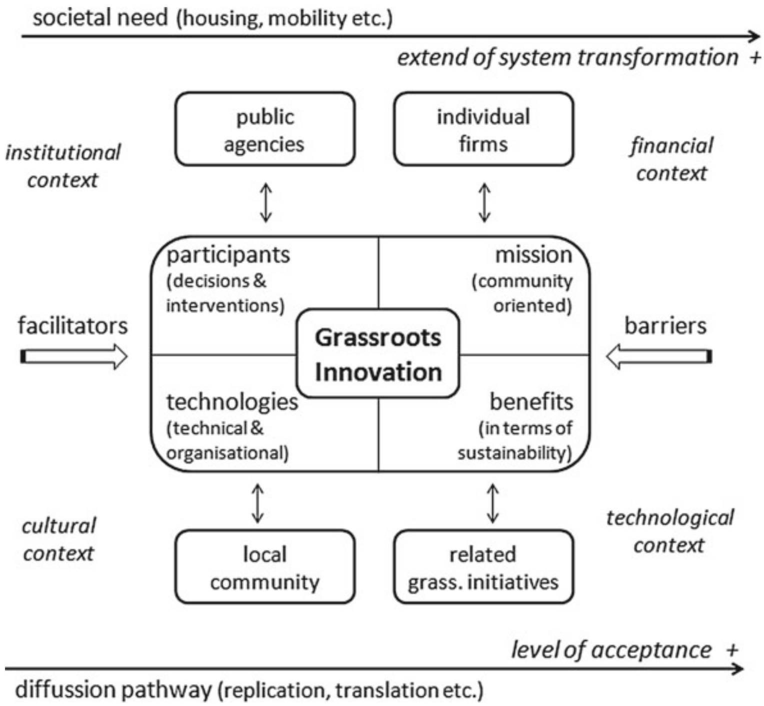

Fig. 6.1 Grassroots innovation: a conceptual model

become more open to interaction with technology producing firms, research institutes, etc.

Individual SGI is formed and operate in diverse institutional contexts where organisations of various forms act as facilitators or barriers. Usually, financial support of SGI projects is not through grants, banks, VCs, etc., but through mutual exchange of goods or even voluntary labour. There are national institutional settings that actively support grassroots initiatives whereas others are relatively neutral. Very important is the role of the local community and other related or unrelated grassroots initiatives regarding awareness of the public. The shape of each factor and the linkages between them determines, to a certain extent, the trajectory of each grassroots innovation initiative. For instance, car-sharing that has in its centre a technological artefact and started as grassroots for reasons of economy rather than sustainability was engaged by local public authorities in Europe as a solution to city-centre traffic congestion problem, while private information and communication technology firms developed innovations for booking cars, charging fees, using shared cars, etc. In another context (USA), private firms, such as Uber, appropriated the value created by grassroots innovators along the lines of platform capitalism [37]. This is an example of an innovation that was shorn of its social value becoming a technical fix [38]. Anti-Gaspi is an opposing example, where the communal and voluntary nature of the organisational innovation persists with the help of low-level ICT. In this case, social value cannot be easily translated into economic value and appropriated by others.

6.4.2 Mapping the Dynamics

The factors which are depicted in the conceptual model offer a plethora of alternatives which can be used for the description/comparison of (the dynamics of) a grassroots initiative and its dynamics.

In the context of this paper, we provide an indicative example of the application of our conceptual framework, and we study the dynamics of the technological innovation of a grassroots initiative. More specifically, we consider that technological innovation has two dimensions: a 'hard' one, referring to technical processes, tools and artefacts, and a 'soft' (organisational) one, referring to organisational methods and business practices. In the previous sections, we provided evidence that all grassroots initiatives have a strong innate (coherent) organisational innovation, stemming from their participants, resources, appropriability, etc. In this vein, we focus on the hard dimension, and we explore the degree of innovation exclusively with respect to technical artefacts and tools. In addition, we distinguish technological innovation in terms of *adoption* of an established environmental technology (which counts as an act of innovation [39], *development* of an eco-innovation 'in-situ' (based on grassroots' resources and capabilities), and *pull* innovation (when a product or service is developed by other organisations in order to fulfil specific needs of a grassroots initiative). Based on these assumptions, we map the dynamics of technological innovation of each case study in Fig. 6.2, and we discuss the results in the next section.

6.5 Conclusions

SGI is a mode of eco-innovation related to alternative modes of production and consumption as well as to more inclusive technology and innovation development processes. In this paper, based on six case studies, we have presented the development of a conceptual model of the factors that determine the dynamics of SGI initiatives evolution. We have chosen one such factor (technological innovation), and by considering the cases longitudinally, we have arrived at the following trends:

Commenting the figures graphs (Sect. 6.4), one may come with the following trends:

- grassroots initiatives are more inclined towards the adoption of an environmental technology, than developing a (technical) eco-innovation
- specific initiatives (car-sharing, co-housing) result in a high degree of eco-innovations. In addition, almost all case studies call for development of related

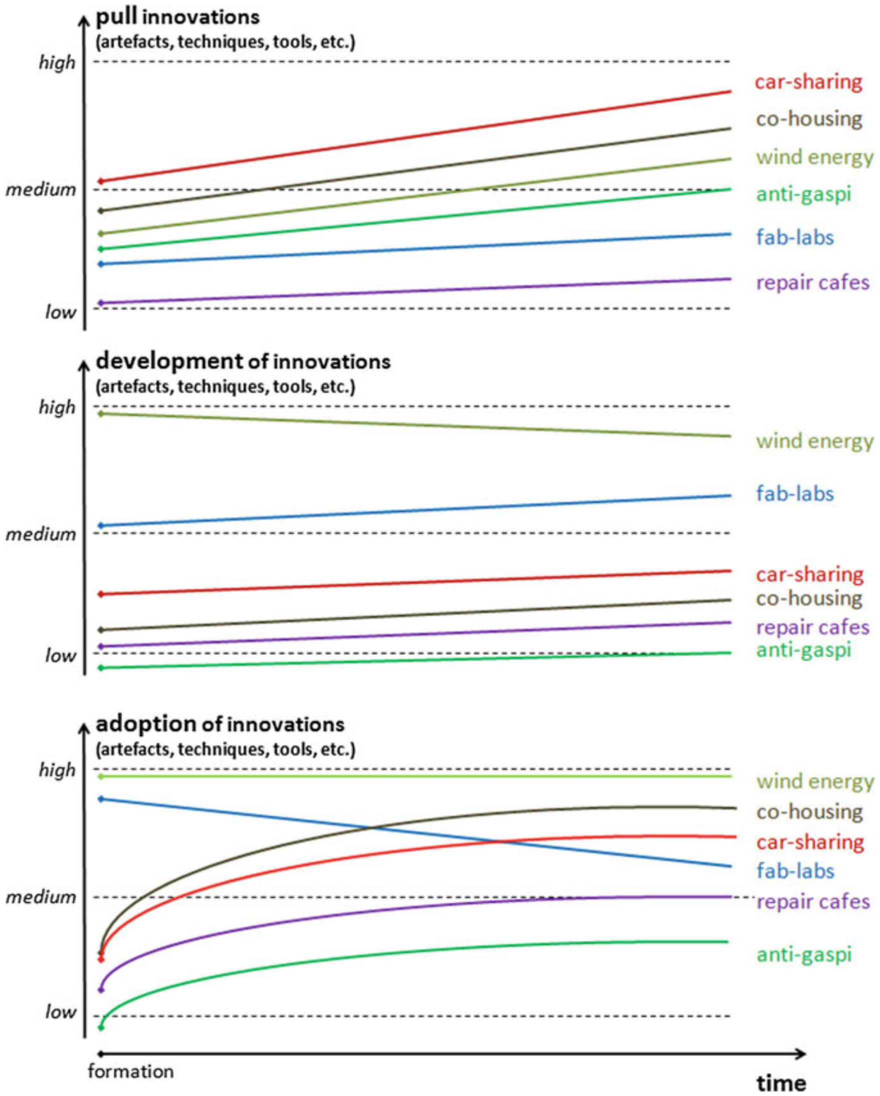

Fig. 6.2 Mapping the dynamics of grassroots innovations

IT applications (intangible artefacts). In other words, grassroots innovations contribute significantly to the development of (technical) eco-innovations

– specific initiatives (Anti-Gaspi, repair cafés) are not strongly connected to the technical side of innovation. This fact shall not lead us to the conclusion that these cases are less sustainable compared to the others.

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Chapter 7
Managing Uncertainties in LCA Dataset Selection

Simon Pfeuffer, Daniel Wehner and Raed Bouslama

Abstract The selection of LCA datasets requires an understanding of the available datasets in a database and awareness about the uncertainties associated with the dataset selection. Therefore, a graphical presentation technique is introduced to support the communication of information about available datasets and uncertainties.

7.1 Introduction

There is a requirement for cost-effective instruments within the aviation industry to become more sustainable. A well-established methodology to evaluate the sustainability of products and processes is provided by the life cycle assessment (LCA). Currently, a trend towards the development of extensive LCA databases on aviation-specific materials and processes can be observed. An example of such databases is the carbon composites database [1]. The database contains 137 datasets showing inventories with associated environmental impacts of manufacturing carbon fibres and carbon-fibre-reinforced parts as well as the associated manufacturing processes. Additionally, the technical specifications of the processes responsible for the environmental impacts are reported (e.g. temperatures, holding times, etc.). While this information offers great potential for environmental optimization, in early design stages, engineers tend to be overwhelmed by the wealth of such information as there is still high uncertainty regarding many environmentally relevant details of their designs, in particular, manufacturing-related aspects. Consequently, comprehensible means to build a thorough understanding of the LCA information in a database are required to support the awareness about the uncertainties of design decisions. Therefore, we work on answering the following questions:

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- How is it possible to cost-effectively communicate the uncertainties regarding the environmental impacts of early design decisions?
- How can the process of selecting relevant LCA datasets be supported visually?

7.2 Background

Obtaining a more detailed overview of the content of a database is a challenge within Pleiades. Pleiades is a project within the Clean Sky II program and aims to improve existing eco-design tools by providing a semi-automated workflow to exchange data between a LCA database and a system for assessing ecological risks associated with design decisions. This system for eco-risk assessment (ERA) system contains information on materials and processes. In the semi-automated workflow, datasets from the LCA database are mapped to the materials and processes of the ERA system through an interface tool. One step of mapping the data is currently done manually and consequently time-consuming.

Furthermore, in early design stages, uncertainties arise from a missing detailed knowledge of future design decisions. These uncertainties may influence the LCA results [2] and have to be communicated when selecting datasets in order to increase the quality of the data exchange between the ERA system and the LCA database.

7.3 Technique

In order to support the mapping of datasets from a database such as the carbon composites database, more advanced techniques have to be considered. The graphical presentation of the datasets and their specific attributes serves as a starting point. A graphical presentation assists the user to understand the different types of uncertainties in early design stages, e.g. when evaluating the ecological impact of various material options. Apart from communicating uncertainties, the graphical presentation makes possible errors resulting from the selection of the LCA dataset visible. The graphical presentations are implemented as a dashboard that provides the user with information about the environmental impacts of the different scenarios represented in the database. The dashboard communicates both, the inherent variability of the datasets in the database and also the environmental improvement potentials of upcoming design decision. As a result, it can further narrow down the design space with regard to material or manufacturing options for example.

7.4 Conclusions

The graphical presentation of the content of the database supports managing the uncertainties in the described design stage by visually communicating the uncertainties in early design decisions. A further development of the technique in the form of interactive elements as part of the visualization can make the communication more cost-effective.

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Chapter 8
Lightweight Design Solutions in the Automotive Sector: Impact Analysis for a Door Structure

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Abstract The paper displays extracts from the results of the Affordable LIghtweight Automobiles AlliaNCE (ALLIANCE) project, funded by the Horizon 2020 framework programme of the European Commission. In this regard, a door demonstrator, that is, currently in series production and mainly consists of steel materials, has been re-engineered making use of state-of-the-art aluminium alloys. The reference and lightweight doors have been assessed regarding the achieved weight saving. A cost calculation has been performed for both variants in order to evaluate the actual lightweighting cost of the aluminium door. The economical impact in the use phase has been taken into account by assessing the influences on the total cost of ownership (TCO). Furthermore, the environmental impact has been evaluated by a life-cycle assessment, taking into account the production, use and end-of-life phase. The methodological approach that has been used to perform the comparative assessment is part of the description.

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8.1 Introduction

The need for sustainable and efficient vehicles is underlined by current discussion related to climate change and increased public environmental awareness. The application of lightweight technologies, especially in the car body, represents one option to address this need. During the last years, extensive research has been carried out in the field of material and manufacturing technologies that brought up innovative solutions based on steel, aluminium, composites and hybrid materials [1]. The majority of the efforts though have typically failed to adequately and comprehensively address the high-cost issue of the innovative solutions often indicated by the cost of lightweighting (cost per kg saved) [2, 3]. The high cost results from many factors ranging from materials acquisition, long cycle times, high investments in new machinery and efforts to adapt existing assembly processes. The car manufacturers might accept these additional costs to a certain extent if they are beneficial for the overall product. This is the case, if either secondary weight saving potentials are enabled in other domains of the vehicles (e.g. by downsizing the engine) or the TCO is reduced by a decreased fuel consumption (FC).

Concerning the environment, the assessment of the entire vehicle life cycle (LC) gains more and more importance in the development process [4, 5]. In this context, lightweighting involves a reduction of the use stage impact, also caused by a decreased FC. On the other hand, innovative materials and technologies generally provide greater impact in the production stage, due to the high energy intensity of raw materials extraction and production processes [6, 7]. Therefore, lightweight technologies are only convenient if the additional impact generated in the production is compensated during the use and end-of-life (EoL) phases [8]. In the light of the above, it appears clear that a holistic view is needed to properly assess the overall sustainability of an automotive asset. The following sections give an overview on how the environmental and economical impact of lightweight technologies can be assessed on component and module level. The illustrated methodologies are applied to the specific use case of a door structure, where a reference steel design solution is compared to an aluminium design.

8.2 Life-Cycle Assessment (LCA)

8.2.1 Motivation and Scope

The scope of the LCA analysis is to compare the reference and the lightweight design variants of the door structure. The functional unit (FU) is defined as the specific module installed on the vehicle over a LC mileage of 230,000 km [9]; the use stage is assessed with the Worldwide harmonized Light-duty Test Cycle (WLTC).

According to the “cradle-to-grave” approach, the system boundaries include all stages that compose a module’s LC: production, use and EoL. Production is divided into materials (raw material extraction and production) and manufacturing (manufacturing activities from the semi-finished to the final product) stages. Assembly activities as well as transportation processes during manufacturing are outside the system boundaries. The impacts are calculated in terms of global warming potential (GWP), expressed in kg CO_2 eq. The CML 2001 method (characterization factors of April 2016) is used for the impact assessment [10].

8.2.2 Life-Cycle Inventory (LCI)—Modelling, Data Collection and Assumptions

A specific modelling method based on LC perspective is developed in order to evaluate the GWP of the considered automotive module. The LCI modelling is carried out by means of GaBi software. Below the LCI modelling and data collection are described for each LC stage.

Materials and production stages. LCI modelling is conducted through a breakdown approach, which provides that each mono-material part is assessed separately. Therefore, the environmental impact for the production of the entire module is obtained as the sum of contributions of the single mono-material parts. The analysis includes also the recycling of scrap materials produced during manufacturing activities (open-loop recycling) taking into account the environmental credits due to raw materials substitution. The modelling is based on the primary data collection coming from the manufacturer through direct measurements on process site. When no primary data are available, secondary data from the GaBi process dataset are used.

Use stage. The use stage takes into account the impacts associated with the module, including both fuel production and CO_2 emissions during car operation. The LCI model of the use stage is based on the fuel reduction value (FRV) approach which is described in the following equations:

$$FC_{comp} = \frac{FRV * m_{comp} * mileage_{use}}{10,000} * \rho_{fuel} \quad (8.1)$$

$$CO_{2\,comp} = CO_{2\,km} * mileage_{use} * \frac{FC_{comp}}{FC_{veh}} \quad (8.2)$$

$$FC_{veh} = \frac{FC_{100\,km}}{100} * mileage_{use} * \rho_{fuel} \quad (8.3)$$

$$FC_{100\,km} = \frac{CO_{2\,km}}{2370} * 100 \quad (8.4)$$

FC_{comp}	Amount of fuel consumption associated with the module (kg)
FRV	0.178 l/100 kg*100 km for gasoline turbocharged *D*-class vehicle [11]
m_{comp}	Module mass (kg)
$mileage_{use}$	Use stage mileage (230,000 km)
ρ_{fuel}	Fuel density (0.741 kg/l)

Table 8.1 LCI primary data collection for EoL stage

	Steel[a]	Aluminium[a]
	LCI data	LCI data
Electricity for shredding (MJ/kg)	0.12	0.12
Recycling rate (both scrap and EoL materials) (%)	98	98
Substitution ratio for recycling of scrap (%)	51	94
Substitution ratio for recycling of EoL materials (%)	33	42

[a]Quality: Secondary

$CO_{2\ comp}$ Amount of CO_2 emissions associated with the component (g)
$CO_{2\ km}$ Per-kilometre CO_2 emissions (192 g/km) [12, 13]
FC_{veh} Amount of vehicle fuel consumption during operation (kg)
$FC_{100\ km}$ Fuel consumption of the vehicle (l/100 km)
2370 Mass of CO_2 per litre of petrol (g/l) [14]

EoL stage. The assumed EoL scenario provides that the module is not processed at the dismantling step, and therefore, it is sent to the shredder together with the vehicle. After the shredding, materials are assumed to be sorted and forwarded to recycling processes (open-loop recycling). The modelling takes into account the environmental credits due to raw materials substitution; the considered factors for the replacement of virgin raw materials are from the GaBi LCI database. Table 8.1 reports LCI primary data collection for the EoL stage of the door module.

8.3 Life-Cycle Costing (LCC)

8.3.1 Motivation and Scope

The analysis presented below intends to provide an estimation of the life-cycle cost of specific automotive parts and allow comparison between different designs. In this particular case, the analysis is performed for a reference door structure and a lightweight variant. The life-cycle costing (LCC) is an economic analysis used to estimate the total cost of a product throughout its life cycle, from production, use, to its EoL treatment. It identifies the relevant cost drivers for each phase and step and estimates the costs attributable to the object of analysis. Combined with an LCA analysis, it allows to assess the holistic impact and effectiveness of the different options for a given application. Unlike LCA, there is no common definition for LCC and, subsequently, no standardized modelling process. For this particular case, the material, production and use phase have been considered for the cost modelling.

8.3.2 Methodology

The door structure is broken down into mono-material parts. The cost of each mono-material part is estimated according to its particular characteristics (type of material, geometry, mass, volume, etc.). All the processes and subsequent steps comprised in the manufacturing of the entire module are identified and broken down, including human and physical capital requirements (machinery, tooling, consumables, industrial space, employees, etc.) and related costs and prices. Therefore, the cost per part is estimated taking into consideration the inherent properties of the part and the specific manufacturing costs. The cost of the overall module is obtained by summing up all the costs of the mono-material parts, taking into account the module structure and assembling sequence. The cost of painting and final assembly are not taken into account, since they are not considered to be relevant for the comparison of the reference and lightweight modules. All in all, the total cost of the module is built as the sum of a number of sub-costs, which are in turn a function of a large number of parameters and variables that intervene in the global manufacturing process. The equations hereunder illustrate the comprehensive assessment of the global vehicle manufacturing cost. The equation below displays the sub-costs in which the total cost is based on, showing thus the basis of the model's approach.

$$\text{Total Cost} = \text{Cost}_{\text{Material}} + \text{Cost}_{\text{Production}} + \text{Cost}_{\text{Use}} + \text{Cost}_{\text{Others}} \tag{8.5}$$

with

$$\text{Cost}_{\text{Production}} = \text{Cost}_{\text{Manufacturing}} + \text{Cost}_{\text{Energy}} + \text{Cost}_{\text{Labour}} \tag{8.6}$$

with

$$\text{Cost}_{\text{Manufacturing}} = \text{Cost}_{\text{Machinery}} + \text{Cost}_{\text{Tooling}} + \text{Cost}_{\text{Consumables}} \tag{8.7}$$

The following relationship shows the principal specific parameters and variables that influence the sub-costs and therefore determine the total cost of manufacturing.

$$\begin{aligned}\text{Cost} = \text{f}(&\text{Material price, Material density, Part box volume,}\\ &\text{Part projected area, Part mass, Manufacturing cycle time,}\\ &\text{Machinery cost, Machinery life time, Tooling cost, Tooling life time,}\\ &\text{Consumables price, Consumables quantities, Employment requirement,}\\ &\text{Labour force, Labour hourly rate, Energy consumption, Scrap rates})\end{aligned} \tag{8.8}$$

8.3.3 Assumptions and Boundary Conditions

The production of the mono-material parts analysed is the result of a combination of one or more manufacturing processes, each consisting of a number of subsequent manufacturing steps as shown in Table 8.2, involving specific machinery, tooling and consumables.

Table 8.3 describes the different model variables. These are primarily distinguished in four different categories (input parameters, model parameters, assumptions and output) according to the source of the data and its function in the model.

Table 8.2 Steps for the various manufacturing processes

Process	Step 1	Step 2	Step 3	Step 4	Step 5
Die casting	Clamping	Melting	Casting	Cooling	Trimming
Extrusion	Preheating	Clamping	Extrusion	Cooling	Trimming
Bending	Clamping	Bending	Annealing	Trimming	
Deep drawing	Clamping	Drawing	Annealing	Trimming	
Roll forming	Clamping	Rolling	Trimming		
Cold stamping	Clamping	Stamping	Annealing	Trimming	
Hot stamping	Preheating	Clamping	Stamping	Cooling	Trimming
Injection moulding	Extrusion	Melt inj.	Water inj.	Cooling	Ejection
RTM	Fabric cutting	Fabric trimming	Clamping	Resin inj.	Finishing
Thermoforming	Heat treat	Punching	Forming	Washing	Ageing

Table 8.3 Model parameters, assumptions and output

Input parameters	Part geometry *X*, *Y*, *Z* (m); box volume (m^3); Mass (kg); projected area (m^2); material type; manufacturing process
Model parameters	Energy consumption (MJ); cycle time (s); scrap rate (%); cost of machinery (€); lifetime of machinery (years); cost of tooling (€); lifetime of tooling (years); cost of consumables (€); volume of consumables (kg) (items) (L); price of material (€); FTE
Assumptions	Cost of electricity (€/kWh): national and average EU-28 values; cost of natural gas (€/kWh): national and average EU-28 values; cost of labour (€/h): labour cost per hour worked per technology for each of the EU-28 countries; annual production (vehicles/year): 100,000 vehicles/year; price of gasoline (€/L): 1.19 €/L (EU-28 average); average car mass (kg): 1392 kg; lifetime distance (km): 230,000 km—ICEV consumption: 5.85 (l/100 km)
Output	Material cost; production cost (machinery, tooling, consumables, labour, energy, use stage)

8.4 Analysis of a Specific Use Case

The displayed methodologies to assess the environmental and economical impact of lightweight technologies are applied to specific use cases within the ALLIANCE project. The following paragraph outlines the results achieved for a door structure of a current M-segment vehicle [15] that is designed in a steel-intensive design in the reference vehicle. The lightweight concept for this door structure foresees mainly the application of aluminium materials from the 6000-series. An overview of primary data collection regarding materials and manufacturing stages is shown in Table 8.4. In total, a weight saving of 8.682 kg could be achieved, equivalent to about 44%.

8.4.1 Comparative Assessment of the Environmental Impact

Figure 8.1 shows total LC impact as well as contribution analysis by LC stage of GWP for the different design options. For both design alternatives, the use stage has a leading role. The quota of production is similar (about 30%) with a contribution of materials higher for the novel module; for both alternatives, the impact of manufacturing does not reach a threshold of 1%. Concerning the EoL, the environmental credit due to materials recycling is definitely higher for the lightweight alternative (−7.4%), while for the reference design, it is less than 1%. Figure 8.2 reports the comparative assessment between the two design variants. The impact of the innovative module is definitely lower with respect to the reference one, leading to a decrease on LC perspective of about 44%; the environmental convenience of the novel alternative is confirmed in all LC stages.

The lightweight design involves a significant benefit from an environmental point of view. The first point is that the 44% decrease in use stage impact leads to the

Table 8.4 Primary data collection for materials and manufacturing stages

	Material composition (kg)		Manufacturing process	Scrap rate (%)
Reference module (total mass: 19.7 kg)	Steel—DC06	16.8	Deep drawing	Range[a] 33.3–60.2
	Aluminium 6060	0.2		
	Steel—DP1000	1.7		
	Steel—DP600	1.0		
Lightweight module (total mass: 11.0 kg)	DIN EN 6016/e170	3.0	Deep drawing	Range[a] 33.3–60.2
	DIN EN 6016/e600PX	3.7		
	DIN EN 6016/e200	2.6		
	Steel—DP1000	1.7		

[a]Variability range depending on specific module part

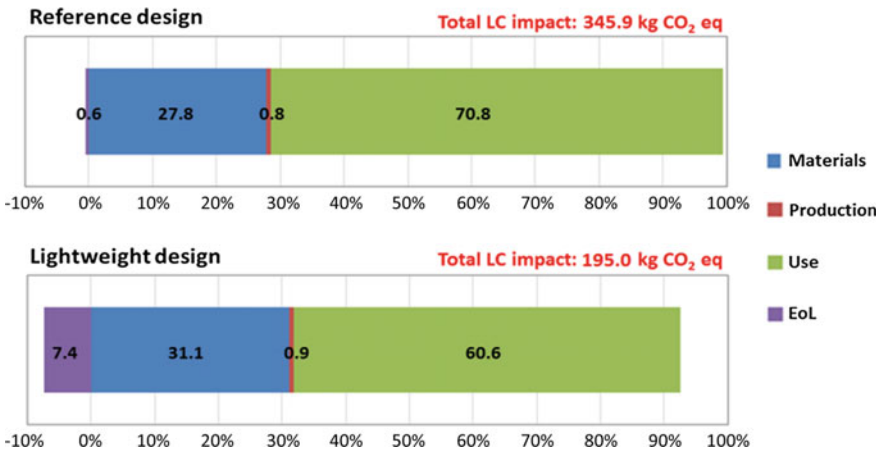

Fig. 8.1 Global warming potential—total LC impact and contribution analysis by LC stage (%)

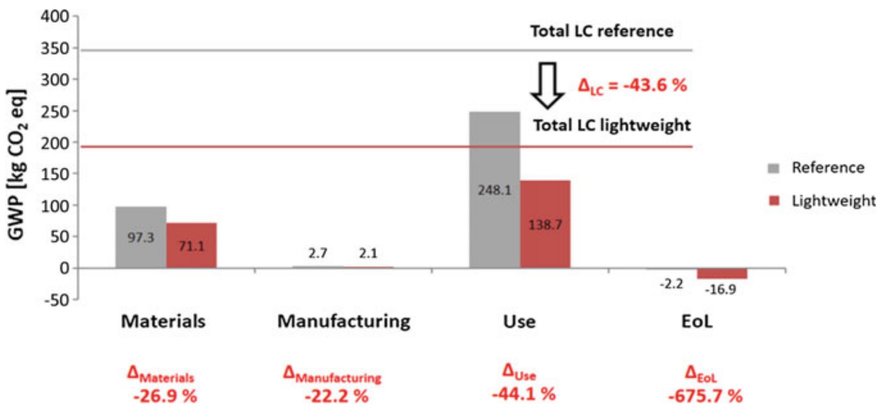

Fig. 8.2 Global warming potential—comparative assessment

highest reduction in absolute terms (−109.4 kg CO_2 eq). Lightweighting involves a reduction of FC, which in turn has a double beneficial effect: on the one hand, the impact reduction for the production of fuel and on the other hand the abatement of CO_2 exhaust air emissions. The second largest GWP saving in absolute terms is achieved in the materials stage (−26.2 kg CO_2 eq). This impact strongly depends on the material composition of the module (see Table 8.4). Despite the fact that raw materials extraction and production processes of aluminium are by far more energy intensive with respect to steel, the lower amount of material used (44% mass reduction) results in a lower impact of the lightweight module. The EoL stage also involves a significant GWP reduction (14.7 kg CO_2 eq). Although in the novel solution, the amount of material forwarded to recycling activities is lower, the environmental credits of aluminium recycling are notably higher with respect to steel. On the one hand,

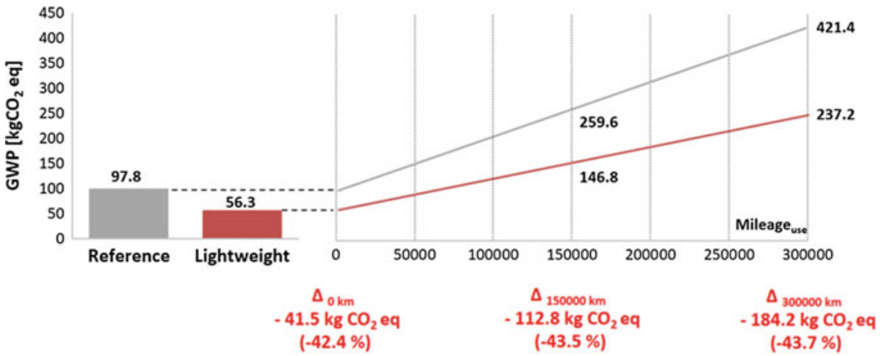

Fig. 8.3 Global warming potential—break-even point analysis

the energy consumption of aluminium recovery processes is lower; on the other hand, aluminium has a higher substitution factor due to the greater economic value of the EoL metal scrap in terms of equivalent of primary materials. The impact reduction in manufacturing stage is quite high (about 22%), but in absolute terms the GWP saving is very small (0.6 kg CO_2 eq). Figure 8.3 investigates the dependence of impact on the use stage mileage by reporting the break-even analysis of the GWP. On the right hand, the impact of use stage is shown in the function of the LC mileage. Data reveal that since the impact of reference design in production and EoL stages is higher than the one of the innovative module, there is no break-even point during use stage. Therefore, the impact of novel design is lower for any value of mileage, making the advantage of the lightweight module larger as LC distance increases.

8.4.2 Comparative Assessment of the Economical Impact

LCC results are provided below for both reference and lightweight module variants.

Figure 8.4 shows the full LCC analysis results per LC stage: material, production and use. The production cost is divided into manufacturing (which is in turn composed of the machinery, tooling and consumables costs), labour and energy costs. The use phase is calculated based on its contribution to the full vehicle's use cost (energy consumption associated with module mass).

Figure 8.5 presents the comparative assessment of the contribution of both designs to each LC stage. The results show opposing behaviours for the material and use stages; while the material cost of the reference design remains significantly lower than the lightweight one, at the use phase, the latter more than doubles. The production phase of the reference design is about 24% higher than that of the lightweight. All in all, when considering the use phase, the overall cost of the lightweight design is about 13% lower than the reference. Figure 8.6 investigates the dependence of impact on the use stage mileage by reporting the break-even analysis of the cost.

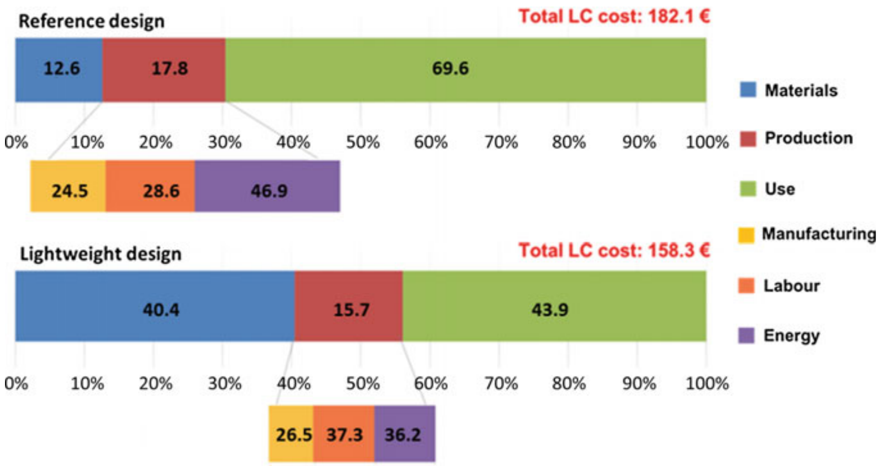

Fig. 8.4 Total LC cost and contribution analysis by LC stage (€, %)

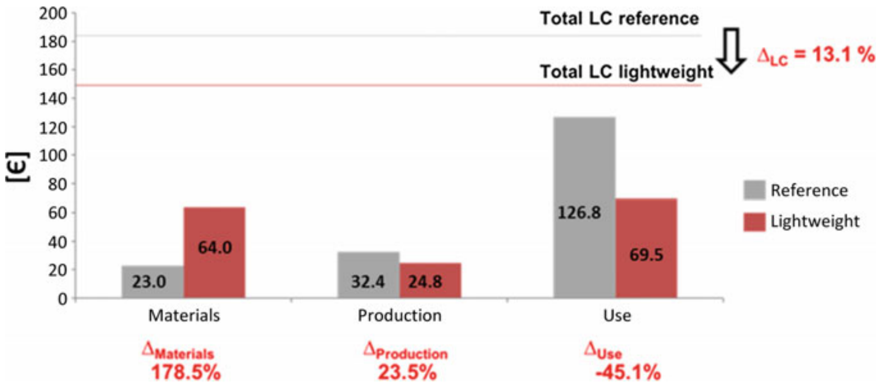

Fig. 8.5 Cost—comparative assessment (€)

The assessment shows that the break-even point of the module occurs at 83,480 km of mileage. After this point, the lightweight version of the door presents the lowest cost, reaching a maximum of 71 € for the LC mileage considered.

8.5 Summary and Conclusion

The study is aimed at outlining the need for a holistic approach to assess lightweight technologies not only in terms of mass saving, but also from an environmental and economical perspective throughout the different LC phases. The door case study shows that significant weight saving can be achieved by a substitution of steel with

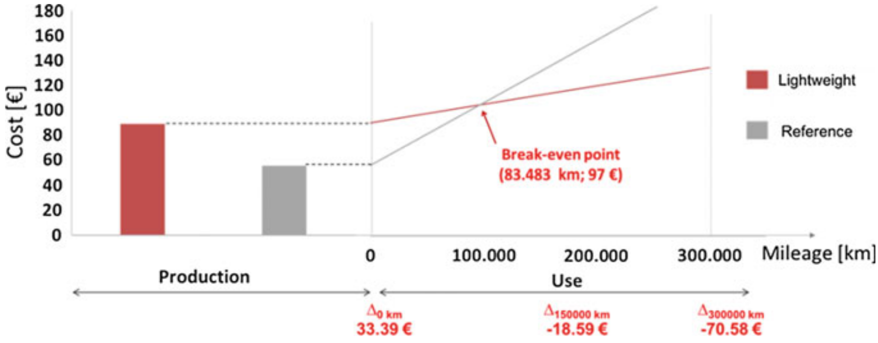

Fig. 8.6 Cost—break-even point analysis (€)

aluminium materials. From an ecological perspective, the lightweight variant generates a reduced GWP in the production phase. Although aluminium materials generally have a higher ecological footprint than steel, in this case the reduced amount of material used in the concept leads to a reduced overall impact in the production phase. Therefore, the lightweight variant is beneficial from the first km onwards. Over the full LC, further savings can be achieved in the use and EoL phase resulting in an overall GWP reduction of 43.6%. The economical assessment has shown that lightweighting cost of 3.83 €/ kg saved needs to be invested, mainly resulting from higher material cost. The consideration of the use phase shows that the invested lightweighting cost can be compensated after a mileage of approximately 83 Tkm by a significant reduction of the TCO. The implementation of the lightweight concept is therefore favourable from all analysed perspectives. The shown approach is applicable to every module and manufacturing process of an automotive asset, provided that inventory data are available. The main limitation of the methodology is the need for an extensive and time-consuming primary data collection (which involves both materials suppliers and original equipment manufacturers) as well as the reasonability of assumptions and hypothesis for the modelling of EoL stage.

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Part II
Sustainable Manufacturing Processes, Technology and Systems

Chapter 9
A Life-Cycle Assessment Framework for Stereolithography

Mattia Mele, Giampaolo Campana and Giulia D'Avino

Abstract Additive manufacturing is nowadays applied in many different fields, ranging from amateur prototyping to industrial production. In particular, small-sized stereolithographic apparatuses are widely spread due to their low cost, high accuracy and easiness of use. Despite the large diffusion of this technology, its sustainability aspects are not enough investigated, and a general lack of tools for the life-cycle assessment can be observed. The present paper proposes a framework for the development of a life-cycle impact metrics of stereolithography production in a certain area. All the contributions to the overall environmental impact of the manufacturing process are attributed to two main parameters, i.e. the amount of polymerised resin and the time of the process, thus allowing to easily integrate the results within the life-cycle assessment of a generic part. The parametrisation of the LCA also allows getting an estimation of the life-cycle impact from a digital representation of the part.

9.1 Introduction

Additive manufacturing (AM) technologies are rapidly extending in many different fields due to their potential in overcoming limitations of traditional processes [1].

In particular, stereolithography apparatus (SLA) offers nowadays a very efficient and easy-to-use solution for the high-definition manufacturing of polymeric parts with small dimensions [2].

The assessment of environmental impacts related to the adoption of these technologies is still an open point in research, also due to the lack of a standard methodology [3]. The sustainability implications coming from the adoption of AM are therefore a topic of discussion for research in sustainable manufacturing [4, 5]. A lot of researches have been recently published in this field: being a complete review out

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of the scopes of this paper, only a few works that present a strong connection with the proposed method are mentioned here.

A global perspective on the adoption of AM in the industry has been offered by [6], pointing out the need for sustainability metrics in order to measure the sustainability implications of these technologies.

The adoption of ProdSI method in order to measure the impact of AMed products on environment, economy and society has been proposed by [7]. Authors demonstrated the effectiveness of this method for the life-cycle sustainability analysis of a product.

A life-cycle assessment (LCA) of products from AM is the fundamental element to enable comparative analysis with traditional processes [8] and providing evidence of the potential benefits in terms of sustainability. In [9], a model based on power consumption to decide between subtractive and additive technologies for part manufacturing has been proposed. Nevertheless, according to the sustainability principles, technology selection has to take into account all the impact contributions of the manufacturing process.

In [10], a predictive model for the prediction of life-cycle impact of products manufactured via additive laser manufacturing (ALM) is presented, while [11] offered an overview on the sustainability reflections of products from selective laser sintering (SLS).

Despite its large adoption in industrial and private applications, also stereolithography (SLA) presents a lack of studies for the determination of process impact.

In [12], a life-cycle assessment for the SLA process by means of the Eco-indicator has been presented. The methodology proposed by [12] divides the process into different phases, which are material preparation, building, post-process, use and disposal. The LCA proposed by [12] considers as a reference to the unit of mass of the product; therefore, all the results of the study are scaled basing on the weight of processed material.

Nevertheless, the energetic evaluations of [9] point out an important role in the production time in determining the whole impact of the process. Other aspects of the impact related to the adoption of this technology have been discussed, as an example, in [13] evaluated the emission of organic compounds during the material transformation. Also in this case, the emission has a deep relation with the duration of the process, rather than with the mass of the component, thus demonstrating the need to take into account the processing time.

In the present paper, a framework for the LCA of stereolithography is presented. The method aims to collect all the relevant data to describe the environmental impact of the process taking into account the adopted machine, materials, working condition and geographical region of the production. Two driving factors are used as parameters for the study, i.e. the mass of transformed material (including both part and supporting structures) and the time of the process. The use of these parameters allows to easily apply the results to a generic component to be produced on the basis of information available during process preparation. Furthermore, the results of predictive LCA can also be integrated within optimisation methods [14, 15] to guide decisions in minimising the whole impact of the stereolithographic process.

9.2 Framework of the LCA

In this section, a LCA framework is proposed including the phases of the product life cycle that are directly affected by the manufacturing conditions. To efficiently describe how the decision process affects the entire impact of the production, the framework includes:

– Material production
– Material transportation
– Part fabrication
– Post-processing
– Disposal

All these phases of the life cycle can be described by means of LCAs having mass or time as a reference unit. Therefore, it is possible to analyse each step separately and later integrate the results in the LCA of a generic part manufactured by SLA.

9.2.1 Material Production

The material preparation is a very important phase for the determination of the whole impact of stereolithography products. In fact, the photopolymerisation bases on materials derived from non-renewable resources, in particular, acrylate and epoxy resins. The composition of resins for SLA also includes photoinitiators to allow the photopolymerization to take place; however, the low percentage of these elements may allow ignoring them in a preliminary analysis.

Therefore, the LCA of the production material has to take into account the consumption of raw materials and, in particular, non-renewable resources.

Furthermore, the energetic consumption of these transformation processes is usually high, thus requiring a detailed analysis of the energy sources exploited.

All these aspects, as well as the emissions to air, water and land, need to be qualified in the specific geographic area where the production takes place, in order to efficiently describe the actual impact of the process.

9.2.2 Material Transportation

The transportation of the material is often neglected in the LCA studies concerning AM processes. Nevertheless, it is a common practice for manufacturers to carry on the preparation of the material in a few centres, so to minimise the costs and shield the industrial secrets.

Therefore, the transportation of the resins ends up to have a significant impact on the whole life cycle. Even more, it has to be considered how SLA has a large diffusion in the production of small components by decentralised users that use to order small amounts of material per time. For this reason, the transportation in many cases cannot be optimised, resulting in a low efficiency of the distribution network.

The distribution usually includes both air and land transportation. It must be also considered the presence of possible intermediate warehousing, e.g. among local resellers of the resin.

The liquid resin is usually transported within a cartridge that is in turn packed in cardboard or other secondary packaging items. The disposal of these packaging materials must be included in order to describe the actual impact due to the transportation of the material. The amount of the packages can be expressed in terms of a unit of product through the amount of resin contained in each cartridge. The volume of the packaging materials also allows expressing the impact related to transportation in terms of unit of mass of the resin.

9.2.3 Part Building

During the building of the part, a laser is driven onto the resin to photopolymerise selected regions of the material. During this step, the main impact comes from the energy consumption of the laser.

Different process parameters are used to transform the contour and the hatching of each layer. Nevertheless, the power difference between these two phases is usually small [2], thus allowing, in a first approximation, to consider an average power W_{av} during the whole process.

The energy consumption during the process can be estimated by multiplying W_{av} by the time of the process t_p.

The impact of the process may also include a fraction of the whole environmental impact of the equipment, i.e. the production and disposal of all the electrical and mechanical components of the machine.

9.2.4 Part Usage

The impact during the use is strictly connected to the part produced. The LCA framework here presented aims to be used in comparative studies of the machining conditions: as a hypothesis, we assume that every machining condition leads to satisfactory results in the product performance.

Therefore, the impacts related to the using phase of the parts are omitted and postponed to the LCA of the specific product.

9.2.5 Post-processing

As well-known, parts produced by SLA require a post-processing phase to reach the desired shape and properties. Usually, this phase includes cleaning, post-curing, support removal and finishing.

The cleaning step is used to remove the liquid non-polymerised material from the surface of the part. To perform this task, a solvent of the resin is usually adopted: in particular, Isopropyl Alcohol (IPA) is largely diffused being a solvent of both acrylate and epoxy resins. After the washing, the IPA has to be disposed of as a hazardous waste, thus resulting in a significant environmental impact. If considering a full immersion of the product in a tank of solvent, in a first instance, the amount of IPA can be assumed to be proportional to the volume of the component and, thus, to its mass. A more accurate analysis should include the geometrical complexity of the part, e.g. by means of its surface to volume ratio.

During the post-curing phase, the part undergoes ultra-violet radiations in a heated chamber, to complete the polymerisation process and reach the final characteristics. The duration of the post-curing and the power adopted (that determinate the whole energy consumption) depends on the mass of the component. Therefore, the partial LCA related to this phase can be performed by using the mass of the part as a reference unit.

The support removal and finishing are related to the geometry of the part and to its design requirements. In the present study, the mass of the support material has been considered within the whole mass of the part. In fact, this material undergoes the same life-cycle steps in terms of preparation, transportation, cleaning, post-curing and disposal. For this reason, the support removal and part finishing are not included in the present framework and are postponed to the specific LCA of the product.

9.2.6 Disposal

SLA adopts thermosetting materials that do not allow to be recycled at the end of the product's life. For this reason, incineration or landfill have to be assumed for the disposal of the part [12].

The impact connected to each of these phases depends on the geographical region and the methods adopted for disposing of, thus requiring an appropriate measurement of impact indices.

This phase has to include both the disposal of the part and of the support structures adopted for its building, even if they actually take place in different moments.

9.3 Parametric Representation of the LCA

Figure 9.1 summarises the flows of the LCA framework outlined in the previous paragraphs.

As previously mentioned, each step of the chain can be considered by means of an autonomous LCA using as the reference the unit of mass of the product or the unit of time of the process. It can be noticed that the only phase of the life cycle depending on the building time is the part fabrication, while all the other steps are functions of the reference mass.

It is worth to remark that the reference mass flow has to include both the mass of the part and all the auxiliary transformed material (e.g. base, supports and surplus material). It can be observed that the mass can be used as the reference flows for all the steps of the LCA, with the only exception of the part fabrication, in which the energy consumption is not proportional to the processed mass.

Nevertheless, the energy demand of the SLA process can be estimated starting from the process duration by considering constant average power consumption, as above mentioned.

The total life-cycle impact ($\mathrm{LCI_{tot}}$) of the process can be thus expressed as a function of the mass m_p and the build time t_p as in Eq. 9.1

$$\begin{aligned}\mathrm{LCI_{tot}}(m_p, t_p) = \mathrm{LCI_{MP}}(m_p) + \mathrm{LCI_{RT}}(m_p) + \mathrm{LCI_{PF}}(t_p) \\ + \mathrm{LCI_{PP}}(m_p) + \mathrm{LCI}_D(m_p)\end{aligned} \tag{9.1}$$

where $\mathrm{LCI_{MP}}$, $\mathrm{LCI_{RT}}$, $\mathrm{LCI_{PF}}$, $\mathrm{LCI_{PP}}$ and LCI_D are the impacts resulting from material production, resin transportation, part fabrication, post-processing and disposal, respectively.

The mass of the product m_p can be easily evaluated starting from a digital representation of the part multiplying the solid volume by the material density.

As well, several different approaches can be adopted in order to estimate the building time starting from the digital representation of the part [16–18].

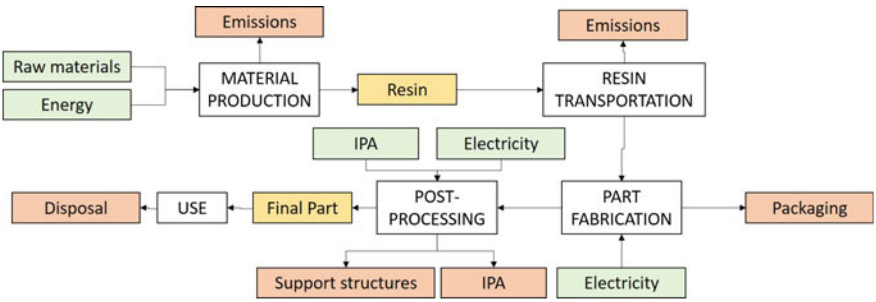


Fig. 9.1 Life-cycle assessment of stereolithography production

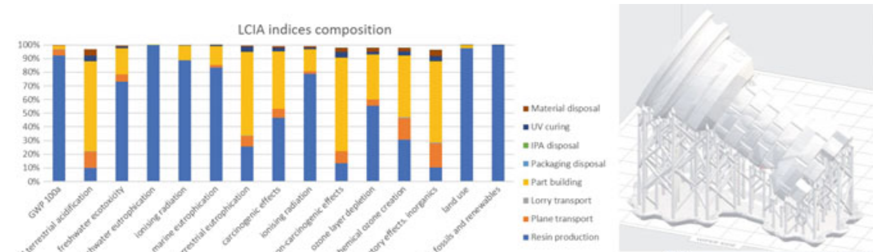
Therefore, once all the sub-LCA concerning different steps are established, it is possible to get an estimation of the life-cycle impact of the production under given conditions starting from the only digital representation of the model within the build chamber.

Thus, this approach has to be intended as a new tool to be used during the process design in order to get information about the environmental impact of the production. This approach leads to a fundamental improvement in giving the necessary advice while relevant decisions concerning the process design can still be made.

9.4 Framework Application

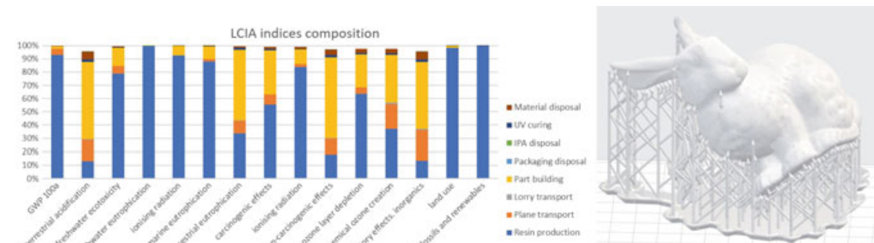
In the present section, the proposed framework is applied to three popular 3D printing models (i.e. Stanford bunny [19], dual rooks [20] and dragonfly pencil holder [21]). The parts have been prepared in PreForm using the one-click print mode, i.e. using the part orientation and supporting structures proposed by the software.

Figures 9.2, 9.3 and 9.4 point out the contribution of the different phases of the life cycle to the impact indices; the volume of material used and the building time are also reported as they are the key factors on the results provided by Eq. 9.1.



Volume	53.31 mL
Build time	7 h 3 min

Fig. 9.2 Impact assessment of dual rook model



Volume	151.13 mL
Build time	13 h 25 min

Fig. 9.3 Impact assessment of stanford bunny model

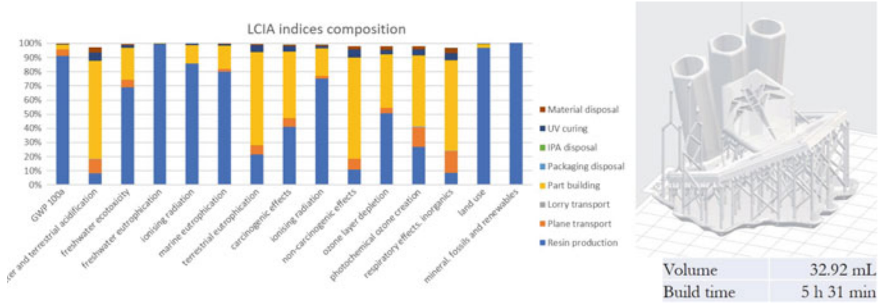


Fig. 9.4 Impact assessment of dragonfly pencil case

It can be noticed that the composition of environmental impacts looks very similar even if evaluated models are strongly different in terms of geometry and dimensions.

In particular, it is evident that most of the contribution to the environmental impact derives from the phase of material production. Furthermore, it can be observed how, even if an SLA with a low power consumption has been considered, the part building has a tangible effect on the ecosystem quality (e.g. freshwater and terrestrial eutrophication) and the human health (e.g. non-carcinogenic effects). This high contribution is mainly due to the long time required for the process.

9.5 Conclusions

The present paper proposes a framework for the LCA of the stereolithography process. The proposed framework includes phases of the life cycle neglected by previous works in the field (such as material transportation and disposal of solvents), thus enabling an accurate analysis of the environmental impact connected to SLA production.

The framework intends to analyse each phase separately by means of an LCA having the unit of mass or the unit of time as reference flow. The different phases are then assembled to get an evaluation of the whole process impact on the basis of the mass of the part, the mass of auxiliary structures and the estimated building time. This approach allows to characterise the specific productive environment and then easily apply the results for predictive comparative LCAs only based on the digital representation of the part. The development of such predictive instruments allows getting quick estimations of the environmental implications of the stereolithographic production during the process design, thus driving the decision-making to more environmentally friendly solutions.

Comparing to a traditional LCA, the proposed method allows to get information in a preliminary stage where decisions can still be made. On the other hand, the method allows to include the detailed data of the life-cycle inventory for an accurate prediction.

The application of the proposed framework to three benchmark parts allows observing how most of the contribution to the whole environmental impact of the process derives from the phases related to the material production and part building. This allows concluding that the research must focus on finding new ways to produce photoresins for SLA and minimising energy consumption during the production process in order to reduce the environmental impact coming from the spreading of this technology.

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Chapter 10
Investigating the Level of Sustainability in Off-Site Construction

Milad Moradibistouni, Brenda Vale and Nigel Isaacs

Abstract Prefabrication or off-site construction is claimed to be more sustainable than traditional methods when it comes to use materials and environmental impacts. After distinguishing the most important factors that make a construction system sustainable, this paper, which builds on an earlier paper (Moradibistouni et al. in evaluating sustainability of prefabrication methods in comparison with traditional methods. Springer, Berlin, 2018 [1]), begins with a literature review to compare prefabrication with traditional methods over the life span of a building. This helps in understanding the stages of a building's life cycle where prefabrication might be more sustainable. A prefabricated house is then compared with three conventional houses in order to examine the energy efficiency of off-site compared with on-site construction. The primary results showed prefabrication is more sustainable than traditional methods regarding the two factors of water consumption and waste generation. However, when it comes to energy use and environmental pollution the differences between prefabrication and conventional methods are not great. This analysis shows it is not possible to compare prefabrication with other construction methods without considering other factors affecting the sustainability of construction such as choice of materials and design approaches. The other point to emerge was the lack of reliable data regarding the benefits and disadvantages of prefabrication over the life cycle of a building.

10.1 Introduction

The global importance and necessity of planning for sustainable living and development became more tangible after the industrial revolution of the eighteenth century, and especially in the last century. The main motives behind this twentieth century worldwide attention were shortage of sources of energy and environmental issues. These concerns led to the creation of the concept of sustainable development, defined

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by the World Commission on Environment and Development (WCED) in 1987 as follows:

> Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs [2].

The concept, which was accepted by the world community, has been further developed during the last decades. Nowadays, the majority of communities and researchers agree that three concepts of economic growth, social equality, and environmental protection contribute to the idea of sustainable development [3–5]. Despite the importance of social and economic sustainability, this paper focuses on environmental sustainability, which includes the sustainable use of resources and environment [6, 7].

Moving toward environmental sustainability is important as human beings are using the available natural resources faster than the ability of the earth to replace them. If nothing changes by 2050 this use would be at a rate at least twice the replacement ability of the earth [8]. In 2015, the overuse of energy resources, mostly fossil fuels, resulted in the highest recorded concentration of CO_2 in the atmosphere in the last 800,000 years [9]. Human activities put pressure on the planet not only by producing more greenhouse gasses but also by destroying the natural forests, which can filter this pollution. A report by the United Nations says:

> There was a net loss of some 129 million ha of forest between 1990 and 2015, about the size of South Africa, representing an annual net loss rate of 0.13 percent [10].

It thus appears that moving toward environmental sustainability is unavoidable and using a sustainable construction method is one of the factors that can help in achieving this goal. This is due to the fact that buildings and people's activities in them, representing embodied and operating energy, are responsible for approximately one-third of global energy use and also CO_2 emissions [11]. Given the importance of sustainability in construction, this paper evaluates prefabrication to see if it is as sustainable as the literature suggests.

10.2 Prefabrication

Prefabrication or off-site construction (Fig. 10.1) means the whole building, or at least its major parts or elements are built in a factory far away from the final location, and then transported and attached to the foundations [12]. Prefabrication has been claimed to be over 50% more efficient in terms of using energy, water, and raw materials, with approximately 30–70% fewer environmental impacts, 65% less waste generation, and 35% fewer CO_2 emissions [13–16]. These potential benefits have led to the idea that prefabrication could be considerably more sustainable than traditional methods [17, 18]. Most of these benefits come from having more control over the production process and environmental conditions in the factory. This paper aims to evaluate some of these claims in more detail to see how sustainable this method might be.

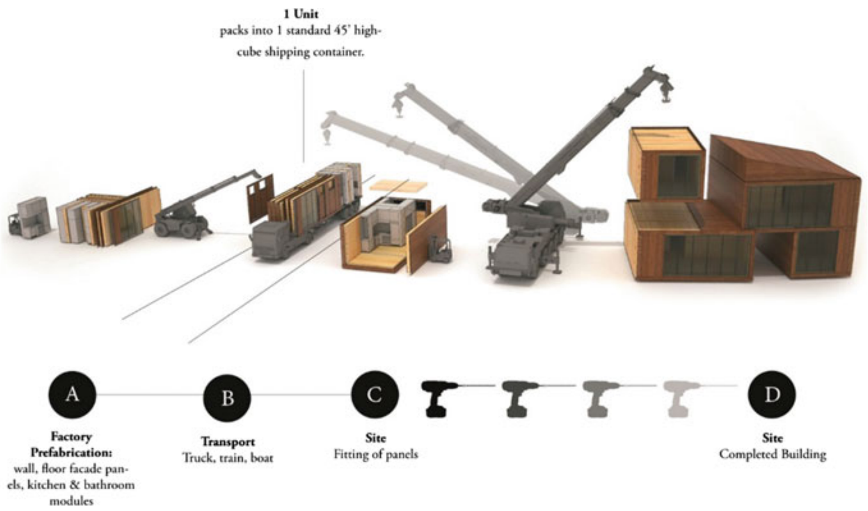

Fig. 10.1 Prefabrication process. *Source* [19]

10.3 Methodology

In order to see how sustainable prefabrication is, this paper first defines sustainable construction and gives the most important factors affecting the sustainability of construction based on analysis undertaken for a previously published paper [1]. Using these factors, the comparison between prefabrication and conventional methods will be conducted in the two stages of pre-use and operation. This will be done to see how sustainable prefabrication is at each of these stages. The after use (demolition) stage is ignored here as broadly it accounts for less than 1% of the life cycle energy (LCE) of a building [20].

10.4 Sustainable Construction

Sustainable construction is the process of constructing a building by maximizing the efficiency of using energy, water and, raw materials, and also minimizing its environmental effects [21]. In sustainable construction, efficient use of materials and environmental impacts should ideally be considered at the stages of pre-use, use, and after use of the building [22]. The parameters to be considered include recycling and reducing the use of materials, as well as the efficient use of energy resources, land, and water, and the effect on ecosystems and the ability for regeneration of the resources used [23].

An earlier study by Moradibistouni et al. [1] showed water, material and energy consumption, waste generation, environmental impacts and emissions, durability, quality and well-being, and cost to be the main factors can affecting the sustainability of construction. However, in this paper, only the top four factors of water and energy consumption, waste generation, and environmental pollution, which were pinpointed by over 85% of the studies investigated, will be used in this analysis.

Although prefabrication has some benefits over conventional methods in all of these four main aspects, the aim here is to find at which stage these benefits occur and how significant they are.

10.5 Water Consumption

Water consumption, which was mentioned in 91% of the 21 articles studies, emerged as the most important factor affecting the sustainability of a construction project. The construction industry is also responsible for 16% of world annual water consumption [24]. However, there is little evidence to support the claim that prefabrication will save water.

> Internationally, it is suggested that prefabricated construction uses less water in construction [up to 50%], although this is not well supported… Due to bulk water metering on-site, the lack of sufficient data for analysis has meant that it could not be established at this time whether there is a difference in water use between traditional on-site construction and off-site prefabrication in New Zealand [25].

The water used during the life of a building can be classified into the same three groups of construction, operation, and demolition. There are no big differences in the amount of water use during the building operation between prefabricated buildings and conventional ones, since the use of water in this period is more dependent on occupant behavior and habits rather than the building design and construction method [26].

The use of water during the construction phase can be divided into the two groups of on- and off-site use. The water used for construction on-site is less than one-third of the water used in the whole construction process [27, 28]. Bardhan (2011) claims that 92% of water used in a construction process is for the extraction and preparation of materials and just 8% is used on-site [29]. Initially, this suggests there is no difference in the use of water between on-site and off-site construction. However, prefabrication has been claimed as using materials over 50% more efficiently, which potentially means a substantial reduction in materials used and the water embedded in them [13, 14]. This would have to be tested further by looking in detail at the types of materials chosen. However, prefabrication tends to imply a dry construction method, such as use of timber components, which would involve less water than, for example, a building made of concrete, although there have been many prefabricated concrete systems, and modern tilt-up panels are a common sight in New Zealand. Typically water forms 14–21% of total ingredients in a concrete mix [30]. The wood in a timber frame requires drying out rather than having water applied, although water will be used in making the steel for the nails. It is the choice of material type rather than being prefabricated which will affect the level of embedded water, so less water in a prefabricated building probably comes from it being made of lighter and more portable timber components.

On a construction site, water is mainly used in any temporary accommodation of workers, for dust suppression, for preparing materials such as concrete, and in hydro-demolition and cleaning [25–28]. Some of these water uses can be cut or decreased using prefabrication and others cannot. For example, the amount of water used in temporary accommodation can be reduced using prefabrication as this method can halve construction time, which means less/no need for on-site accommodation [14]. Moreover, toilets and showers used in factories are more efficient than those in temporary use on-site [25]. So, using off-site methods can slightly reduce the on-site water consumption of construction process, but there is a greater potential reduction from the choice of materials, which tend to be dry construction for ease of transportability.

10.6 Waste Generation

Unlike water consumption related to construction projects, which suffers from a lack of data, there have been more studies of waste generation. The majority of researchers agree that prefabrication can reduce the amount of waste creating during construction and demolition, and the only differences are in the level of this reduction, which range from 52 to 87% [15, 31–34].

Reducing waste generation is an important component of sustainable construction as it is far easier to not produce waste at the beginning, rather than manage it after it has been generated [35]. Vivian (2014) investigated the main sources of waste generation in a construction process and found these were from cutting materials, over ordering, damage during transportation, loss during installation, poor workmanship, and design changes [32]. Of these factors prefabrication should aid in reducing waste from cutting, over ordering, poor workmanship, and design changes. Design standardization and tighter control over the production process in the factory can reduce defects in the final products by up to 60% [13, 16]. Also, due to the modular concept of off-site construction, prefabricated elements could be reused in another project, when a change is needed in one project.

10.7 Energy Consumption and Environmental Emissions

Energy consumption and environmental emissions are the last two factors to be discussed in this paper. These two factors have a close relationship, so can be studied together. Over 99% of world CO_2 emissions come from oil, natural gas, and coal, which all are non-renewable sources of energy [33], so using more energy is in a construction project is equal to creating more emissions and vice versa.

Previous studies suggest prefabrication is over 50% more energy efficient than traditional methods with 35% fewer CO_2 emissions [13, 16], which seems substantially more sustainable. However, there is no clarity in the literature over whether this 50% is just for the construction stage, or relates to embodied energy, or to the whole lifetime energy of the building life cycle. There should be no major difference in operating energy for a building using the same materials and techniques constructed on-site or off-site. However, prefabricated buildings have fewer defects and energy leaks on completion, so their operating energy use could potentially be slightly less than conventionally made buildings. As a result, it can be concluded that energy reduction from prefabrication comes mainly from the reduction in embodied energy through less wastage of materials.

Boafo (2016) claims that operating energy is responsible for 70–98% of a building's life cycle energy use [36]. Similarly, Ramesh (2010) studied the life cycle energy of 46 residential buildings, and 27 office buildings made of wood, steel, concrete, steel frame and concrete, brick veneer, clay bricks, cement, and reinforced concrete [20], coming to the conclusion that during the life span of these buildings 80–90% of all energy was consumed during operation and just 10–20% was embodied energy [20]. However, this percentage will vary based on the target of the design. If the aim is to design a zero-energy building then embodied energy will form a much larger percentage of the life cycle energy because the operating energy is so small. The total energy saved from using prefabrication thus also depends on how energy efficient the building is to be, and a life cycle energy analysis (LCEA) is needed to see if prefabricated buildings are more energy efficient than conventional ones. In an ongoing study of making a prefabricated zero energy Accessory Dwelling Unit (ADU), which is a second complete dwelling put on an existing plot, the LCEA of the ADU design in Wellington, New Zealand was compared with that of three other houses in three locations. The first was the super-insulated BIAC House in New Zealand, the second the Melbourne Green Home in Australia, and the third the zero fossil fuel energy UK Hockerton Houses [37, 38]. The first two were designed to be low energy and the third to be zero heating energy, like the prefabricated ADU. Figure 10.2 compares the life cycle energy of the prefabricated ADU with that of the other case studies.

Obviously, this comparison is not truly valid because the operating energy depends on the different climates. However, two useful comparisons can be made, that between the two New Zealand houses, and that between the two houses designed to be zero heating energy. Figure 10.2 shows the LCE of the ADU is slightly higher than that of the BIAC House, which is timber frame and super-insulated. This suggests there are no LCEA gains from being prefabricated. However, the BIAC house is lightweight, having a suspended insulated floor, whereas the ADU sits on an insulated concrete slab. To see how this affects the LCE, the BIAC house floor embodied energy (initial construction) is 30 MJ/m^2 which is 2% of the total initial embodied energy of the house. This compares with over 1000 MJ/m^2 for the floor of the ADU, which is over 33% of total. Additionally, the ADU is insulated with expanded polystyrene in its prefabricated structural insulated panels, which has a higher embodied energy than the fiberglass insulation of the BIAC house. Each cubic meter of polystyrene has an embodied energy of 1400 MJ, which is 40% more than that of fiberglass [39].

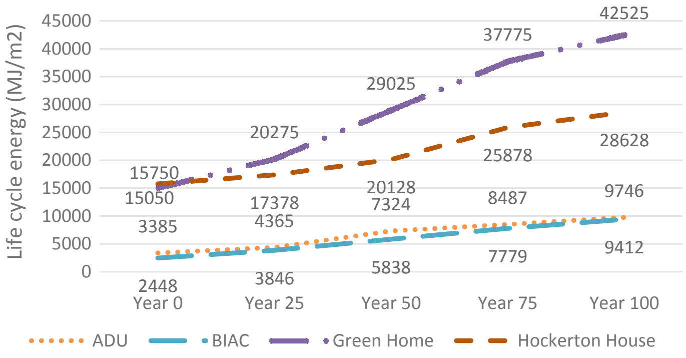

Fig. 10.2 Lifecycle energy comparisons (MJ/m^2)

The LCE is thus dominated by the choice of materials rather than the method of construction.

When it comes to the zero energy house comparison, colder climate of the UK required more mass in the form of a concrete structure to store heat from summer to winter [40]. This dominates the embodied energy and hence the LCE. The insulated concrete slab which also forms the floor at year 0 has an embodied energy of 6.8 GJ/m^2, and this forms 31% of the total mass of the house [41], whereas the prefabricated ADU has an initial embodied energy of 1 GJ/m^2 and effectively accounts for 100% of the total mass. This suggests that it is simplistic to say prefabrication can save more energy as it also depends on the local climate.

The other factor that needs to be considered regard energy consumption and CO_2 emissions of prefabrication is transportation. In off-site construction, the materials need to be transported to the factory to be assembled and then to the final location. However, in conventional construction, materials are directly transported to the final location to be assembled on-site. So, off-site manufacturing has extra transportation compared with conventional methods, which could affect emissions, although more investigation is needed to see how significant this might be.

10.8 Discussion and Conclusion

Given the use of energy resources by humans and the accompanying environmental pollution is more than the recovery rate of the planet and this threatens the ability of coming generations to enjoy the benefits the earth as at present it is necessary to move toward a more sustainable situation as fast as is possible, and this includes the construction industry. As a result, this paper set out to evaluate the sustainability of prefabrication in comparison with conventional building.

The first issue to emerge was the lack of measured data on the effectiveness of prefabrication in reducing resource use and environmental pollution. There is limited evidence from the literature that prefabrication can save water and also reduce the waste associated with construction. However, the water saving does depend on the choice of materials for the prefabricated building, and since dry materials, like timber, are also lighter for transportation, this may be where the savings are coming from, although a deeper investigation is required.

When it comes to the use of energy resources and consequent environmental pollution, the literature claims prefabrication can save both energy and CO_2 emissions. However, this investigation revealed that efficient use of energy resources in a construction project is more dependent on design approach, and the type and amount of materials used than whether constructing on-site or off-site. In turn, the choice of materials depends on how the building will perform in the local climate. Making a zero heating energy building in a cold climate like the UK requires the incorporation of more mass than making a zero heating energy building in the warmer climate of Wellington, New Zealand. Mass is heavy to transport and the example discussed in this paper was the prefabrication dry and lighter weight components for an ADU that are to be attached to the heavy insulated slab on-site.

In the end, it should be said that with current knowledge it is impossible to claim prefabrication is more sustainable than traditional methods in all aspects. Everything depends on the choice of materials and how the building performs, and a full LCEA needs to be done to be sure that energy and pollution are both minimized.

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Chapter 11
Future Direction of the Sustainable Turning of Difficult-to-Machine Materials

Jasmine Rance, Stephanie Hall, Andrea de Bartolomeis and Alborz Shokrani

Abstract Ensuring the sustainable future of machining is becoming a growing concern in industry. Conventional machining approaches pose problems and cannot be continued at the level required in all three areas of sustainability—social, economic, and environmental. Therefore, alternatives to traditional techniques are being sought. One of the major barriers to sustainability in machining is the use of cutting fluids due to their high costs, harmful health effects, and environmental impact. However, cutting fluids play a vital role in the cooling and lubrication required during machining. In particular, the turning of difficult-to-machine materials is usually associated with high temperatures, high energy usage, and low productivity. Furthermore, the selection of cutting parameters currently prefers productivity to sustainability. This paper collates and presents the popular ideas that are presented in state-of-the-art literature for alternatives to cutting fluids and the optimization approaches that ensure the sustainable future of turning. The authors conclude that the future of sustainable turning of difficult-to-machine materials will comprise of closed-loop internal cooling of the insert, combined with external minimum quantity lubricant. However, to ensure that these technologies remain sustainable, without sacrificing productivity and part quality, optimization techniques should be applied. In particular, multi-objective optimization of environmental, social, and economic impacts should be undertaken in conjunction with intelligent algorithms.

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11.1 Introduction

Traditional cutting techniques are no longer viable, since they cannot be maintained in a social, environmental, or economical capacity; these each form the three pillars of sustainability. The detrimental effects of these conventional techniques are exacerbated due to the fundamental nature of the manufacturing sector in all industrialized countries [1]. In 2018, the manufacturing sector was responsible for the second highest energy consumption (23%) behind transport (36%) [2]. Therefore, the importance of sustainability in machining has come to the forefront of the manufacturing industry [3].

The dominant issues in the sustainability of machining are as follows:

- health risks and poor working environment [4];
- cutting fluids and their associated cost, environmental and health risks [5, 6];
- poor tool life with its cost and environmental impact [7];
- high energy usage [1].

Although these problems apply to all machining processes, each one requires different solutions. Conventional hard turning is considered one of the most crucial forms of machining in the aerospace [8], biomedical [9], electronics, and automotive [10] industries.

Upon reviewing the literature, the authors have identified that there are two main branches to be taken into consideration, in order to overcome the prominent issues in the sustainability of turning as shown in Fig. 11.1.

This work reviews novel and state-of-the-art techniques that have been presented in the literature as alternatives to conventional turning in the two branches identified in Fig. 11.1. The most advantageous solutions from each branch have been presented, and the sustainable future direction of turning is outlined.

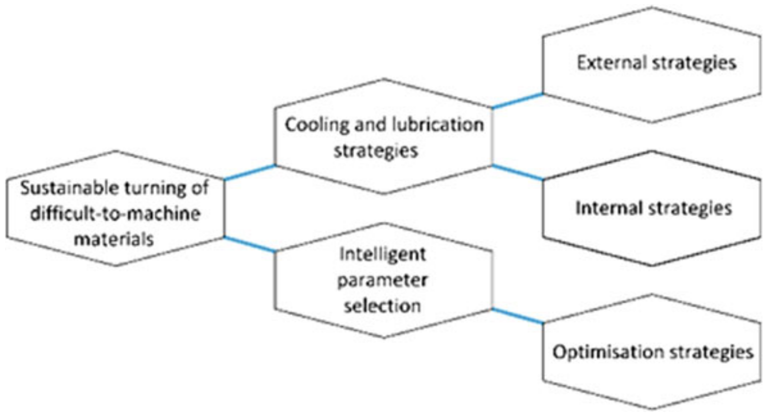

Fig. 11.1 Branches identified to improve the sustainability of turning

The first two sections contain the state-of-the-art alternative cooling and lubrication branch in attempts to eradicate the use of environmentally harmful, health hazardous, and costly cutting fluids. The final section explores the potential in the optimization of the machining process in order to effectively identify and refine all parameters to provide the most sustainable turning process.

11.2 External Alternatives to Cutting Fluids for Cooling and Lubrication

Cutting fluids are an engineered mixture of oil, water, and chemical additives. They are particularly useful in the machining of difficult-to-cut materials because they provide four major benefits—cooling, lubrication, chip flushing as well as chemical protection.

Since 1907, the use of cutting fluids has been firmly established in the machining industry [11] with an average consumption of several billion liters of fluid per year [12]. Despite their vast popularity, cutting fluids are associated with environmental pollution and are detrimental to operators health—in some cases causing lung cancer, asthma, and genetic disorders [4]. Additionally, the introduction of governmental regulations limiting their use and increasing the waste disposal cost by up to four times the original purchase cost has incentivized the eradication of cutting fluids from manufacturing [13]. Hence, a more sustainable solution is being sought to replace conventional wet machining with cutting fluids. Current state-of-the-art literature highlights the following alternative options:

- Dry machining [14];
- Cryogenic cooling (cryo) [13, 14];
- High-pressure cooling (HPC) [15, 16];
- Minimum quantity lubrication (MQL) [17, 18];
- Solid lubrication [18].

The optimal alternative to remove cutting fluids from manufacturing is dry machining as the use of cutting fluids is completely avoided. However, unsurprisingly, dry is unable to achieve sufficient productivity and acceptable workpiece quality due to overheating [17].

Overheating can be controlled with cryogenic cooling techniques, where a super-cold liquefied gas, usually nitrogen, is supplied onto the machining area at −195.8 °C [14]. Cryo has shown to have unparalleled cooling in comparison with both traditional and all alternative options of external cooling [19]. Furthermore, the evaporation of liquid nitrogen eliminates the requirements of filtering and disposal of fluids. Cryo is considered as an environmentally conscious option to replace cutting fluids [19]. Yet due to the hazardous temperatures and the detrimental effects it can have on tool life, cryo is not a socially or economically acceptable method of machining [20].

The HPC method delivers traditional cutting fluids under high pressure to the cutting edge. These act as a hydraulic wedge allowing the fluid to reach and cool the frictional area of the cutting zone. HPC exhibits particularly high productivity, mainly due to the prolonged tool life it provides, for example, an extension of up to 740% over the conventional wet environment [15]. However, this method requires a greater amount of hazardous cutting fluids and higher energy consumption. In fact, HPC requires 1.2×10^6 to 3×10^6 ml of fluid an hour [15] that is an order of magnitude higher than for wet [18] and triple the specific energy consumption [16].

MQL presents as a more sustainable solution, requiring only a minimal amount of vegetable oil (10–100 ml/h) to lubricate the frictional area and prevent overheating. As well as tool life extension, it has been reported that MQL provided a 14% reduction in cutting forces and 51% improvement in surface finish over dry turning [21]. The major drawback, however, for MQL is that there is a lack of cooling at high cutting speeds, resulting in limited productivity [22].

MQL has been adapted by replacing the oil droplets with MoS_2 or graphite, forming the solid lubrication alternative [14]. This emerging technology eliminates the use of oil and so, is considered even more socially acceptable. However, the productivity of solid lubrication in turning is lower than that of conventional MQL and considerably lower than HPC [15].

Figure 11.2 depicts a qualitative overview of the sustainability of current state-of-the-art external cooling and lubrication technologies.

It is easily observable that there is no optimal technique. While HPC has the best productivity, MQL, cryo, and solid lubrication are more sustainable solutions. From these solutions, MQL is the most promising alternative and the authors believe that in the future its inadequate cooling can be overcome by utilizing internal cooling strategies.

It is also believed that the capabilities of external cooling in turning will always be limited due to the high heat flow (500 W/cm^2) across the small tool-chip contact area (1 mm^2). This causes the minimal obtainable tool-chip temperature to be reliant on the material properties and tool geometry [23].

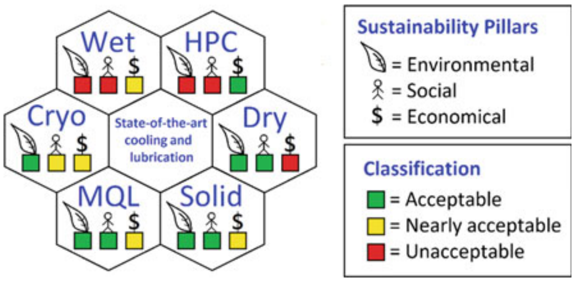

Fig. 11.2 Sustainability of state-of-the-art cooling and lubricating technologies

11.3 Internal and Indirect Cooling

Over the last 20 years, methods to internally or indirectly cool cutting tools during machining have been developed. These thermally stabilized cutting tools fall into three predominant categories: closed loop internal cooling (CLIC) [7, 23–26], open loop internal cooling (OLIC) [27–30], and indirect tool holder cooling (ITHC) [30–38]. CLIC passes fluid through a coolant passage that runs into the insert and backs out through the tool holder. OLIC delivers cutting fluid directly to the cutting zone through holes in the insert. ITHC cools the tool via a reservoir, heat pipe, or radiator of liquid that is located at the contact between the insert and tool holder.

The predominant research and patent activity is in relation to OLIC and ITHC. ITHC has shown to be a sustainable addition for turning [31, 39], exhibiting improved surface roughness, greater scope for cutting speeds, and improvements to the health and environmental impacts [32–34], in addition to a 5–15% reduction in cutting zone temperature and 5–20% enhancement in tool life in comparison with dry machining [34–37, 40]. OLIC strategies have shown to also reduce the environmental impact [30], and the results for OLIC were particularly favorable when a cryogenic coolant was utilized, outperforming dry, flood cooling and external cryogenic delivery [27].

However, despite these results, OLIC and ITHC alone are not economically feasible options in comparison with flood cooling due to their insufficient temperature reduction, the practical costs, and the continued use of external cutting fluids [23]. Therefore, there has been a lack of uptake in the industry as a result of the problems left to overcome [7].

Literature and research on the third internal cooling option, CLIC, is limited. However, the preliminary results in effectively cooling the insert are promising. In contrast to dry machining, the potential reduction in the tool temperature has shown to be up to 17% [26, 41]. However, the reduction is greatly influenced by the diameter of the pipe [41] and the proximity to the cutting edge [24].

Simulations have shown that introducing CLIC had no negative effects on the tool life and mechanical stresses met the tolerable limits [26].

Nonetheless, CLIC has shown to have a lower standard of surface roughness (depths of approximately 2 μ) and greater cutting forces in comparison with dry machining [26]. Rozzi et al. [23] also highlighted that the removal of heat with internal cooling is challenging without the use of a fast flowing multi-phase coolant.

These problems have been approached by Bleicher et al. [7, 25] by investigating the use of both CLIC and HPC, focusing on the effects on BUE and wear on inserts. From several investigations, they found that the production of built-up edges was significantly reduced; for their selection of flow rates (240 and 265 ml/min), they achieved a reduction of 66% to almost 100% in their tribo-chemical reaction. As the tribo-chemical reaction decreased, so did the cutting forces. They also found that the improvements in tool life were double that experienced when using HPC only. Further, Bleicher and Reiter [7] discovered that no notch wear appeared, the local temperature was considerably reduced, the production costs of parts would be reduced, and sustainability would be increased compared to HPC alone.

These results show that the combination of both internal and external cooling is a positive. However, as highlighted in Sect. 11.2, HPC is not a sustainable form of external cooling. Therefore, a different form of cooling should be considered. Neto et al. [38] suggested combining ITHC with cryogenic machining. However, literature shows that the main problems that need to be overcome are mainly from the lubrication side, and cryogenic is not the most sustainable option. Hence, the authors propose that the sustainable future of turning for difficult-to-machine materials should combine CLIC with external MQL.

11.4 Application of Optimization Techniques

The use of optimization and simulation techniques is vital in order to use recent advances in cooling and lubrication. The impact and benefit of these cooling and lubrication methods can be determined, while enabling the prediction of aspects such as tool wear, surface integrity under different cooling, and lubrication methods—without sacrificing objectives such as productivity and part quality [42].

Alongside cooling and lubrication, the proper selection of machine and tool parameters is a primary concern within machining and the high performance of the process depends on this [43, 44]. Traditionally, cutting parameters are selected based on experts experience or technical handbooks, where the focus is placed mostly on economic values, along with costly and limited experimental tests. Some aspects such as energy consumption and fluid consumption are often neglected in favor of quick outputs at an acceptable standard [44, 45]. It is imperative that in order to move forward to a truly sustainable machining process, all three pillars of sustainability, economic, environmental, and social, must be considered as objectives to optimize.

As highlighted in literature, difficulty arises when considering a singular sustainable objective [1]. Hence, the current challenge is to ensure all three are acknowledged. This means that classical optimization methods are generally not suitable and care must be taken to find an appropriate optimization technique. Xiong et al. [44] provide a comparison between the method of single-objective and multi-objective optimization. They discovered that multi-objective is far superior as it provides more realistic machining requirements. It also prevents the potential for negative effects that occur on the non-optimized parameters in single optimization. However, these methods become increasingly more complicated. In general, for non-trivial problems, there will not be a single solution that can fully optimize every objective. Computational efficiency must also be considered with this approach. Zhou et al. [45] were successful in finding optimal parameters using non-cooperative game theory, yet suffered in time complexity.

Researchers have noted the significance of the cooling parameters on the outputs. Jiang et al. [46] used cutting fluid consumption and process cost as the optimization objectives. Applying a hybrid genetic algorithm (GA), they managed to reduce the fluid consumption by 17%. Park and Nguyen [47] combined numerical simulations and optimization algorithms to improve the energy efficiency by 18% and reduce the

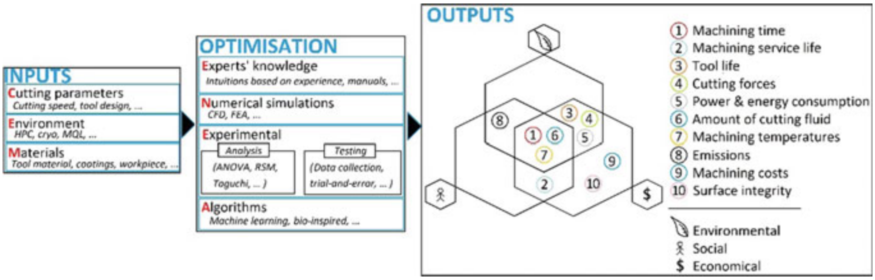

Fig. 11.3 Inputs, outputs, and optimization techniques highlighted by the literature

specific cutting energy by 14%. Sivaiah and Chakradhar [48] employed the Taguchi optimization method, using the cooling environment as a fourth parameter alongside speed, feed, and depth of cut. They found that this technique significantly reduced the surface roughness and flank wear, by 53.5 and 31.18%, respectively.

Many different techniques and algorithms have been utilized by researches when attempting to find the optimal parameters for their chosen objective(s). For example, the use of Taguchi optimization [48], fuzzy algorithms [49], artificial neural networks [50, 51], game theory [45], and other bio-inspired algorithms [43, 52]. With the availability of computer power and software, machine learning and artificial intelligence soft computing techniques have been 'flourishing' in recent years [53]. This trend is also aided by the abundance of machining data and improved ability to monitor the process and parameters closely. Using more intelligent algorithms in combination with large amounts of data will give a more accurate picture of what is happening in the process and the influence chosen parameters have on the output values.

The authors have collated the input, optimization approaches, and outputs arising from the literature in Fig. 11.3. They observed that the inputs fell into three categories and the outputs could be classified by their applicability to the different sustainability pillars. In combination with the information presented in this section, the authors believe that the important optimization techniques are heading in the direction of intelligent algorithms that attempt to include as many of the sustainability objectives as possible.

11.5 Conclusions

This paper identifies the sustainable future of turning of difficult-to-machine materials by reviewing state-of-the-art literature. Two main branches of research that would provide potential solutions to major challenges in the sustainable machining were highlighted. From these, the following main conclusions could be drawn.

CLIC and MQL both present as the most sustainable solutions in their respective research areas but neither are widely accepted in industry due to their drawbacks, for

CLIC, the lack of lubrication and chip removal and for MQL, the lack of cooling. However, CLIC and MQL are complimentary and therefore, in conjunction, should provide a sustainable solution that can be easily adopted by industry.

However, the application of CLIC and MQL cannot be considered as a sustainable solution in isolation. The optimization of the input parameters that are detailed in Fig. 11.3 is vital in order to ensure the sustainable outputs are maximized. To ensure that the most sustainable solution is found, multi-objective optimization for the three pillars of sustainability and the implementation of intelligent algorithms to large, readily available data sets should be utilized.

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Chapter 12
Multimodal Freight Transportation: Sustainability Challenges

E. I. Udo, L. Huaccho Huatuco and P. D. Ball

Abstract Due to globalization in trade, the development of multimodal cargo shipments and the related transport needs have created a range of challenges. Interestingly, sustainability of multimodal freight transportation is still subject to minor consideration, on the grounds that economic interests are frequently positioned much higher than social or environmental objectives. This proposed research plan is needed to assess whether and to what extent the multimodal freight system is achieving the results in the sustainability dimensions: economic, social and environmental. Thus, it will carry out a critical appraisal of the multimodal freight transportation sector to provide an up-to-date knowledge on the sustainability challenges and the potential solutions through doctoral research. This paper structured to present a review of existing literature on freight transportation and multimodal freight transport highlighting the sustainability concerns with multimodal freight transport systems. It also highlights the gaps in knowledge with a justification on the need to address these gaps for the system to function optimally. It also covers the methodology that would be applied and the sources of data that would be reviewed to ensure the aim and objectives are clearly addressed. The paper concludes by discussing the significance of the expected findings in the light of sustainability in multimodal freight transport to the academia, policy makers and the freight transportation industry.

12.1 Introduction

This paper aims to present an overview of multimodal freight transport system with a view to highlighting the major sustainability challenges and the existing knowledge gaps which must be addressed if multimodal freight transport must function optimally. Multimodal freight transport can be seen as a combination of several modes of transport within a national or international transport operation, aimed at providing door-to-door services, under the charge of a single transport operator [1]. To para-

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phrase the Brundtland Commission's definition of a sustainable planet [2], it can be derived that a sustainable multimodal freight transportation system is a system that meets the needs of multimodal freight transportation today without compromising the ability of future generations to meet their own multimodal freight transport needs based on Black [3]. Multimodal freight transport connotes one transport operator carries out all transport functions, using various modes of transportation, under one contract. While this creates a certain level of ease in the contract and makes it less cumbersome, the sustainability of this has to be considered. The effectiveness of this method has to be taken into account as well as the general environmental impact caused using this mode as well as potential options and alternatives. The upsurge in the flow of knowledge, goods, services as well as resources among nations which has occurred as a by-product of globalization (interaction coordination of world economies) has led to a major increase in transport activity over the years [4, 5]. This has impacted the environment in several ways including increased economic activity, fluctuations and changes in production location and developments in the types and modes of transportation needed to support global trade.

The transportation framework is one of the key facilitators of trade logistics. In developed countries, organizations experience the best logistics and transportation experts, frameworks, and infrastructure in the world, but this may not be the same in developing countries due to outmoded production, distribution and supply systems; poor transportation infrastructure and inefficient third-party transportation; bureaucracy; political instability; and shortage of investment funds [6]. Transportation expenses are higher when managing shipping materials in international trade due to long distances [7]. As expressed in the Action Plan for Freight Transport Logistics [8], logistics is "the oil in the EU's financial machine". Economic activities rely on logistics coordination to supply materials to industry and to move items along the organization's network and in the long run to the final consumer, developed or developing nation notwithstanding.

This paper presents a review of existing literature on freight transportation and multimodal freight transport highlighting the sustainability concerns with multimodal freight transport systems. It also highlights the gaps in knowledge with a justification on the need to address these gaps for the system to function optimally. It also covers the methodology that would be applied and the sources of data that would be reviewed to ensure the aim and objectives are clearly addressed. The paper concludes by discussing the significance of the expected findings in the light of sustainability in multimodal freight transport both to the academia and the freight transportation industry.

12.2 Literature Review

Every transport system has its own complexities which occur as a result of the multi-dimensions of hardware being used (vehicles and supporting infrastructure) as well as social nature of the organizations and people involved. This type of complexity can be multiplied with the use of multiple modes with the associated interface with several regulatory bodies, legislative bodies, financial systems, technology, service providers and varying human behaviours. Several studies have shown that multimodal transportation evolved as a combination of numerous transport modes aimed at improving trading efficiency [1, 9]. This combination further complexes the use of multimodal freight transport, resulting in both positive (short transport time, reduced cargo damage, inventory reduction, improved quality of freight) and negative (safety, traffic congestion, infrastructural damage, fuel consumption, air pollution, noise, etc.) effects on sustainability issues.

Thus, with these challenges of complexity and sustainability effects, it becomes imperative for organizations to incorporate sustainability development frameworks into their corporate governance to cover such aspects as: economic viability, technological feasibility, social and environmental sustainability of their operations [10–12]. Hence, at this point it is important to provide a critical understanding of how freight is transported and the major stakeholders within this industry.

12.2.1 Freight Transportation

Russo and Comi [13], while analysing urban freight transportation, argued that there are two main freight movements. These are elucidated as follows:

(a) End-consumer movements: These movements occur when freight is moved by the end-consumers (private or business customers) that purchase and consumes the goods. That is, freight movement is conducted by generic purchasers who buy items from a shop and then transport them to a different place where the goods are consumed. Russo and Comi [13] opined that in this type of movement, it may be hypothesized that end-consumer is the decision maker.
(b) Logistic movements: For logistic movements, freight gets to the facilities where it is delivered to the markets for producing other products (goods) or services (i.e. freight movement from the warehouse to the retail outlet) or directly delivered to the end-consumer/customers. It involves several decision makers and functional relationships in the trade schemes. These include: (i) trade without any contact points (directly), e.g. online shopping and direct delivery to end-consumer; (ii) trade with one contact point (the retailer), where the producer engages networks of retailers to access the target market (or consumption zone); and (iii) trade with more than one contact point usually employed to consolidate or deconsolidate the load. These trade scheme aims to reduce the cost of logistics and transportation.

12.2.2 Multimodal Freight Transport

Several authors have explained the concept of international multimodal transport in different ways; however, the most legitimate definition of the term is provided by the United Nations Conference on Trade and Development (UNCTAD) [14]. The "multimodal transport" concept is viewed as a combination of several transport modes utilized as a part of a national or global transport operation, which offers door-to-door services, under the obligation of one single transport operator [13]. The "Multimodal Transport" term was initially used by the UNCTAD on international multimodal transport of goods in 1981 [15].

The person or organization in charge of the whole carriage is called a multimodal transport operator. By definition, the multimodal transport operator is any individual who, by him/herself or through someone else or other organizations, closes a multimodal transport contract, who acts as the principal, not as an agent or for the benefit of the consignor or of the carriers partaking in the multimodal transport operations, and who accepts accountability for the execution of the agreement [14].

The multimodal transport operator is responsible (in a lawful sense) for the whole carriage, despite the fact that it is performed by a few distinct methods of transport (by rail, water and road, for instance). However, the multimodal operator does not need to own every one of the methods for transport and in practice, typically does not, carriage is frequently performed by subcarriers (often called in legal terms, "real carriers"). Rawindaran et al. [16] likewise certified that the expressions, "through transport", "consolidated transport", "multi-purpose transport" and "multimodal transport", are altogether utilized as a part of the setting of cargo movement from beginning to end, essentially including the use of containers. These four terms are fundamentally the same in significance, that is, the transportation of goods by more than one mode of transport and a through single cargo rate contract.

The rise of the container technology and of the multimodal transport originated from and facilitated increasing international trade [14]. The idea of international multimodal transport covers the door-to-door movement of goods under the duty of a solitary transport operator, though the idea may not be new, utilized as a part of the late 1950s by Malcolm Mclean and his trucking operation [17, 18].

Containerization adds to a higher productivity in the advancement of multimodal transport operation. Keeping in mind the end goal is to accomplish efficient and effective multimodal transport, intense cooperation and coordination among transport modes are important. The emergence of containers had allowed for a global reach through an expansion in trade volume with increment of operational effectiveness, which allows multimodal transport to be used in most global transport operations [19]. Hence, advancements of standard units, including containers, with enhanced ease of transfer, support multimodal transport. Preceding United Nation's formalization of Multimodal Transport in 1980, the phrasing has experienced a few phases of changes before it acquired its official status by the UNCTAD/ICC in 1992.

The development of multimodal cargo shipments and the related transport needs have created an extensive variety of challenges that are mostly noticeable in metropolitan and urban locales. These challenges are generally as a result of capacity and sustainability requirements of the present distribution framework, of which capacity is acknowledged as a genuine test for policy, planning and strategy. In the use of a single mode of freight transport, the sustainability challenges are slightly more specific in comparison with multiple transportation modes. For with the use of road transport, the challenges may include congestion, emission of GHGs such as CO_2 and utilization of space and these would be different from the challenges of rail transportation which may include noise pollution among other challenges [20–22]. According to the Oslo/Paris convention (for the Protection of the Marine Environment of the North-East Atlantic) (OSPAR Commission) [23], sustainability concerns for sea freights border on such issues as the consequences of consumption of non-renewable fuel sources, SO_2 emissions (both at the ports and at sea), discharge of sewage and garbage, contaminants from ballast water, space occupation which has the potential to interfere with the natural ecosystem and habitats, ocean acidification and fluctuations of pH levels due to CO_2 and SO_2 emissions, whereas with air transport, the sustainability challenges may include noise, contamination of land, incidental pollution of water and habitat disruption [24].

Thus, it is expected that multimodal freight transport which incorporates various combinations of the modes of transportation highlighted above would feature the specific sustainability challenges identified/associated with each mode of transport and their associated actors to ensure that end users receive their desired product and service. This implies that the issue of sustainability should be placed at the forefront of multimodal freight transport especially as there a lot more factors to be considered and addressed if multimodal freight transport is to be operated optimally. This view is supported by Carlier et al. [9] who argued that the aggregated performance of a multimodal transport system cannot be fully understood from the separated performances of the component systems. Interestingly, sustainability of freight transportation is still subject to minor consideration, on the grounds that financial interests are frequently positioned much higher than social or ecological objectives. However, air contamination, commotion discharges and infrastructural degradation, principally brought on by heavy-duty vehicles, ships and trains, occur at a specific cost to the environment and society—also the exceptional need for space at major passage areas for warehousing, vehicle operations, trans-shipment or the storage of containers which are not in use [25]. This implies that researchers need to consider if the multimodal freight system is effectively achieving the results for which it was set up, and if it is, at what financial and environmental cost. Are the current practices sustainable at all and what future effects will multimodal freight have? What are the current industry best practices in other countries and are there alternatives? These and other important questions are expected to be answered in the course of this research.

12.2.3 Sustainability in Multimodal Freight Transport

The World Trade Organization says that globalization and international trade provide long haul relationship between economies where one entity has the capacity to impact on the management of an element occupant in another economy [26, 27]. Thus, globalization permits organizations to pick up international experience necessary for survival in today's dynamic business world and allows countries and regions to accomplish economic development. Notwithstanding, neither international trade nor globalization is conceivable without transport as trade and transport are inseparably connected: effective transport administrations are essential to successful international trade. Remarkably, international trade comprises utilizing more than one mode of transport for some interfaces and modes are explored during the time spent moving merchandise starting with one country then onto the next.

According to Russo and Comi [13], there is a recent worldview focused on setting out and clearly outlining sustainable development strategies, through which to continually deliver long-lasting improvements in quality of life. They argued that this could be achieved through the creation of sustainable communities which are able to manage and utilize resources more effectively and efficiently. Also, sustainable development can be achieved through the identification and use of the ecological and social innovation potential of the economy, thereby ensuring economic prosperity, environmental protection and regeneration, as well as social cohesion and stability. But what really does it mean to have a sustainable multimodal freight transportation system?

In multimodal freight operations, this implies that sustainability practices observed using one mode of transportation or with one sub-carrier does not necessarily lead to a total sustainability in the whole transport system as this implies the use of various modes and several carriers. Hence, sustainability practices must be evenly applied throughout the multimodal freight system. This raises sustainability issues in and of itself about the effectiveness and efficiency of multimodal freight transport especially in the achievement of business viability and economic development, so this leads us to ask the question, does multimodal freight transport achieve expected results and with what financial and social implications? However, while addressing this question, we should also ask what the effect will be on the environment.

The use of multimodal freight transport implies the use of various carriers, various transportation methods and the involvement of several organizations scattered in several countries and locations. This connotes that varying practices among the various actors, for the various modes and in the different location. This leads to the question, what are the current industry practices in comparable countries and regions? This has created a necessity for this research to fill in the knowledge gaps in this regard by offering the most complete and comprehensive answers to four key objectives and questions within this theme, which include:

- Does multimodal freight transport achieve expected results and with what financial and social implications?
- What are the current industry practices in comparable countries and regions?
- What are the future effects of multimodal freight transport on the environment and businesses?
- Are there any alternatives to current and future freight transport practices?

12.3 Methodology

The research will use a case study methodology which allows the researcher to carry out a thorough investigation. The case study, as a research methodology looks into and searches through reports of past studies, permits the investigation and understanding of complex issues. It is a powerful research technique used especially when a comprehensive, thorough examination is required. It is viewed as an instrument in numerous social sciences, the role of a case study strategy in research turns out to be progressively noticeable when issues concerning social sciences [28], education [29] and challenges affecting specific communities [30] are being investigated. Thus, this method will allow for interactions with the participants in order to gain access to the participants' social meaning. The research will also employ the use of industry expert interviews to triangulate findings.

Both primary and secondary data will be applied in this study to fully address the research questions and objectives. This research will carry out semi-structured interviews to allow in-depth discussions with participants as the primary method for data collection. The research will also review documents as listed in the section for sources of data as the secondary data collection method. The adoption of multiple data collection methods and techniques will allow for the different research objectives and questions to be fully explored.

In the first stage of the work, extensive analysis of academic work and qualitative data from different international organizations will be used to build the background of multimodal freight transport, with focus on the UK in relation to its trade partners in the European Union, given the current Brexit context and Nigeria for a comparison between developed and developing countries. Based on the data collected, comparative analyses will be made with data collected in the next stage, in order to shed a light on several research questions.

The second stage will capture data obtained from observation of actual industry situations in different cities within the UK/EU and Nigeria in order to find out how to develop a framework that would offer the best course of action in terms of the efficiency and sustainability of freight transport. In addition, there may be qualitative interviews with several industry experts who may be willing to participate.

12.4 Sources of Data

The accessibility and availability of relevant data are the most vital aspects of any research, and in this proposed study, it is expected that relevant data may be scarce probably because not so much research has been previously done in this area. Thus, the data sources that will be consulted include:

- research and data sets from industry experts and organizations within EU countries and partner countries;
- secondary data from researches carried out by scholars in developing countries as well as the UK;
- data set from UNCTAD, World Trade Organization (WTO) and other relevant international organizations.

Primary data from multiple case studies will consist of semi-structured interviews with senior managers (industry experts), direct observations and historical data from relevant multimodal freight organizations.

12.5 Conclusions

Though environmental sustainability is only one aspect of the triple bottom line effect, it is important across all industries of human endeavours as they need to show commitment to making their operations environmentally sustainable and meeting consent standards relevant to attaining national and international legislations protecting the environment [31]. When operations of companies pose threats of harm to human health or the environment, precautionary measures should be taken even when cause and effect relationships are not fully established scientifically [32]. Thus, such companies must undertake adequate and satisfactory risk assessment and risk management approach for their operation beyond regular environmental impact assessment requirements [33]. Thus, it has to be adopted as a key element for policy decisions concerning environmental protection and management of such companies.

In view of the above, this research contributes to the existing body of knowledge which future researchers and academicians can build up on. The research is of great significance to policy makers and industry representatives in the transportation and logistics industry. It also draws on the findings from publications in the field to present the state of knowledge regarding the operation of the freight industry. It is evident that even though these studies have highlighted key aspects of freight services and have established some key framework upon which the sector has been regulated, there are, however, existing gaps in knowledge with regard to the effectiveness and efficiency in its application as a viable business model and adequate tool to be utilized to drive economic development. These must be addressed if freight operations are to be conducted with a sustainability consciousness.

Thus, it is imperative for more research to expand on existing knowledge in an attempt to find out if multimodal freight systems are effectively achieving the results for which they were set up. And if they are, at *what financial and environmental cost are these being delivered?* Also, *are the current practices sustainable at all?* and *what potential future effects will multimodal freight have? What are the current best practices in other countries and are there alternatives?* The resulting information will be of immense significance and benefits especially to the major stakeholders within the industry. This is because this information will create a more transparent policy framework which runs on an environmental sustainability consciousness adopted at an industry-wide framework. Finally, the importance of sustainability cannot be overemphasized and this research positions to provide at the very least, more knowledge and potentially impact on future policies to be made in the transport and logistics industry.

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Part III
Systematic Innovation Tools for Eco-Design: Products, Processes and Assessment Methods

Chapter 13
A Web-Based Portal for Eco-improvement Containing Guidelines and Environmental Benefits Estimator

Davide Russo and Christian Spreafico

Abstract This paper presents a web-based portal for eco-improvement, called I-Tree Guidelines Portal, containing a set of guidelines and an integration with an eco-assessment tool, called I-Tree Configurator, used for assessing the environmental criticalities of a product, to suggest how to improve it and to evaluate the achieved environmental benefits. The I-Tree Configurator automatically processes the manually entered data about the analyzed product and shows the most environmentally impactful entities, i.e., components, transports, consumptions, etc. These are used to automatically filter the guidelines contained within the I-Tree Guidelines Portal in order to propose to the user only the most suitable ones to solve the main problems. The guidelines are structured into different parts, according to well-known conceptual design frameworks, such as Function-Behaviour-Structure (FBS) methods and similar, and they aim to solve problems in inventive ways, by including the principles of TRIZ, widely reviewed and contextualized to environmental problems. The idea generated for each guideline is immediately evaluated by assessing their environmental impact saving on the considered items, through the same I-Tree Configurator, and ranked to provide a base for decision-making.

13.1 Introduction

During the years, several methodologies for supporting eco-improvement have been proposed by academia and industry. To date, just using the query "(eco OR green OR environment OR environmental) AND (assessment OR evaluation OR measuring)" for title, abstract and keywords in Scopus DB, we obtain more than 637 thousand documents.

The proposed methodologies are of different typologies: guidelines, checklists, questionnaires, etc.

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One of the most diffused are is he Ten Golden Rules, developed by [1] that are a series of 10 guidelines containing a synthesis of the possible suggestions to make eco-improvement and based on a huge collection of academic case studies. Other long known methodologies are the Life-Cycle Design Strategy Wheel [2] that includes strategies of eco-improvement divided into six classes (i.e., rethinking, reduce, replace, recycle, reuse, repair), Ecodesign Checklist Method [3], The Fast Five of Philips [4] and the Smart Ecodesign Checklist [5], which all include check-list in addition for filtering the most suitable guidelines, among those contained. Differently to the previous ones, some other methods are instead more specific and focused on specific aims related to environmental improvement: disassembly (e.g., [6]), remanufacturing (e.g., [7]), recovery (e.g., [8]), material recycling (e.g., [9]) and energy efficiency (e.g., [10]).

However, despite the many efforts spent, these methodologies still struggling to spread in industrial contexts, due to some open problems that, according to [11], are: time, economic, and staff resources required, the high number of the guidelines and their high specificity, the absence of multi-objective analysis, in addition to external context limitations such as market and customer and legislation.

In addition, we personally retain that a further limitation of eco-design methods can be the lack of an approachable to guide the designer in selecting alternative directions of intervention from different areas and to fully support him in facing the selected one.

Thus, in order to overcome these limitations, since 2009, we are working on our own set of guidelines for supporting eco-design, by integrating tools from problem-solving theories, i.e., TRIZ [12], in order to improve the efficacy of the guidelines especially for inventive and contradictory problems, as it has been done by other authors for different cases of applications and with different results [13].

The first set of guidelines [14] was strictly based on the Laws of Technical System Evolution, from TRIZ, and they rigorously conserved their jargon. However, from their testing in SMEs within the European project REMAKE emerged that the guidelines were able to ensure, only to TRIZ experts to achieved interesting results in the proposed case studies, if not preceded by a small introductory course. The second set of guidelines [15] has instead been developed in order to transform these guidelines from suggestions for experts to suggestions for novices.

We have then proceeded in this way [16, 17], both by introduce a specific ontology, based on the principles of rational design methods, i.e., Function–Behaviour–Structure, and by introducing an interactive web-based portal.

The plan of the paper is as follows: Sect. 13.1 provides the introduction, Sect. 13.2 presents the proposed web-based portal, Sect. 13.3 presents a case study, and Sect. 13.4 draws the conclusions.

13.2 Proposal

In the last proposed version [16], each proposed guideline was addressed to improve a phase of the product life cycle (pre-manufacturing, manufacturing, product use and end of life), by achieving a goal (e.g., rethinking the packaging) and sub-goal related to the goal (e.g., act on durability) through a suggestion along with an example. The guidelines were contained into a web-based portal where they were classified according to their constituting parts (i.e., phase, goal and sub-goal) that they were selectable by multiple menus of selection. In addition, this tool also included a filter that allowed the user to obtain the most suitable guidelines for the kinds of interventions he was able to make on the product (e.g., the choice of the suppliers, the decision-making during conceptual design, the managing of the logistic).

With the new proposed version, the guidelines have been improved in the content of the suggestions and in their organization; the goals are now expressed through a couple verb+parameter (e.g., Reduce Mass), while the sub-goals are the entities related to the product life cycle (e.g., Packaging).

I-Tree Guidelines Portal has been improved in order to enlarge the support to eco-design process by including the assessment also the improvement phase.

The introduced features are:

(1) the integration with an eco-assessment tool, called I-Tree Configurator;
(2) the automatic filtration of the guidelines on the basis of the data from the assessment;
(3) the evaluation of the benefit provided by the selected guidelines, in terms of saved environmental impact.

Figure 13.1 represents the scheme of functioning of the deriving methodology for eco-design including the I-Tree Guidelines Portal and the I-Tree Configurator.

The process begins with the information gathering about the main information (e.g., masses, materials, distances, energies) of the items related to the product to be

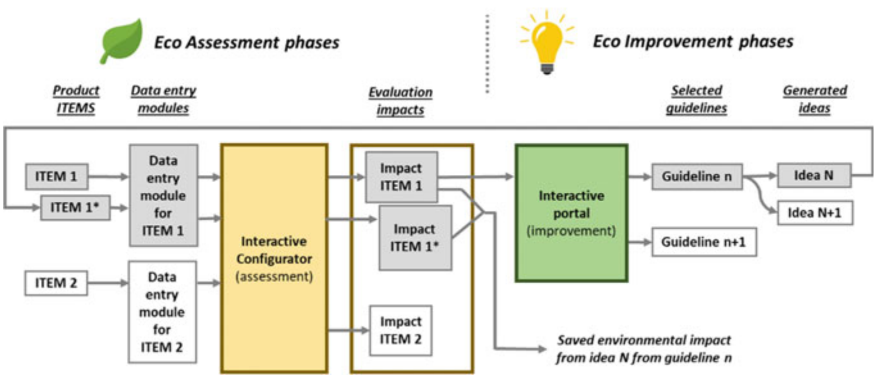

Fig. 13.1 Main steps of the proposed methodology

analyzed (e.g., components, transports, packaging). Then, these data are entered into the I-Tree Configurator, through the data entry modules, where they are elaborated for calculating their related environmental impacts that are finally ranked from the most to the less severe.

On the basis of the obtained results (i.e., the most impactful items and the data entered by the user: kind of item and related phase during product life cycle within the I-Tree Configurator), the most suitable guidelines of the I-Tree Guidelines Portal are automatically filtered.

At this point, the user can apply the guidelines to generate ideas about the considered items (e.g., ITEM 1 in the figure), to improve them. The improved entities (i.e., ITEM 1*) are then analyzed again, by reentering their modified data within the I-Tree Configurator for calculating their new environmental impacts (i.e., impact ITEM 1*) that are compared to the previous ones for showing the related saving.

This process can be repeated for all the most impactful items and for all the ideas generated that are finally ranked on the basis of their related environmental impact saving in order to provide an objective framework for supporting the successive decision-making.

In the following, the main functionalities of the proposed I-Tree Guidelines Portal are presented.

13.2.1 Entering the Main Data About the Product

At the beginning of each session, the user enters the name and brief description of the project, as shown in the initial screen of the I-Tree Guidelines Portal (Fig. 13.2).

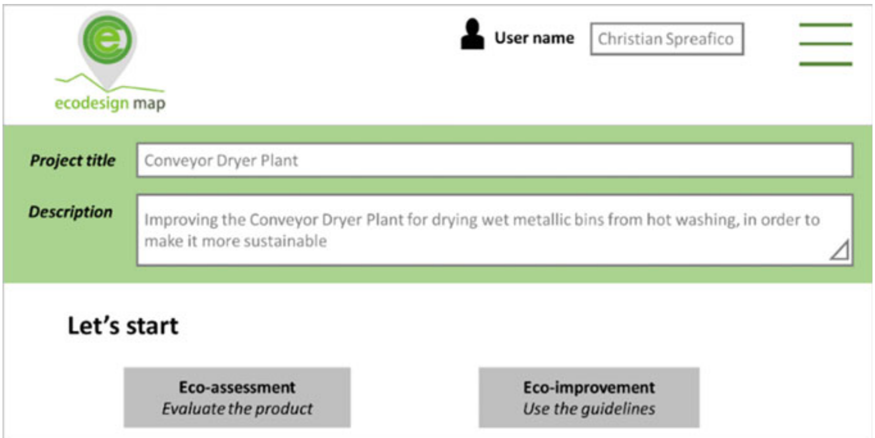

Fig. 13.2 Introduction module

13.2.2 Eco-assessment

Then, the I-Tree Guidelines Portal addresses the user to I-Tree Configurator for assessing the environmental impact of the considered product, where he/she manually enters the data (i.e., masses, energies, and displacement) about the constitutive materials, packaging, and transports.

With them, the I-Tree Configurator automatically calculates the environmental impact (kg CO_2) of each item by using the data about unitary impacts (e.g., kg CO_2/kg of stainless steel) stored within an included DB.

The impacts are then ranked according to their magnitude, and they are used by the I-Tree Guidelines Portal for filtering the most suitable guidelines for facing the main criticalities. The way of functioning of the filter is the following: The I-Tree Configurator stores for each impact all the information previously entered by the user for its calculation which is used by the I-Tree Guidelines Portal for finding the correspondence with the guidelines on the basis on preestablished criteria. For instance, in order to reduce the impact of the item "Delivery packaging" the provided guidelines are those working in the phase of "Product use" (if the packaging was related to the phase of use by the user during the data entry), containing the goals "Reduce Mass" or "Select other materials" of the entity "Packaging."

13.2.3 Selecting the Suggestion

The organization of each guideline within the I-Tree Guidelines Portal is shown in Fig. 13.3.

The work of the filter on the I-Tree Guidelines Portal is to reduce the number of showed guidelines and consequently of the items addressing them, within the menu and the sub-menu.

By selecting the phase in the main menu (Section 1), the user access to the secondary menu (Section 2) where he/she can select the goal (e.g., Reduce Mass). Consequently, the left frame is composed with the sub-menus (Section 3) and the Guidelines (Section 4). An example for each guideline is shown in the right frame (Section 5), along with the links to one or more tool (e.g., the list of the structural resources) that can be applied for exploiting the guideline (Section 6).

Finally, once the user formulated an idea from this guideline, he/she can calculate the related environmental impact saving by accessing to the specific module through the specific link (Section 7).

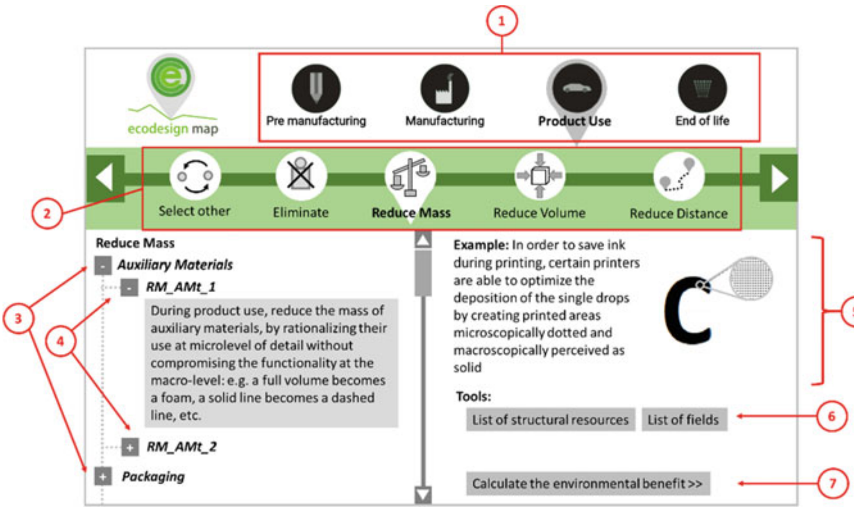

Fig. 13.3 Presentation of a guideline

13.2.4 Calculating the Environmental Benefits of the Idea Derived from the Guidelines

The ideas for each guideline are collected within the I-Tree Guidelines Portal, and their related environmental impact savings are evaluated through the I-Tree Configurator, by using specific modules for data re-entry (i.e., material substitution/reduction, transport substitution/reduction, and energy substitution/reduction).

Figure 13.4 shows an example module used for collecting an idea dealing with the material substitution of an item. Section 1 and Section 2 require the name and a brief description of the idea. Sections 3 requires the user to select the item to modify, among those previously entered.

Sections 4 and 5 contain the initial information about the item (previously entered in the I-Tree Configurator). Sections 6 and 7 allow to enter the modifications deriving from the idea (i.e., the new material and the new mass).

Then, by the selection of the button "Calculate," the I-Tree Configurator evaluates the environmental impact saving achieved through the current idea that is shown within the I-Tree Guidelines Portal.

At the end of the session, the user can access the summary of the entered ideas for improving the considered product, showing the overall environmental impact saving (i.e., the sum of the savings of all the entered ideas) and the ranking of the ideas according to their theoretical environmental impact savings (Fig. 13.5).

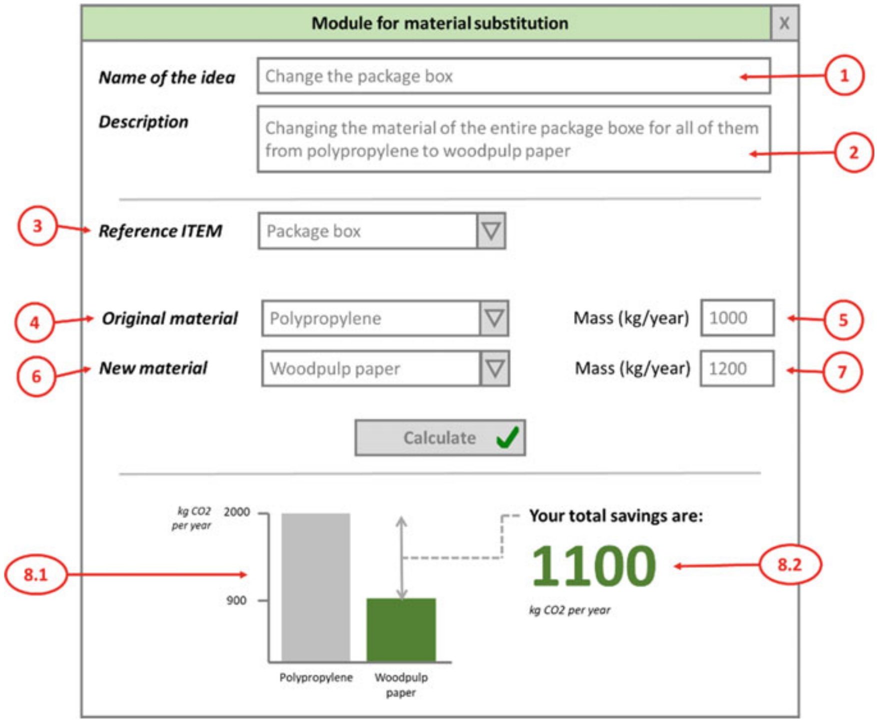

Fig. 13.4 Example of a module for collecting and evaluating an idea from the guidelines. Example for the substitution of the distribution packaging

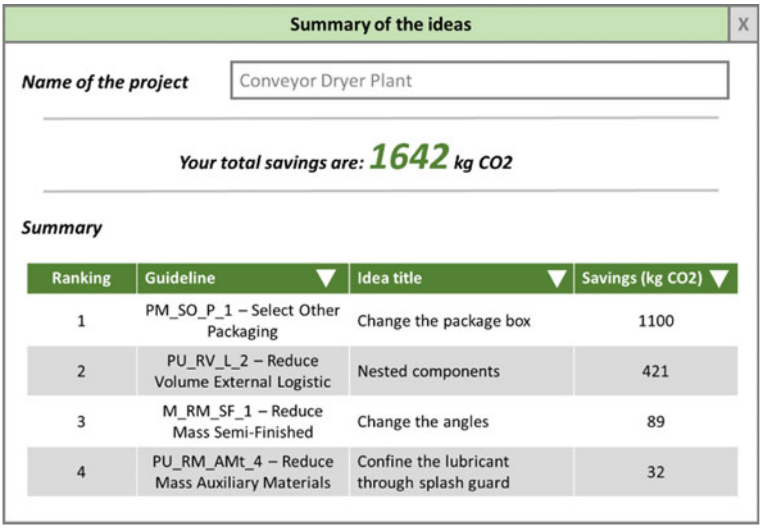

Fig. 13.5 Summary of the saved environmental impacts for the proposed ideas. Example for a Conveyor Dryer Plant

13.3 Case Study

The proposed approach has been applied on a real industrial case study dealing with the eco-improvement of an industrial device for the Oil & Gas industry.

The considered component is constituted by five main ferrous components that are manufactured and assembled within the company through operations of cutting, bending, welding, and painting. All the raw materials come to the company by truck from different suppliers, located not so far, while are moved within the productive plant through overhead crane and forklift. The final product is packed and transported by truck to the nearest port where it continues its journey by ship. During the use, the product requires interventions of maintenance every two years, which consists of the replacement of the Consumables.

13.3.1 Eco-assessment

After the assessment phase, carried out through the I-Tree Configurator, emerged that the most impactful items (see Fig. 13.6) are the "Consumables" (for the maintenance) and the "Component 4".

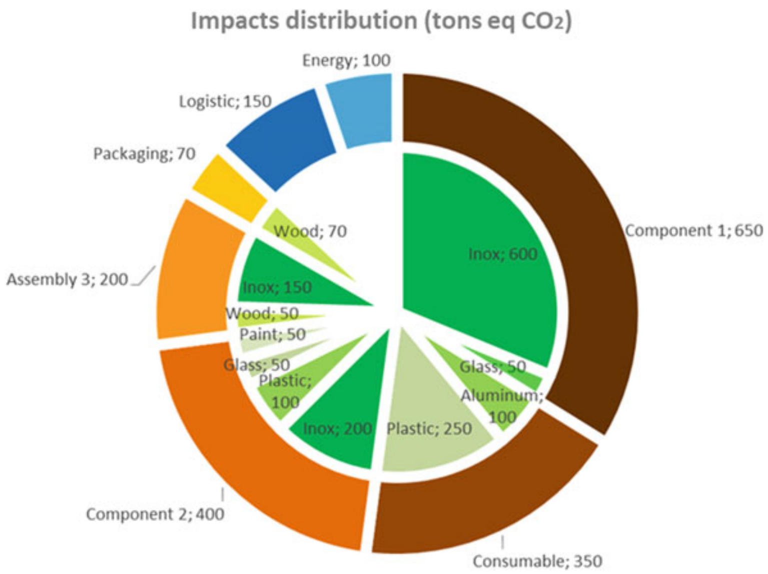

Fig. 13.6 Main sources of impact

13.3.2 Selecting the Suggestions

On the basis of the provided results, we have then selected, among the items, the Consumables, by automatically obtaining, through the filter from the I-Tree Guidelines Portal, the following guidelines, which are all related to the use phase:

- PU_SO_C—Select Other Consumables;
- PU_RM_C—Reduce the Mass of the Consumables;
- PU_RD_C—Reduce Distance for carrying the Consumables.

By proceeding in the order, we have then considered the first one, whose complete text is: "*Change the material of the most impactful consumable with one less consumable and able to perform the same function.*"

Among the possible deriving ideas, we chosen to change the most impactful consumable, i.e., the aluminum oxide, used as desiccant, with the silica gel, which allows similar drying performances while maintaining the same mass of the aluminum oxide, and it is characterized by a lower environmental impact (0.58 kg CO_2 against 1.38 kg CO_2).

Another idea, deriving from the same guideline, deals with the substitution of the aluminum oxide, with a synthetic absorber resin that, as the silica gel, has a lower impact, even if it requires an increased mass due to its lower absorbent capacity.

By selecting instead, Component 4, one of the provided guidelines has been: "PM_SO_RM—Select Other Raw Material" acting during the pre-manufacturing phase and its resulting is to substitute its constituting painted steel with a Corten steel.

13.3.3 Calculating the Environmental Benefits

From the re-calculation of the environmental impact savings, through the I-Tree Configurator, by considering only the better idea from each guideline (i.e., with a greater environmental benefit) emerged that the overall theoretical benefit is more than 12 kg CO_2 eq.

Table 13.1 shows the savings calculated for the ideas described before.

13.4 Conclusions

In this paper, a web-based portal for supporting eco-improvement, called I-Tree Guidelines Portal, containing guidelines has been presented. The tool has been integrated with another home-built software for the eco-assessment, called I-Tree Configurator, able to automatically filter the suitable guidelines for facing the most environmental criticalities.

Table 13.1 List of the proposed ideas

Heading level	Example	Environmental benefit (CO_2 eq)	Selected guidelines
PU_SO_C	Substitute the aluminum oxide of the Consumables with silica gel	7.2	✓
PM_SO_RM	Substitute the painted steel of Component 4 with a Corten steel	2.4	✓
PU_SO_C	Substitute the aluminum oxide of the Consumables with synthetic absorber resin	0.4	
…	…	…	✓

The guidelines are based on TRIZ, and they have high efficiency in robust solutions generation.

Finally, the ideas generated from all guidelines can be instantly assessed through the I-Tree Configurator by determining the related environmental impact savings.

The method has been applied on a real case study during an industrial collaboration, by allowing to achieve interesting results, and it is planned to be taught in university courses, for enlarging the base of the application.

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Chapter 14
Generating Infographics for Environmental Product Declarations (EPDs) with I-Tree Software

Christian Spreafico and Davide Russo

Abstract This paper presents an interactive tool called I-Tree for supporting eco-assessment according to LCA approach. It works with two levels of detail. Through the introduction of a software framework working as a product configurator, LCA data are gathered in an aggregated form. The final impacts are updated in real time during Data Entry and final results about impacts visualized by infographics in order to have the clear picture in the most concise way. Indeed, infographics allow the user to understand where are the main criticalities of the products in terms of environmental impacts, according to the different life cycle phases and then deepen in a second round of information gathering only the components that affect more on the final result. Test on industrial case studies demonstrated important savings in terms of time and resources.

14.1 Introduction

The "environmental labels and declarations" have been created to disclose, according to precise rules, information about the environmental performance of a product or service, with the aim of helping information recipients (intermediate or final consumers, public or private) to choose products with lower environmental impact. According to the classification of the International Organization for Standardizations (ISO 14020), three types of eco-labels can be distinguished: Type I: certified eco-labels, Type II: product self-declarations and Type III: environmental product declarations (EPDs).

The Type III eco-labels, as defined by ISO/TR 14025, provide standardized LCA-based information on a product or a service, through diagrams presenting a set of relevant environmental indicators (global warming, resources consumption, waste, etc.), accompanied with an interpretation of the information.

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The conduction of a LCA (International Organization for Standardization, Geneva, 2006) represents the main part of the process to get an EPD. Life cycle is the most adopted approach specific for eco-assessment, while many other methods integrate the assessment with the improvement phase, by providing specific guidelines (e.g., [1–4]).

ISO/TR 14 025 is an international standard defining the overall characteristics that EPDs should fulfill. For instance, verification of LCA results is required when they are used for public disclosed comparative assertions, while some EPD programs require that the verification is done as a certification by an independent third body, but not necessarily certified.

The EPD is only a "declaration" tool; it is not evaluative. Therefore, the product equipped with an EPD does not meet predetermined environmental performance, as in the case of Type I environmental labels (e.g., European Ecolabel). The environmental preferability of a product can only be deduced from the direct comparison between different EPDs, belonging to the same product group. To allow the comparison between the EPDs of different products belonging to the same group, the product category rules (PCR) are defined, which identify the specific criteria of a homogeneous group of products per functional unit. In other words, the EPD enables the delivery of information to the supply chain as well as the consumer.

It also facilitates the process of product development, the continuous improvement of environmental management systems, and allows purchasers to compare the environmental performance of products and services. Recent studies [5] show that most EPDs belong to companies located where national environmental program operators are stronger (i.e., PEP and FDES in France, IBU and IFT in Germany). According to [6], the highest number of EPDs was Italy followed by Sweden and Switzerland.

There is convergence on the fact that half of EPDs are written in local languages highlighting the fact that a great number of EPDs are developed for national market or national tenders.

During the years, several methods to support eco-assessment for EPDs have been proposed, both for managing complexity during data collection in systems with very large bill of materials and visualization of results according to LCA requirements. Indeed, each element constituting the system has to be evaluated in terms of environmental impacts according to its mass, energy, transport, packaging and recyclability.

To speed up Data Entry, many software has been launched on the market that involves environmental impacts directly in CAD modeling software, but to date they do not seem to have been very successful (i.e., tools such as CATIA (e.g., [7]), Solid Edge (e.g., [8]), Solid Works (e.g., "SolidWorks Sustainability") 2013) and Inventor (e.g., "EcoAudit", 2013).

In this paper, a new software for supporting Green Passport activity is presented.

In the first part, we show how results of an environmental assessment can be summarized by concise infographics. In Sect. 14.2, we face the main problem of all assessment tools: their inability to work at different levels of detail. In fact, for carrying out the analysis of the impacts, they require to the user to enter all the data about the product, their constituting entities, the consumptions and the transports. The problem of this way of proceeding is that it requires an enormous amount of work in terms of data gathering, which is then not justified by the results provided since some source of impact can be inferior to other even of different orders of magnitude. On the contrary using a software platform able to visualize real-time final results, user can understand how deep to move into the analysis, choosing if it is sufficient to describe the assembly or if it is necessary to break down the system in every single element.

Such an iterative approach for Info Gathering can drastically shorten time and efforts.

Finally, Sect. 14.3 draws the conclusions.

14.2 A Software for Creating a Green Passport

With the aim to overcome the main limitations of the methodologies at the state of the art, we proposed our own methodology, based on a home-built interactive configurator called I-Tree Configurator.

The proposed approach is based on four main phases: (1) Info Gathering for collecting the main information about product life cycle (i.e., materials, masses, energies and movements); it can be performed at different levels of aggregation; (2) Data Entry of the product data within the interactive configurator; (3) Automatic Processing, performed by the interactive configurator with the instant calculation of the impacts and the visualization of the results, refinement of the Data Entry, and of the Info Gathering, limited for the most impactful entities and production of the draft for a Green Passport; (4) Manual Review, for commenting to the results provided within the draft.

Figure 14.1 summarizes the main steps of the proposed methodology.

In the following, the main steps of the methodology are explained in detail.

14.2.1 Infographics for Data Visualization

One of the basic requirements of an EPD deals with its degree of synthesis. In a few sentences, the company must communicate the goodness of its design choices to make the product green. For these reasons, we decided to adopt infographics.

In the proposed infographics, we try to show in a comparative way the decomposed system in the different materials of which it is constituted, which elements (grouped in groups/subsystems/single elements) associated with the most impacting materials are more critical, and what affects the most critical to energy consumption, packaging and transport. Putting together all this information is not always possible, but in many cases, it is and when this happens, the result is immediate as seen in Fig. 14.2. One of the secrets to doing this is to be able to group the elements into impact groups, which is the particularity allowed by our system and presented in the next chapter. The system has been developed in Excel in order to meet the requirements of compatibility of the

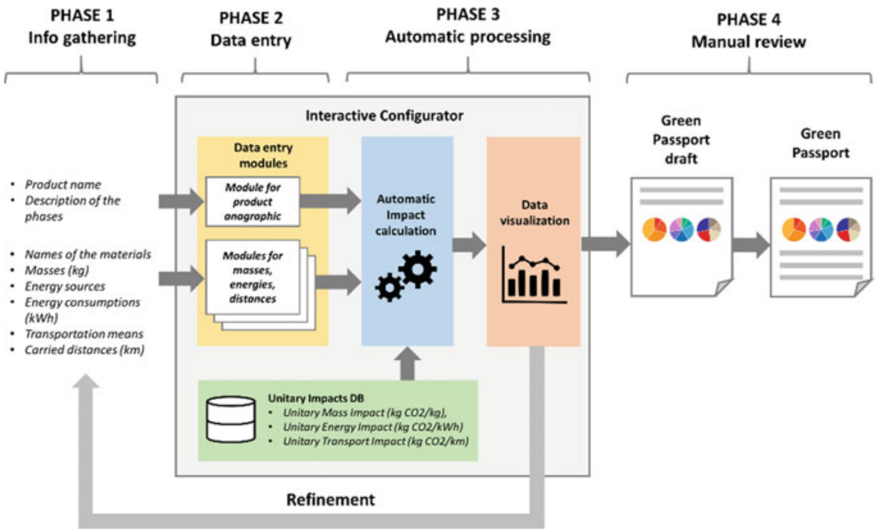
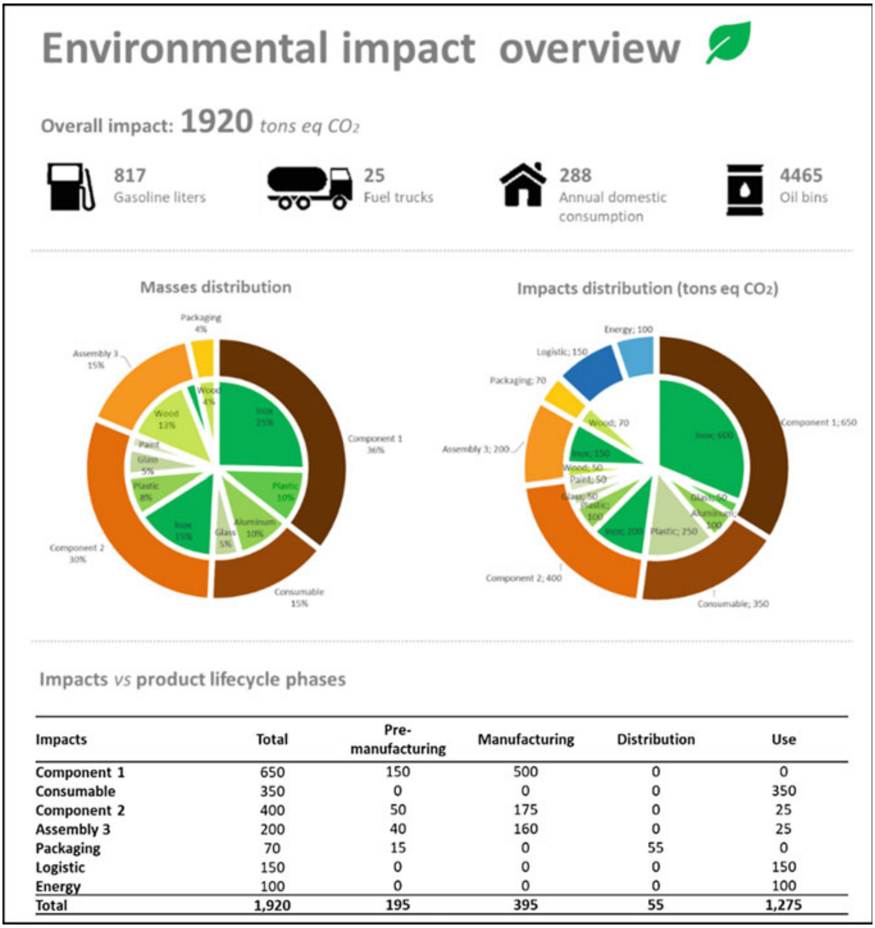


Fig. 14.1 Main steps of I-Tree Configurator

companies. The shown information comprehends: the overall impact, the equivalent indexes, the mass distribution of the components and their materials, the impacts distribution and the impacts compared to the phases of the product life cycle.

More in specific, the infographics include the data about the overall impact of all the items (components, logistic, packaging, consumption, etc.) and the equivalent indexes of conversion. Then, the data about the distribution of the masses and the environmental impacts of the components are compared in relation to their constituting materials. In particular, within the graph of the impacts, also the logistic and the product energy consumption have been taken into account. The showed results depend on the choice of the level of detail of the analysis, which is selected by the user during the compilation of the Data Entry modules of the assembly and the parts.

In addition, I-Tree Configurator is also able to compare the environmental impacts deriving from different scenarios of functioning. That in Fig. 14.3 compares the distribution of the between the impacts of manufacturing and use phases in two geographical areas where the analyzed plant can be installed: arctic and desert. In the first case, the plant work with a greater efficiency and a higher load; for this reason, the use phase is more impactful than in the second case. In addition, also the manufacturing phase is more onerous in the first scenarios, since some additional components (e.g., filters) and special treatment (e.g., extra-painting) are required.



Impacts	Total	Pre-manufacturing	Manufacturing	Distribution	Use
Component 1	650	150	500	0	0
Consumable	350	0	0	0	350
Component 2	400	50	175	0	25
Assembly 3	200	40	160	0	25
Packaging	70	15	0	55	0
Logistic	150	0	0	0	150
Energy	100	0	0	0	100
Total	1,920	195	395	55	1,275

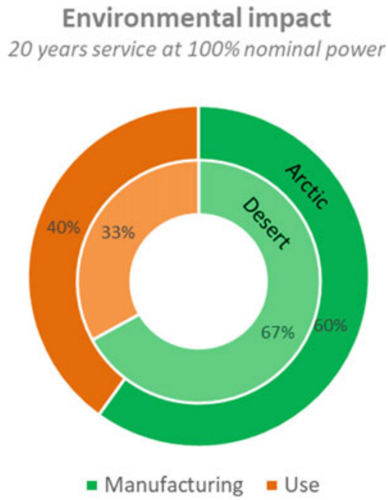
Fig. 14.2 Infographics obtained from I-Tree configurator

14.2.2 Modules for Data Entry

During the Data Entry, the user enters the date for each ITEM, by selecting them from the main menu of selection as shown in Fig. 14.4.

Within the configurator, the data entered by the user specify the name and a brief description for each item, in addition to a generic description, and other information (mass, distance and energy), within specific text input modules. For each selected ITEM, all the entered data are summarized within a summary interface, from which it is possible to call the various modules.

The module for the material composition collects the masses of the materials (kg), and their names (e.g., carbon steel), used directly for making the components of the product, for the packaging or for the auxiliary materials used during manufac-



(tons eq CO2)	Arctic	Desert
Manufacturing	935	915
Use	625	450

Fig. 14.3 Infographics obtained from I-Tree Configurator, describing two different scenarios of functioning

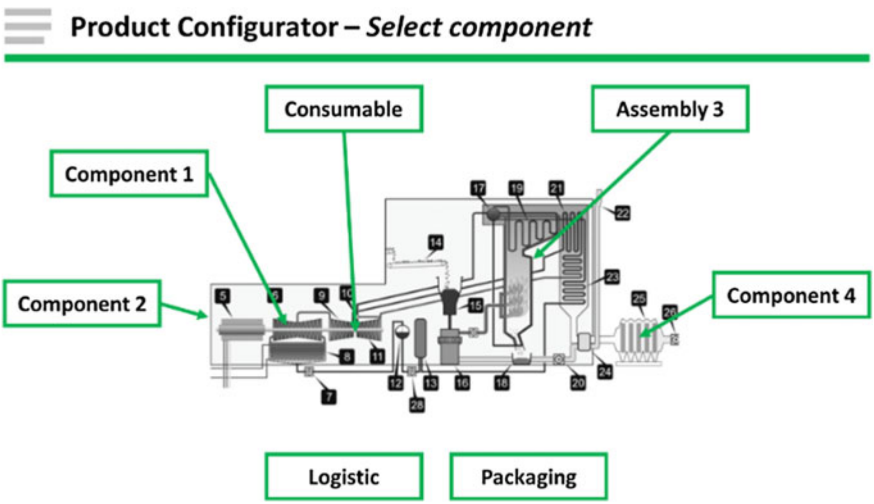


Fig. 14.4 Main menu of selection of I-Tree Configurator

turing (e.g., filler metal for welding), product use (e.g., gasoline) and maintenance (e.g., oil).

The module for the energies collects the quantities (kWh) and the related source (e.g., electric energy from nuclear plant), spent during manufacturing operations or during the product use (i.e., consumption).

The module for the transports collects the information about the covered distances (km) and the carried load of all the transportation means involved within the internal and external logistic during supply, distribution and disposal, with the indication of the kind of mean (e.g., truck, ship, overhead crane).

Figure 14.5 shows the summary module and the interactive modules for Data Entry.

During Data Entry, the data are automatically processed, and the Data Visualization section is updated.

The environmental impacts, showed within the Data Visualization, are expressed in terms of kg of equivalent CO_2 and they are determined for each filled module, by

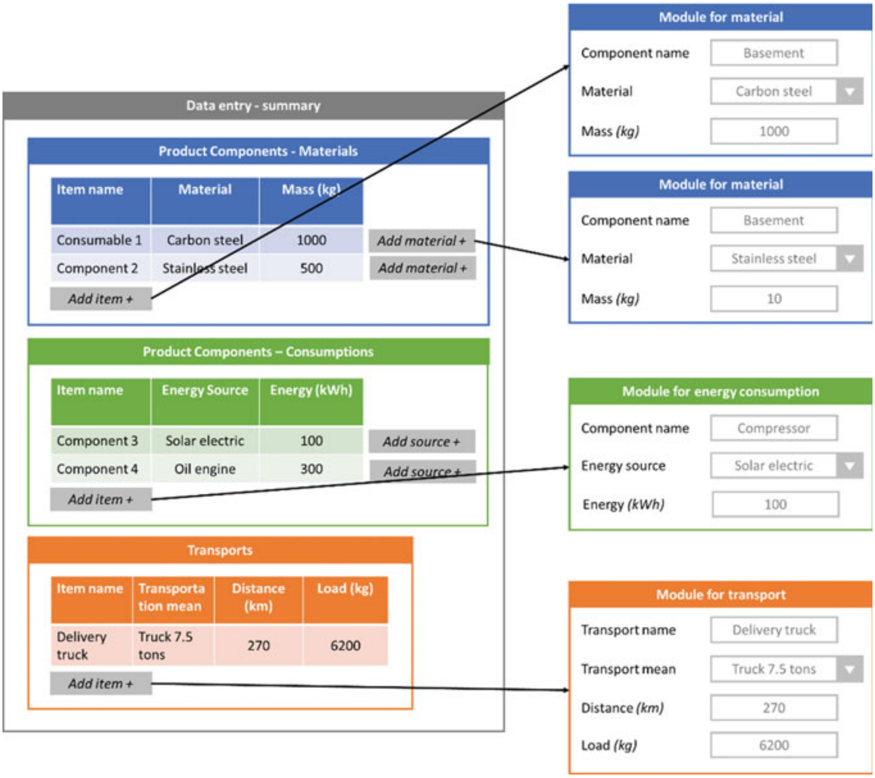


Fig. 14.5 Three kinds modules for Data Entry: **a** Module for material composition used for entering a new component (Consumable 1) and the same used for refining the Consumable 1 with a secondary material (i.e., stainless steel in addition to the more massive carbon steel), **b** module for energy consumption and **c** module for transport

multiplying the entered mass, energy or distance of each material, source or transportation mean for their respective unitary environmental impacts (in turn expressed in kg CO_2 per kg, kWh, km). These latter are collected within a specific database, called Environmental Impact Database. In this way, by monitoring the obtained results, the user can continuously refine and enter new data, by enriching those most significant sources of impact, until they are quite satisfying according to the aim of the work.

Then, the user can export the draft for the Green Passport that is generated on the basis of the combination of the impacts, as a .doc file, with a pre-built template.

Within the GP, the single impacts are then aggregated in different ways in order to provide the total impact of a certain product phase (e.g., impact of the manufacturing), a determined material (e.g., impact of the carbon steel) and the total impact for the entire life cycle. In addition, the GP provides detailed graphs for those most impactful items (e.g., components) that have been refined by the user, through further Data Entry.

Figure 14.6 shows the Data Entry modules within the I-Tree Configurator.

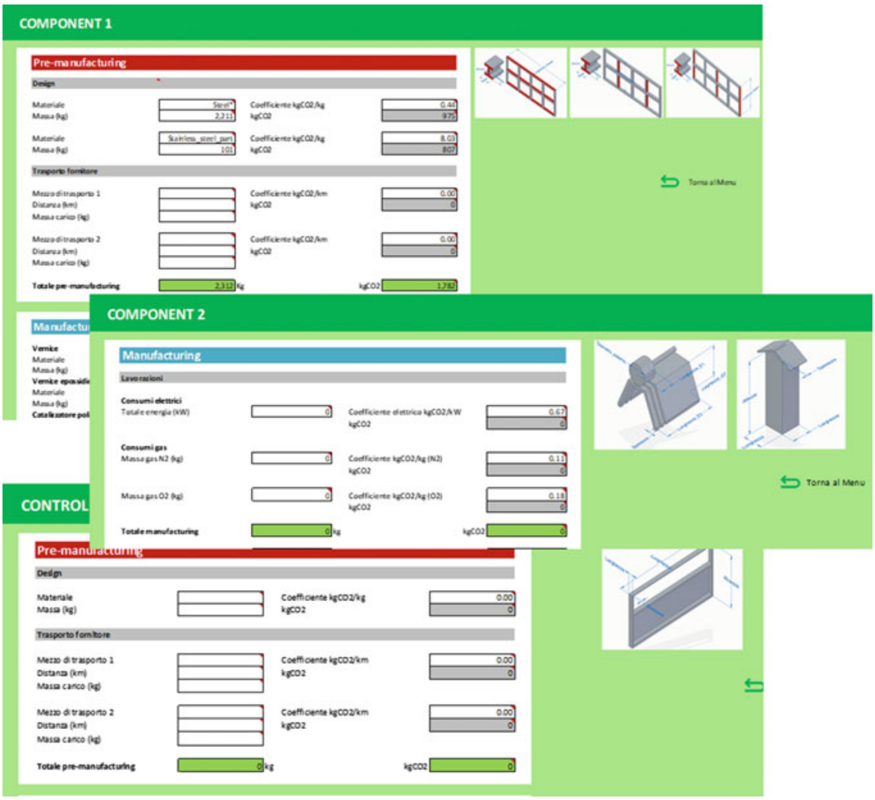


Fig. 14.6 Data Entry modules within the I-Tree Configurator

14.3 Conclusions

In this paper, a novel methodology for the semiautomatic creation of Green Passport or other kinds of EPDs, supported by a home-built interactive configurator, has been proposed.

The main advantages of this tool deal with its ability to work as a product configurator for supporting design activity with environmental considerations, thanks to the proposed way of working based on two levels of detail.

The first one, more aggregated is limited to the main components, consumptions and transfers of the product during its life cycle with the objective to highlight the main environmental criticalities, which, and only them, are deepened with a high level of detail during the second round of use.

In this way, the designer thanks to the first indications about the most impactful items during the first round can save a lot of time, otherwise spent in Data Entry and analysis of all the considered items.

Future developments of the software deal with the development of a Web-based interface in order to improve the user interface in addition to the introduction of an interactive platform shared between different users in order to share the information among all the designer involved in the design process of the product, contrary to the current logic of individual use.

The configurator has been tested with local companies in some cases, where it demonstrated a saving of time both in data collection and elaboration.

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Chapter 15
Eco-Design and Sustainable Development: A Speculation About the Need for New Tools and Knowledge

Lorenzo Maccioni and Yuri Borgianni

Abstract Many outputs of the application of eco-design principles and guidelines result in solutions that slightly differ from previous ones. Although the environmental advantages of new solutions are evident, the extent of achieved benefits fails to pursue the objectives of sustainable development. The latter requires disruptive change and the contextual demise of old generations of products with worse environmental performance. This is made possible just when environmental friendly product transformations positively capture the social and the economic dimension too, as these are accompanied by changes in people's habits and fueled by customer satisfaction. However, few enterprises are available to engage in radical innovation, as it is generally understood as a risky endeavor. The situation is made more complicated by the relatively poor availability of design methods that target radical product redesign. Proactive design methods and thinking strategies are commonly in play when substantial design changes are expected, but no standard methodological reference has been established so far. Based on theoretical reflections and literature evidence, the paper outlines the need for new knowledge, as the foundation of new methodological frameworks to enable the design of products whose environmental, social, and economic sustainability is ensured.

15.1 Context of the Research

Many eco-design methods focus on the reduction of the environmental impact across the product life cycle, but this does not always result in ipso facto in an effective capability of driving design toward sustainable development. The latter can be defined as the "development that meets the needs of the present without compromising the abil-

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ity of future generation to meet their own needs" according to the World Commission on Environment and Development.

One of the causes can be identified in the disregard of human behavior and social issues demonstrated by many eco-design methods [1]. For instance, eco-design offers several design strategies to extend product life span. For some products, extending longevity beyond a certain point might not be environmentally beneficial [2]. Moreover, for some product categories, the end of the life span is not caused by technical issues, but it is more likely due to psychological obsolescence, i.e., a product is discarded because of changes in users' perceived needs, desire for social status emulation or new trends in fashion and style [3, 4]. This calls into question, among others, effective and value-related aspects of green products. The growing awareness that the interaction of consumers with products heavily affects the environmental impact has led to the development of design for sustainable behavior. Although studies that aim to drive user behavior may have positive effects in the sustainability field, there is a concern regarding the extent to which designers and companies are entitled to drive user behavior [5].

In order to make the innovation of eco-designed products more systemic, the literature stresses the importance to innovate business models through the creation of new paradigms aiming to revolutionize the economic context by leveraging eco-design rules contextually [6–10]. Sustainability can be seen as a driver for innovation itself, as demonstrated by a number of new entrepreneurial initiatives and sustainability-fostering policies undertaken by well-established companies [11–15]. Here, the concept of sustainability is also implicitly linked with the capability of achieving success, especially if social and economic aspects are considered beyond the environmental ones. For instance, to support this process, principles that address to servitization include indications for transformations in the ecological and economic senses. It is worth noting that the economic sphere cannot be neglected in this context, as market success of eco-designed products is the key to the demise of old product generations. Indeed, success allows the benefits of more environmental friendly products to be enjoyed, which is an enabler of sustainable development. At the same time, the need to produce a considerable level of changes makes the objective of coming up with radical innovation apparent when sustainable development goals are in play.

On the one hand, in order for success to be achieved, it is fundamental to carry out the early design phases carefully. All design objectives have to be selected and clarified adequately from the beginning of design tasks. This applies to sustainability objectives, besides all the other product performances, which have to be considered already in the Fuzzy front end (FFE). On the other hand, radical innovation can take place just when the FFE is carefully carried out in the design process.

To this respect, it seemingly emerges that the framework for designing products while pursuing sustainable objectives is consistent, as attention to the early design phases could be considered as the key to sustainable development. The sections that follow (2 and 3) indicate that this process is not straightforward, that methodological guidance is inadequate, and that a general consensus on the forms of innovation necessary for sustainable innovation has not been completely reached either. Section 15.4 builds on the evidence and outlines possible ways to support the design of products whose goals mirror the objectives of sustainable development. The paper ends with some comments to the surveyed literature, gaps in the creation of new design tools and the authors' research agenda in the field (Sect. 15.5).

15.2 Sustainability and Radical Innovation

While bearing in mind the growing population and the growing demand of the emerging and developing countries, the sustainable requirements would be effective only if eco-efficiency decoupled [16]. This means that no partial modification, no incremental innovation of employed technologies, and no re-designing of the existing systems can ensure sustainable development [2]. This supports the importance of radical innovations, not just at the technological level, but also at the cultural level.

The design approaches employed in product innovation are crucial to reduce the environmental impact of products and production processes. However, although they are fundamental and necessary, they are not sufficient to obtain the radical improvements required to achieve sustainability. Indeed, even if these innovations can bring about improvements in products' environmental performance, it is also true that these enhancements are often counterbalanced by increasing consumption [17, 18]. For example, "the environmental gain achieved through the improvement of car efficiency in the last 15 years (10%) has been more than offset by the increase in the number of cars on roads and by the related increase (30%) in the overall distance traveled" [1, 19]. Thus, there is a need to move from a specific focus on product improvements toward a holistic approach to structural changes in the way production and consumption systems are organized.

The above evidence supports the need to embrace radical innovation strategies for sustainable product development, which is prevalent in the literature [20–22]. However, sustainability-oriented innovation is inherently featured by both radical and incremental moves [23]—just their suitability to the scope might differ. Szekely and Strebel [24] individuate even more nuances of these kinds of innovation ascribable to sustainable targets. Both radical and incremental innovations are required according to [25], who illustrate the factors that favor the two. Smaller companies, thanks to their flexibility, have more chances to give rise to disruptive innovation in the sustainability context [26]. Eventually, more articulated studies individuate the social dimension as a key to radically innovative sustainability solutions, which, on the other hand, might be of limited profitability [27].

15.3 The Articulation of the Fuzzy Front End and the Triggers for an Effective Sustainable Design

The change requested is achievable just if we put into question the design choices that underlie the current products. In order to explain how design choices affect the product's innovation-level in a new product development (NPD) process, it is essential to present the schematization of the design process introduced in [28]. The designers' task is to design products (and services) in order to satisfy the needs, requirements, and expectations of human beings [29]. Therefore, the objectives of the designer include the translation of human needs into technical solutions. Hence, it is possible to assert that the design process begins with the acquisition of abstract design inputs, where consumer needs are described, and it ends (at least in its first comprehensive iteration) with the realization of the project documentation which allows a company to start the production phase.

Making once again reference to sustainability issues, Vezzoli and Manzini [2] highlight how greater effectiveness in terms of sustainable innovation is achieved by acting on early design phases, i.e., product planning (PP) and conceptual design (CD), which constitute the FFE. Indeed, no innovation in later phases allows designers to achieve the requested sustainability objectives. The ability to deal with objectives in abstract terms during the FFE prevents designers from focusing on existing solutions. New solutions are explored, which enables enhancements in designers' creativity and increased capability to propose innovative ideas.

Although it is essential to intervene in the FFE, it is appropriate to distinguish between potential innovations coming from PP or CD, whose outputs are the problem definition and the conceptual problem solution, respectively. In the first case, defining the right problem is seen as the most critical factor for achieving success. In the second case, solving the problem defined in the PP in a creative way allows the fulfilment of the FFE objectives, but, if the problem defined in the PP is not viable to drive toward successful development, any efforts made in CD (and in the subsequent detail phases) will result useless in this sense.

In addition, it is claimed that the key to achieve business goals is to be more effective and efficient than competitors in identifying and satisfying the needs of target markets [30], by developing and delivering products and services that are valued by customers [31, 32]. To this respect, two main categories of PP approaches are defined in the literature, namely responsive and proactive methodologies [33]. While the former aim to unveil customer preferences and use them as fundamental competing factors, the latter focus on industry exploration in order to individuate differentiation opportunities.

Responsive approaches reduce the level of uncertainty related to the market response toward new product ideas [34, 35] but do not support the exploration of new features and market contexts. Not surprisingly, many authors [36, 37] have argued that customers are not able to conceive the benefits of radically innovative products. Therefore, anticipating what customers will value cannot be achieved just by becoming familiar with their preferences, experiences, and clearly defined expectations.

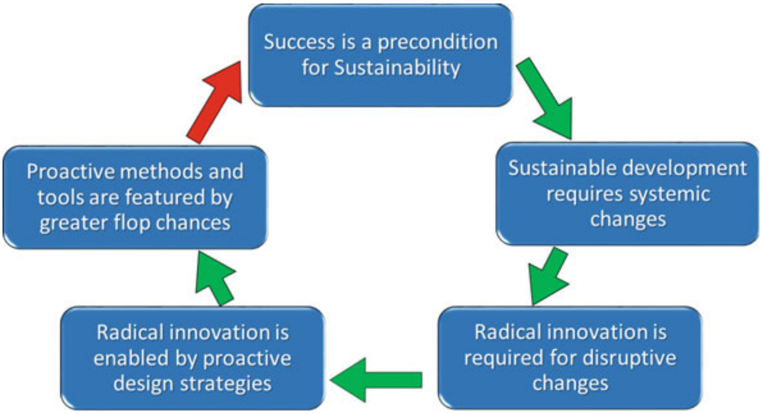

Fig. 15.1 Extant conflict (featured by the red arrow) in the strategy for designing products aligned with the goal of sustainable development

Proactive strategies in the NPD boost the chances of developing successful innovations [38]. However, it is shown that proactive approaches might guide the designer toward product ideas that result too distant from customer expectations [39]. Reid and De Brentani [40] claim that these kind of strategies, as opposed to responsive methodologies, are quite complex and produce (potentially) radical innovations whose market results are considerably uncertain. Many scholars claim that radical changes, driven by proactive strategies, are likely to lead to failure or are, at least, featured by high unpredictability of market results [40, 41]. Consequently, a dichotomy is to be faced: while the pursuance of sustainable objectives calls for radical innovation, this might give rise to flops, which, in turn, conflict with the initial (sustainability) goals, as illustrated in Fig. 15.1.

Not surprisingly, the necessity to both innovate in a radical way and ensure the development of a successful product triggered the creation of hybrid tools, identified from Bacciotti et al. [33], in which customers play very diverse roles.

15.4 Tools and Requirements for Radically Innovative Sustainable Design: Inferable New Areas of Knowledge to Explore

While social aspects are attributed to major interest, also because overlooked so far, integrating radical changes in a social context is an ambitious challenge. Design knowledge might be insufficient to pursue the scope of unfolding social benefits through developed products. The design goal should be at least extended to the development of products/services or systems capable of delivering value for all the stakeholders that interact with the new design during its whole life cycle. As highlighted in the introduction, many eco-design methods are unsuitable for addressing the ideation of benefits product design should deliver because they address strategies in order to limit environmental damage rather than promoting new value propositions. At the same time, general-purpose idea generation tools do not usually show any specific preference for sustainable aspects [42], as their overall purpose is the identification of unexplored market opportunities irrespective of the value drivers they exploit.

Given the shifted shortcomings of eco-design and idea generation approaches, a valuable goal is represented by the development of tools that are capable of both focusing on sustainability issues and stimulating value-adding creativity. To the scope, it is necessary to shed light on the actual mutual relationships between value innovation and sustainability. This kind of interplay is argued in the literature and, as a consequence, the way to overcome possible conflicts has been designed. At the present stage, a first research issue is represented by the need to provide a major understanding of this subject.

Then, the distinction between sustainable and unsustainable products is a tough (and rather imprecise) task if the broad technological, social, and evolutionary contexts are not defined. Products existing nowadays and considered sustainable can be seen as the expression of designers, whose endeavor was not limited to considering sustainability but has rather tried to include value dimensions. Indeed, these "win-win" products have thrived by fulfilling stakeholders' needs beyond taking sustainability into account. As mentioned, products that were just oriented on environmental friendliness and that have showed limited consumption levels have resulted in useless production cycles and have become rapidly obsolescent. On the other hand, the characteristics of the recalled win-win products should be studied advantageously. With an empirical approach, suggestions might arise from a study activity that aims at elucidating common features or principles of successful and sustainable products. Many proactive strategies have been developed according to heuristic approaches based on specific taxonomies, which, subsequently, are proposed to designers in order to repeat similar analogical patterns. For instance, we can mention the Blue Ocean Strategy [31], the Design Heuristics [43], and iDea [44]. Hence, a specific taxonomy could be created from scratch to describe successful (unsuccessful) and, at the same time, sustainable products. Principles and invariants included in the existing taxonomies might be likely combined and/or integrated.

Moreover, it is necessary to understand the perception of sustainability according to different perspectives. In a certain sense, limiting the perspective to designers or consumers would give rise to the same dichotomy that was pointed out with regard to proactive and responsive methods. Indeed, accounting only designers' viewpoint would recreate those conditions that lead to purely proactive development. On the other hand, the sole consideration of the stakeholders' requirements would likely drive to responsive and incremental innovation, which, as already mentioned, does not guarantee the kind of the development requested to face the huge sustainability challenges. To this respect, the mentioned hybrid methods (at least the most traditional ones) have not succeeded in both achieving radical innovation and minimizing uncertainties with respect to future success outcomes [45] and no standard methodology has emerged as well. In other terms, the consideration of a multi-faceted perspective on value and sustainability might allow the highlighting of those dichotomies to overcome in a more evolved design strategy. It is worth noting that the relationship between the capability to deliver value and sustainability can be considered as a specific aspect of the conflict between environmental friendliness and profitability. As achievable, e.g., from a case study presented in [46], strictly following the principles of sustainability can lead to a worsening of some general performance and to the decrease of value perception enjoyed by some stakeholders. According to [47], trying to develop a product that overlooks customer requirements for increasing environmental benefits is counterproductive. On the other hand, the environmental consequence of mass manufacturing and mass consumption has led to social and institutional awareness regarding the need to pursue sustainable development. Thus, stakeholders perceive product sustainability as a source of value per se [47].

15.5 Implications, Final Remarks, and Future Work

The present paper has presented a number of issues, supported by literature sources that constitute hurdles to the fine-tuning of design tools that target sustainable development. Different views emerging in the literature lead to a series of conflicts, which have to be overcome in order to enable the development of appropriate (eco-) design instruments. The authors report here the main points that have arisen in the analyzed literature.

- Although radical innovation is thought as a necessary vehicle to sustainable development, forms of incremental sustainability-oriented innovation are the most diffused (and should be fostered as well).
- Radical innovation is generally achieved by means of proactive design strategies, which are featured by significant risks; on their turn, diminished success chances contradict sustainability objectives, as the latter require that commercial failures are avoided.
- While economic aspects are diffusely taken into account (at least the objective of customer satisfaction is normally considered), the social aspects are not well integrated into eco-design. This happens although sustainable development requires systemic changes that should affect the social sphere.
- At the design level, the shifted pros and cons of responsive and proactive methods for the product planning are recognized. No established methodology can claim to have solved this dichotomy and, while this conflict affects engineering design in general, it impacts on sustainable-oriented design and innovation even more severely.

Section 15.4 has already highlighted some research issues emerged by considering the above problems altogether. According to the authors' view, these issues cannot be tackled with the present level of available knowledge and they have individuated the relationship between sustainability and value as the most critical aspect to be clarified. The clarification of this relationship can take place at the individual level, as value is properly defined at that scale, or at the social level, if success is considered as the manifestation of collective value, which justifies positive economic outputs or large repercussion on the society itself.

Consistently with this key of reading, the authors are intentioned to undergo studies aimed at the following objectives.

- The analysis of determinants or invariants found in eco-designed products that have achieved success in the marketplace.
- The individuation of successful eco-design tools, which can be revealed, e.g., by the set of eco-design principles that have proven to favor market success.
- The understanding of the shift in value perception of eco-designed products with respect to more common and less environmentally friendly product versions. Here, the concept of value has to be holistically considered, by addressing both its utilitarian (conscious) and hedonistic (unconscious) dimensions. A first step in this direction has been made in [48].
- The capability of design tools that push toward non-trivial product changes to support the shift of eco-design toward an adequate level of innovation for sustainable development. In this context, the research group will benefit from previous exposure into TRIZ, with a particular reference to instruments capable of providing holistic views of the problems [49] and proven combinations with other design methods [50].

All these studies can be firstly treasured in guidelines that support designers in sustainability-oriented innovation. The guidelines should be capable of anticipating the outcomes of sustainability-oriented moves or eco-design principles in terms of not just environmental benefits, but also potential value repercussions and linked success chances.

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Chapter 16
Environmental Lifecycle Hotspots and the Implementation of Eco-design Principles: Does Consistency Pay off?

Yuri Borgianni, Lorenzo Maccioni and Daniela Pigosso

Abstract Structured approaches to diminishing products' environmental footprint include the identification of hotspots, e.g., lifecycle phases or aspects that feature criticalities in terms of environmental sustainability. Still in these approaches, measures are taken consistently by investing eco-design efforts to improve the situation in the identified hotspots. However, many products implement eco-design principles irrespective of hotspots, i.e., without taking into account the major sources of environmental footprint. A sample of products has been analyzed in terms of hotspots, and lifecycle stages are affected by the implementation of eco-design principles and achieved success. The study reveals that, while eco-design principles in the use phase of the product favor success, the consistency between the hotspot and the lifecycle stage does not modulate the relationship between implemented eco-design principles and success. As a result, while the identification of hotspots is a best practice as for the attempt to maximize environmental benefits brought on by eco-design initiatives, it plays a limited role in terms of customer's acceptability and appreciation of new products.

16.1 Introduction and Background

The need to design more sustainable products and encourage sustainable consumption practices is of anecdotal evidence. The variety of instruments to pursue this objective and the numerous eco-design principles (EDPs) available clarify that the

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paths to achieve more sustainable designs are various. Improvements can regard, among others, toxicity of materials, need for packaging, energy consumption, recyclability, and reusability. Every product is characterized by some of these aspects that, at the present stage, represent major environmental concerns. Formally, the term "hotspot" is used to characterize dimensions attributed to greater environmental criticalities and the circumstances in which they occur. Once identified, hotspots suggest which measures should be prioritized in order to minimize the product's environmental footprint. Despite their relevance, the definition and categorization of hotspots are not univocal; scholars attribute the term "hotspot" to phenomena that have a relevant negative impact on a system's environmental profile. In most of the cases, such a system is represented by a product or a family of products, while the hotspot is the lifecycle stage ensuing major environmental concerns [1]. Also in this case, the subdivision of the product life cycle into stages or phases is not universal.

In the literature, the identification of environmental hotspots represents a fundamental step when systematic design approaches are proposed [2], as they reveal major environmental aspects to take care of. Their identification has to take place in a continuous manner, as design modifications, product improvements and changes in the value chain can alter hotspots themselves [3]. Technological changes represent a considerable trigger for the need to reconsider hotspots [4]. The systematic identification of hotspots can also be seen as a checklist for visualizing redesign possibilities and deadlocks in the attempt to improve the environmental profile of the developed products, e.g. [5]. Furthermore, individual companies manufacturing akin products might find different hotspots in different sections of their process or the product life cycle [6]. Although hotspots are usually referred to environmental challenges, the social and economic dimensions should be also considered to target sustainability as a whole [7].

Traditionally, different design methods are normally chosen for tackling environmental issues belonging to different product lifecycle stages; the concept is extended to information management in [8]. In several contributions, different hotspots are linked with TRIZ or eco-design tools to disclose the most promising heuristics for obtaining improvements [9, 10]. The individuation of hotspots is relevant for the application of circular economy strategies within new product development initiatives too [11].

Lifecycle assessment (LCA) is classically used as a tool to identify hotspots; applications in different industries are illustrated in the literature. [12–16]. It is claimed that the information required to use LCA is often too complex to be available [17], especially in initial design phases [1, 7]. Actually, changes that are consistent with LCA outcomes and the identified hotspots are feasible also in late design stages, e.g., when performing geometric modeling [18], but the early design phases are susceptible of higher potential benefits [19]. Obstacles to an effective and quick execution of LCA are tackled by means of simplified procedures that allow for the determination of hotspots [20].

Despite the standard approach to investing design efforts in hotspots, i.e., where enhancements are supposed to provide the largest environmental benefits, these have to be considered also in terms of practicability and ease of interventions [6]. This aspect might lead product developers to channel eco-design resources in lifecycle stages irrespective of the major environmental burdens. The present study is concerned with the effects of the choice of lifecycle stages affected by implemented EDPs in relation to the presence of hotspots. These effects are evaluated in terms of products' market success. The research objectives are detailed in Sect. 16.2. Section 16.3 presents methods and materials required to investigate the research question. The results of the study are presented in Sect. 16.4, which is followed by discussion and conclusions (Sect. 16.5).

16.2 Research Objectives

Many products are developed and eco-design efforts can be recognized that have led from previous generations to the current one. More specifically, their design is featured by the implementation of one or more EDPs; a tentative list of these principles can be found in [21]. Details of the design process are generally not available; in particular, it is not known whether the changes brought on by new designs have been envisioned based on previous analysis of the products, e.g., including the identification of lifecycle hotspots. In principle, the application of EDPs that tend to minimize the environmental footprint in the most critical lifecycle stage (hotspot) results in larger environmental benefits and can be able to provide, as a consequence, greater customer value. This is supposed to take place if consumers diffusely recognize efforts aimed at improving products' environmental profile and contextually hotspots. As a result, those products capable of targeting hotspots by means of suitable EDPs are attributed of major success chances. This phenomenon, which can be hypothesized, has to undergo scientific verification. The research objective is therefore the verification of the following hypothesis.

> The selection of EDPs that affect the life cycle stages identifiable as environmental hotspots boosts the chances of new products success in the market.

In other terms, the consistency between EDPs and lifecycle hotspots is supposed to give rise to a (positive) effect in the relationship between the implementation of EDPs and market success.

16.3 Materials and Methods

In order to answer the research question, the following methodological steps have been considered necessary. At first, a set of products showing design efforts aimed to improve some environmental metrics has to be built (Sect. 16.3.1). All the products were then characterized in terms of:

- Lifecycle hotspots (Sect. 16.3.2)
- Implemented EDPs ascribable to product lifecycle stages (Sect. 16.3.3)
- Achieved success (Sect. 16.3.4).

16.3.1 Set of Products

A large set of products was identified by benefitting from established literature sources [21–24] that leverage examples to explain principles and techniques referable to eco-design, design for environment or design for sustainability. The authors selected products and services for the construction of the dataset, while stories about firms or trademarks were not relevant for the present study. These choices led to the determination of a product database including 178 unique products.

16.3.2 Lifecycle Hotspots

As mentioned in the introduction, the characterization of products in terms of environmental hotpots is not a standard process. The most common approach stands in the segmentation of the product life cycle into stages and the identification of the stage(s) where the most severe criticalities lie. In the present study, the authors required a taxonomy to subdivide lifecycles sufficiently general to be applicable to all the products. Based on the examples shown in the reviewed papers, the authors opted to schematize the lifecycle into:

- Raw materials and manufacturing (RMM);
- Distribution and packaging (D&P);
- Use phase (USE);
- End-of-life (EOL).

The attribution of the hotspots, i.e., one of the above stages, to products took place with a consensual technique. The starting point was the approach used in [1]; i.e., the reference hotspot is the one featured by the predecessor in a product family. This is appropriate for the present study, as it is here critical to compare previous criticalities (and not those ensuing after the introduction of the new design) with the actually implemented EDPs. All the authors analyzed the products separately and indicated what they deemed as hotspots. The results were compared and, in all those cases of misalignment, a discussion was carried out until an agreement was found. This eventually led to the attribution of the environmental hotspots for all the gathered 178 products.

16.3.3 Eco-design Principles

The authors used an established reference [21] to characterize the products in terms of EDPs. Here, a list of 31 EDPs is made available to readers and reported in Table 16.1. Although there is no shared taxonomy for EDPs, the mentioned source can be considered as the most acknowledged reference in this domain. In addition, the structuring of EDPs in terms of the lifecycle stage they affect eases the subsequent steps of the study, i.e., matching eco-design efforts with the lifecycle stages they have brought on benefits in (see Table 16.1).

The authors have attributed a number of EDPs to all the products by following an akin consensus technique. As for the products extracted from [21], a preliminary set of EDPs had been already considered. In any case, the authors added other EDPs by benefitting from the details provided in the description of the products and the EDPs. A new or additional EDP was assigned whenever the implementation of that EDP seemed reasonable. Particular attention was paid to the transformation of the product from the previous standard version to the new design.

16.3.4 Success

Also in this case, there is no universally recognized procedure to assess or evaluate a product's success, because the most established terms that feature success:

- Are predominantly of financial nature and are unknown to the public;
- Depend on companies' objectives related to the launch of a specific product, which represents another piece of information that is very difficult to obtain.

Given these obstacles, scholars devised a procedure to evaluate success based on available information accessible from the Web and the scientific literature [25]. They developed a seven-level success scale, articulated as follows.

- Level 1: information states that the product is a flop or it has never entered the marketplace after a large amount of time.
- Level 2: very scarce information is found about the product, which is then considered as an example of oblivion.
- Level 3: contradicting information about success and failure of the product has been retrieved.
- Level 4: success is suggested by information showing that some argued success indicators are fulfilled.
- Level 5: success is demonstrated by information showing that some undisputed success indicators are met.
- Level 6: information stating that the product was successful is found, but this takes place in Web sources only.
- Level 7: the same as level 6, but the information is accessible in the literature sources, i.e., more reliable sources, too.

Table 16.1 Eco-design principles extracted from [21] and used in the study; they are associated with affected lifecycle stage

EDP	Explanation	Lifecycle stage
01	Design for appropriate lifespan	EOL
02	Design for reliability (simplify, reduce number of component)	USE
03	Facilitate upgrading and adaptability	USE
04	Facilitate maintenance	USE
05	Facilitate repair	USE
06	Facilitate reuse	EOL
07	Facilitate remanufacturing	EOL
08	Intensify use (share, multifunction, integrated, on demand)	USE
09	Minimize material content or dematerialize, digitalize, miniaturize	RMM
10	Minimize scraps and discards	RMM
11	Minimize packaging (avoid, integrate, drastically reduce)	D&P
12	Minimize material consumption during usage (select more consumption-efficient systems)	USE
13	Minimize materials consumption during usage (engage systems with dynamic material consumption)	USE
14	Minimize energy consumption (during pre-production and production)	RMM
15	Minimize energy consumption (during transportation and storage)	D&P
16	Minimize energy consumption (select systems with energy-efficient operation stage)	USE
17	Select non-toxic and harmless materials	RMM
18	Select non-toxic and harmless energy resources	RMM
19	Select renewable and biocompatible materials	RMM
20	Select renewable and biocompatible energy resources	RMM
21	Adopt the cascade approach	EOL
22	Facilitate end-of-life collection and transportation	EOL
23	Identify materials	EOL
24	Minimize the overall number of different incompatible materials	EOL
25	Facilitate cleaning	USE
26	Facilitate composting	EOL
27	Reduce and facilitate operations of disassembly and separation	EOL
28	Engage reversible joining systems	EOL
29	Develop services providing added value to the product's life cycle	USE
30	Develop services providing "final results"	USE
31	Develop services providing "enabling platforms for customers"	USE

The attribution of success levels to the products of the dataset took place by following the designation procedure widely described in [25].

16.4 Elaboration of Data and Results

The gathered data have been organized as in Table 16.2. As it was one of the main objectives of the study, the authors determined if the implemented EDPs were consistent with the hotspot (last column of Table 16.2). The parameter *consistency* holds the value 1 (156 cases out of 178) if at least an implemented EDP belongs to the lifecycle stage that features the product hotspot, 0 otherwise. For instance, the value 1 is assigned to the second product in Table 16.2; the identified hotspot is USE and the EDP 16 belongs to the corresponding lifecycle phase USE; here, the EDP 18 (RMM) plays no role in the determination of *consistency*.

The data were then statistically analyzed with the software Stata 13.0 in order to address the research question. In the first step, the direct relationship between *success* and *consistency* was investigated through a regression in which the former is the dependent variable and the latter is the regressor. This regression and the others that follow are all ordered logistic, due to the ordinal nature of the dependent variable. According to the output of the regression, *consistency* tends to diminish the value of *success* ($\beta = -0.380$), but this indication is not reliable due to the high level of the *p*-value (0.343). Subsequently, the authors investigated the moderating role of *consistency* for each specific lifecycle stage. Four new regression analyses (one for each lifecycle stage) were performed, in which *success* is kept as a dependent variable, while the regressors were:

1. The presence of EDPs affecting the lifecycle stage (0/1), designated as Reg1;
2. The lifecycle stage being the hotspot for the product family (0/1), Reg2;
3. The multiplication of the two factors above (0/1), Reg3, which makes it possible to discover if the latter is a moderator for the former.

The results of the regressions are presented in Table 16.3, which includes, for each lifecycle stage (first column), the regression coefficients β and the corresponding p-values for the above three regressors. The data show that the sole coefficient featured by a p-value minor than 0.05 is the presence of EDPs ascribable to the use phase. The effect of this variable on success is positive.

16.5 Discussion and Conclusions

The main finding of the study is the rejection of the hypothesis formulated in Sect. 16.2. This means that the matching between environmental hotspots and the lifecycle phases in which EDPs are implemented does not result in greater success chances. It follows that eco-designed products can achieve success irrespective of

Table 16.2 Illustrative set of products, for which the following designations are indicated: success level (Sect. 16.3.4), hotspot of the product family (Sect. 16.3.2), implemented eco-design principles (numbered as in Table 16.1) separated according to the affected lifecycle stage (Sect. 16.3.3)

Product	Success level	Hotspot	EDPs RMM	EDPs D&P	EDPs USE	EDPs EOL	Cons
Tiles made of cement and mussel shells by Jan Velthuizen	1	RMM	10, 17, 19	–	–	–	1
Fria refrigerator designed by Ursula Tischner	1	USE	18	–	16	–	1
Whirlpool Green Kitchen	2	USE	20	–	08, 16	21	1
Edible packaging for chocolates, Eckes	2	D&P	10, 17	11	–	01	1
Refillable glue stick, Henkel	3	RMM	–	–	–	06, 24	0
Procter and Gamble toothpaste	3	RMM	09	11	02, 08	01, 24	1
Tupa bamboo beds	4	RMM	14, 17, 19	11, 15	08	01, 06, 24, 26	1
Pedal-powered washing machine	4	RMM	18	15	16	–	1
The Klippan sofa by Ikea	5	RMM	–	–	03, 04, 05, 25	07, 27	0

(continued)

Table 16.2 (continued)

Product	Success level	Hotspot	EDPs RMM	EDPs D&P	EDPs USE	EDPs EOL	Cons
Solar-powered mower, Husqvarna (Electrolux)	5	USE	–	20	–	–	1
gDiapers	6	EOL	17, 19	–	01, 03, 04, 05	06, 26, 27, 28	1
Hire Fitness equipment	6	RMM	–	–	03, 04, 08, 29, 31	06	0
Nested chairs	7	RMM	–	15	–	27	0
Patagonia common Threads Garment Recycling Program	7	EOL	10, 17, 19	–	–	06, 07, 21, 22, 23, 24	1

The parameter "consistency" is consequently determined (Cons in the last column)

Table 16.3 Outcomes of the regressions (regression coefficients β and p-values) investigating the moderating role (Reg3) of the consistency between hotspots (Reg2) and lifecycle phases affected by eco-design principles (Reg1) in the relationship between the latter and the success achieved by products

Lifecycle stage	β Reg1	p Reg1	β Reg2	p Reg2	β Reg3	p Reg3
Raw materials and manufacturing	−0.066	0.851	0.017	0.971	−0.481	0.415
Distribution and packaging	0.265	0.401	0.013	0.976	Omitted by the regression because of the limited number of data	
Use phase	1.28	0.030	1.18	0.447	−1.28	0.416
End-of-life	−0.389	0.168	13.2	0.976	−12.4	0.977

the individuation of the principal environmental criticalities. From this result, it is inferable that consumers have limited interest or experience problems in recognizing the effectiveness of and the benefits emerging from a product development process that starts with the identification of priorities in the environmental sense.

Another phenomenon could be ascribable to people's perception of value and benefits. One of the side results of the study is the fact that eco-design efforts involving the use phase of products, differently than all the other lifecycle stages, affects success chances—the effect is positive. Changes in this stage might result straightforward to consumers, as opposed to lifecycle phases they have more limited sensitivity toward and control over. Consequently, the easily recognized (sustainability-related) advantages can be seen as a source of value with positive repercussions on market success. This gives rise to a relevant research issue; i.e. the need for a better understanding about the importance of the effective perception of value is enabled by eco-designed products.

Although the main output of the study, i.e., the poor relevance of environmental hotspots in products' success, emerges clearly, some limitations have to be laid bare in order to consider possible sources of bias.

- The sample of selected products is large, but resulted insufficient to establish strong statistical relationships (see Table 16.3). This is also due to the uneven distribution of hotspots and lifecycle phases affected by EDPs. The authors benefitted from products described in the literature sources to create a sample of convenience and did not force the process toward a better balance among involved lifecycle phases;
- All the designations of the parameters attributed to products are featured by some extent of subjectivity, although performed with consensual techniques;
- The study assumes that greater environmental advantages are achieved when EDPs' corresponding lifecycle stages match the hotspots. This effect is intuitive, but cannot be demonstrated in the chosen case studies. At the same time, the relatively large number of implemented EDPs (average 4) represents a potential source of unbalance also for the parameter *consistency*, which features a predominant number of values equal to 1.

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Chapter 17
Emotional Design and Virtual Reality in Product Lifecycle Management (PLM)

Maria Grazia Violante, Federica Marcolin, Enrico Vezzetti, Francesca Nonis and Sandro Moos

Abstract As the potentials of technology grow, the embedding of IT advances in different fields and applications increases. A recent example is virtual reality and in particular the virtual product. The possibility of having a product in a virtual form allows creators and designers to efficiently manage the cycle of a product generation and evolution. The key advantage of the "virtual" is to have the product in advance, even in the conceptualization phase, with clear benefits in terms of consumptions of resources and, hence, sustainability. A potential customer could thus interact with a product-to-be and provide feedback about its look and feel, its usability, and, most of all, give an emotional response. In this context, the interaction between the virtual product and the future customer becomes a core point for the new approaches related to user-centred and user experience design, giving birth to a design methodology called "emotional design". In particular, the study of facial expressions seems to be the more reliable and attractive aspect of it.

17.1 Introduction

Product lifecycle management (PLM) is of great significance as it can improve the development of new products and reduce manufacturing costs and the ecological footprint by controlling the products through their life cycle. A product's life cycle always includes three periods: beginning of life (BOL), middle of life (MOL), and end of life (EOL) [1]. BOL includes the phases of design and production. Marketing analysis and product design make up the design phase while the production phase involves procurement, product manufacturing, and equipment management. The MOL period consists of logistics, utility, and maintenance phases; in the EOL period, the only focus is how to process obsolete products. Within the various IT applications, virtual reality (VR) is widely employed in the product life cycle because it addresses all the

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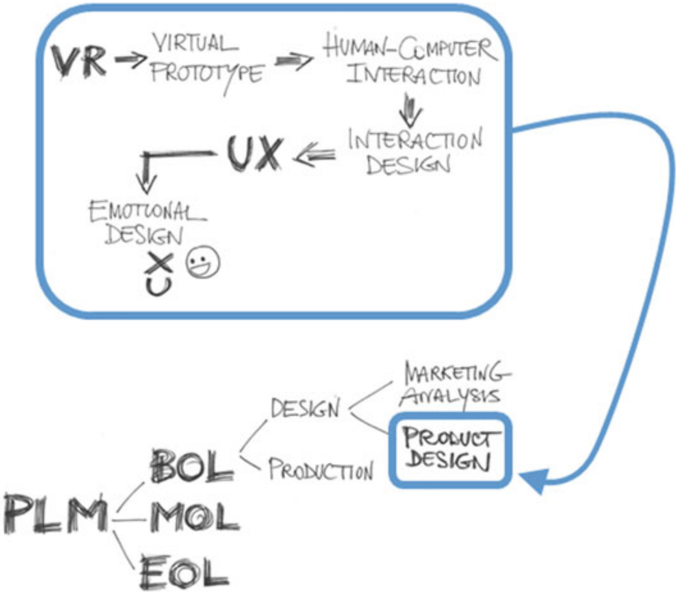

Fig. 17.1 Scheme representing how emotional design, virtual reality, and PLM are connected according to the proposed integrated approach

requirements in each product development stages thanks to its capability of solving engineering design concerns of the developer, process concerns of the manufacturer, logistical concerns of the maintainer, and training and programmatic concerns of the operator. In particular, the role of VR is widely adopted in the design phase (BOL), as it allows to create a virtual product which could be managed by the user in advance, without the involvement of a (costly and timely) physical product. The approach proposed by this work relies on the adoption of VR techniques to realize a virtual prototype of the product that could be put in interaction with the future user/customer, so that his/her emotional feedback is analysed via user-centred design methodologies and emotion recognition techniques. The emotional feedback is used to modify the product conceptualization, benefiting of the reduced cost and time advantages of the "virtual". The scheme in Fig. 17.1 shows the roadmap of the approach.

17.2 Virtual Reality

VR has emerged as a technology that provides users with realistic, interactive computer environments and offers innovative modes for delivering memorable experience [2–4]. In the past, VR technology was used primarily only in the development of premier products because it was known for its low return on investment due to its high costs. However, today, VR technology has become common in industry and has gained in cost competitiveness. The feeling of presence lies at the centre of all immersive virtual experiences [5–7]. Traditionally, "presence" has been conceptualized as the degree to which one feels present in the mediated environment instead of in the immediate physical environment [7] or as a psychological state in which the "virtuality" of experience is unobserved [8]. According to Vergana et al. [9], VR applications can be classified according to visualization and interaction devices into two wide categories:

- non-immersive (the well-known window in the world), where the user's vision to the world is by means of the flat screen of a computer acting as a "window";
- immersive, which completely introduces the user into a virtual world by using glasses with two small screens placed in front of the user's eyes.

VR immersive applications are also subdivided into two subcategories, according to the visualization system of the virtual world [9]

- the head-mounted display (HMD), which consists of active glasses with a small screen placed properly in front of each eye [10–12];
- the virtual CAVE (cave automatic virtual environment), where the virtual world is projected on the walls, ceiling, and floor of a room by diverse stereoscopic projectors. In this last case, the user must wear passive stereo glasses [13, 14] to achieve a 3D view of the virtual world.

Nowadays, several models of VR devices are available in the market with a high variety of cost and user immersion degree. Thus, two categories of the current commercial devices (not considering research laboratories) can be distinguished [9]:

- low cost and low immersion level, e.g., Google Cardboard and Samsung Gear VR;
- average cost and acceptable immersion level, e.g., Oculus Rift and HTC Vive.

17.3 Virtual Reality in PLM

VR's applications have been employed in various industries; e.g., aerospace, automotive, shipbuilding, marine, biomechanics, defence, machinery, sports, and entertainment, and they are spread to all phases of a product life cycle. Conceptual design is the first and also the most important step of product design processes, in which designers need to determine the future designing direction of the entire product [15]. In this stage, designers will define the concept, aesthetics, and the main functions of the new product [16]. The designer, moving from his/her vision and values and the knowledge of consumers' needs, produces a set of plausible conceptual design alternatives among which to choose the best design candidate for the development of the project by means of a formal decision model. Virtual and physical prototypes allow testing concepts during the development of new products and enable to explore design candidates more timely and better than in the past, improving their quality and their chances of success [16]. In particular, virtual prototypes (VPs) help to evaluate and optimize the product and process performances by means of virtual tests, since the very beginning of the life cycle, when nothing is created yet [16–18]. VR provides a virtual environment for the designers in the conceptual design stage of designing a new product; the designer could produce 3D "sketch" of a product in the virtual environment [19]. At this stage, functional experimentation of mechanical features such as hinges, assembly could be performed to evaluate the conceptual design and modifications could be made as required. Once the designers are satisfied with their design, then the design could be detailed to make the necessary modifications. Indeed, as Gomes de Sá and Zachmann (1999) stated, the early design phases can impact on up to 70% of the total cost of a product [20]. In this scenario, VR can reduce cost and time by replacing physical mock-ups with virtual ones [21, 22]. This can support the simplification of the review process by avoiding the rebuild of physical mock-ups in case of design errors or changes [23, 24]. Another utility of VR in design is the possibility of having multidisciplinary teams and teams spread across the world, to work together on the same prototype at the same time [19]. The designers can readily identify design mistakes which are not foreseen in the stage of defining functionality (e.g., collisions) [25]. Moreover, computer visualization can be used to optimize designs especially regarding ergonomics. In fact, during the design process, engineers underestimate some factors such as ergonomics. In consequence, many products surrounding us have not been designed to respond to end-user expectations, including their need for usability [26, 27]. Usability represents the product's ease of use. In this scenario, VR technology seems to be mature enough to support efficient and effective product development thanks to improvements in visualization and interaction [28].

17.4 Customer Involvement

Don Norman states that a design is a success only when the final product is successful in making customer buy it, use it, and enjoy it and spread the word of the product to others. He claimed that designers need to ensure that the design satisfies people's needs, in terms of functions, usability, and the ability to deliver emotional satisfaction, pride, and delight [29]. The market success of a modern company significantly depends on customer satisfaction. For this reason, it is important to involve customers continuously in the creation of product value, including the early conceptual stages of product design [30]. Methods for the product design that start from the users' needs and expectations are called user-centred design (UCD) methods. The term UCD was coined by Donald A. Norman's (2004). His book includes principles of building well-designed products [31]. His recommendations are based on the needs of the user, leaving aside what he considers secondary issues like aesthetics (en.wikipedia.org/wiki/User-centered design). This includes how convenient the product is in terms of its usage, manageability, effectiveness and how well the

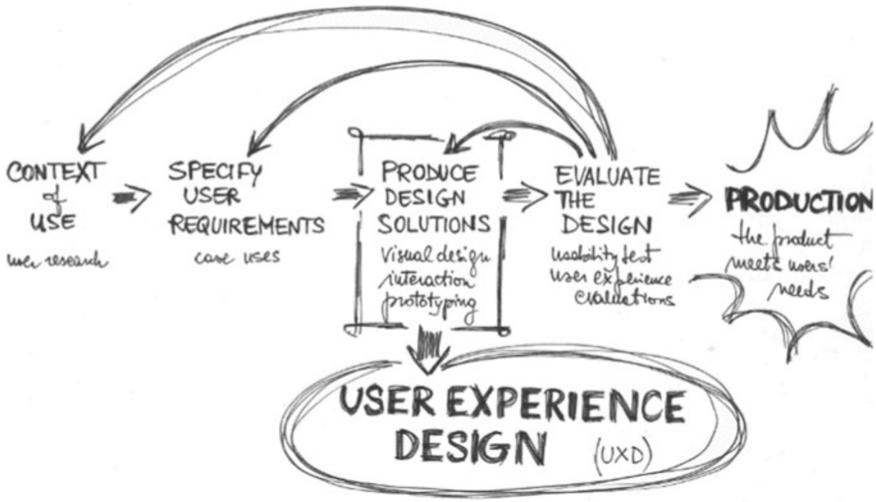

Fig. 17.2 UCD process

product is mapped to the user requirements. Below are the general phases of UCD process, which are schematized in Fig. 17.2.

- Understand context of use
  Identify who are the primary users of the product, why they will use the product, what are their requirements and under what environment they will use it.
- Specify user requirements
  Once the context is specified, it is the time to identify the granular requirements of the product. This is an important process which can further facilitate the designers to create storyboards, and set important goals to make the product successful.
- Produce design solutions and prototype
  Based on product goals and requirements, start an iterative process of product design and development.
- Evaluate the design
  Product designers do usability testing to get users' feedback of the product. Product evaluation is a crucial step in product development which gives critical feedback of the product. In the design domain, usability has been defined as the interaction between the user and the product, "mainly focused on how people use the product" [32].

In the context of the interaction of users with products, user experience design (UXD) is the process of enhancing user satisfaction with a product by improving the usability, accessibility, and pleasure provided in the interaction with the product [33]. UXD refers to the application of user-centred design practices to generate predictive and desirable designs based on the consideration of users' experience with a product.

It is concerned with all facts of the overall experience delivered to users and includes elements of the following disciplines:

- visual design (represents the aesthetics of the product);
- usability (what exactly makes a product "easy to use"? Answer: 5 Es efficient, effective, engaging, error tolerant, easy to learn);
- cognitive psychology (understanding of how knowledge is acquired (how people think, perceive and remember a product) is the backbone of UX design);
- interaction design (it is an essential part of user experience (UX) design, centring on the interaction between users and products. The goal of interaction design is to create a product that produces an efficient and delightful end-user experience by enabling users to achieve their objectives in the best way possible. UXD investigates the experiential and affective aspects of human–product interaction. In the first case, it mainly addresses usability issues when users interact with a product. It measures how easy using a product is, errors made, comfort, etc. In the second case, it is more focused on studying the feeling and emotional responses when interacting with a product).

17.5 Emotional Design

Emotional effects refer to the feelings evoked in customers while and after buying a product. The quality and reputation of the brand as well as the characteristics of the product play an important role in stirring feelings in customers [34]. The feelings can be contentment, anger, excitement, etc. Those are typically subjective, temporary, and emotional effects. It is important that all these issues are considered at the design level. While attributes and functional characteristics have been studied for years, using well-established methods, such as realistic rendering, functional simulations, usability studies, etc., the emotional aspects have been addressed only recently, and appropriate methods are still under investigation [35]. It is crucial to capture their emotional feedback on the products, because consumers tend to make buying decisions increasingly emotionally, avoiding the rational processing of large quantities of information [28]. In order to design a product that elicits positive emotions, it is necessary to define and be able to predict the target users' emotional responses early in the design process [35]. In other words, the aim is to understand which are the more relevant and influential attributes or characteristics, and how we can correlate these attributes and properties of a product with the elicitation of certain emotions. The possibility to have a virtual product, especially 3D, responds to this need. Indeed, virtual reality is a form of human–computer interaction providing a virtual environment that one can explore through direct interaction with our senses. In the VP case, the design must be modified if it does not meet the users' expectations and consequently and accordingly the virtual prototype [35]. Indeed, the modifications performed on a virtual product are easier and faster to implement compared to the same ones made on a physical product [35]. This is one of the reasons why it is

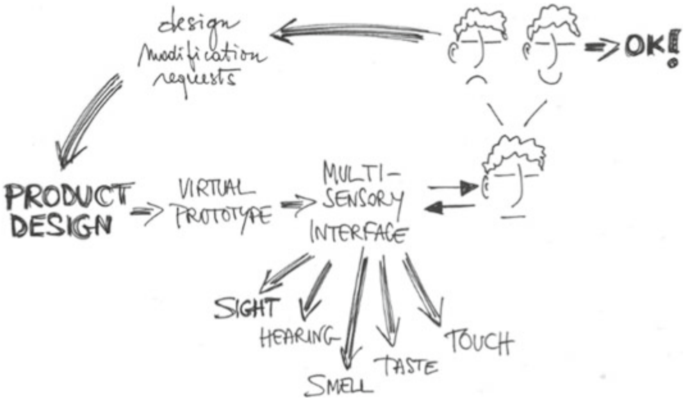

Fig. 17.3 Virtual prototype for the evaluation of a product design with emotional feedback

preferred, when possible, to evaluate and test the design of a new product by using virtual instead of physical prototypes [35]. Reliable capturing of emotional customer feedback to future products, during the concept stages of their development, offers enormous potential for early identification of successful customer-oriented products. Figure 17.3 shows how the VP and emotional design intervene in the conceptual design.

The study of the emotional customer feedback with virtual reality requires a combination of:

- technologies for experiencing and interacting with three-dimensional virtual products;
- methods for performing emotion recognition and capturing emotional feedback (e.g., facial expression recognition system) [30].

The three main method groups for capturing emotional feedback are: questioning methods; physiological measurements; observing methods. They are reported in Fig. 17.4 with some examples [30].

The questioning methods aim to capture the customers' written or oral emotional feedback in the form of answers to certain questions. Kansei and Kano are two examples of approaches for translating feelings, emotions, and impressions into product development [30]. Physiological measurements are based on the quasi-continuous gathering of: central (electroencephalography) signals; peripheral physiological signals (electromyography, blood volume pulse, electrodermal activity, etc.) of individuals. Observing methods (or behavioural methods) rely on objective or subjective insights gained from the careful observation of the individuals experiencing the product. Measures of expressive behaviour include the description of facial expressions, bodily movement's gesture, and posture [35, 36] and vocal nonverbal parameters. Research for each of these modalities of expression of the emotions has been conducted so far mainly in a separate way, so that no multimodal study of emotional expression exists. Facial expression is the most studied modality and probably the

Fig. 17.4 Methods for capturing emotional feedback

one for which the more reliable results are available [37]; this is also due to the existence of a widely agreed upon coding system [38, 39]. Facial expressions are studied by researchers in the fields of behavioural psychology, neuroscience, computer vision, and pattern recognition. Various methodologies for automatic facial expression recognition which rely on facial images and 3D facial models have been recently developed based on feature extraction and deep learning techniques [40, 41]. The adopted database for the testing is the Bosphorus database and BU-3DFE, which contain different subjected acquired at various emotional states. The research in this field is still ongoing and at an ascending level of interest by the research community, as the algorithms are rapidly improving their performances but results are not ready for the market yet, especially with 3D data.

17.6 Discussion and Future Work

The contents here presented are not relevant just in a market perspective, but also from the environmental viewpoint. The possibility to have a virtual prototype in an early design phase allows to avoid the manufacturing of physical prototypes at intermediate steps of PLM. The result is an optimized approach which guarantees an efficient and effective product life cycle and a sustainable orientation of the technological development. It is sufficient to think about the resources spent uselessly to manufacture and distribute unsuccessful products that are not purchased and used [42–45]. Attention on the design phases and the methods/techniques have, indeed, the potential to limit these detrimental effects on the environment.

The present approach also has a technological advantage, as it is strictly linked to the recent advances in Computer Vision and Pattern Recognition. The fields connected to this research area deal with human face analysis and recognition of emotions, individuals, attitudes, poses, and other relevant states. The novel outcomes in this sense rely on feature extraction and deep learning techniques, which are the current core elements of interest in the research in computer science. The link between PLM and these scientific advantages offers a compelling edge for the academic community, as it opens a pathway to the market and chances of collaboration.

Future research hints rely on identifying more in detail the customer involvement both in terms of simple needs and inner/unconscious requirements [46, 47]. Facial expressions should be studied and analysed in this sense also for detecting micro-expressions and quick attitudes. Generally speaking, the customer involvement practices and guidelines are to be outlined and detailed in the future steps of the research in this field. This way, the proposed methodology will take a sustainable path in the manufacturing of ad hoc products, respondent to customer's needs, focused on avoiding wastes and on optimizing the resources.

17.7 Conclusions

Emotions and in particular facial expressions have been investigated in the last decades for applications such as marketing, safety, security, and advanced learning. The approach proposed in this work aims at connecting this field to PLM, especially in the product design phase. Virtual reality, appreciated for its advantages in terms of cost and time, is the link between the two, as it allows designers to have a virtual prototype of the product-to-be. Potential customers, thus, are involved in an early design phase, put in contact with the virtual prototype of the product, and asked to provide a global feedback of it. The possibility to understand their emotions with a facial expression recognition technique allows gaining their emotional feedback, in terms of inner requirements and impulsive needs, which seem to be the core agents of the new purchase mechanisms.

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Chapter 18
An Investigation of the Relations on Business Areas and Recycled Materials in Circular Economy

Matteo Spreafico, Pierre-Emmanuel Fayemi and Giacomo Bersano

Abstract This paper presents a semi-automated state of the art related to the concept of circular economy and focuses on technical problems identification methods based on syntactic dependency patterns, for ameliorating supervised state of the art and patent intelligence. The data and information used in this paper were collected from patents and scientific publications dataset. Through parsing the patent text, very precise lists of recycling materials are automatically extracted without the user being an expert in the problems of the sector. An exemplary case dealing with circular economy is proposed, stressing what types of business areas are nowadays related the most from the materials that are being recycled. This paper contains the results of this analysis and the related comments.

18.1 Introduction

During the last decade, an increasing importance has been paid to the concept and the development of the model of circular economy, with the purpose of providing a better alternative to the dominant economic development model [1].

The conception of a circular economy model has its origins in industrial ecology, which foreseeing a form of material symbiosis between different companies and production processes [2]. The industrial ecology evidences the benefits of recycling residual waste materials and sub-products, for instance, the development of complex relations, such as those in the renowned industrial symbiosis projects [3].

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Over the years, researchers have produced analysis related to the circular economy from its fundamental concept to its practical implementation. Many scholars, booster of the circular economy approach are strong proponents of material reuse and recycling [3]. Environmental economics offers an analytical approach that can be of great help in identifying which material streams and which recycling options provide the greatest benefits to the economy [3, 4].

According to [5, 6], it is not well defined how far should society go in the recycling of materials. While the first and most straightforward recycling options provide evident benefits, once the recycling road is embarked upon, the subsequent benefits gradually become more and more difficult to achieve. It has to be acknowledged that at some stage there will be a cut-off point where recycling will become too difficult and burdensome to provide a net benefit. A circular economy cannot promote recycling in perpetuity. Many adherents of the circular economy approach are strong proponents, on environmental and ethical premises, of material reuse and recycling in perpetuity [2].

More generally, there is a preponderance of qualitative approaches. The lack of quantitative and objective data is noticeable. There is a need for consistent methods for the assessment and selection of available eco-design methodologies, in order to help designers in choosing the suitable tool for their needs [7, 8].

In this paper, the authors focus on to carry out a survey on which metals are recycled in a dataset including patents and scientific articles related to the circular economy theme, showing which materials are most recycled and the impact that this can have in the current system. The potentials in the automatic understanding of the analysis contest have been outlined and a set of terms difficult to find with traditional tools to carry out this type of research have been identified.

The plan of the paper is as follows: Chap. 1 provides the introduction, Chap. 2 the methodological proposal to retrieve the state of the art and the way of proceeding conducted in this study, Chap. 3 presents the methodological approach used to conduct the study reported in this article and the research strategy, Chap. 4 the classification of the text and, at the end, Chap. 5 draws the conclusions.

18.2 Proposal

As a means to test the method proposed in this work, the authors have considered the extraction in full text (i.e., title, abstract, description, claims and priority dates) regarding the whole patent set and all scientific publications (from scientific journals, books and conference proceedings) of which they have been extracted the following sections (author/s, title, year, abstract, author keywords, index keywords) concerning the field of circular economy.

18.2.1 Scientific Paper and the Patent Corpus

The authors used Orbit Intelligence (www.orbit.com) to querying the worldwide patent DB and Scopus (www.scopus.com) in order to interrogate scientific literature. The goal is to extract the largest set of documents with the aim to study the problem in a complete and exhaustive way. According to author's strategies, all semantic network among words has been extracted.

18.3 Methodological Approach

The flowchart in Fig. 18.1 describes the methodological approach followed in this study:

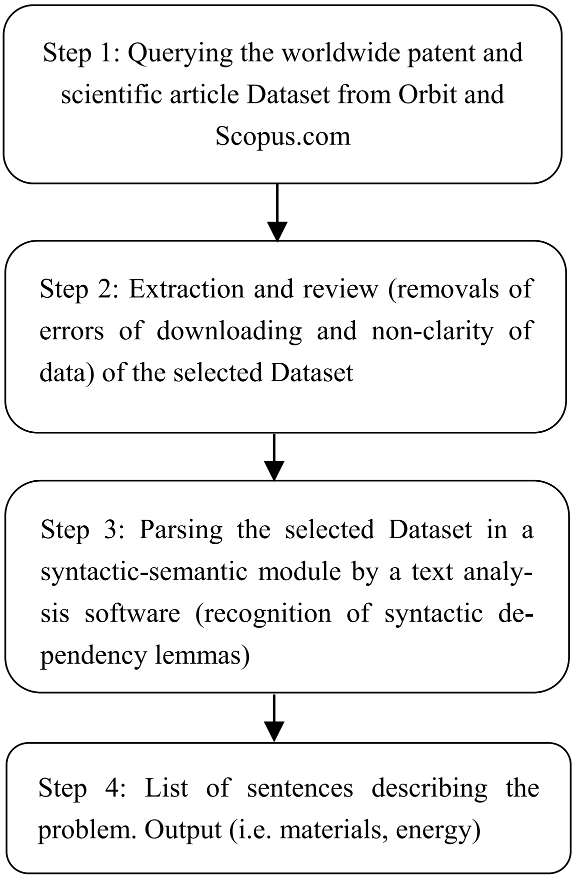

Fig. 18.1 Graphical representation of the operations performed in this study

Step 1: Querying the worldwide dataset concerning patents and scientific articles. The extraction of the files took place using the XML format, a structural document with pre-defined tags, XML is a document that acts as a container to store data that can be used by other software and easy to open.
Step 2 and 3: Revision of the file from a semantic point of view in order to prepare the file to be searched according to complex and linguistically motivated queries. The procedure starts analyzing the raw text through a set of algorithmic operations that enrich the above-mentioned text with additional features.
Step 4: The proposal aims to give a sample to be read the list of functions and technical problems through the parsing of the patent and scientific articles dataset. The tool gives, as a final output, a list of sentences describing the problem aggregate by their representative syntactic-semantic construction.

18.3.1 Search Strategy

The objective of this research is to understand which materials, or energy sources or waste materials are most recycled in a dataset of document (patents and scientific publications) concerning the field of circular economy. In order to do this, the authors investigate the corpus created through a series of generic verbs generically linked to the context of the reuse in the circular economy (i.e., reuse, recycle, recover …).

These verbs are then refined with technical terms on the basis of the iterative knowledge gained during the process and also through the use of synonyms. The goal is to identify, from the semantic results that the software elaborates and shows to video (modifiers or objects of these inserted verbs) which are the materials or energy or waste materials that are most used in a specific sector of circular economy linked in a semantic way to the inserted verbs.

To obtain these results, the authors exploit the semantic potentials provided by the tool used through a study of ontology of terms that allow to build a thesaurus, from which it is possible to improve and filter, obtaining better and better results. The results and the materials obtained can then be grouped and classified, analyzed through graphs and created different relationships (as shown in Table 18.1) (Table 18.2).

18.3.2 Search Strategy and List of Recycled Materials, Energies and Waste Found

The total documents, including both patents and scientific publications relating to the circular economy set, were processed through the use of the semantic software in order to find relationships that would allow, following the introduction of a specific term (name or verb, part of the speech, i.e., recycle and its synonyms) to extract

Table 18.1 List of queries and related results

	Search queries	# of results
Patent corpus	(CIRCULAR+ W ECONOM+)/TI/AB/IW/TX AND (RECYCL+ OR RECOVER+ OR REUS+ OR REDEMPLO+ OR REEMPLO+ OR REALLOCAT+ OR REPROCES+ OR REVAL+ OR REINT+)/TI/AB/IW/TX	991
Scientific publication set (first query)	(CIRCULAR ECONOMY) AND (RECYCLE OR RECOVER OR REUSE OR REDEMPLOY OR REEMPLOY OR REALLOCATE OR REPROCESS OR REVALUATE OR REINTEGRATE)	478

Table 18.2 List of synonyms of "recycle" obtained from semantic software

	Occurrence
Recycle and/or …	475
Recover	101
Reuse	46
Rigenerate	9
Remanufacture	9
Collect	6
Reprocess	6
Treat	5
…	…
Redemploy	3
Reemploy	2
Reallocate	2
Revaluate	1
Reintegrate	1
Reprocess	1

a very precise list of materials that are used in terms of recycling and related in a semantic way to the specific invariant of entry.

The following table is shown an extract of the materials that are obtained from the semantic software and linked to "recycle," "recover" and "reuse" that are some keywords used as input to querying into the dataset. The use of keywords is the main tool from which to start the research phase on a given topic, to deepen the knowledge of a given sector and evaluate the trend.

Table 18.3 List of materials obtained from semantic software

Recycle	Recover	Reuse
Materials object of "recycle"	*Materials object of "recover"*	*Materials object of "reuse"*
Waste	Metal	Polyester
Liquor	Copper	Paper
Oil	Oil	Wastewater
Water	Ammonia	Steel
Polyester	Water	Lithium-ion-battery
Metal	Aniline	Ash
Plastic	Ethanol	Fuel
Toner	Polyester	Sewage
Clothing	Gas	Hydrocarbon
Wastewater	Liquor	Phosphorous
Solvent	Ingot	
Asphalt particles	Nutrients	
Dust	Liquid	
Phosphorous	Phosphorous	
Gas	Sulfur	
Pulp	Waste	
Slurry	Zinc	
	Resin	
	Acid	
	Wood	
	Alcohol	
	Dioxide	
	Aluminum	
	Iron	

The results obtained were those that showed the highest number of results related to the input keywords. In this analysis, searches were also carried out by inserting additional terms (e.g., reprocess, reemploy, redemploy, etc.) (Table 18.3).

18.3.3 Search Strategy and List of Recycled Energies and Waste

For the sake of knowledge, another example is provided regarding the energies that, in a process of circular economy, are reused in a system. Also for this specific case, a list of forms of energy are provided, as reported in Table 18.4.

Table 18.4 List of energies and wastes obtained from semantic software

Energy	Resource	Waste	Garbage	Dross
Materials object of "energy"	*Materials object of "resource"*	*Modifiers of "waste"*	*Modifiers of "garbage"*	*Modifiers of "dross"*
Thermal	Natural	Industrial	Kitchen	Boron
Geothermal	Renewable	Organic	Household	Silicon
Wind	Mineral	Kitchen	Wrap	Aluminum
Solar	Water	Agricultural	Agriculture	Stannate
Electrical	Non-renewable	Food	Compound	Hydrate
Cold	Sulfur	Medical	Building	Iron
Renewable	Geothermal	Construction	Domestic	Sodium
Fossil	Coal	Fabric	Organic	
Kinetic		Cotton	Urban	
Light		Ceramic	Fertilizer	
Biomass		Plastic	Sewage	
Mechanical		Demolition	Sludge	
Cryogenic		Plant	Acid	
Chemical		Alkaline		
Green		Litter		
Flood		Packaging		
Alternative		Liquid		
		Polyester		
		Acidic		
		Biodegradable		

As in the previous case, the investigation concerning the reuse of energy sources in the field of circular economy takes place by querying the corpus through a series of nouns linked to "energy" through the study of an ontology that allows me to create a thesaurus of terms. The definition of the underlying list is obtained through some keywords used as input to querying into the dataset. The keywords used are "energy" and "resource."

18.4 Classification of the Text

In order to show the contribution object of this publication, the authors will provide a classification of the text starting from the recycled materials found in the previous analysis (as reported in Sect. 18.3.2) and extracting relationships in a graphical point of view. As reported previously, the use of keywords is the main tool from which to start the research phase on a given topic, to deepen the knowledge of a given sector and evaluate the trend. A further aspect to be considered concerns the semantic research itself, which focuses mainly on the meaning of words and not on simple counting of the same.

Based on these aspects, the possible problems that are found when doing a search of this type are connected to the search by keywords and concern the synonymy and the polysemy, for example, the semantic field identity between two words that have the same or equivalent meaning.

The methodological approach on the basis of the classification of the text starts from the list of materials found in Sect. 18.2.1. In detail, of the semantic relationships that the software provides, we proceed to the manual grouping of similar terms, that is to say the terms whose meaning is connected to a given aspect of the selected theme. This operation makes it possible to highlight the main topics dealt with in the patents or the scientific publications constituting the analyzed corpus.

This research approach aims to provide a global vision of the selected field and, consequently, a more in-depth analysis of a specific theme associated with this.

Below is a list with the steps carried out to classify the text.

- From the list of materials identified in Sect. 18.2.1 supplied by the parser, the authors proceed to the manual grouping of similar terms;
- Identify the most significant categories, i.e., those categories whose meaning is connected to a given aspect of the selected theme;
- Starting from the categories identified, process them in Orbit or Scopus and crate charts.

Each class represents a group of words with similar meaning or connotations. In each class, all the terms connected to an aspect taken into consideration have been grouped together. To do this analysis, the authors read sentences of the original patents and scientific articles in order to rebuild as accurately as possible the grouping of materials to the relevant class. The above-mentioned classification is based on preexisting surveys, [9, 10] (Fig. 18.2).

18.5 Definition of the Queries for Each Class and Graphs

Once the seven classes have been identified, the queries are defined. The queries were constructed by relating the set of key terms on which the research is set (metallic materials, etc.) with the set of terms representative of each class.

Example queries related to the first class. The same procedure was performed for all the classes found. For each query is reported the number of patents that, in the initial pool of documents, studies the material that is being recycled (Table 18.5; Fig. 18.3).

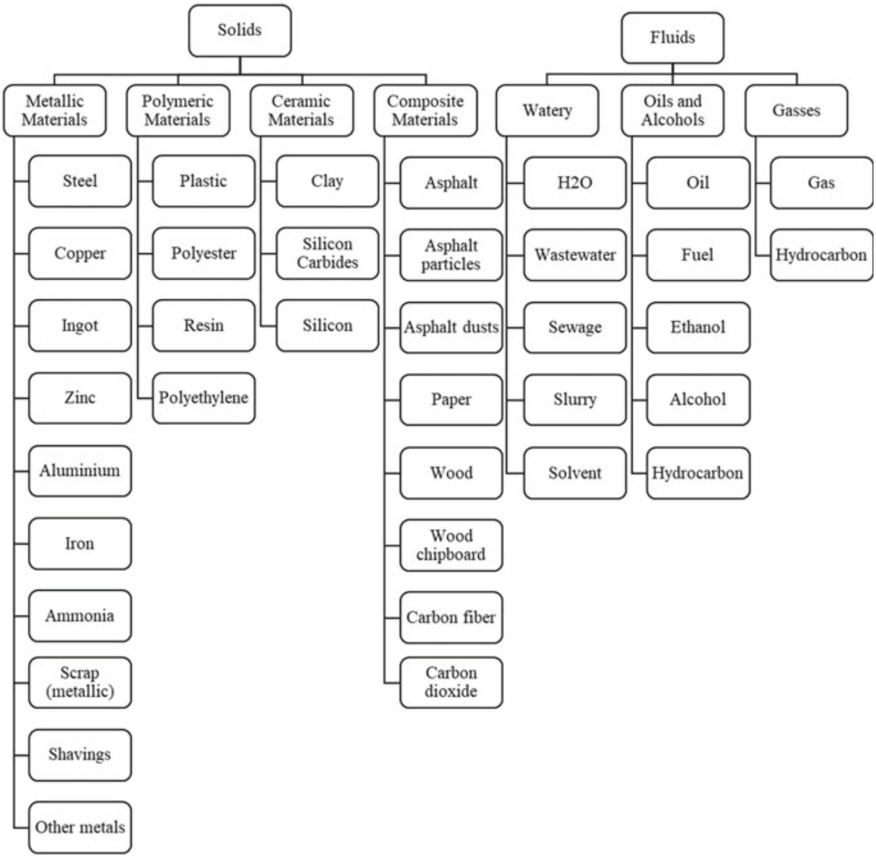

Fig. 18.2 Manual classification of classes of materials to be recycled

Table 18.5 Search queries and numerousness of results

Search queries	# of results
(RECYCL+ OR RECOVER+ OR REUS+ OR REDEMPLO+ OR REEMPLO+ OR REALLOCAT+ OR REPROCES+ OR REVAL+ OR REINT+) 3D (METAL+ OR STEEL+ OR COPPER+ OR INGOT+ OR ZINC+ OR ALUMIN+ OR IRON+ OR AMMONIA+)	404
…	…

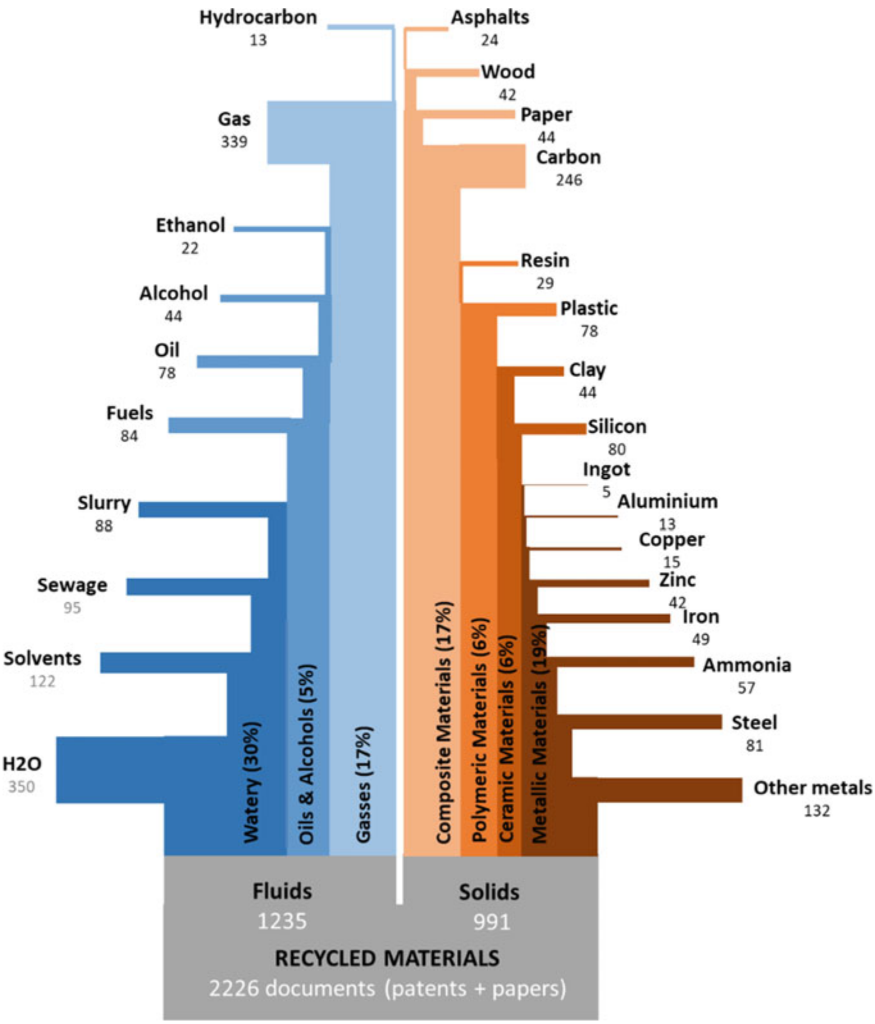

Fig. 18.3 Graphical representation of the results obtained from the classification of the text

18.6 Conclusions

In this paper, a semi-automated state of the art related to the concept of circular economy is provided, showing what types of business areas are nowadays related the most from the materials that are being recycled.

The main theme of this article was treated by building a dataset of patent sources and scientific articles. This information was then processed using advanced tools that contain innovative research strategies such as Kompat Cognitive and Sketchengine.

These tools have made it possible to classify waste materials with a view to circular economy, obtaining useful results, even for those who do not have knowledge of the sector, in order to classify information to bring out the aspects dealt within the document sets and technology transfer.

Future developments will be to expand the current research carried out in this article with the aim of understanding and finding connections among the materials that are being recycled and the potentials industrial applications or social problems that will be result from the recycling of that particular material and understand which trend or targets could be there (being able to build cause-effects bonds).

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Part IV
Supply Chain Management and New Business Models in the Circular Economy

Chapter 19
Closed-Loop Supply Chains in Circular Economy Business Models

Maria Holgado and Anna Aminoff

Abstract With the emergence of the circular economy (CE) approach into business models, there is need for deeper understanding of resource loops activities and how current supply chains can support the development of emerging CE business models. However, there is still limited research addressing the conceptualization of closed loops in the supply chain literature. This work addresses this research gap and proposes a typology for closed loops that is independent from the type of product under concern. Our findings suggest that there are two types of closed-loop supply chains in circular business models. Further work is envisaged to understand how companies can effectively develop their closed-loop supply chains as part of their transformation towards a more circular business model.

19.1 Introduction

The circular economy (CE) can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing and recycling [1]. An extensive introduction of these new activities into current industrial systems may create positive environmental benefits while disrupting the way how currently organizations and supply chains work. In this regard, it is necessary to redesign current supply chains. The concept of closed-loop supply chains (CLSCs) emerges as a response to this need to reinterpret supply chains within the CE. Research efforts frequently focus on closed loops at the end-of-life (EOL) of consumer products. However, closing the loop happens all along product life cycles and for other types of primary and secondary products. Interestingly, only few contributions try to differentiate different kinds of closed loops in supply chains. For example, Wells and Seitz [2] propose four

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types of closed loops—internal or within manufacture, post-business, post-consumer and post-society—and discuss different characteristics and challenges for each type. This limited analysis of closed loops invite for further research in this topic, especially as new CE practices and business models gain popularity in businesses.

In this work, we adopt a view of supply chains based on Carter et al.'s [3] proposal of considering supply chain linked to one product and one agent. Thus, we study cases referring to one type of product, the product at the origin of the loop and one focal agent, the CE business. Taking the loop characteristics as starting point for analysis, we differentiate between CE cases involving a CLSC and an open-loop supply chain (OLSC) and eventually identify two types of CLSCs within CE business models.

CLSCs are at the core of CE business models; however, they have been mainly studied as separate research streams. Moreover, there have been limited efforts to clarify the relationship of CE and sustainable supply chain management (SSCM) literature and practice. With this in mind, the aim of this work is to investigate the conceptual connection between CLSCs and emerging CE business models. Our work contributes to advance the knowledge on CLSCs by proposing a set of closed-loop types within CE business models and deriving a conceptualization of CLSCs that is illustrated with real-life examples. This work will ultimately bring support to companies in the design of the CLSCs and CE business models, thus facilitating the uptake of these practices in current businesses.

19.2 Background

The CE calls for a new relationship with products and materials, which is more labour intense and less resource intense [4]. Lacy and Rutqvist [5] explored how companies can benefit within the CE by 'creating value from waste'. They identified 'Recovery and Recycling' as a business model type within the CE, in which everything that used to be considered as waste is revived for other uses. They identified two variations within this model: the recovery of value from EOL products and the recovery of waste and by-products from a company's own production process and operations. The latter includes the concept of industrial symbiosis (IS) which refers to the output waste and underutilized flows of one organization being used as valuable and productive inputs for another organization [6, 7]. In a typical organization, finding suppliers and customers of these materials is under the purview of supply chain management (SCM). Thus, to make an effective IS application and relationship, SCM is a prerequisite [8, 9].

According to Stahel [4], CE business models can be categorized in two groups: those fostering reuse and product life extension via repair, remanufacture, upgrades and retrofits and those obtaining new resources from old products via recycling their materials. Recycling has not been considered a high-value solution as the material value is reduced during the recycling process. It is often energy-intensive and not free of environmental impacts [10]. However, within the CE recycling is seen as an enabler of a cascaded use of resources, thus facilitating multiple use phases with declining product or material value and diverting resources from landfill [11]. When recycling processes mean transforming the old product or material into something of higher value, it is named as 'upcycling' [5]. In this work, we adopt this conceptual differentiation between recycling and upcycling.

Creating new CE business models has been a subject of interest in academia for several years. In this regard, there is an interest for understanding the process of developing sound business models within the CE [12, 13]. Three mechanisms have been identified as basis for building business model strategies within the CE [14]: (1) slowing resource loops, by extending or intensifying the utilization period of products, e.g. product life extension through repair or remanufacturing; (2) closing resource loops, by enhancing recycling practices, e.g. post-consumer plastics recycling; (3) narrowing resource loops, by reducing the amount of resources per product.

The SSCM and the CE concepts are both overlapping and supplementing each other [15, 16]. Within this view, the evolution of supply chains leads to an integrated approach considering both forward and reverse supply chains simultaneously, populated as CLSC [17]. Reverse supply chain includes activities dealing with value recovery of EOL products either by the original product manufacturer or a third party [15, 18, 19]. EOL products are collected from customers, and the appropriated processes are then performed, such as repairing, disassembling, remanufacturing, recycling and disposing of them in an environmentally sensitive manner [19]. It is worth to note a terminology discrepancy between the business model mechanisms and the supply chain literature. In fact, CLSC literature refers to repair and remanufacturing as a mechanism to close the loop of a specific product whereas the above CE business model literature considers repair and remanufacturing as part of 'slowing the loop'. This is an example of the fragmentation of the CE thinking across several research fields, as highlighted by De Angelis et al. [20] and calls for increasing efforts to develop a common understanding between fields. Some authors make a distinction between open-loop and closed-loop SCM [15]. In a closed-loop cycle, a component will be reused or recycled for the same application, whereas in an open-loop view, the materials or components enter another application [21, 22]. CLSCs deal with taking back products from customers and returning them to the original manufacturer for the recovery of added value by reusing the whole product or part of it [19]. OLSCs involve materials recovered by parties other than the original producers who are capable of reusing these materials or products [21]. Often the line between closed-loop and open-loop approaches is a very thin one; moreover, the main purpose is recovering added value and avoiding waste, which is supported by reverse logistics activities [23].

19.3 Research Framework

Our initial categorization of CE businesses considered the loops they are creating with their operations. We differentiate between industrial (upstream) activities and

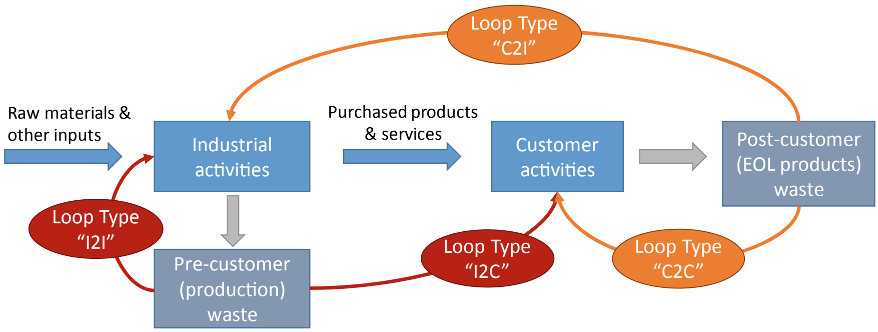

Fig. 19.1 Overview of the loops typology used to categorize the cases

customer (downstream) activities. Both industrial and consumer goods markets are included in the customer activities depicted in the framework (see Fig. 19.1). Arrows represent the stages from where and to where the loop occurs. We define the 'loop origin' as the stage where the 'origin product' exits its current linear journey and 'loop termination' as the stage where the 'new, transformed or treated product' is used and initiates its new lifetime. We identified four types of loops: (I) from pre-customer waste stage to industrial activities, or 'I2I'; (II) from pre-customer waste stage to customer activities, or 'I2C'; (III) from post-customer waste stage to industrial activities, or 'C2I'; and (IV) from post-customer waste stage to customer activities, or 'C2C'. Loops 'I2I' and 'I2C' are related to the internal and post-business loops proposed by Wells and Seitz [2] while loops 'C2I' and 'C2C' are related to their post-business, post-consumer and post-society loops. This new approach served our categorization purposes which needed to be independent of the type of customer and the type of product involved in the loop. It represents a more holistic view of those CE business models, whose final products are sold equally in both industrial and consumer goods markets (e.g. cases 8 and 11). Our categorization provides a comparison of the loops themselves, and of the type of recovery activities, as independent as possible from product type and other contextual factors.

19.4 Research Design

We have selected and analysed 20 cases of supply chains in CE businesses, including exemplary cases from USA, Europe and China from a variety of sectors. The search for cases was done in repositories of case studies, sustainability-oriented blogs, news and in academic publications. The information available in those sources was complemented with information from the company website. Particularly, the repositories of cases studies used were those developed by the Ellen MacArthur Foundation,[1]

[1] https://www.ellenmacarthurfoundation.org/case-studies.

the Remanufacturing Network[2] and SITRA.[3] A variety of sectors were addressed in the selected cases; however, it seems worth remarking that most cases found, and therefore selected, are in the textile, fashion and clothing sectors (7 out of 20).

For all the cases, the product at loop origin was identified as well as the focal company. Data collection included information of supporting actors or partners mentioned in the case descriptions and company website, a high level description of the activities carried out to close the loop, the new product obtained at the end of the loop and, whenever applicable, the activities at the EOL of the new, transformed or treated product. Table 19.1 presents an overview of the cases.

19.5 Findings from the Cases

In this section, we present five observations from the cases and then present a conceptualization based on these observations.

Observation 1: The most common loop type found in the repositories is C2C.

This loop type closes the loop between post-customer wastes and customers activities. In contrast, it has been challenging to find cases of loop type 'C2I'; the underlying reason might be that showing to public audiences a finished product is more appealing and engaging than intermediary industrial input material that create the finished product. For example, showing a recycled nylon yarn would attract less interest from the public than showing how the carpet tiles made with that yarn look in a finished carpeted floor. Loop type 'C2I' could be interpreted as an intermediary step of loop type 'C2C' in some cases. For example, case 3 describes how Interface closes the loop by transforming old fishing nets into carpet tiles. For this, they collaborate with Aquafil that has the technology to make the actual transformation of nylon waste (from old fishing nets, among other sources) into nylon yarn, as described in Aquafil case. The nylon yarn is subsequently converted into carpet tiles in Interface case. Loop type 'I2I', that implicitly regards IS activities, was also less frequent in these online repositories. This might be explained similarly as loop type 'C2I'; both types concern industrial waste and activities.

Observation 2: The value recovery activities when products or material remains the same or is used in the same application are direct reuse (after some cleaning or inspection)*, refurbishment, remanufacturing* and, *in some occasions, also recycling.* Table 19.2 provides an overview of the activities found in these cases. These cases are those that the SCM literature refers to as CLSCs.

Observation 3: The value recovery activities when the product or material is transformed are either recycling or upcycling. In the cases in which the origin product/material is transformed it into a different product/material (here called transformed product) employ either recycling or upcycling as activities to perform the transformation. These cases are those that the SCM literature refers to as OLSCs.

[2] https://www.remanufacturing.eu/case-study-tool.php.

[3] https://www.sitra.fi/en/projects/interesting-companies-circular-economy-finland/.

Table 19.1 Overview of cases

Case #—Focal company (country)	Loop type (origin product to new, transformed or treated product)	Application after loop
1—Elvis & Kresse (UK)	C2C (old firehoses to luxury accessories)	Different
2—Elvis & Kresse (UK)	I2C (leather cut-offs to luxury accessories)	Different
3—Interface (USA)	C2C (old fishing nets to carpet tiles)	Different
4—Aquafil (Italy)	C2I (nylon waste, incl. old fishing nets and carpets to nylon yarn)	Same
5—Purewaste (Finland)	I2C (textile production waste to new fabrics and garments)	Different
6—MUD Jeans (NL)	C2C (old unusable jeans to new jeans)	Different
7—Gazelle (USA)	C2C (old electronics to certified refurbished electronics)	Same
8—Alisea (Italy)	I2C (graphite scrap to graphite pencil)	Different
9—Guangzhou Huadu (China)	I2C (used transmission boxes to certified spare parts)	Same
10—MBS (Germany)	C2C (used diesel engines to refurbished engines)	Same
11—Rype Office (UK)	C2C (plastic waste to table tops)	Different
12—Finlayson (Finland)	C2C (old linen sheets to rag rugs)	Different
13—Finlayson (Finland)	C2C (old jeans to towels)	Different
14—Niaga (NL)	C2C (old carpets to new carpets)	Same
15—Toast Ale (UK)	I2C (surplus bread to beer)	Different
16—British Sugar (UK)	I2I (surplus CO_2 and heat to glasshouse plants)	Same
17—Desso (NL)	C2C (old carpets to new carpets)	Different
18—Fescon (Finland)	I2I (blast furnace slag to fluidized bed material for power plants)	Same
19—Ecoalf (Spain)	C2C (PET bottles to garments and accessories)	Different
20—Ecoalf (Spain)	C2C (old tyres to flip flops)	Different

Table 19.2 Overview of activities when the product/material remains the same

Case #	What actions are performed within the loop?	Activity category
4	Depolymerization and ECONYL© process, then polymerization and yarn production	Recycling
7	Light refurbishment based on a 30-point functional and cosmetic inspection	Refurbishment
9	Disassembly and remanufacturing of parts	Remanufacturing
10	Disassembly, cleaning, change or refurbish parts as needed, reassembly, painting	Remanufacturing
14	Separating material layers and using them to create new carpets	Recycling
16	Reuse directly for new purpose	Direct reuse
17	Separating yarn and fibres from the backing; the yarn gets purified and returned to yarn manufacturer	Recycling
18	Reuse directly for new purpose	Direct reuse

Further information was collected in these cases to understand what happens to the newly created products at their EOL. Table 19.3 provides an overview of the activities found in these cases regarding the transformation process and the EOL options.

The analysis of the cases brought up additional insights in terms of the role of recycling and CLSCs development in CE business models. Unlike other activities, recycling is used both when transforming the origin product into a different kind of product or material and when the origin product is recovered and used as the same product or material again. An example of the latter is the well-known activity of recycling glass bottles into new glass bottles that has been happening for decades in household waste management practices. In our cases, this can be observed in cases 4, 14 and 17. Alternatively, recycling is a process used to transform a product or material into something different. This use is key to enable the cascading use of materials within CE business models, as described in cases included in Table 19.3.

Observation 4: The EOL of transformed products needs to be taken into consideration. The identification of the EOL activities for the transformed products coming out of OLSCs of the origin product provides a more systemic view of system in which the transformed product is involved in its lifetime. We have found that companies initially performing activities such as recycling or upcycling in an OLSC for the origin product often address the EOL of the new product as part of their business model. Alternatively, in some cases, the transformed product is recyclable by the same means again and again. In other cases, such as the graphite pencil or beer production, the new product will be fully consumed. We argue that these cases are enabling a CLSC for the new product, which is aligned to the cascaded used of resources and the CE.

These observations lead to the conceptualization of CLSCs in CE business models as shown in Fig. 19.2. Two types of CLSCs can be identified if we look holistically

Table 19.3 Overview of activities when the product/material is transformed

Case #	What actions are performed within the loop?	What happens at EOL of new product?	Activity category within loop/at EOL
1	Disassembly, cleaning and treatment to make the material reusable	Repair is offered to customers	Upcycling/Repair
2	Cutting into small shapes to be assembled to form the new product	Repair is offered to customers	Upcycling/Repair
3	Using the ECONYL © process with partner Aquafil, then weaving the yarn into tiles	Product recyclable after use	Recycling/Recycling
5	Sorting by colour, refibering and spinning into new yarn	Product recyclable after use	Recycling/Recycling
6	Shredding old jeans, blending with organic cotton to create new pairs of MUD Jeans	Product recyclable after use	Recycling/Recycling
8	graphite powder is moulded into pencil shape, then attaching the coloured eraser	Product can be used up completely	Recycling
11	Shredding plastic materials and moulding then into table boards	Repair and refurbishment is offered to customers	Upcycling/Repair, refurbishment
12	Washing linen, sewing together and cutting into streams, then winding and weaving them into rag rugs	Product recyclable after use	Recycling/Recycling
13	Crushing the jeans and spinning the fibre into new yarn to be used in towel production	Product recyclable after use	Recycling/Recycling
15	Incorporating the surplus bread into the brewing process to make beer	Product can be used up completely	Upcycling
19	Cleaning and shredding plastic bottles; then treatment and spinning to obtain yarn	Product recyclable after use	Recycling/Recycling
20	Separating rubber and turning it into powder and then compressing it without glue to create the flip flops	Product recyclable after use	Recycling/Recycling

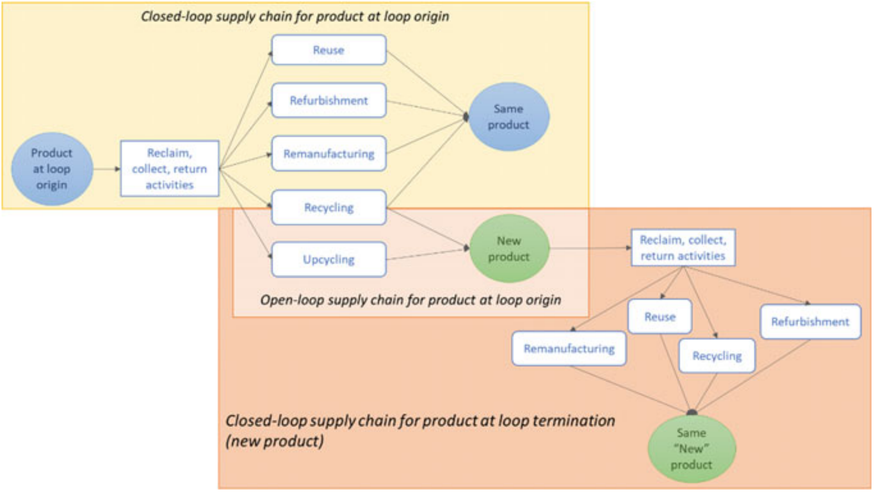

Fig. 19.2 Closed-loop supply chains in circular economy business models

at both the product at the origin of the loop and the product at the termination of the loop.

The *first type regards the closed loop of the origin product* and involves different activities such as direct reuse, refurbishment, remanufacturing and recycling into the same material. This type is illustrated inside the yellow square in Fig. 19.2.

The *second type concerns the closed loop of the transformed product*. While the initial transformation involves recycling and upcycling activities, the closed loop of the transformed product (called 'new product' in Fig. 19.2) is afterwards performed by recovery processes such as direct reuse, refurbishment, remanufacturing and recycling into the same transformed product. This type is illustrated inside the orange square in Fig. 19.2.

19.6 Concluding Remarks

Previous studies have referred to the potential connection and synergies between CE and SCM topics [16, 24, 25]; however, their conceptual linkages are not explored in depth. This work brings together CE and SCM fields by studying the concept of closing the loop in CE business models. We adopted the view of supply chains linked to one product and one agent [3], and we differentiated between recycling and upcycling activities and focused on slowing and closing mechanisms for the development of CE business models. We studied 20 cases of circular supply chains and draw two main contributions from the analysis. First, we developed the loop typology that, independently of the type of product, models the loop origin and termination according to production and consumption perspectives (Fig. 19.1). This brings a higher level of abstraction to the conceptualization of closed loops and does not constraint the CE efforts to a particular market. Indeed, companies like Rype Office (case 11) serve their transformed products to both other businesses and consumers. This typology represents an attempt to overcome the issues brought up by Wells and Seitz [2] regarding difficulties in theory-building and generalizability due to closed-loop characteristics being highly conditional on product type and contextual factors. Second, we identified two different types of CLSCs within CE business models, those that close the loop for the origin product and those that close the loop for the transformed product, after the transformation happens within an OLSC of the origin product. In contrast with current complex/extensive typologies of business models (see [26, 27]), this differentiation brings a more holistic, while simplified, view of the system in which resources are kept and regenerated in the CE. These two conceptualizations might help future research on understanding the supply chain implications of CE business models.

By advancing the knowledge on CLSCs, this work provides support to improve scalability and replicability of CE business models which are key aspects limiting the wider implementation of CE in businesses [28]. Thus, further research will address how this conceptualization can lead to a supporting decision-making tool to facilitate the development of CLSCs and their integration in current business models and operations.

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Chapter 20
Turning Finland into a Country of Circular Economy: What Kind of a Process of Change Should We Seek?

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Abstract In recent discussions and policies, circular economy (CE) has been perceived as a promising way to solve environmental problems caused by our current economic system. To become reality CE calls for extensive, systemic changes in the design and production of goods, in consumption patterns, and in the ways in which companies create value. Though the transition characteristics of circular economy are self-evident, thus far few researchers have analysed it from transition theory perspectives. Transition approach could greatly enhance our understanding of processes aiming to achieve CE, including barriers and incentives that might affect them. Finland has often been seen as a forerunner in the change towards CE. We organised four workshops to explore how Finland could promote the change towards CE. In this chapter, we describe and analyse outcomes of the workshops focusing on the looked-for characteristics of a CE transition process in Finland. The findings point to a direction of a purposive transition with coordinated action, shared use of resources and shared creation of knowledge.

20.1 Introduction

Circular economy has in recent discussion and policy programmes risen as one means to solve, in an economically sustainable way, the environmental problems caused by production, consumption and the excessive use of natural resources [1–4]. The EU has adopted an action plan on CE [5], updated its waste management regulations based on the principles of CE [6] and worked on defining the relationship between CE and critical resources [7]. Finland has launched a strategy on bio-economy and

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CE as a key project of the current government programme, based on a road map published by the Finnish Innovation Fund Sitra [8]. Several actors have actively set out to promote CE, aiming to build Finland into a model country of CE.

In this study, we examine workshop series organised to explore how Finland could promote the change towards CE (see also [9]). We describe these workshops and analyse especially on the opportunity statements focusing on the CE transition process in Finland. We suggest that the findings could assist other countries and areas to find suitable ways towards CE. We use as our frame of analysis a typology of socio-technical transition processes [10, 11], where the nature of the processes varies dependent on how the pressure for change is perceived, the degree to which the change is coordinated by the incumbent regime, and what kinds of external or internal resources (economic capital, material input, skills and political resources that support the regime) are available to the actors. Socio-technical transition model has been used to understand the transition towards CE mainly from production perspective (e.g. [12–15]); the relevance of our contribution is that case studies for a wider analysis about a social and political change have been rare. We will bring together the issues of systemic change and socio-technical transition model in order to understand better how the change towards CE could be promoted in society.

The literature underscores systemic change [2, 4] as a prerequisite for a transition towards CE. Four key factors of change are proposed in production and economy based on the basic principles of CE: (1) change in production design and production processes [2, 4]; (2) new business models that steer companies' value creation and consumer behaviour in a resource-efficient direction [16–19]; (3) proper and usable data on materials and their flows. The data make it possible to manage value networks and reverse logistics, as well as the take-back of materials [3, 20]. This in turn requires comprehensive data collection and thus collaboration between the different parts of the supply chain so that material flows can be directed back to production [2]; (4) broad-based collaboration and its development [1, 2], because autonomous operators (e.g. companies, state) do not have sufficient resources to achieve the large-scale changes.

The transition towards CE can be perceived through the framework of socio-technological transition [10, 11], where existing production structures, business models, products and consumption practices undergo a fundamental change. Achieving and managing the transition primarily involves negotiation between internal and external actors in the established system under study and the dominant regime, where the ways to respond to the pressure for change caused by different factors are chosen (10). The actions that cause the transition can be highly context-dependent [10, 21, 22]. The power structures, institutionalised operating models, available resources, need for and nature of the pursued change all have an impact on what kind of action is born. Berkhout et al. [10] typifies the transition context and processes according to the extent to which the transformation is coordinated. What are seen as necessary resources are economic capital, sufficient (e.g. technological or business) knowledge, the available material resources and natural resources, but also support from political decision-making, which in turn reinforces the acceptability of the regime's actions [10, 11, 23].

Four different socio-technological transition contexts can be mapped depending on the locus of resources and the degree to which the transition is coordinated: (1) endogenous renewal is possible when the actors in the socio-technological regime (companies, customers, supply chains and regulators) make conscious efforts to find ways of responding to the competitive threat. In this situation, the pressure to change the regime is a result of high coordination. (2) Reorientation of trajectories may occur when the degree of coordination from within the regime is low and a sufficiently strong external shock (change in regulation, unpredicted technological innovations, etc.) forces the regime to transform radically. Despite the low degree of coordination, the actors are quite organised. A transition caused by a radical external shock can be quite rapid, even though the degree of coordination may be low. (3) Emergent transition can arise when several concurrent internal and external events lead to an uncoordinated change. (4) Purposive transition arises when different actor sectors, such as research, the public sector and industry, are co-opted to a vision to form a powerful grouping.

We will describe the expert statements produced in the workshop using this taxonomy of socio-technological transition processes as our frame of analysis. Through the framework, we aim to illustrate what kind of a transition towards CE the experts describe in their statements.

20.2 Participatory Workshops in Finland as a Method

In the following, we describe the workshops held in Finland and the method used.

We organised four workshops in Finland 2017–2018. The workshops explored the opportunities of CE value creation from the perspectives of different stakeholders, as well as the preconditions for and obstacles to its becoming reality. The national-level workshop was preceded by three regional workshops (Kokkola, Satakunta and South Karelia) where CE-related development needs regarding collaboration within the industry at large and purposeful networking between sectors were identified. The participants in the regional workshops included local companies, regional development organisations and national-level actors. The last workshop was a national workshop, where individual companies, employee organisations and environmental organisations were excluded. The business standpoint is indirectly expressed through the individual companies and regional business and development organisations that took part in the regional workshops. The outcomes of the regional workshops (outcomes summarised in Fig. 20.1) were made available to the participants in the national-level workshop.

The participants in the national workshop were eight Finnish experts working with CE-related issues, from the Ministry of Economic Affairs and Employment, the Ministry of the Environment, the Finnish Innovation Fund Sitra, Motiva Oy and the VTT Technical Research Centre of Finland. Experts from two regional development organisations (Prizztech Oy and Wirma) also took part in the workshops. The representatives of the regional development organisations and VTT had participated in the

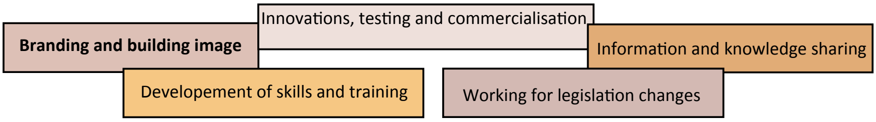

Fig. 20.1 Key outcomes of the regional workshops in Finland

earlier workshops organised at regional level. The organisations and the experts in the national-level workshop were selected on the basis of the work carried out in the earlier workshops, with focus on organisations that were seen to have a significant role in terms of the goals and realisation of CE in Finland. The ministries oversee and put to practice-related measures and policies within their specific mandates. Sitra is an important actor at national level for CE issues in Finland, well recognised at international level as well. The regional development organisations that took part in the workshop coordinate development and research projects with CE relevance, involving businesses, higher education institutions and other research organisations in their respective regions. They were thus able to present views from a wide range of actors on how CE can be promoted in Finland. The organisations that took part in the workshop have the opportunity to influence the goals and measures through which a transition towards CE could be directed.

All the workshops utilised the participatory methods and tools (e.g. stakeholder mapping, value explorer and transformation tools) developed by the Centre for Industrial Sustainability at the University of Cambridge, which systematically analyse questions of ecologically, economically and socially sustainable value creation from the standpoints of different stakeholders [16]. The workshops started with an analysis of the current situation and proceeded from there to a mapping of future opportunities. This was realised in three phases: In the first phase, the participants defined, together and under guidance from a facilitator, different concepts of CE and the concrete goals of the workshop. The group furthermore defined the key stakeholders in efforts to turn circular economy into reality and for the organisations represented by the participants. In the next phase, the participants analysed, through the stakeholder perspectives, the strengths, successes and failures in promoting CE.

Based on these reflections, the group identified future opportunities that would support the transition to CE. Next, ideas on achieving the goals were formulated, in concrete and practical form, based on the identified opportunities. Eight statements from the national workshop were compiled as an outcome of the workshop series work on how a transition to CE could be achieved in Finland.

20.3 Statements on the Opportunities of CE in Finland as Outcomes

In the following, we describe the opportunity statements produced by the workshop participants for how a transition towards CE in Finland could be advanced and compare them to the central areas of change for CE.

In Table 20.1, we compare the statements produced in the workshop with the needs for change identified on the basis of research literature. The table depicts statements on the rows, and the central areas of change in the columns. Each statement has been linked to the most central area of change (dark grey) and, when necessary, also to other central areas of change (light grey). The novel contribution to CE literature is presented in the last column.

All the statements identified in the workshop connect to several areas of change central to CE; the opportunities converge and contain features that partly overlap.

Skills and change regarding product design and production processes

One key area of change frequently mentioned in the statements is product design and production know-how. The workshop participants emphasised the importance of more efficient innovation processes, from the development to the commercialisation and dissemination of technologies. This in turn relates to the statement on engaging SMEs in problem-based, practical research projects and developing their intellectual capital through further training or experimentation in vocational basic education (#6). A culture of experimentation at all levels of education (#6) can also been seen as one part of improving the conditions for innovation activity (#2). This involves the development of technologies, business models and professional degrees through experimentation. Developing the mentioned areas also calls for collaboration in a broad range.

New business models

Making the opportunities of CE visible and attractive to investors and companies also links in with the development of business models through the commercialisation of technologies—with how an idea or invention can be turned into an innovation that succeeds in the markets, a competitive and economically viable solution to some definable CE problem. The issue of conceiving and developing of business models was addressed directly in one of the statements (#5), and indirectly in two of the statements (#4 and #8). The ideas regarding a culture of experimentation in the educational system can also relate to the development of business models, if the education is designed to be problem-based and includes the solving of both technological and business-related questions. The question of CE business competence emerges also in the context of technological development and commercialisation and ties in with the marketing and promotion of new technologies (IoT, Bid Data, processing and recycling of materials).

Managing data on material flows, value networks and reverse logistics

In the context of managing material flows, the statements underscored the need for new kinds of data. At the core of this statement (#5) is the idea that efficient use of side streams and value creation require reliable information on the properties and

Table 20.1 Comparison of the workshop statements and the central areas of change for CE

Workshop statements		Central areas of change identified for CE in research literature				Identified new area
		Skills and change in product design and production processes	New business models	Management of material flows data, value networks and reverse logistics	Broad-scale collaboration	Education in CE competence
1	Strengthening regional and cross-regional networks and collaboration within and between different industries	Sharing of best practices A stable foundation for research and development activities Pursuing shared added value			Acting equitably in the interest of all the actors	
2	Creating a culture of CE experimentation in the educational system	Multi-disciplinary and problem-based training for solving questions in business activity and CE			Close cooperation between the Ministry of the Environment and the Ministry of Education	Integrating CE and sustainable development goals in curricula Multidisciplinary and problem-based education
3	Creating a platform or network for discussing and planning new ideas	Opportunity to discuss innovation ideas and potentials and to plan their implementation		Opportunity to discuss innovation ideas and potentials and to plan their implementation	Building a technical platform and network Common rules of the game, neutral actor and funding	

(continued)

Table 20.1 (continued)

Workshop statements		Central areas of change identified for CE in research literature				Identified new area
		Skills and change in product design and production processes	New business models	Management of material flows data, value networks and reverse logistics	Broad-scale collaboration	Education in CE competence
4	Accelerating the development, commercialisation and dissemination of new technologies	IoT, data mining, processing of materials and raw materials and developing recycling technologies	Collaboration is a precondition for the realisation of CE business and export opportunities	Developing IoT, data mining and technologies for processing and recycling materials and raw material	Technology innovators into collaboration with innovators in other fields and political decision makers	
5	Making CE opportunities visible and attractive to companies and investors	Information on the availability, properties and potential usages of materials	Data for identifying business opportunities	Practical data for developing the usage of both materials technologies	Developing and utilising holistic indicators	
6	Including SMEs in local/regional problem-solving research projects; offering training to current employees and/or finding new employees with CE competence	Developing the CE knowledge of SMEs			More extensive cooperation between businesses and research organisations Teaching materials produced in collaboration between teachers and representatives of industry	Integrating CE knowledge into education at all levels Training new CE professionals, professional further training

(continued)

Table 20.1 (continued)

Workshop statements		Central areas of change identified for CE in research literature				Identified new area
		Skills and change in product design and production processes	New business models	Management of material flows data, value networks and reverse logistics	Broad-scale collaboration	Education in CE competence
7	Establishing a joint summit/seminar for social partners with the objective of finding new questions, commitments and measures				Developing collaboration between employer and employee associations	Paying attention to and collaboratively developing the educational dimension
8	Establishing new anchor organisations	Efficient use of resources and avoiding overlap in the activities	Supporting business development		Permanent, long-term activities and a clear division of responsibilities	

volumes of the materials, the stability of the flows, usage potentials and the economic aspects of the related activity. The data would also advance the development of direct markets for production side streams and products processed out of them. This in turn calls for the development of shared national and regional data resources and tools for the analysis. The collected data should include ecological, economic and social indicators, and the focus should be placed on development of the activity.

Broad-based collaboration

The statements highlighted the importance of broad-based cross-sectoral and cross-industry collaboration. There is a considerable amount of purposive activity centred on the development of CE, but some of it overlaps. A technological platform as well as a network that interlinks with it can be regarded as one part of the process of developing and coordinating these communities. They can for their own part facilitate the creation of direct dialogue between companies and research communities with regard to research ideas and development needs. Through a shared technological platform, actors in the public sector could articulate their needs and ideas and research organisations and companies could seek partners for research and development. The opportunity statements stressed as one concrete area of development crucial to the functioning of databases the solving of questions regarding the intellectual property (IP) rights to the recycled materials and data ownership. For the platform to benefit a wide range of actors, a neutral and reliable organisation is needed to maintain and develop it.

Education in CE

Another special feature in the statements was an emphasis on the importance of education. The role of education has not been highlighted in previous literature on CE, but in the workshops it especially stood out in three of the statements (#2, #6 and #7). Integrating CE into different levels of education requires a new kind of collaboration between companies, teacher associations and public administration, through which companies could, for example, take part in the development of teaching material, offer teachers training and build up cooperation with educational institutions.

20.4 Desirable Transition Towards CE

The statements produced as an outcome of the workshop offer possibilities to examine different ways in which CE can be pursued and what kind of a transition is seen as desirable. The statements also speak of the preferred direction of change (holistic change or an operational change within individual organisations, a technological change or a wider societal change). Based on the statements, CE is understood as a coordinated and purposive change; i.e., transition to CE can be seen as a process of change [10, 11] where several actors pursue a common goal in a coordinated manner (Fig. 20.2).

None of the statements is limited solely to the activities within individual organisations (options 1 and 2). Instead, broad-based collaboration (options 2 and 4) is addressed either directly or indirectly in all the statements. This suggests that CE is

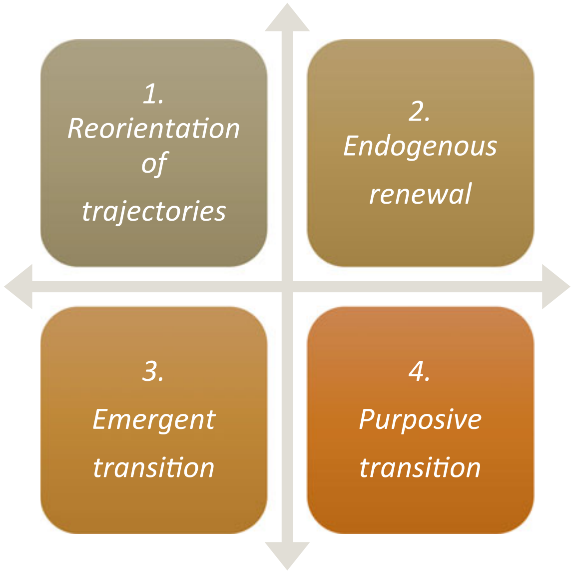

Fig. 20.2 Desirable transition towards CE in Finland is option 4. Purposive transition. The horizontal arrow shows the level of coordination—low in the left, high in the right—and the vertical arrow shows the resources—on the bottom there are resources from several levels and actors, and on the top there are only inner resources from one organisation

seen as a transition of some degree which calls for collaboration from both public and private sector actors in the key areas identified in research literature: product design and production know-how, business models, management of material flows, and cross-sectoral and cross-organisational collaboration, as mentioned. Individual actors do not have enough knowledge, financial resources or power to achieve the change autonomously or within a certain sector. According to the statements, Finnish experts support a purposive change [10, 11] where the different sectors and actors are joined behind a shared ideal of CE.

It is commonly believed that the realisation of CE requires that SMEs are more strongly engaged in research and development and their knowledge basis is expanded. The market actors are relatively small, and they do not currently have enough skills (or resources) for research and development work. A neutral and well-resourced anchor organisation is needed to coordinate the activities—teaching at every educational level as well as a strong role of universities and research institutes as producers of information and solutions. All the statements call for broad-based collaboration between the different actors. Previous research [24] has shown that the perception of CE shared by the business and public sector and academia is somewhat limited, with a strong focus on materials and recycling. More profound, cross-sectoral collaboration could for its own part diversify the perception and thus advance the realisation of the CE goals and the required innovations.

According to the statements, one way to advance the transition to CE would be to steer the central actors to work in collaboration across sectoral and organisational boundaries. This can be interpreted to mean that Finland should pursue a purposive process of change through which different actors would join forces to achieve the transition. This could be an option for European-level policy, too. In our view, the collaboration does not mean that the public sector or some strong interest group should coordinate or lead the action. It seems to be more a question of sharing information, funding opportunities and innovation needs, and finding a way to construct generally approved and shared courses of action to advance change. To us, this seems to represent a purposive transition process in the sense that the existing financial resources (funding opportunities and knowledge) could be utilised and directed more efficiently. The space that enables collaboration can also be understood as a "transition arena"—a safe space to develop collaboration and innovations [25].

20.5 Discussion and Conclusions

Our case study from Finland shows that all the key areas of CE development were addressed in the statements [4], but they also brought up some new viewpoints and contradictions to current European CE policy [26]. In the statements, the need for knowledge concerning business is mainly connected to financial support with which already existing technologies could be commercialised. Green-tech and clean-tech innovations play a key role in CE thinking [2, 27], but business and organisational innovations are also important to a transformation of the economic logic [4]. They are needed on a wide scale, from improving the efficiency of material flows to directing consumption, meaning that the new business models would moreover support the actualisation of sustainable lifestyles. New questions of service businesses developed for consumer or business customers (service-product packages, value creation, etc.) are not addressed in the statements. This is hardly surprising since the consumer perspective is featured to a rather limited extent in current CE policies [26]. In the reflection on innovations and commercialisation, the role of different innovators was seen as important, alongside technological skills. It does appear that turning CE into reality would require not only technological change but also a broader social understanding of the goals and the nature of the innovations as well as understanding of the direction of the change. This also seems to reflect commitment to coordinating the action.

Business skills were mentioned indirectly in, for example, the context of commercialisation of new technologies. Alongside the goals of CE, it would be at least equally important to reflect on business models and the change in business practices from the perspective of what needs the new products or services would offer solutions to and what kind of added value they would produce for the different stakeholders [16, 28]. Previous research [29] has shown that companies have not adopted CE business models to any large extent, and therefore CE business skills need to be advanced at practical level. The differences and similarities in the new CE-based business models need to be examined more carefully also in the light of consumer and business-to-business services.

Our results are to some extent contradictory to the choices made at the political level in Europe, where CE is seen especially as a transition produced by the independent actions in business and local actors, supported by individual states or the EU through legislation [5–7, 26] and research funding, avoiding detailed regulation (on, e.g., the technologies chosen). It could lead to a situation where the goals of policy programmes are not reached within the given schedules or other agreed-upon parameters. It would thus perhaps be wise to listen more to actors, businesses and citizens at local and regional level in the goal setting and choice of measures to ensure that the political goals for achieving CE, the different resources directed to it and the action would coincide more effectively.

Compared to earlier studies, what is new and special in the Finnish context is that the idea of teaching CE principles and contents in both basic and secondary-level vocational education was strongly addressed with regard to the development of a culture of CE experimentation, SME skills and collaboration between employer and employee organisations. Education was seen to have a central role in the development of technological and business skills. The issue of changing the educational system so that it would pay attention to ecological sustainability and wellbeing with a more holistic approach has been brought up in the Finnish context before [30]. The importance and integrative role of education in, for example, collaboration between the educational system and industry in producing teaching materials or developing a culture of experimentation supports the notion that the pursuable transition to CE is understood as purposive. According to the statements, education brings different actors together behind the same goal (well-functioning CE). It also serves towards a more efficient use of existing intellectual and economic capital. It does not make sense for individual organisations or small networks to engage in overlapping activities.

When examining the results of the study, one should note that the experts who participated in the workshop worked in organisations that were committed to promoting CE in Finland. The ministries coordinate activities in their respective mandates and, for example, implement the goals of the government programme. Sitra's operations and views on CE affect other actors through, for example, the fund's programme recommendations and project activities. These actors can thus for their own part influence what kind of a transition process resources and actions are focused on in the advancement of CE. Had the experts' occupations (e.g. more business-oriented) and general level of knowledge of CE been different, the results might have turned out quite different. It should be mentioned, though, that the need for purposive transition did arise in all workshops, and was perhaps even stronger in business-oriented workshops than in national level. That may reflect to the fact that the regional workshops wanted to send a message to the national level what is needed from political actors to help regions and businesses to move towards CE.

The results probably also reflect the Finnish society and operating culture. In some other country, the role of companies and business models might have been seen as much more central compared to, for example, the role of collaboration and interest groups. The strong emphasis on collaboration and coordination does not rule out the possibility that the transition could very well mean redirecting the economy or a transformation within different sectors. It is not possible to conclude on the basis of the results how profound or radical the changes need to be for CE to become reality in Finland. Answering these questions falls beyond the scope of this study.

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Chapter 21
A Cross-Sectorial Synergies Identification Methodology for Industrial Symbiosis

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Abstract Circular economy is the model the European Union opted for to make its production and consumption system more sustainable. Industrial symbiosis is one of its operational implementation strategies. This concept aims at redesigning industries supply chains by creating new interconnections between traditionally independent chains, new sources of raw materials and new market opportunities for wasted resources. This paper introduces an innovative methodology, developed within the SCALER project that aims at facilitating substitution synergies identification between cross-sectorial supply chains. Synergy ideas are automatically generated thanks to dedicated algorithms performing matching queries on input and output data of 17 industrial sectors. Data is generic and collected from publicly available sources. The methodology's deductive approach has the benefit of proposing relevant synergy ideas for industries without asking confidential operating data. A total of 1000 relevant synergies were already identified. Development perspectives are to reinforce the methodology with additional technical data sets such as treatment technologies, geolocated facilities databases and European economic activity/waste codes.

21.1 Introduction

The European Union (EU) is highly engaged in setting up sustainable development. The circular economy (CE) model is seen by both politicians [1] and most academic researchers [2] as one of the solutions to achieve this goal. A CE is an economic system of stakeholders (citizens, companies, nations, etc.) who implement business

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models based on reducing use, reusing, recycling and/or recovering materials in production, distribution and consumption processes [3]. End-of-life and linear economy paradigms are switched to a more circular one [4] promoting a development mode that protects the environment while facilitating sustainable economic development [5, 6].

Industrial symbiosis (IS) is considered as an operational strategy for CE implementation [7]. It identifies business opportunities that leverage underutilised resources, between organisations which are traditionally separate [8, 9]. IS redesigns industries' supply chains and creates new interconnections (synergies) between sectors, provides new sources of secondary raw materials such as heat, combustible or material and ensures viable market opportunities through substitution—i.e. wastes, by-products and emissions—or mutualisation—i.e. expertise, service, capacity, assets and technologies [10, 11]. It improves material use rate, increases competitiveness and environmental performance of the whole industrial system and individual companies [12].

The EU invested more than €130 million since 2006 in research projects to facilitate IS uptake and dissemination thanks to methodologies, tools or networks development [13]. SCALing European Resources with industrial symbiosis (SCALER) is one of them and provides answers to targeted IS implementation issues, i.e. lack of inter-sectorial knowledge sharing, difficulties to identify and manage relevant industrial data for IS and lack of innovative synergies identification for process industries. SCALER's overall goal is to develop action plans and provide adapted solutions to process industries for a wide IS uptake. To draft tailored strategies, the EU IS potential must be assessed and its techno-economic, environmental and social impacts must be quantified. For this purpose, a methodology to identify synergies has been created. This paper introduces the methodology, its preliminary results and some development perspectives.

21.2 Background

IS development is a journey of five steps: opportunity identification; opportunity assessment; barrier removal; commercialisation and adaptive management; and documentation, review and publication [14]. Each of them requires levers to be triggered, supported and perpetuated. Potential levers are mostly qualitative methodologies, research projects, IT tools, workshops, platforms and public programs. Focusing on IT tools, literature review reveals that most of them support the synergy identification stage, but they are not widely operational due to some limitations: geographic and sector/resource scope restriction; short lifetime due to unviable exploitation business model; lack of end users' and industries' feedback during tools development; lack of tacit knowledge integration; and inefficient ontologies [14–16]. While newer European IT tools are eliminating some of the previously detected gaps, better mechanisms are needed to make available R&I projects progress to industries [13]. Most tools are still generally not comprehensively documented, not accessible for external participants or require additional development to be fully operational [17]. By building on past projects outcomes, SCALER provides a methodology to fulfil the IS implementation gap and thus increase the porosity between IS research and industry spheres.

The proposed methodology assists practitioners in their synergy identification journey by limiting their efforts and involvement. Characterised by its deductive approach [18], it proposes theoretical synergies based on generic information analyses. Methodology is mainly inspired from Looplocal [19], a tool that aims at gathering and linking varied source of information (resource composition, facility databases, LCI databases, IS experiences) in order to map the resources available in a region and propose synergy opportunities, and ISDATA [20], a web platform providing a set of information sources and a diagram with their interrelations. Some limitations are identified such as the difficulty to provide accurate synergy ideas without industrial data and the lack of details on information sources preventing synergies identification for complex materials, with a wide variety of potential names, or requiring intermediary treatment (e.g. purification). Confidentiality issues and management of synergies for complex resources are two key challenges for a tool dedicated to process industries.

SCALER's methodology tackles these issues in building on other projects' outcomes and especially from the concept of sectorial blueprints developed in the EPOS project for four sectors [21]. As process industries are relatively standardised in terms of raw materials, products and emissions, generic profiles can be defined providing average qualitative and quantitative information on resources. This methodology created generic profiles for 17 sectors. Outcomes from the project eSymbiosis [22] dedicated to provide ontological solutions were also an inspiration source. Ontology is a way to integrate tacit knowledge in the methodology that not only increases the accuracy of identified direct synergies but extends the opportunities to indirect synergies thanks to additional technical knowledge such as potential uses and chemical composition. A proper ontology has been developed to match with process industry sectors' requirements.

21.3 Proposed Methodology

21.3.1 Scope Definition

SCALER targets in priority SPIRE's[1] sectors due to their importance for the European economy and their significant environmental footprint. Solutions must be found to reinforce their competitiveness and optimise resources use. Other sectors are added to widen the synergy opportunities range as each additional sector multiplies the chance to identify synergies. Selection process criteria are prioritised as: (1) publicly

[1] See: https://www.spire2030.eu/.

Table 21.1 Industrial sectors covered

SPIRE sectors	Cement; Ceramics; Chemicals (organic and inorganic); Non-Ferrous metals; Minerals (lime); Steel; Water[a]; Engineering[a]
Additional sectors	Energy (oil and gas refining, combustion plant); Glass; Fertilisers; Paper, pulp and wood; Waste management (waste treatment and incineration); Food and drink; Pharmaceuticals[a]; Textile[a]; Slaughterhouses and animal by-products industries

[a]These sectors are not yet integrated into the database and require manual treatment

available detailed data, (2) high footprint and/or energy/material intensives, and (3) a significant number of facilities in Europe. Covered sectors are shown in (Table 21.1).

Technical information for these sectors is gathered in a repository. While it does not include contextual tacit knowledge (e.g. infrastructures, regulation), it integrates precious technical knowledge at several levels: sector/subsector/process (productive systems characterisation); resources (name, qualitative and quantitative characteristics of the resources); and elements (characteristics of the elements constituting resources).

Significant information is available in public technical sources, for free or with payable access. The main methodology sources to fill the database and test methodology results are the so-called BREFs reports (Best available techniques REFerence documents) for the sectors of interest. Complementary sources are industrial partners; professional technical documents such as the journal Technique de l'ingénieur; academic literature (e.g. Industrial & Engineering Chemistry Research; Journal of Cleaner Production; and Journal of Hazardous Materials); and IS repositories (e.g. ISDATA [20], MAESTRI's Library of case studies [23], SCALER's Best Practices Deliverable [24]).

21.3.2 Database Creation

The first methodology challenges are to analyse information sources and massively extract, organise and store quantitative data on processes and flows characteristics in a database. Several tables are created for this purpose and organised as in (Fig. 21.1).

The table "sector" gathers the 17 covered industrial sectors. A sector is defined as a segment of an economy gathering companies with the same main productive activity (e.g. iron and steel production sector). While they are quite well standardised, production specificities exist within the same sector. Depending on their complexity, two specification levels are defined independently for each individual sector. The first level corresponds to the table "subsector" and is linked to "sector" through the ID sector code, defined for the database's operation. A single sector might produce various type of end products (e.g. soda ash, phosphates, calcium carbide, etc. in the

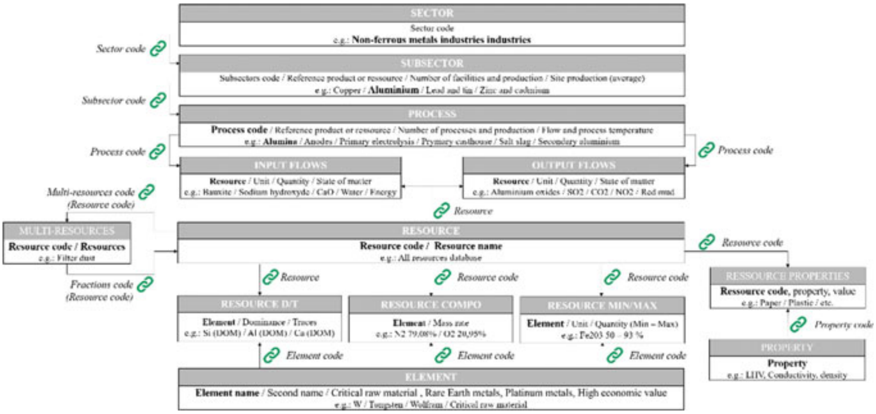

Fig. 21.1 Database structure and links

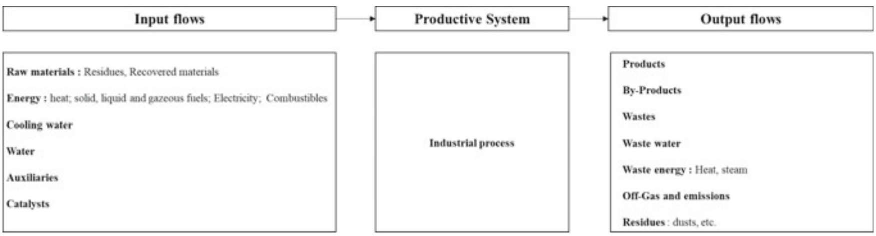

Fig. 21.2 Industrial process system approach

organic chemical sector), have several intermediary products (e.g. coke, sinter, etc. in the steel sector) or several production routes for the same standardised final product (e.g. steel production through blast furnace or electric arc furnace), influencing the used inputs and emitted outputs. "Subsectors" gathers information about facilities (e.g. number in Europe, volume of reference product, etc.). The second level corresponds to the table "process" and is linked to "subsector" through the ID subsector code (also proper to the database). Similar information as previously is gathered but at the process level, i.e. different type of technologies and techniques used in a subsector (e.g. for the subsector "titanium dioxide", two processes are available: "chloride process" and "sulphate process").

All materials and energy vectors that pass through a process are considered as productive system's inputs and outputs. Relevant information (e.g. unit, flow rate per ton of process' reference product, state of mater) feeds, respectively, the tables "inputs" and "outputs" which consist in repositories detailing qualitative and quantitative characteristics of all the resources involved in industrial sectors studied (Fig. 21.2).

These two tables are linked by the ID name to the table "resource". However, the database development revealed ontological issues when defining resources' name. Many identified resources are a mix of different substances (e.g. the "electrolyte bleed" effluent is composed of acid and nickel fractions), some resource names are not detailed enough (e.g. the resource "salt" can refer to potassium chloride et/or sodium chloride) or resource names from the literature refer to group of resources (e.g. "carbon waste" in the cement sector gathers tar and bitumen). In the perspective of identifying numerous and innovative synergies, resource specification details were integrated. "Resources" are thus a buffer between "input" and "output" tables and six additional tables for detail.

"Elements" is a table gathering all the individual chemical elements contained in "resources". This table is highly relevant in the IS context as resources might be valorised for some contents, not for the whole substance (e.g. slags are of cement industry's interest due to their silica, aluminium, calcium and iron content). "Element" includes also specific characteristics, such as critical raw material status [25], rare earth and metals, and high economic value elements. "Resource_min/max", "resource_composition" and "resource_dominance" are three tables providing information on the resource composition, depending on the information level gathered in the literature. They are, respectively, used and filled if range values (e.g. 200–500 gCH_4/m^3 of off-gas), detailed compositions (e.g. 23% CO, 45% H_2, 32% CO_2) or qualitative indications (e.g. traces of sulphur) are collected. They make the link between "resource" and "element". "Multi-resources" is a table that gives the decomposition of mixed or grouped resources in individual resources (c.f. electrolyte bleed and carbon waste examples). Finally, "properties" are a table providing flexibility when attributing characteristics to each input and output. It gathers specific parameters such as pH, conductivity, calorific value, density and C-N-P ratio. This list can be extended all along with the database life.

21.3.3 Synergy Identification Process

Tables provide necessary information for a robust and accurate synergy identification process. The main approach is based on matching names and/or chemical element compositions of input and outputs across sectors. Depending on the synergy typologies, several matching algorithms were developed to proceed with queries.

"*Resource matching*" is a query enabling the identification of substitution synergies when an output resource's name from a sector A corresponds to an input resource's name of a sector B (e.g. the output "sulphuric acid" from the steel sector corresponds to the "sulphuric acid" bought on the market by chemical industries). "*Multi-resource matching*" follows the same principle. This algorithm identifies synergies by using output and input resource's names belonging to "multi-resources" (e.g. "Fe" from the output "steel scrap" can be used to substitute a "Fe" source). "*Element matching*" provides more details than "resource matching" and enables the identification of synergies through the decomposition of resources into elements. Targeted queries can pinpoint recovery opportunities for high valuable elements (critical raw material, rare metals, element with a high economic value). "*Heat recovery*" indicates waste heat/steam recovery opportunities from process outputs to be used directly as heat or to produce steam for electricity production. “*waste as combustible*” identifies all output flows which can be used for fuel preparation in waste treatment industries. “*Use of alternative combustible*” provides all sectors likely to use secondary fuel from waste treatments industries. “*Combustible match*” identifies direct combustible synergies between sectors by comparing the state of matter and LHV of conventional combustibles to all other potential wastes combustibles with similar properties. Thanks to these seven algorithms, a wide range of synergy typologies valorising varied resource natures can be identified.

21.3.4 Overview of the Methodology Uses and Users

While this methodology has been created for a research purpose within SCALER’s framework, wider uses are foreseen for several stakeholders (e.g. industries, academics, clusters, local public authorities, etc.).

The first purpose is territorial knowledge creation. The methodology can be used to make global research on all matching opportunities between sectors on a defined geographic scope. Expected results are a full list of available cross-sectorial synergies describing the territorial IS potential and the characterisation of diffuse valuable material deposits (e.g. biomass, critical raw materials). Such use can be managed by researchers to make accurate IS development recommendations (original SCALER purpose) or by public (e.g. local public authority) and private (e.g. facilitator) actors in different European territories and at different scales to define long-term CE strategies, make territorial marketing (e.g. foster key additional industrial activity implementation) or even give waste valorisation targets between structuring sectors.

A second goal is to facilitate R&D. Some synergies valorising a specific resource are not implemented due to technical difficulties or lack of required treatment technologies. Public and private research centres could use the methodology to target high potential resources and develop unlocking technical solutions for IS development.

The third main use is operational and inspired from MAESTRI [26]. Users can focus on a targeted sector and identify all the potential material/energy exchanges as a receiver/emitter. For industrial companies or industry associations, it provides generic valorisation ideas for waste management and sustainable supply opportunities. For IS facilitators, they can provide their clients with new synergy ideas. Users can also focus on an individual resource/element and research valorisation opportunities. Industries, associations and facilitators might find innovative solutions for problematic streams (e.g. waste sent to landfill) and sustainable supply solutions for their raw materials (from wastes but also from traditional products if relevant). Waste management companies are also potential users in the perspective of characterising some resource deposits on territories and evaluate the possibility to build a treatment facility, massifying large amount of resources necessary to unlock business viability. For example, if a company requires hydrogen as raw material, the “resource matching” query identifies all hydrogen releases from other sectors process outputs. Table 21.2 shows that inorganic and organic chemical sectors are potential providers.

Table 21.2 Hydrogen synergies opportunities

Type of data	Potential sender n°1	Potential sender n°2
SENDER SECTOR	INORGANIC_CHEMICALS	ORGANIC_CHEMICALS
SENDER SUBSECTOR	SODIUM_CHLORATE	LOWER_OLEFINS
SENDER PROCESS	SODIUM_CHLORATE_PRODUCTION	STEAM_CRACKING
NUMBER OF FACILITIES (WHOLE SENDER SECTOR)	15	39
BY-PRODUCT VOLUME	6183–19,236 t/y	7,000,000,000–100,000,000,000 t/y
RECEIVER SECTOR	REFINING_MINERAL_OIL_AND_GAS	REFINING_MINERAL_OIL_AND_GAS
RECEIVER SUBSECTOR	HYDROCRACKING	HYDRODESULPHURISATION
RECEIVER PROCESS	HYDROCRACKING_PROCESS	HYDRODESULPHURISATION_PROCESS
NUMBER OF FACILITIES (WHOLE RECEIVER SECTOR)	38	309
RECEIVER SECTOR DEMAND	260–400 t of h2/t of feed	7 and 100 billion t/y
TYPE OF SYNERGY	INDIRECT	INDIRECT

21.4 Preliminary Results

The methodology revealed to be successful as about 10,000 potential synergies were identified with the different matching algorithms for the 17 sectors. They were short-listed to the 100 most promising synergies for the purpose of SCALER. Selection criteria are partly inspired from practitioners' feedbacks [24] and are among others: variety of state of matter, synergy typology (heat, combustible and material), resource type; homogeneous sector distribution; economic (high market values); strategy (rare earths and critical raw materials); high volume; high facilities number; and significant footprint.

The sample of 100 synergies is introduced in Fig. 21.3, showing the sectors couples in a Sankey diagram. Steel sector has a high potential to send outputs, while non-ferrous metals and cement sectors can be provided with a wide range of secondary resources. 54% of synergies valorise solid resources, a convenient state of matter for recovery and transport, while 21% are liquid and others concern gas, particles and energy. Only 21 synergies fuel-based were selected to focus further analyses on more ambitious synergies. Seven resources are listed for thermal energy recovery on nearby facilities or electricity production. A total of 47 are direct and 52 indirect (requiring particles extraction, separation, cleaning or transformation). One synergy is both, depending on the resource's purity.

BREFs and MAESTRI's Library of case studies [23] were used to test the methodology robustness. Among the 100 synergies, 61% are at least in one information repository. This test proves that the methodology is able to identify relevant synergies. It also shows the methodology's added value as 39% of the synergies are new and original.

21.5 Conclusions and Development Perspectives

An increasing number of tools supporting IS are on the market or emerging. While the majority focuses on the opportunity identification stage, none of them are dedicated to the process industry for such a wide range of sectors and resources. The proposed methodology efficiently responds to IS implementation barriers and especially confidentiality and technical detail integration issues. Thanks to its deductive approach and the use of generic detailed data, the methodology generates promising synergy ideas without requiring in-site data. Results can trigger decision-makers' interest and push for further research using then industrial operating data. The methodology has a real potential to accelerate the IS dissemination by reducing efforts to identify opportunities and could be of interest for a wide range of stakeholders: industrial sites, industry associations, academics, IS facilitators, public authorities at different scales and technology designers. It is an appropriate lever to implement CE strategies in industries and help redesign and complexify supply chains with new interconnec-

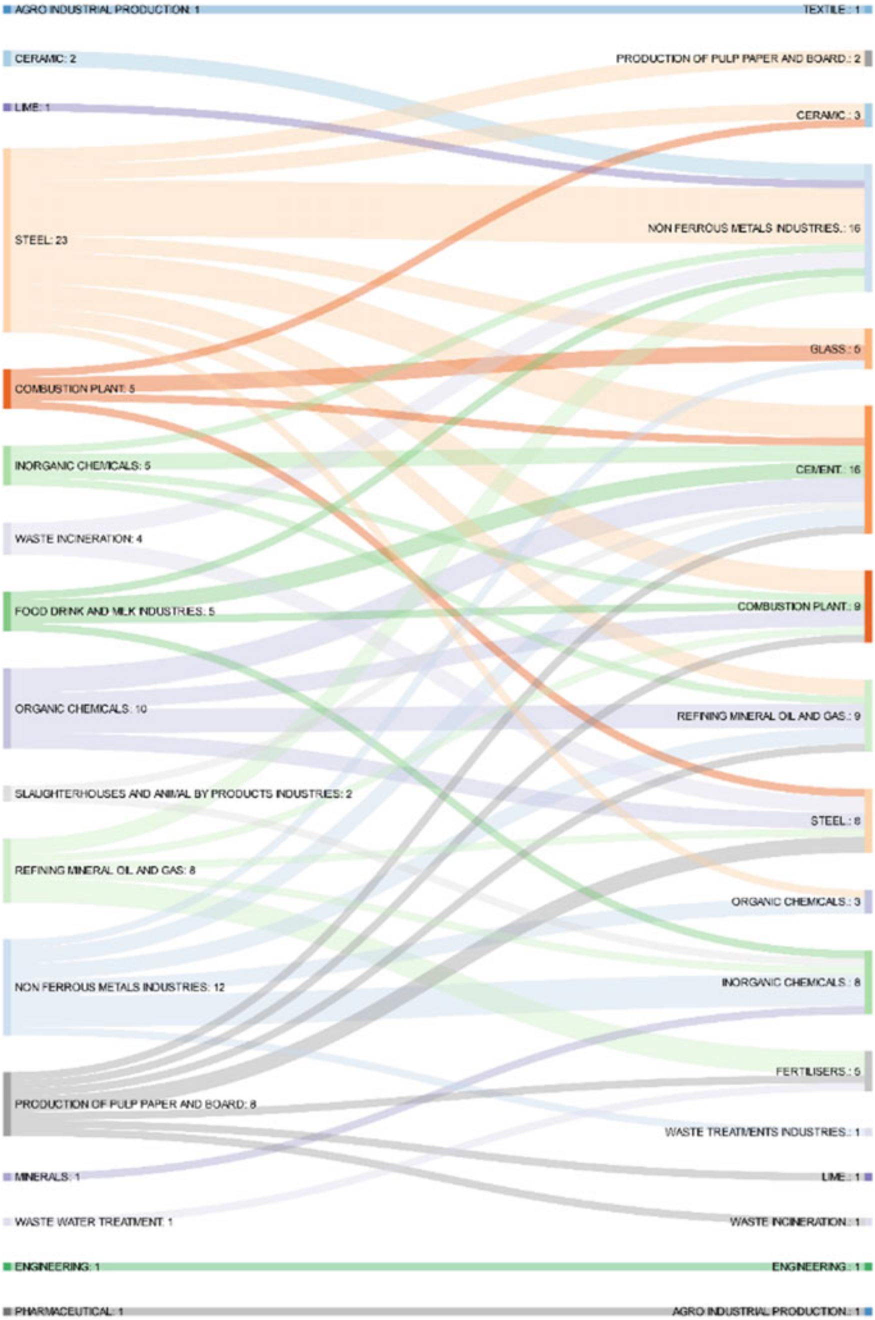

Fig. 21.3 Sectorial couples for the synergy sample

tions. Supply chains are more sustainable, more competitive but also more resilient by extending the supply alternatives.

Some methodology limits are identified leading to development perspectives. First, the methodology requires an important manual post-treatment to remove irrelevant synergies. Matching thresholds, depending on resources similarity rate, should be developed in queries to automatically filter results. Second, the actual volume of metadata to qualify resources is limited. Other sources of information (e.g. LCI, NACE, EWC and chemical thesaurus) are required to reinforce the existing semantic thesaurus and should lead to the creation of additional tables, associated with the existing database through handmade correspondence tables or artificial intelligence (e.g. native language processing, web scraping). Integration of in-site data is also a perspective if the methodology is operated in a commercial way. Third, the methodology is limited to a few industrial sectors of the whole productive system. Additional sectors could be added, while for some of them it is challenging (e.g. plastic sector) as their processes are poorly standardised. Fourth, a "technology" table for existing or under development operations such as resource treatment, extraction, separation or cleaning is under development to extend the identified synergies scope and validate their technical feasibility. Finally, the development and use of the methodology currently requires a certain level of expertise and knowledge about the existing database formalism. A user-friendly interface and data integration modules should be developed for a better user experience.

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Chapter 22
Creating a Taxonomy of Value for a Circular Economy

M. Haines-Gadd and F. Charnley

Abstract Many studies have explored the integration of Circular Economy thinking within a business model context, however, researchers have yet to identify and demonstrate the full range of benefits and value that is available if organisations were to transition to a circular model. Through a literature review and analysis of ten case studies of sustainable businesses, this paper uncovers the categories and types of value that are available within a Circular Economy system and consolidates them into taxonomy and framework of value. Through the use of affinity mapping, the taxonomy of value identified and included: categories of value, tangible/explicit value, intangible/implicit value; methods and strategies for generating value and stakeholders for whom value is created. This paper outlines these values in more detail providing a clear starting point for organisations to realise the benefits that a Circular Economy system affords.

22.1 Introduction

Within recent climate change reports, policy makers have been warned that human activity is continuing to create negative demands on the environment, and recommend that these could be mitigated if the industry were to adopt measures of responsible production and consumption [1]. However, addressing these systemic issues requires a significant shift in manner and mindset in how industry currently operates [2]. The Circular Economy has been suggested as one such solution.

A system that is restorative by design, the intentions of a Circular Economy are to narrow and slow down material and energy loops, to maximise value, and minimise waste and the use of natural resources, thereby reducing the burden that industrial systems place on the environment and society [3, 4]. Within Circular Economy literature, business model innovation has been identified as the key factor for facilitating

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these changes to occur, especially if we look to move beyond typical efficiency and productivity measures [5].

While there have been advancements in the development of new business models, Bocken et al. [2, 6] especially in regard to Product Service Systems [7], there is, as yet, no classification that demonstrates the full range of benefits that exist within more sustainable models. Therefore, the aim of this paper is to identify and classify the types of value that exist within the Circular Economy and create a value framework to support academics and practitioners in the transition towards a more circular model. The framework will demonstrate the types of value that are available within a circular system and the benefits that can be gained from the adoption of circular approaches to business. However, before building this new framework, a taxonomy of value must first be devised, to ensure, we fully understand the types and classifications of value in the system. This led to the definition of two central research questions: (i) How has value been identified, categorised and discussed within Circular Economy literature? and (ii) what types of value are available within a Circular Economy System?

22.2 Methodology

To investigate these two Research Questions, a review of sustainable business model literature and a case study analysis of ten secondary sources from the Ellen MacArthur Foundation case study database was undertaken. The insights drawn from these two activities were then clustered and categorised using affinity mapping to develop an initial taxonomy of value, which is presented in the following sections. The literature review was conducted using Scopus and Google scholar adopting the key terms: 'Circular Business Models', 'Sustainable Business models', 'Value', 'Circular Value', 'Economic Value', 'Social Value', 'Environmental Value' and 'Circular Economy'. The articles that were uncovered were reviewed and selected based upon whether or not they discussed notions of value directly within the research. The next section of the paper presents the results of the review and the key themes that emerged.

22.3 What Is Value in a Circular Economy?

Value as a concept can be understood in a number of different ways; within the Merriam-Webster dictionary, it is defined as 'a fair return or equivalent in goods, services or money for something exchanged; and the relative worth, utility or importance' [8]. From a sustainability perspective, value or 'sustainable value' is defined as the benefits resulting from stakeholder exchanges, which actively considers the environment and society factors as well as the economic [9]. However, from a broader Circular Economy viewpoint, it is mainly discussed as a factor that must be maximised in relation to how resources are utilised within production [10, 11]. Within a Circular Economy system, the main aim is to 'keep products, components and materials at their highest utility and value, at all times' p. 17 [4], so we can preserve the environmental and economic value of materials, components and products for as long as possible [12]. This can be achieved through the looping back of resources, stakeholder collaboration, and a redesign in the way products and services are delivered, in order to ultimately decouple economic growth from resource use [10, 11].

22.3.1 Value Mapping

One method for understanding and redefining value within sustainable and circular systems is Value Mapping. Initially established by researchers Bocken et al., [13], they proposed that: 'The value mapping tool assists companies in embedding sustainability into the core of the business model through an improved understanding of the value proposition. It supports an iterative process for analysing sustainable value creation opportunities from a multi-stakeholder perspective' p. 493 [13].

Developed and tested through workshops with industry, the tool includes two main features, firstly it considers values exchanges from a variety of stakeholders (customers, environment, society, employees, etc.); and secondly, it highlights different representations of value that could exist within the system, namely:

Value captured: the current value proposition, what the model already does;
Value missed or destroyed: what the model misses out, squanders or disregards;
Value opportunities: new opportunities for additional value creation and capture through new activities and relationships [2, 13].

These three categories of value have been integrated into other tools including the 'Sustainable Value Analysis Tool' by Yang et al., [9] and 'The Cambridge Value Mapping tool' [14]. However, both of these tools expanded the meaning of 'Value missed or destroyed' and referred to it as 'Value Uncaptured' and included the additional categories of value surplus and value absence. Regardless, the inclusion of the triple bottom line, a multiple stakeholder perspective and three central categories of value, in each of these Value Mapping tools demonstrates their importance when attempting to understand value within sustainable business models.

22.3.2 Value Within Circular Business Models

Within conventional business model innovation, value is discussed and presented in three significant ways, through the:

Value proposition: value that is offered to a customer through a product or service;
Value Creation & delivery: activities, resources, capabilities, channels and partners;
Value Capture: cost structure and revenue streams [15–17].

Fig. 22.1 Adapted sustainable business model canvas [6]

These three components represent different dimensions for how value exists within a business model system, whereby the creation/delivery/capture element represents how to obtain and produce value within the system, and the proposition represents what value is being offered. However, as established in the previous section, for circular systems, rather than focusing solely on developing economic and customer value, which most traditional business models do [6], a broader societal and environmental stakeholder perspective needs to be actively deliberated as well [18]. The main aim of a circular business model is to enhance the quality of life through the creation, delivery and capture of value through the implementation of circular strategies resulting in an extension in the lifetime of resources within the system [19, 20]. Therefore, this will require researchers to contemplate, develop and redefine what a value proposition would mean within a Circular Economy context [21].

The most current thinking on the topic has been proposed by Bocken et al. [6], who adapted these three components in relation to the Business model canvas. As shown in Fig. 22.1, the revised canvas reframes the value proposition to include customer, societal and environmental perspectives.

Similar to the value mapping tools mentioned above, both sets of researchers are attempting to find ways of embedding triple bottom line thinking into their tools and processes. However, beyond the inclusion of people, planet and profit perspectives, little consideration is given to what kinds of value could be generated for each of these stakeholders.

22.3.3 Other Values Discovered in Circular Economy Literature

Beyond those already discussed, another type of value was uncovered referred to as the Consumer Lifetime Value. A metric more commonly associated with marketing research [22], the study by Aboulamer [23] adapted traditional thinking in relation to the Circular Economy and proposed it as a metric for quantifying the 'dollar value of future cash flows obtained from consumer retention' p. 768 [23]. While this type of metric could be useful for demonstrating the value of switching to delivering services over products, it is only one example of the financial gains of transitioning to more circular practices. Scholars agree that there is a gap in literature that examines the economic value of adopting a circular business model [6, 24–26]. However, due to the complex nature of a circular business model and the typically higher initial cost and investment required for implementation [27], a great deal of advances in economic model innovation will need to be made if we are to effectively shift industry away from the linear business model [26].

Whilst there has been research which attempts to measure the environmental value [28–30] and social impact of alternative business models [31, 32], there is, as yet, no research that considers this from a broader systems level perspective. And so, there is a need to consolidate and analyse the different types of value that are offered in this context, which is the gap that this paper attempts to address.

22.3.4 Key Findings from the Literature—Defining Circular Value

Considering the literature presented in this section, several key insights were identified concerning how value can be understood within a Circular Economy context. Specifically, these were:

- Assets within a Circular Economy that have been or could be assigned a value (resources, components, products, materials)
- Methods to enhance value (increased utility, collaboration, life-time extension)
- Categories of value there are available (captured, uncaptured, created)
- Stakeholders who are intended to benefit (consumer, environment, society, economy).

Considering these factors it is possible to propose a new definition of Circular Value:

Circular Value is the environmental, societal, economic and consumer benefits that are available within closed loops systems which are generated through partnerships and maximize the utility of resources across the entire value chain of the system.

In summary, while the literature was useful for identifying practical categories for how value can be viewed such as Value that is captured, Value that is missed/destroyed and Value that can be created; further analysis is required to identify exactly what types of value there could be in the system. For this reason, the research analysed the Ellen MacArthur Foundation data base of case studies which showcases best practice in circular and sustainability businesses propositions and will be presented in the next section of this paper.

22.4 Case Study Analysis

To gain a broad picture of the value available within a Circular Economy system, ten case studies were selected across different sectors (fashion, fast-moving consumer goods, electronics, agriculture, consumer products, hospitality) and which operate using different business model architypes identified by Moreno et al., [33], i.e. circular supplies, resource value, product life extension, sharing platforms and extending product value. The case studies were analysed using content analysis which is a systematic technique for categorising textual data using a set of rules and/or coding [34] and were examined considering these key questions:

- What are the primary benefits of the proposition?
- How are these benefits generated?
- Who benefits and how did they benefit?

The results of the analysis have been consolidated into Table 22.1.

22.5 Results and Discussion

Throughout this process of review and analysis, two main insights emerged regarding the types of value that are available. Firstly, the development of partnerships and relationships was shown to be a key factor within the case studies for Braiform, Lufa farms, Mazuma Mobile and CBPak. As stated in the literature, collaboration is a key principle for delivering a successful circular economy [11, 35] and these organisations leveraged these relationships with other actors within the system in order to deliver key benefits.

While Braifrom and CBPak use partnerships to facilitate collections systems and Mazuma to refurbish their main product offering, these kinds of partnerships one could argue are just an example of traditional forms transactional partnerships. Whereas the partnerships that Lufa Farm engage in are different in the sense that they develop a relationship that is much more symbiotic in nature and ultimately elevating it to something that is more robust and integral, essentially making their partner a key stakeholder. While this kind of symbiosis is common within natural systems, within business contexts, it can be hard to achieve and measure, and could be considered as a benefit that is more intangible in character. Expanding upon this further, the types of relationships that a business has with its consumers, and the relationships

Table 22.1 Case study analysis of ten sustainable businesses

Name and description	Business model	Primary benefits of the proposition	How the benefits are generated	Who benefits and how do they benefit?	Key values
Braiform: A coat hanger manufacturer who developed a closed loop reusable hanger system	Product life extension and Resource value	Coat hanger is collected and reused multiple times increasing the utility of the product	Created partnerships with retailers to collect and return the hanger	**Company**: hanger can be resold many times to manufacturers **Environment**: product is less likely to end up in landfill	Partnership value Lifetime extension
		Lifetime of the coat hanger is extended regardless of different branding requirements	Uses circular design principles durability, modularity and conscious materials choices	**Company**: modular design means the same hanger can be resold multiple times to different manufactures **Environment**: Reduces the amount of natural resources needed to produce the product	Circular design
		Broken hangers are recycled and material used to make new hangers	Ensure pure waste streams by sorting and collecting hangers themselves	**Company**: reduces the amount of virgin material they need to purchase creating stability and control over material flows reducing risk of fluctuating material prices **Environment**: pure waste streams means longer material utilisation	Pure waste stream Stability and control

(continued)

Table 22.1 (continued)

Name and description	Business model	Primary benefits of the proposition	How the benefits are generated	Who benefits and how do they benefit?	Key values
CBPak: Developed a bio-based, entirely bio-degradable single-use food container	Circular supplies	Entirely bio-degradable packaging	Uses a renewable, bio-based resource (cassava) which is abundant and local to Brazil	**Company**: valorises a non-edible component of cassava creating a new revenue stream **Environment**: Massive reduction in carbon released and water required to produce a comparable product, reduces the amount packaging that ends up in landfill **Consumer**: easy and guilt-free disposal of the product	Bio-based material
		Used product can become feedstock for composting industry	Created partnerships with potential retailers and vendors to collect product after use	**Company**: can potentially sell their used product to compost industry as feedstock, these partnerships created more robust systems **Environment**: waste product generates soil, which actively nourishes the system	Feedstock Partnership value

(continued)

Table 22.1 (continued)

Name and description	Business model	Primary benefits of the proposition	How the benefits are generated	Who benefits and how do they benefit?	Key values
Coca cola: Began collecting their downstream waste to create new recycled bottles	Resource value	Recycling in closed loop system—their single-use bottles are being collected and recycled to produce new bottles	Localised recycling and manufacturing centres collect, recycle and produce new coke bottles	**Company**: stability and control over material flows. Increase sustainability brand image **Environment**: reduces the amount virgin materials being shipped around the world and natural materials needed to make new bottles **Society**: creates jobs as recycling plants are decentralised	Localisation Stability and control Material value Employment
Desso: A floor tiles manufacturer who creates a cradle to cradle product	Circular supplies, resource value, product life extension and extending product value	Floor tiles are recaptured reducing the risk of ending in landfill	Product is Leased to customer and recollected at the end of the contract	**Company**: retains material value of the product so can be recycled or reused and leased to another customer **Environment**: reduces the chance that product ends up in landfill **Customer**: product is leased installed and maintained by the manufacturer reducing the time and hassle	Product as a service

(continued)

Table 22.1 (continued)

Name and description	Business model	Primary benefits of the proposition	How the benefits are generated	Who benefits and how do they benefit?	Key values
		Created a fully recyclable floor tile	Designed so that all main fibres and components can be separated, creates pure waste streams (design for disassembly)	**Company**: can recycle their fibres to create new floor tiles, sells their waste materials to other industries **Environment**: reduces the need for virgin materials	Material value is retained
		Uses renewable energy in some of their manufacturing plants	Uses hydropower in two of their product locations	**Company**: creates self-sufficiency and reduces overheads **Environment**: reducing emissions created by fossil fuels	Renewable Resource input
Fat Lama: A peer to peer renting platform that allows users to rent out idle/not often used products	Sharing platforms	Reduces idle capacity of products	Online platform facilitates quick, easy, insured and localised peer to peer renting of products	**Company**: takes a percentage of the rental cost (airbnb business model) **Environment**: overall it reduces the demand for the number of products that exist, which reduces amount of resources need to produce the product **Consumer**: gains access (rent) products they might only need for a short amount of time **Society**: facilitates sense of community between people, potentially in the long run could shift mindsets relating to ownership	Increased utilisation Behaviour change

(continued)

Table 22.1 (continued)

Name and description	Business model	Primary benefits of the proposition	How the benefits are generated	Who benefits and how do they benefit?	Key values
Lufa Farms: Creates urban small scale farms on roofs tops in urban environments	Circular supplies and sharing platforms	Localised urban food production that reduces food miles and increases the quality of produce	Partners with building owners to use their unused rooftop spaces to create small scale hydroponic farms, that uses rainwater as a source of water	**Company**: simplifies the supply chain, symbiotic relationship with partner, creating a more robust relationship **Partner**: provide cooling and insulation to the building reducing their overall energy costs, as well as additional protection from attenuate run-off from rain, creates a revenue stream from idle resource **Consumer**: get fresher food that has not been harvested early to prevent spoilage in transit, better quality food **Environment**: Hydroponic uses 90% less water than traditional farming, 50% less heating than ground level greenhouses, harvests rainwater, and reduces energy for refrigerating and transporting food, more green spaces means more carbon capture **Society**: creates jobs in urban context	Partner as a stakeholder Localisation Employment Symbiosis Better quality product

(continued)

Table 22.1 (continued)

Name and description	Business model	Primary benefits of the proposition	How the benefits are generated	Who benefits and how do they benefit?	Key values
Mazuma mobile: Collect, refurbish and resell mobile phone handsets	Product life extension and Resource value	Reuse and refurbish—still functioning mobiles are given a second life increasing the utility of the product	Collects, manages the refurbishment and reselling of handsets to emerging markets and insurance dealers	**Company**: revenue from resale of refurbished handset **Environment**: reduces the likelihood of product ending up in landfill, need for resources to produce new phones **Consumer**: cash for their unused phones, hassle-free process for discarding old handsets, reduction in clutter **Society**: feeds second-hand market providing more affordable handsets to emerging markets	Collection systems Lifetime Extension
		Recycle—irreparable handsets are recycled and spare components kept	Partners with refurbisher so the product is disassembled and the components and materials are recovered	**Partner**: can bank up spare parts of broken phones to fix others **Environment**: reduces the likelihood of product ending up in landfill, waste streams are being more effectively managed allowing the materials to retain its integrity and potential value	Material value Partner/ Relationship value

(continued)

Table 22.1 (continued)

Name and description	Business model	Primary benefits of the proposition	How the benefits are generated	Who benefits and how do they benefit?	Key values
Mobike: Use mobile technology provide bicycle renting scheme in china	Sharing platforms and Product life extension	Provides access to a greener form of transportation within cities which reduces pollution	Uses mobile technology to provide simple, quick and easy bike rental process	**Company**: high product utilisation **Environment**: large reduction in CO_2 emissions **Consumer**: convenience of having a bike that can be used whenever they want without needed to own one **Social**: less traffic and cars on road creating a nicer, cleaner city environment, encourages healthier lifestyle and exercise	Technology Enablers (IOT) Increased well-being
		Bike is designed to be durable and repairable	Through circular design strategies, modular design and ease of repair and maintenance, use plastic non inflatable tires	**Company**: bikes are easy to repair and maintain maximising the efficiency of their process **Environment**: increased utility and lifetime results in less overall resources needed to make products	Circular Design
		Utilises solar energy to power battery and smart locking system	Developed and patented these technologies in-house	**Company**: can licence their technology to others **Environment**: no fossil fuels needed to power electronic smart lock	Patent/knowledge value

(continued)

Table 22.1 (continued)

Name and description	Business model	Primary benefits of the proposition	How the benefits are generated	Who benefits and how do they benefit?	Key values
		Uses data to predict and manage demand in the system	Bikes are dock-less so can be left anywhere within a city; consumers are incentivised to distribute bikes in busier locations	**Company**: doesn't have to install docks in cities, bikes can be easily distributed to high demand areas, increasing customer satisfaction	Data value
Replenish: Produce a reusable, refillable cleaning bottle system	Product life extension	Reusable, refillable bottle for cleaning products, reducing the amount of plastic required	Circular design strategies—Modular design of product allows company to provide consumable part (new cleaning fluid) to consumer when needed	**Company**: reduces material costs, retains consumer base **Environment**: reduces amount of resources needed, material and manufactured value of the product is retained, less plastic bottles in the system less likely to end in landfill **Consumer**: pays less for product over time	Circular Design Material Value Consumer lifetime value
		Uses local resources to produce the	Uses local resources available within the home (water)	**Company**: reduces transportation costs **Environment**: uses local resources (water), reducing energy needed for transport **Consumer**: requires less space to store	Localisation
		Cleaning fluid is natural, and eco-friendly	Uses 99% plant-based components	**Company**: Eco product, selling point **Environment**: less harmful substances in the water system **Consumer**: not inhaling potent chemicals	Eco-friendly factor

(continued)

Table 22.1 (continued)

Name and description	Business model	Primary benefits of the proposition	How the benefits are generated	Who benefits and how do they benefit?	Key values
Winnow: Provide data and advice to commercial kitchens on their food wastage	Resource value	Reduces the amount of food waste produced in commercial kitchens	Data-driven platform that weighs food waste and provides advice on purchasing and cooking practices which reduces overproduction	**Company**: reduction in food waste increases profit margins, CRS selling point regarding waste reduction, educates kitchen staff encouraging better overall practices **Environment**: overall would reduce demand for food production, i.e. Water, carbon, etc., reduces CO_2 produced through decomposing food	Data driven value
		Facilitates behaviour change beyond the commercial kitchen	By directly links waste with sales provoking better awareness which filters down in home practices as well	**Company**: could create a more frugal employee who wastes less in other areas of the company **Environment**: more waste conscious people in the world in general would benefit the environment	Behaviour change

that consumers have with each other, can also be viewed as more meaningful within the context of Circular Value. For example, as shown in the case with Replenish and Desso, the relationships that are created have the potential to be longer lasting and evolutionary, which is a feature that Aboulamer [23] proposed can be measured in terms of consumer loyalty and consumer lifetime value. Considering these factors above, Relationship Value was shown to be a new sort of value within the Circular Economy and added as key type of value for the taxonomy.

Secondly, data and knowledge also emerged as a key factor and new kind of value as demonstrated in the case studies for Winnow and Mobike. While Winnow utilises data to generate insight and provide tailored advice to their customers on how to reduce waste within their production processes, Mobike uses data to manage demand within the system which feeds into consumer satisfaction. While in both of these examples, data is used in the more traditional sense to generate knowledge and manage the efficiency and impact of a system, there is an alternative perspective that is which is related to the commodification of data. While from an economic perspective monetary gains can be acquired from the selling of this data, potentially this is not in the spirit of what a Circular Economy is trying to achieve, but is a factor that could be explored by organisations as an alternative form of value their product or service is also generating. Lastly, Mobike also develops another kind of value from knowledge and patent innovation; as a company, they developed their own clean energy hardware which they can now licence to others. This not only enriches society by developing new sustainable innovations but also provides potential revenue streams in the future. Considering the factors identified above, Data/Knowledge Value was added as key type of value and added to the taxonomy.

22.5.1 Developing a Taxonomy of Value

As a result of the literature review and analysis of secondary case studies, many different types of key values were identified; some are methods and strategies for generating value, such as *Increased Utilisation, Circular design, Lifetime Extension and Localisation*; others are types of value that could be capitalised upon such as *Material Value, Resource Value* and *Data/Patent Value*. While this type of value could be considered to be tangible and explicit in terms of what it offers, there are other benefits such as *Stability and Control* and *Behaviour Change* which are intangible and implicit in what is offered. Consolidating all insights uncovered from both activities, key components of the taxonomy have been identified and developed in Table 22.2.

The taxonomy of value has been constructed to allow for flexibility and adaptation. For example, the Tangible/Explicit Values and their subcomponents, i.e. Product, materials, consumer benefits, data and patents could be elaborated upon in more detail and made more specific to individual sectors or companies. Additionally, if any further benefits or values are identified over time, these can be easily added beneath

Table 22.2 Key components of the taxonomy of value

Categories of value	Tangible/explicit value	Methods and strategies for generating value	Intangible/implicit value	Stakeholders for whom value is created
Existing value (value your model currently attains) **Value missed or destroyed** (value missed or squandered) **Value** **Opportunities** (value that can be created)	**Resource value** (Product, materials, energy, processes, space, waste streams) **Consumer value** (Benefits provided to the customer, convenience, quality) **Relationship value** (Value of networks and partnerships, community, consumer loyalty) **Data/knowledge value** (Data generated from the product or service, patents, innovations)	**Methods** Lifetime extension Product as service Remanufacture Reuse/Second life Waste as feedstock Collection systems Pure waste streams Recycling Localisation Circular Design IOT technology **Strategies** Increased utilisation Increase efficiency	**Stability and control** (resource security, lower risk, more robust systems) **Positive social impact** (job creation, community, increased well-being) **Symbiosis** (Benefits and resilience received from partnering) **Altruism** (Open innovation; intent to actively benefit the system) **Behaviour change** (habits as producers and consumers that benefit environment and society)	Consumer Environment Society Economic

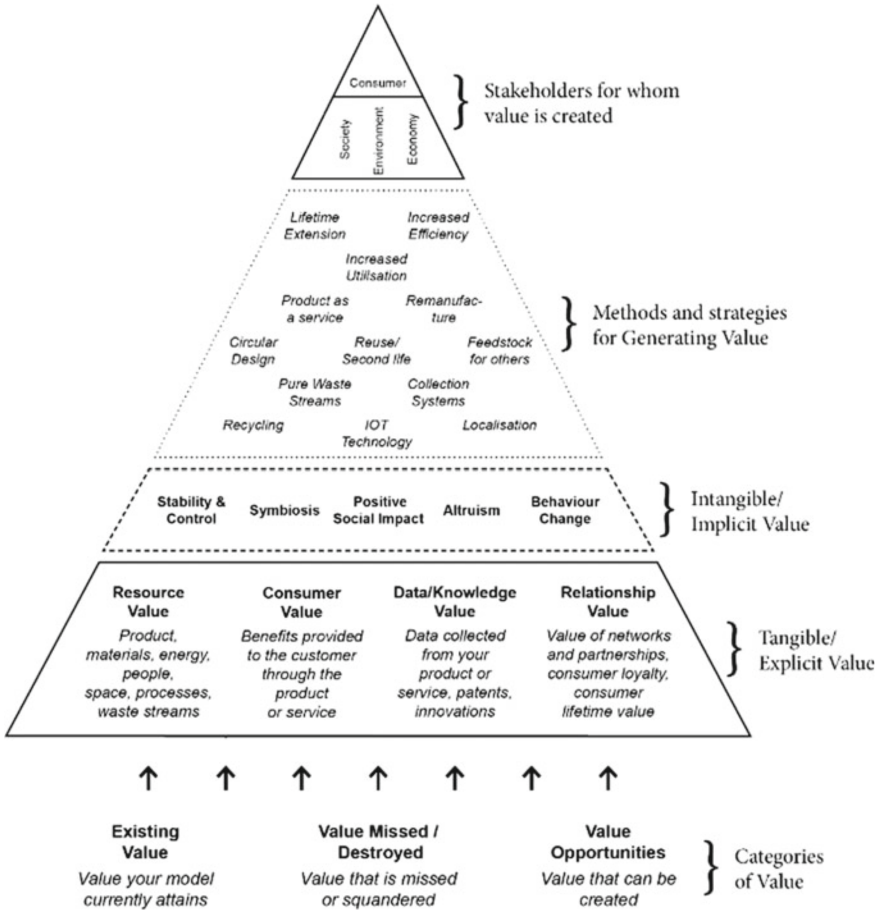

Fig. 22.2 Circular value framework

any of the three defined categories: Tangible/Explicit, Methods for Generating Value and Intangible/Implicit Value.

The representations of value identified by Bocken et al., [13] have been classified within the Taxonomy as 'Categories of Value' as shown in the first column of Table 22.2. These components were included because they provide a structured, system-level description for what types of value is available within a Circular Economy system. They provide a tangible starting point for organisations to realise the full scope of value that could be attained, and what is also falling out of the system. To understand how these types of values relate to one another in a more meaningful manner, a Circular Value Framework is proposed in Fig. 22.2.

The triangular format represents the emergence of circular value creation from bottom to top, whereby the most tangible, easily identifiable forms of value are located at the bottom and the more intangible value following next. These values are then generated through the different methods and strategies in the next section which are finally delivered to the stakeholders at the top. The stakeholders are arranged in this manner with the consumer or customer at the very top because it is argued that fundamentally the purpose of a circular business is to deliver value to a customer, and that next the societal, environmental and economic factors should be considered of equal importance. While different organisations such as NGO's or non-profit organisations may place a different stakeholder at the top (such as environment or society), essentially within a Circular Economy business model context, all four stakeholders must be actively deliberated.

22.5.2 Limitations and Future Work

This research analysed only ten secondary source case studies, and so there are elements of the taxonomy that could be developed, contextualised and tested in more detail. Firstly, it was observed that the strategies and methods primarily relate to resource value, and so further research could be done on what approaches relate to the other tangible values. Secondly, the taxonomy was developed based on secondary case studies, however, due to the rapidly developing nature of the Circular Economy, it would be valuable to further develop and test it with businesses and start-ups as they develop their ideas as new forms of value may arise.

22.6 Conclusions

Based upon the knowledge and insights uncovered through a literature review and case study analysis, this paper presents an initial taxonomy that identifies and describes the types of value that are available within a Circular Economy system. Five core components were identified, namely: ***categories of value*** (Existing, Missed/destroyed, opportunities) ***tangible/explicit values*** (Resource, Consumer, Relationship, Data/knowledge), ***intangible/implicit values*** (Stability and control, Sustainability Image, Symbiosis, Altruism, Behaviour Change); ***methods and strategies for generating value*** (localisation, increased utility, reuse, remanufacture, etc.) and ***stakeholders for whom value is created*** (consumer, environment, society, economy). These components have been developed into a circular value framework to be tested and validated further in future studies.

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Chapter 23
Development Strategies for Closing the Loop: The Roles of the Major Economies in the Transition Towards Circular Economy

Mika Naumanen

Abstract This paper investigates the key development trends related to the transition towards the circular economy and the roles of the major economies in this transition. Answers are sought for through analysing research articles, business papers and conference proceedings. Emerging technology areas and national emphases are identified by using a generative probabilistic model, latent Dirichlet allocation (LDA). The analysis covers altogether about 10,000 references. We divide the references into four stages in the circular economy process: raw material production/collection and energy use; product design and manufacturing; product use; and end-of-first-life and closing the loop. The results from publication analysis are presented for China, European Union and the USA.

23.1 Introduction

In recent discussions and political programmes, the circular economy has emerged as one of the possible ways of solving the environmental problems caused by overproduction and using natural resources in an economically sustainable way [1–4]. For example, the European Union has published a circular economy action programme [5] and reformed the waste management code in accordance with the principles of the circular economy [6, 7].

The circular economy can be understood as an umbrella concept [8], which brings together the research traditions of industrial ecology and industrial symbiosis [3] as well as newer concepts of the platform and sharing economies [9]. In a circular economy, the production system is built to maximize the efficiency of the resources used in the production processes, keep them in the cycle of optimum time and utilize the materials of the removed products. The products are basically designed for long-term, reuse (repair/refurbishment) and the materials used are easily recyclable, thus

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minimizing the amount of new raw materials and waste generated in production [2, 3]. The goal is to change production and consumption practices so that natural resources are used efficiently, no waste is generated, but the materials that are tied to the products are returned to production (technological cycle) as efficiently or safely as possible back to nature (biological cycle) [1, 4, 9]. This contributes to building an ecologically and economically sustainable future [10].

United Nations Environment Programme (UNEP) develops a model with four main lifecycle stages: raw material production and energy use/recovery from geological or anthropogenic stock; product design, fabrication and (re)manufacturing; product use; and end-of-first-life [11]. Our analytical framework follows from these approaches. In the change of production and economy in accordance with the principles of the circular economy, the research literature has highlighted the related key factors.

The amount of research on the circular economy has increased rapidly, and the number of scientific articles published on the topic has grown rapidly [1, 8]. This led us to aim to answer the following research question: what are the key development trends related to the transition towards circular economy and the roles of the major economies (China, European Union and the USA) in this transition? Answers are sought for through literature analysis, concentrating on scientific research articles, business papers and conference proceedings. The details of our bibliometric analysis are presented in Sect. 23.2, results in Sect. 23.3 and discussion and conclusions in Sect. 23.4.

23.2 Literature Review

23.2.1 Identifying National Emphasis Areas and Emerging Trends

This study identifies the national emphasis areas by using a generative probabilistic model, latent Dirichlet allocation (LDA), to discover key topics from documents [12, 13]. We identify emerging topics using the abstracts of scientific articles covering the circular economy and circular business development. Our approach is to examine both the structured and unstructured data. First, text mining is applied to the abstracts of scientific articles, seminar presentations and business papers covering circular economy and circular business development. Then, LDA, a topic modelling technique, is performed to identify the emerging topics in this textual data.

Many researchers have used text mining to extract valuable information based on textual data. The text mining of unstructured data can be important when analysing emerging technology areas and areas of economic and political interest [14]. It is a knowledge-discovery methodology that enables researchers to discern patterns and trends and possibly extract hidden knowledge. Bibliographic analysis can support the study of prioritisation of R&D programmes [15] and technological assessment of competitors [16], for example.

23.2.2 Bibliometric Analysis

In our bibliometric analysis, we use data from scientific articles, seminar presentations and business papers. We searched the literature related to circular economy and circular business development using the search engine Web of Sciences (core collection). The assumption in bibliometric analysis with the text mining approach is that the high probability of occurrence of one specific term or phrase (combination of a few words) in a title or abstract of research papers is a good indicator for its relevance to one technology area or industry.

We included in our search the literature available from 1990 to end of January 2019 using the following search terms, on the one hand, circular or recycl* or remanufact* or reus*, and on the other hand, business or economy. Our search produced 10,207 references. We dropped 228 articles because they did not include abstract or other similar summary of the article's contents. Lastly, 30 articles were dropped because they were not allocated in any topic in the latent Dirichlet allocation process. Hence, our database includes 9949 references. About one-fifth of the articles originate to the Republic of China, followed by the USA, Great Britain and Germany. Our bibliometric analysis includes descriptive statistics such as number of publications per year; geographical distribution of publications by country (based on authors' affiliations); most popular publication platforms, such as scientific articles, business papers and conference proceedings. This information is directly derived from the Web of Science records. Furthermore, the analysis includes a list of salient keyword terms associated with the overall corpus and twenty topics, with a list of associated topic-specific keywords. The twenty topics or clusters with their characteristic keywords and summary statistics are presented in Table 23.1. Our focus is on changing the unstructured part of research papers (e.g. title, abstract), which contains valuable economic, technical and political information, to structured data (numbers) to facilitate its analysis.

23.2.3 Latent Dirichlet Allocation

Latent Dirichlet allocation (LDA) is a statistical process that falls into the family of topic models and is generally considered the simplest of topic models. The goal of topic modelling is to automatically discover the topics from a collection of documents. Topic models can help move us "…(B)eyond an understanding" of "how texts are being said" to a broader understanding of "what is being said" [17]. The LDA is used commercially also. For example, the New York Times uses LDA to

Table 23.1 Twenty clusters and their summary statistics

Topic	Characteristic terms	#Journal articles	#Seminar papers	#Business papers	Total	Included in analysis
1	Business process management, business process modelling	291	152	190	633	Stage 2
2	Product design, value chain, product development	357	85	65	507	Stage 2
3	Economic growth, resource efficiency	171	64	71	306	
4	Model based, model driven, business rules	112	96	145	353	
5	Knowledge management, information systems	149	80	109	338	Stage 3
6	Environmental protection, environmental pollution	463	105	143	711	
7	Web services, service oriented architecture	955	256	244	1455	Stage 3
8	Municipal solid waste, solid waste management, resource recovery	123	151	119	393	Stage 1
9	Software development, software engineering	276	38	45	359	Stage 3
10	Literature review, future research	328	59	36	423	
11	Global economy, general equilibrium, environmental policy	141	102	105	348	
12	Energy consumption, low carbon, climate change	111	78	96	285	
13	Closed loop, reverse logistics, supply chains	383	32	15	430	Stage 4
14	Renewable energy, fossil fuels, carbon dioxide	258	37	49	344	
15	Environmental impacts, environmental benefits, lifecycle assessment	316	222	229	767	

(continued)

Table 23.1 (continued)

Topic	Characteristic terms	#Journal articles	#Seminar papers	#Business papers	Total	Included in analysis
16	Wastewater treatment, water resources, human health	575	93	86	754	
17	Natural resources, material flow analysis, resource management	89	98	93	280	
18	Industrial ecology, industrial symbiosis, eco-efficiency	205	54	73	332	
19	Low-cost, cost-effective, green chemistry	369	81	58	508	
20	Recycling and reuse, raw materials, value added	127	162	134	423	Stage 1

recommend articles to subscribers by inferring topics from articles they have read and identifying articles with similar content [18].

We formally define a topic to be a distribution over a fixed vocabulary. This statistical model reflects the intuition that documents exhibit multiple topics. There are a set number of topics possible for each document, and within each topic, there is a distribution of words used for that topic. Each document exhibits the topics in different proportion. The distribution that is used to draw the per-document topic distributions is called a Dirichlet distribution. A given word may be used in more than one topic, but its relative probability would vary across topics. "Latent" refers to the fact that LDA is designed to infer the underlying topics in a document, and "allocation" refers to the fact that the estimation allocates words to topics. By using an entire set of documents (referred to as a corpus), a researcher can generate the set of topics in the corpus.

We programmed the model to highlight twenty topics. To describe each of the topics, we extract the key sequences of words that have the highest weights in the topic. These sequences of words are the most important terms in defining the topic. The specificity of the keyword is calculated as the ratio of the frequency of the keyword in a certain topic to the overall keyword frequency in the overall corpus [19]. Based on the given keywords, we interpreted the meaning of each topic. We selected those clusters for the study that related most directly to the four stages of the product lifecycle model and dropped the ones that seemed to relate more to the economic, modelling, energy, environmental and natural resources related aspect of the CE.

Based on the salient keywords and topics revealed by the bibliometric analysis, we perform a conceptual analysis to identify possible national development focus areas in each topic. The requirement of twenty topics is an arbitrary figure; we believe that it produced a fine-grained enough division of topics so that it allowed to pick and combine the ones that deem suitable for our analysis. In what follows, we focus on the four stages in the circular economy process. We identify national development strategy aspects within economical, technological, social/consumption and political/environmental dimensions and discuss these emphasized aspects for each of four stages. The selected topics and their relation to the four stages in the circular economy process are shown in Table 23.1.

23.2.4 Temporal Patterns

We pose and consider the problem of analysing the temporal development of a document collection. Our work bears similarity to timeline creation [20]. Timeline creation seeks to correlate real-world events with the text used in the document collections. There is an implicit assumption that as real-world events change, the text used in the documents will change as well. Words that nobody used at one time may become widely popular, e.g. words describing a new technology or new idea, the bursts seem to correspond to the rise and fall in popularity of research topics.

For each term, we compute the number of documents that have appeared before and after the year 2010, mark these as "old" and "new" and calculate the new one's share of all the references for each of the terms in the database. This newness index presents the changes in each term's popularity over time. While the latent Dirichlet allocation does not take time into account when clustering the documents, this last step relates keywords and terminology to time.

When presenting our results, to save space and to make the developments easier to grasp, we need to discuss larger concepts that summarize a number of developments than single keywords with exact newness indices. Hence, we are talking about temporal averages. We use four time categories: very recent, having approximate newness index of over 0.9; recent with newness indices typically around 0.7–0.9; middle with newness indices typically around 0.5–0.7; and early with newness indices less than 0.5. The "middle" time period can have two kinds of publications: on one hand, ones that have been discussed for a long period of time and are still on agenda and, on the other hand, ones that had their culmination around the late 2000s–early 2010s.

23.2.5 Quality and Specialization

In order to estimate an article's quality, we used the SCImago Journal Rank (SJR) indicator from the SCImago Journal and Country Rank portal. It is a publicly available portal that includes the journals and country scientific indicators developed from the information contained in the Scopus® database (Elsevier B.V.). Citation data is drawn from over 34,100 titles from more than 5000 international publishers and country performance metrics from 239 countries worldwide. SCImago is a research group from the Consejo Superior de Investigaciones Científicas (CSIC), University of Granada, Extremadura, Carlos III (Madrid) and Alcalá de Henares, dedicated to information analysis, representation and retrieval by means of visualization techniques.

On the basis of the aforementioned articles' qualities with each theme in each nation, we calculate each theme's (if applicable) specialization indices for each nation. They look at various themes and quality weighted references in the textual data:

$$q_{it} = \frac{e_{it}}{e_i} / \frac{e_t}{e}$$

where i is the country or area, t is the circular economy theme, e_{it} is the quality weighted number of references in the area i in the theme t, e_i the total number of quality weighted references in the area, e_t is the total quality weighted number of references in the theme t and e total number of quality weighted references. The larger the q_{it} the more the quality references in the theme are concentrated in that particular area and the more specialized the area is in the theme.

When presenting our results, we divide our concepts to three categories with respect to the average impact the references behind that concept have typically received: as "Academic" the ones with the highest average impact, as "Practitioner" the ones with the lowest average impact, and as "Academic/Practitioner" the ones in between. Typically, business journals do not have an impact factor. The average impact factors were 1.09 for journal articles and 0.25 for seminar papers. We used these values for references with missing impact factor values and seminar papers' average for business papers also.

23.3 Results: National Emphases and Development Trends with the Four Stages in the Circular Economy Process

23.3.1 Raw Material Production/Collection and Energy Use

From a systemic perspective, the circular economy can be understood as one approach to achieving the so-called sustainability change. Sustainability change refers to a long-term multidimensional transformation process (transition), during which established consumption and production systems are directed in a more sustainable direction through the actions of many different actors [21]. An individual actor is unable to bring about such a change, but companies, political decision-makers and other social actors influence each other as well as the extent and direction of change [22, 23]. This quest for systemic change can be seen in our research results. Compared to the other three stages in the CE process, many more articles in raw material production/collection and energy use stage deal with political themes and have been published in respected academic journals.

In the very recent period, critical metals and rare earth elements have attracted interest both in Europe and in the USA. Many of these materials come from China, and their availability seems not to be an issue there. There seems to be other areal emphases also: plastics and plastic waste are an important concern in Europe; in China, electronic waste and other consumer products more so. Relatedly in the USA, attention has shifted from organic to bio-based materials. Organic materials include organic polymers that are derived from fossil fuels, while bio-based materials exclude those (Table 23.2).

We can see how the circular economy concept and supporting technologies gradually shift from two separate entities into a united whole. Previously, construction waste and recycled concrete was an important topic in Europe. Now, the focus has shifted to sustainable construction and building materials. This same phenomenon can be seen even more clearly in the next, product design and manufacturing stage.

In China, some of the business relevant themes in the collection and raw materials are waste valorization, construction waste, cost of waste and cost of recycling. Indeed, it is argued that for the realization of the circular economy, information is needed on the economics of material flow utilization [24]. Promoting recycling seems to be an important theme in China. There are plenty of references on domestic waste also.

In India, some of the business relevant themes in the collection and raw materials are infrastructure development, municipal solid waste management and waste minimization. Within social and consumption aspects, packaging recycling and recycled paper are important themes. Technological aspects include waste management combined with recycling and management of recycling. In Japan, there is a number of quality references only in political/environmental theme. These include landfill mining, landfill tax and waste prevention.

Recovery efficiency is an important business theme in Australia. Recent political and environmental themes include critical metals and recycling metals and, similar to the USA, bio-based economy. There seems to be interesting in sustainable, secondary raw materials and building materials.

23.3.2 Product Design and Manufacturing

The transition towards designing circular products is important since thermodynamic and/or economic limitations mean that it is not always possible or cost-efficient to unmix metals constituents from an alloyed form, or from other product constituents. These physical realities have consequences for all the links in the chain of activities that support recycling. Certain losses are inevitable based on the product design. This type of "loss by design" has been characterized in a study published by Cluster researchers [25].

In the product design and manufacturing stage, we can see the same gradual merger of circular economy concept and supporting technologies to a united whole as in the

Table 23.2 Development trends in raw material production/collection and energy use stage

Area	Theme	#References	Orientation
Very recent			
Europe	Sustainable construction and building materials	100–200	Academic/Practitioner
	Municipal waste management, landfill mining	50–100	Academic
	Critical metals	<30	Academic/Practitioner
USA	Informal economy and waste	50–100	Academic
	Bio-based economy, use of biomass	30–50	Academic
	Rare earth elements	30–50	Academic
Recent			
China	Recycling metals, consumer products and electronic waste	>200	Academic
	Municipal solid waste management and its strategies	50–100	Academic
	National policy	<30	Academic
Europe	Recycling rates and resource recovery efficiency	>200	Academic
	Waste prevention, economy of waste and incentives for efficient use	>200	Academic
	Urban and household waste streams and their treatment	>200	Academic
	Secondary resources, reuse of materials	100–200	Academic
	Sustainable waste management, management of recycling	100–200	Academic
	Construction waste and recycled concrete	30–50	Academic/Practitioner
USA	Waste minimization	100–200	Academic
Middle			
China	Promoting recycling, recycling technologies, local authorities' role	>200	Academic/Practitioner
Europe	Plastic and packaging materials recycling, plastics waste	50–100	Academic/Practitioner
USA	Organic materials, recycled fibres	30–50	Academic/Practitioner

material production/collection and energy use stage. First, design and recycling we discussed as separate concepts (but in the same article), then modular designs and designing disassembly—hence, the requirements of reuse and recycling are started to be taken into account in the product design. Finally, the discussion has shifted to circular products and designing them. That is, a circular product is an objective, and company processes are set up to support its achievement. Similarly, the discussion of manufacturing processes and circular economy (as two separate entities) has shifted to discussing sustainable manufacturing (as one united entity). References on business development have developed to addressing sustainable business models directly. Indeed, the transition to a circular economy benefits from the emergence of new business models that seek effective ways to collect products back into production processes, find solutions for shared use of goods and seek new solutions to extend product life, for example by updating features, or through a variety of product service packages [26–29].

Precise manufacturing of components and products can be achieved by 3D printing (additive manufacturing), and this new technology is often flagged as an important strategy for using less materials. In Italy and Spain, a number of quality references deal with additive manufacturing. In the automotive industry, lightweight design and material substitution are two of the dominant innovations supporting reductions in emissions and fuel demand (Table 23.3).

In China, some of the business relevant themes in design and manufacturing are improving quality, business process management, innovation management and business process models. Technological aspects include lifetime extension and lifecycle management.

Within social and consumption aspects, an important theme in Europe is product service systems. In product service systems, businesses combine products and services to deliver an outcome, so that the consumer pays for a service or access to a product [30]. By altering the way businesses and consumers interact with physical and digital assets and enabling dematerialization, digital technologies can transform value chains, so they are decoupled from the need for additional resources for growth. The combination of digital technology and circular thinking can be powerful in reshaping value chains [31].

Consumer preferences are an important business theme in the USA. In Japan, some of the relevant business themes are sustainable business models, business process management and business process models. In Australia, on the other hand, start-ups and product innovation seem to be high on the agenda. Within technological aspects, manufacturing processes, process management and process improvement are important themes.

Among larger EU countries, technological aspects of design and manufacturing focus on manufacturing and combining it with the requirements of circular economy and recycling. Eco-design, design and recycling and modular design seem to be important issues. Accordingly, the products are made using renewable and more easily recyclable raw materials [8]. Different from the collection and raw materials stage, few references cover political and environmental aspects. These focus on

Table 23.3 Development trends in product design and manufacturing stage

Area	Theme	#References	Orientation
Very recent			
Europe	Sustainable business models and business model innovation, job creation	>200	Academic
	Circular products and their design	100–200	Academic/Practitioner
	Product service systems	50–100	Academic/Practitioner
	Fashion industry	<30	Practitioner
Recent			
China	Improving quality, lifetime extension	50–100	Academic/Practitioner
Europe	Sustainable manufacturing	100–200	Academic/Practitioner
	Business development, value propositions, start-ups	50–100	Academic/Practitioner
Middle			
China	Business process and innovation management, business process models	>200	Practitioner
Europe	Manufacturing processes, process management, improvement, maintenance and repair	>200	Practitioner
	Modular design, design and recycling	>200	Practitioner
	Design disassembly, green product	>200	Academic/Practitioner

sustainable manufacturing and improving sustainability. Job creation seems to be an important political theme in Great Britain.

23.3.3 Product Use

Circularity introduces a strict differentiation between consumable and durable components of a product. Consumables in the circular economy are largely made of biological ingredients or nutrients that are at least non-toxic and possibly even beneficial and can safely be returned to the biosphere, either directly or in a cascade of consecutive uses. Durables such as engines or computers, on the other hand, are made of technical nutrients unsuitable for the biosphere, such as metals and most plastics. These are designed from the start for reuse, and products subject to rapid

Table 23.4 Development trends in product use stage

Area	Theme	#References	Orientation
Very recent			
China	Big data	30–50	Practitioner
Europe	Cloud computing, Internet of things	100–200	Academic/Practitioner
Recent			
Europe	Data analysis and business intelligence	100–200	Academic/Practitioner
USA	Data integration and information retrieval, decision support	50–100	Academic/Practitioner
Middle			
China	Knowledge management and information sharing	>200	Practitioner
	Data mining and decision support systems	100–200	Practitioner
	User requirements and service composition	100–200	Practitioner
India	Customer service and service development	30–50	Practitioner
Europe	Enterprise resource planning	50–100	Practitioner
	Service orientation, quality of service	50–100	Practitioner
	Business agility, process re-engineering	50–100	Practitioner
Early			
China	Web services, business applications	>200	Practitioner
Europe	Semantic web technologies, business services and software developers	>200	Practitioner
	Fault tolerance, access control	50–100	Practitioner
USA	Asset management, ERP systems	100–200	Practitioner
	Web applications	50–100	Practitioner

technological advance are designed for upgrade [32]. For products that remain idle or underutilized for large parts of their product life, material efficiency can be increased through increasing the intensity of use (Table 23.4).

The construction of closed, efficient and safe material cycles requires adequate and correct information about the materials and their properties so that they can be utilized in the production processes [4]. Digitalisation of production (Internet of things, Industry 4.0, big data) is seen as helping to produce and exploit such information [33, 34]. It seems that businesses have started to use the same information communication and software technologies in all geographic areas at around the same time: web technologies, services and applications in the early period; enterprise resource planning in the middle period; data analysis and decision support in the recent period; and the use of big data and cloud computing in the very recent period. This is not surprising as multinational enterprises and global consultants quickly disseminate the best ICT practices to new locations, for example. Similarly, service composition and service development were emphasized in China and India around the same period of time.

Within this stage, the only political/environmental theme that appears within the EU, and in Italy particular, is the role of regional governments. On the other hand, a number of technological aspects come up and include data collection, process re-engineering and ERP systems in Germany; information quality and knowledge transfer in Italy; geographic information systems in Spain; and big data, cloud-based operations, Internet of things, data analysis and machine learning in France. The same applies to other regions; only few political or social themes come up for this stage. On the other hand, a vast number of technological issues do come up and seem to be practitioner-oriented.

23.3.4 End-of-First-Life and Closing the Loop

The realization of the circular economy is seen to require information about the material flows throughout the supply chain [35]; information about where and how the material to be utilized in the different production processes is available; how the quality of the materials can be verified; and how return cycles can be as stable as possible [34]. It seems that textile industry has arisen as an experimentation area besides automotive industry for end-of-first-life and closing-the-loop development projects (fashion industry appears in product design and manufacturing stage). To be sure, recycling cotton saves 20,000 L of water per kilogram of cotton [36] (Table 23.5).

Logistics processes and reverse logistics were important concepts in China and in the USA in the middle period. It seems that the focus has now shifted in involving the whole supply chain in the process: in China, academics and practitioners talk about reversing supply chain and closed-loop supply chain; in Europe about inventory management and product recovery planning. Indeed, information sharing in product supply chains must exist not only for product design, but for disassembly, quality checking, sub-component sourcing, reassembly and testing. The compilation and utilization of supply chain information are only possible when the various actors in the supply chain cooperate and form functioning networks [1].

In China, some of the business themes in closing the loop are production strategies, transportation costs and minimizing costs. Within social and consumption aspects of closing the loop, spare parts and product returns seem to be important topics. Among EU countries, some of the business themes in this stage are recycling networks and transportation costs in Germany, and automotive and textile industries in Italy and

Table 23.5 Development trends in end-of-first-life and closing-the-loop stage

Area	Theme	#References	Orientation
Very recent			
Europe	Textile industry	<30	Academic
Recent			
China	Reversing supply chain, closed-loop supply chain	100–200	Academic/Practitioner
Europe	End-of-life products and circular supply chain	100–200	Academic
	Remanufactured products, remanufacturing process and its costs	50–100	Academic
Middle			
China	Logistics processes, product returns in it, transportation costs	100–200	Academic/Practitioner
Europe	Inventory management and product recovery planning	100–200	Academic/Practitioner
	Cost of quality	50–100	Academic/Practitioner
	Automotive industry	30–50	Practitioner
USA	Reverse logistics and its management	30–50	Practitioner

in Spain—as well as in EU in general. Cost models, total cost and cost of quality appear as important business topics for this stage in Europe.

23.4 Discussion and Conclusions

The amount of research on the circular economy has increased rapidly. This led us to investigate the key development trends related to the transition towards the circular economy and the roles of the major economies in this transition. In our analytical framework, we study and present results along the four stages in the circular economy process: raw material production/collection and energy use; product design and manufacturing; product use; and end-of-first-life/closing the loop.

From the results presented in this paper, we can see how the circular economy concept and supporting technologies gradually shift from two separate entities into a united whole. For example, design and recycling we discussed first as separate concepts, and then, modular designs and designing disassembly took place. Now, we are talking about circular products and how to design them. That is, a circular product is the objective and company processes are set up to support its achievement. Similarly, references on business development have developed to addressing sustainable business models directly.

Research literature emphasizes systemic change as a condition for the transition towards circular economy. This quest for systemic change can be seen in our research results. Compared to the other three stages in the CE process, many more articles in raw material production/collection and energy use stage deal with political themes and have been published in respected academic journals. National political themes are well presented. For example, recycling municipal solid waste and municipal solid waste management, promoting recycling, national policy and local authorities' role are important themes in China. In Europe, plastic packaging, packaging recycling and plastic recycling have attracted plenty of attention. In the USA, the focus has shifted from organic to bio-based materials. In the very recent period, critical metals and rare earth elements have caught attention both in Europe and in the USA. Many of these materials come from China, and their availability seems not to be an issue there.

Within the design and manufacturing stage, business-related aspects are more present. Sustainable business models and business model innovation, innovation management, job creation, circular products and their design and product service systems, that is, the way businesses combine products and services to deliver an outcome, are some examples of the very recent discussion themes.

Technology and business-related aspects dominate the product use stage. The construction of closed, efficient and safe material cycles requires adequate and correct information about the materials and their properties. Digitalisation of production is seen as helping to produce and exploit such information. It seems that businesses have started to use the same information communication and software technologies in all geographic areas at around the same time: web technologies, services and applications in the early period; enterprise resource planning in the middle period; data analysis and decision support in the recent period; and the use of big data and cloud computing in the very recent period.

It seems that the automotive industry was the forerunner in applying closing-the-loop business practices, but now the textile industry has appeared as a new field of experimentation in this regard. In the end-of-first-life/closing-the-loop stage, logistics processes and reverse logistics used to be important concepts, but it seems that the focus has now shifted in involving the whole supply chain in the process: reversing supply chain, closed-loop supply chain and product recovery planning are more recent discussion topics.

The current exercise involved plenty of manual work: over 10,000 keywords and term combinations were distilled to illustrations of few development paths in the circular economy. In future research, it should not be too complicated task to automate this procedure further and let the software to do at least part of the process. For example, we could start with letting LDA first to identify say 1000 topic clusters. Then, we could use temporal and regional reasoning to combine these to reach say 100 "clusters of topic clusters", which would be a manageable level of granularity for a study.

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Part V
Energy Efficiency Opportunities in Manufacturing Processes and Systems

Chapter 24
Life Cycle Assessment of Graphene as Heating Element

Araba Darkoa Ampah, Emanuele Pagone and Konstantinos Salonitis

Abstract Among the various applications of graphene is the heating purpose due to its promising thermal conductivity. This paper presents a life cycle model of graphene, capturing the "cradle-to-gate" approach, focusing on energy consumption and environmental impact of graphene. The embodied energy consumption was calculated based on empirical data in scientific papers, patents and databases, while life cycle assessment modelling software was utilised for analysing its environmental impact. The result from the analysis shows that the embodied energy for the synthesis of 1 kg of graphene ranges between 264 and 304 MJ. Further analysis shows that 42% of graphene-embodied energy is consumed from powder preparation through to graphitisation process. Moreover, the result obtained from the modelling shows dust particles and CO_2 emissions into air during graphene production. This paper should be followed by further study on graphene use and end-of-life phases to establish a comparison with the traditional heating materials.

24.1 Introduction

Graphene, a two-dimensional honeycomb carbon lattice, has drawn attention of research focus on multitude of different graphene-related areas including graphene as heating elements [1–3] as energy storage [4], as semiconductor [5], as structural reinforcement [6] and as membrane for liquids [7] or gas [8] separation. Graphene firstly obtained in 2004 using sticky tape on graphite (micromechanical cleavage) and reported to have thermal and electronic properties [9] is a promising material to replace several materials commonly used in today's devices in the future. Life cycle assessment (LCA) is defined in the 14040 ISO standards as a way of addressing the

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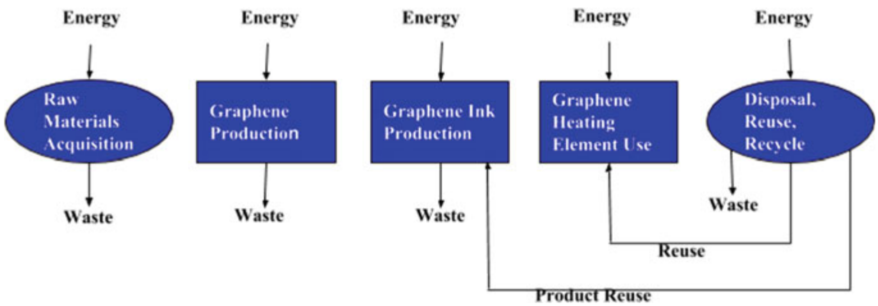

Fig. 24.1 Representation of the "cradle-to-grave" approach of graphene product life cycle. Adapted and modified [10]

environmental impacts (resource use and its effects on the environment) of a product's life cycle from the acquisition of raw materials through production, use and end of life (recycling and or final disposal, i.e. "cradle to grave"). The "cradle-to-grave" approach, as represented in Fig. 24.1, includes the energy utilisation that occurs during resource extraction and processing, production, use and end-of-life processing of graphene. This holistic and comprehensive approach aims at avoiding shifting environmental burdens from one stage of the life cycle to another, and a complete picture of graphene properties can be ascertained.

Recent research publications on the numerous applications of graphene, due to its mechanical, thermal and electronic properties, have led to several concerns over the economic and environmental burdens that this material might have on the society [11]. There is the need for investigation on the economic and or environmental burdens as associated with a product or system when produced in commercial scale thus, to put down measures to reduce or avert these burdens that may occur before the full development of the product or system. Graphene with very high thermal conductivity above 3000 W/(m K) [12] and able to withstand extremely high densities of electric current (a million times higher than copper) [13] is possible to be highly suitable as heating element. The high thermal conductivity property indicates that it can outperform carbon nanotubes regarding heat conduction [14]. With the threat of global warming and climate change, technological advancement is no longer the only priority as there is now a necessity of abating the environmental impacts and risks associated with emerging technologies. Also, the LCA approach avoids shifting the environmental burden from one impact category to another [11]. These necessitated a comprehensive study to investigate the energy consumption of graphene, hence the application of LCA technique.

This paper aims to institute a life cycle model of graphene, capturing the "cradle-to-gate" approach. The paper focuses on the energy consumption and overview of environmental impact associated with industrial production of graphene as heating element.

24.2 Graphene Production

Graphene is produced primarily from graphite, either highly oriented pyrolytic graphite (HOPG—artificial) or graphite flakes (natural) [9, 15]. HOPG production processing which was invented and firstly produced by E. G. Acheson in 1896 [16] is made up of filler and binder components. The filler constituting over 80% of total raw materials mass [17] is normally chosen from carbon materials that graphitise readily, whereas the binder, usually coal tar pitch, represents about 15–30% of the total material mass [18].

A loss of 25% carbon is assumed after the graphitisation process for every 1 kg of graphite with density range of 2.1–2.3 g/cm when produced [18]. Based on the volatile mass loss and the ratio of filler to binder, it can be deduced that every 1 kg of graphite produced requires about 1.25 kg raw materials of which 80% is coke and 20% pitch. Graphene production methodologies can be classified into: exfoliation (dry, liquid phase (LPE) [19], and electrochemical exfoliation (EE) [20], chemical and thermal routes and chemical vapour deposition (CVD).

24.2.1 Graphene as Heating Element

Graphene ink can be used for heating element as in the case of conventional heating systems made from copper or alloy. It is reported that the commercial film-like heater made from strips of a Fe–Cr–Al-based alloy has many disadvantages including complicated fabrication process, opacity, heavy weight, rigidity and low heating efficiency [1–3]. Possibly, graphene ink can be used to replace the conventional heating elements due to its various properties including thermal, conductive, lightweight and flexible among others.

Graphene Ink. Zaier et al. documented that the coating strategy of graphene ink works with a variety of substrates (textile, paper, glass, wood, plastic and stainless steel) [21]. Possible graphene ink can be applied on board (plastic, wood or stainless steel) to replace the existing heating elements as shown in Fig. 24.2, due to its conductive property [22]. High conductivity of graphene permits electrons to travel about one-third of the speed of light and its low thermal mass [23, 24] expedient heating (instant) without wastage of energy heating up the heater itself.

Graphene Ink Production. The production of graphene ink requires basic elements comprising of conductive or functional material, binder and carrier [25, 26]. The functional material normally an electrically conductive form of carbon such as graphite, carbon black or activated carbon powder should be at least 30% of the wet weight of the ink [25]. The binder holds the conductive material (graphene) together while allowing to flex. Grisales et al. [25] further documented that the preferred binder's dry weight should range from 3 to 5.18% by of the wet weight of the composition and the binder, usually used in a solution in water. The composition should be about 30–50% of wet weight of the binder solution [25] which can be deduced

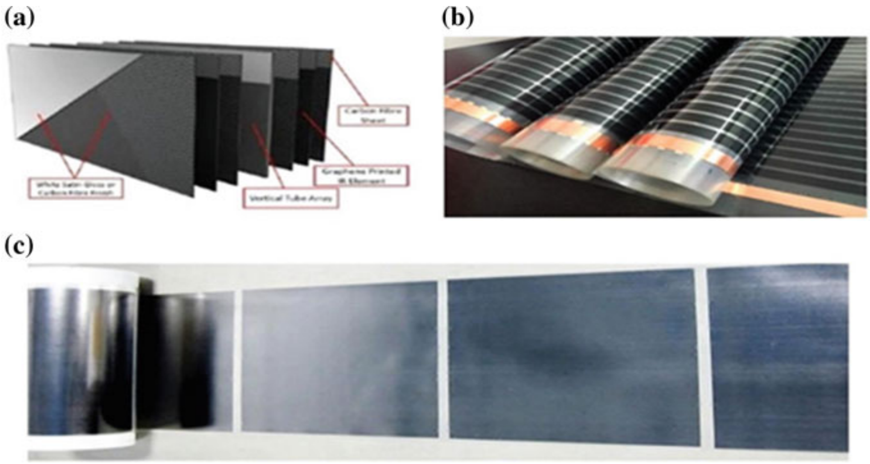

Fig. 24.2 Graphene heating elements: **a** graphene radiator, **b**, **c** forms of graphene underfloor heating element

that the dry binder and water ratio should be approximately 1:10, respectively. A conductive graphene ink can be produced by dispersing exfoliated graphite (EG) flakes in DMF [27] with a high concentration (10 mg/mL) followed by sonication [27, 28] for 20 min [27]. This method of graphene ink production seems promising for industrial scale since the sonication process promotes quick and even dispersion of graphene in the solution compared to the stirring method employed by Murray-Smith [26]. The weight of graphene in the ink contributes to the properties of the ink and its application. Ink for heating purpose may have high concentration of graphene due to the thermal, conductive and transfer of heating properties required for such application.

24.2.2 Environmental Impact of Graphene Production

Nanosafety which can be defined as all the safety issues related to nanotechnology is required to interpret any future development of new nanotechnologies into action, from commercial applications to healthcare approaches [29, 30]. Graphene-related materials (GRMs) are possible to have risks on health or environment as shown in Fig. 24.3. It is essential to discover the level of toxicity and to establish, if required, constraints for safety of use [31–36].

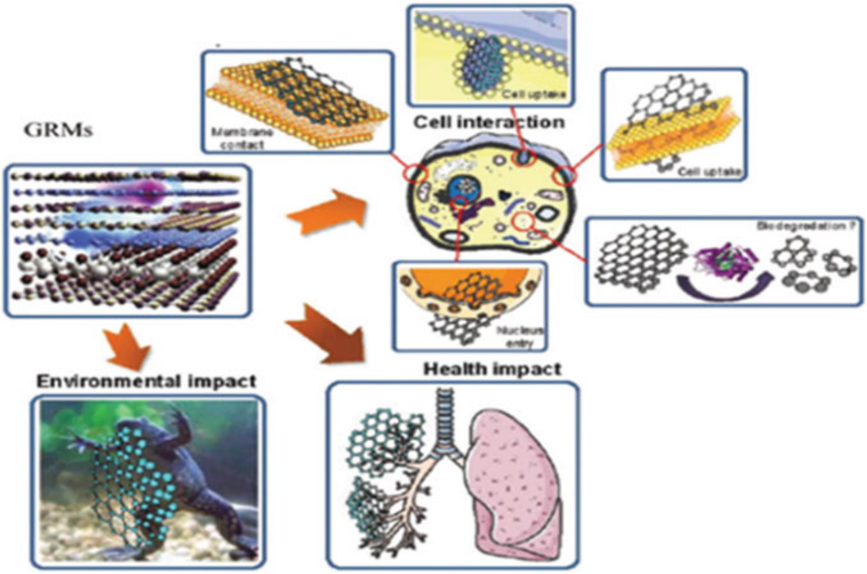

Fig. 24.3 Possible interactions of graphene-related materials (GRMs) with cells, organs (i.e. lung) and living organisms (i.e. amphibian) [36]

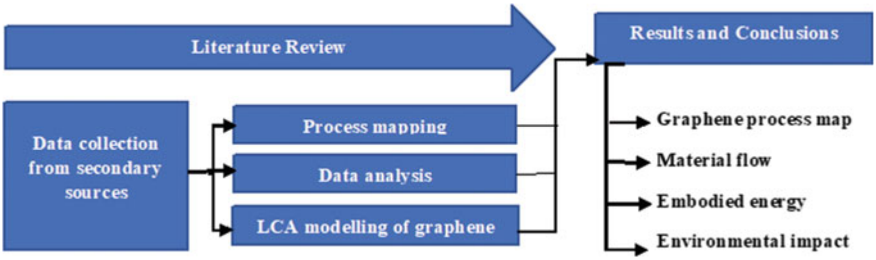

Fig. 24.4 High-level approach adopted in obtaining research results

24.3 Methodology

The approach adopted in obtaining the results is graphically represented in Fig. 24.4.

24.3.1 Process Mapping

The project first saw the process mapping of graphene using flowcharts to capture relevant processes from its feedstock through to graphene ink production. After which IDEF0 was used to further develop the map to capture the necessary production details including inputs, outputs, temperature, equipment and process time as indicated in Fig. 24.5.

Raw Materials Energy Calculation. To calculate the HOPG energy, 80:20% representing coke and pitch quantity flow was applied [17, 18]. Their equivalent production embodied energy quoted in [37] served as foundation to the energy calculation of graphene ink production. About 1.25 kg of both coke and pitch was used to calculate the production of 1 kg of HOPG. To obtain graphene processing energy, the contribution of coke- and pitch-embodied energy was subtracted from the graphite-embodied energy.

The primary production (energy and CO_2) and material processing (energy and CO_2) were added to obtain graphite-embodied energy. The quantity of H_2SO_4 used in the analysis was derived from the graphite-to-solution ratio quoted in [38].

Production Processes Energy Calculation. The energy requirement at the pretreatment of graphene was calculated based on the embodied energy of sulphuric acid quoted in [39]. Microwave expansion energy was obtained using a power of 1100 W [38] for a time of 5–10 s [20]. 150–300 W per litre solvent for 30 min was applied for the ultrasonic exfoliation energy calculation. The process energy is calculated assuming a constant power level for the time required by the process. The results from all the processing energy were added to the raw material energy to derive graphene-embodied energy result.

Graphene Ink Energy Calculation. The ratio 30:70% of graphene to dimethylformamide (DMF), respectively [25], was used in the ink energy calculation. The cumulative energy demand (CED) for 1 kg of DMF recorded in [40] was applied. The sonication process energy was calculated based on the power reference quoted by Zhamu and Jang [41] with process duration recorded by Parvez et al. [27]. The energy and materials mass flow for graphene ink production are graphically represented via Sankey diagram.

24.3.2 Environmental Impact

GaBi software was used in modelling the LCA of graphene production. The modelling captures the high-level production processes of graphene from its feedstock through to graphene ink production. Most of the data fed into the system were identified and retrieved from GaBi database with few entered manually from the results of the analysis. Data fed into the system were then analysed by GaBi software to obtain the environmental impact results of graphene production.

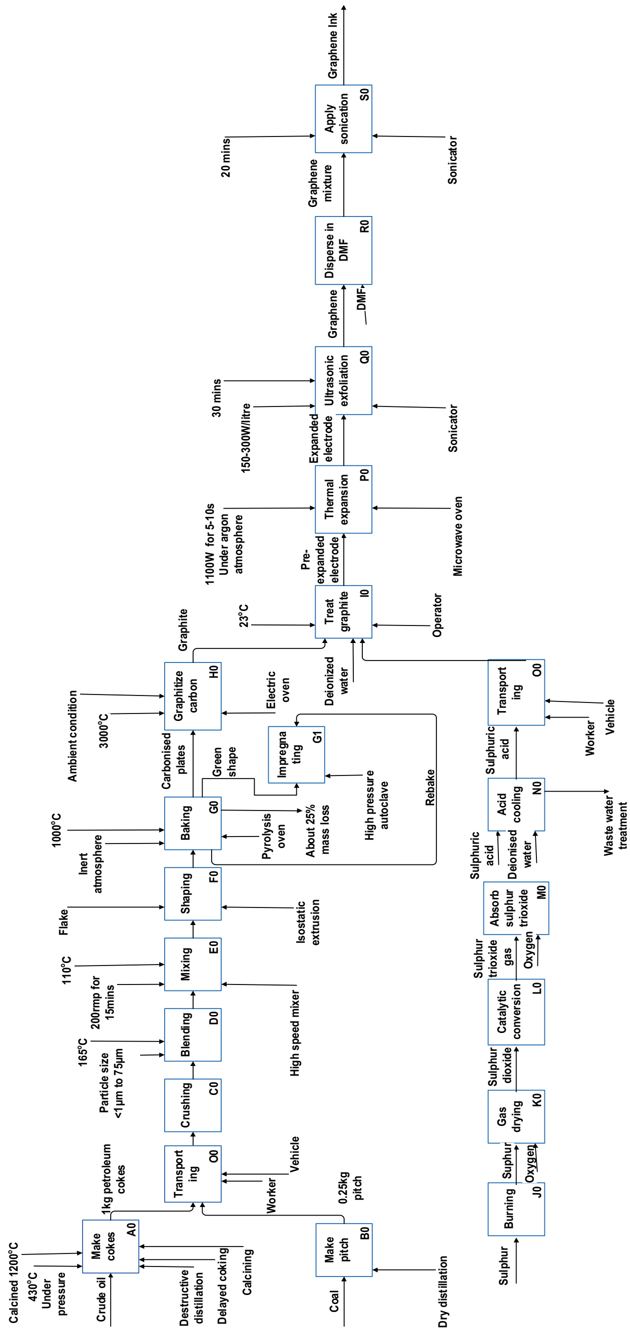

Fig. 24.5 Graphene process map capturing the "cradle-to-gate" approach

24.4 Results

24.4.1 Graphene Process Map

From a high-level point of view, a graphene process map is represented by Fig. 24.5 and comprises three major steps: graphite production, graphene production and graphene ink production. These processes represent raw material acquisition, graphene production and graphene use phase in Fig. 24.1, respectively. The temperatures, pressure, time, equipment and inputs contribute to the energy consumption at each process as indicated in Fig. 24.1, and the waste is denoted by the losses that flow out of the processes. Figure 24.5 shows that graphite production demands the production of both coke and pitch which is captured as "make petroleum coke" and "make pitch" respectively. The first production process after transportation is the powder preparation which begins with crushing of the raw materials through to the mixing to obtain an even mixture. The powder preparation occurs below 200 °C followed by shaping the mixture, referred to the output as "green shape". The baking process occurs in high temperature of about 1000 °C in inert atmosphere, and this leads to volatile mass loss when temperature is about 300–550 °C. The mass loss estimated to be about 25% of the total mass of the coke and pitch mixture occurs at this stage. The carbonised material is impregnated with coal tar and baked again before the next stage. Graphitisation, the final process of graphite production, is very significant because at this stage, the carbonised material is transformed into graphite. Graphitisation process uses high temperatures, up to 3000 °C, which is three times higher than the baking temperature.

24.4.2 Material Flow

The flow of materials or processes associated with graphene ink production is graphically shown in Fig. 24.6. It has three main subdivisions including inputs (materials on the left-hand sides), processes (grouped in the middle of the flow) and outputs (materials at the right). Figure 24.6 shows that some output like graphite and graphene serves as input to pretreatment and sonication, respectively. Water represents the high flow of 20 kg, followed by DMF of 2.2 kg. Unexfoliated graphite represents the low flow of about 0.05 kg out of 3.2 kg of graphene ink. Figure 24.6 indicates that 95% of the HOPG is exfoliated into graphene (0.95 kg) indicating high efficiency of the process.

Unexfoliated graphite, 0.05 kg, accounts for a loss of 5% (maximum) for every 1 kg of graphite used which depicts less energy wastage under the material flow. The use of 30:70% ratio of HOPG to DMF, respectively, results in ink of high-level graphene concentration required to possess thermal and conductive properties needed for heating purposes.

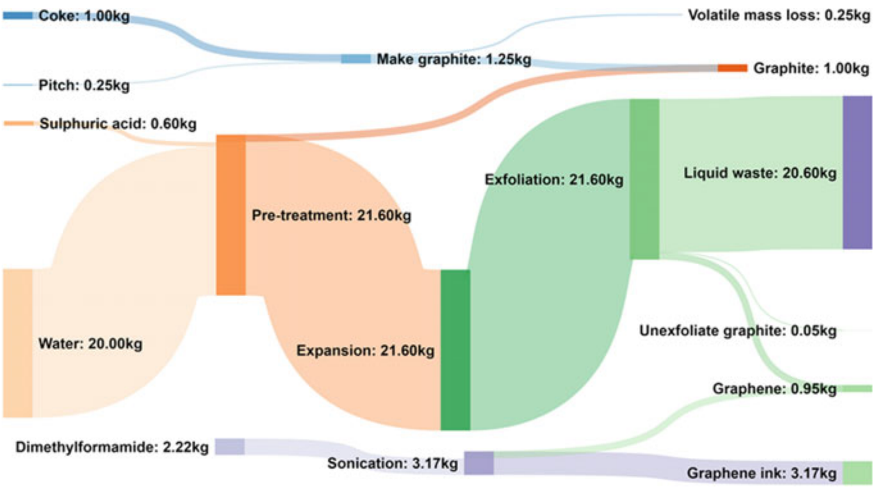

Fig. 24.6 Mass flow of processes or materials to produce about 3.2 kg of graphene ink

24.4.3 Estimated Embodied Energy

Graphite, the primary raw material for graphene production, requires about 237–260 MJ for every 1 kg produced. Table 24.1 shows the energy consumption of graphite production accounting for embodied energy of 1 kg of petroleum coke and 0.25 kg of coal tar pitch as 31–35 MJ and 90–103 MJ, respectively. The production processes including powder preparation, baking, impregnation and graphitisation require about 114–123 MJ of energy for every 1 kg of graphite produced and are captioned as “make graphite” in Table 24.1.

From Table 24.2, the embodied energy to produce about 0.95 kg of graphene is estimated to range between 252 and 290 MJ. This accounts for the energy consumption for the production of sulphuric acid at pretreatment (1.19 MJ), expansion (7.92–15.84 MJ) and ultrasonic exfoliation (5.83–11.66 MJ) processes as shown in Table 24.2.

The energy to produce 20 kg of water used in the pretreatment process is captured under miscellaneous in Fig. 24.8. Further analysis indicates that the estimated energy

Table 24.1 Estimated embodied energy for the synthesis of 1 kg of HOPG

Process/material	Quantity (kg)	Embodied energy (MJ)
Petroleum coke	1	31.94–35.17
Resin impregnated carbon	0.25	90.23–102.64
Make graphite	1.25	114.35–122.6
Graphite	1	236.52–260.41

Table 24.2 Embodied energy to produce about 0.95 kg of graphene

Process/material	Quantity (kg)	Embodied energy (MJ)
Graphite	1	236.52–260.41
Pretreatment	0.6	1.19
Microwave expansion	21.6	7.92–15.84
Ultrasonic exfoliation	21.6	5.83–11.66

Table 24.3 Embodied energy to produce about 3.2 kg of graphene ink

Process/material	Quantity (kg)	Embodied energy (MJ)
Graphene	0.95	251.46–289.1
DMF	2.22	201.97
Sonication	3.17	0.57–1.14
Graphene ink	3.17	454–492.21

to produce 1 kg of graphene ranging between 264 and 304 MJ is higher compared to 141–157 MJ of energy consumed for every 1 kg of copper produced [37]. This implies that every 1 kg of graphene produced requires about 90% more energy than 1 kg of copper produced.

Table 24.3 shows that every 3.2 kg of graphene ink produced consumes about 454–492 MJ of energy. This includes the energy usage for graphene production (251–289 MJ), DMF (202 MJ) and the sonication process (0.57–1.14 MJ). Further analysis shows that every 1 kg of graphene ink produced about 142–154 MJ of energy is consumed. This implies that every 1 kg of graphene produced uses 52% more energy than for every 1 kg of graphene ink produced.

24.4.4 Energy Flow

Figure 24.7 shows the flow of energy for graphene ink production. The dispersion process accounts for the high energy consumption representing about 202 MJ out of the average 473 MJ required for the graphene ink production. Next to dispersion is make graphite representing 119 MJ followed by pitch, 94 MJ and coke 34 MJ. Sonication represents the low energy usage of about 0.9 MJ during production of graphene ink. Miscellaneous (1.3 MJ) captures water and other raw materials which are used but not considered in the energy calculation.

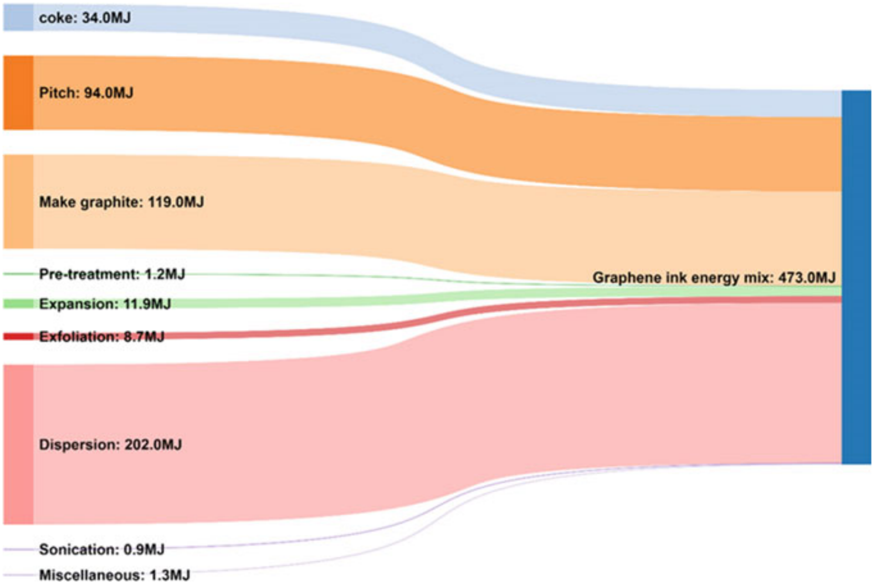

Fig. 24.7 Energy flow of processes/materials to produce 3.2 kg of graphene ink

24.4.5 Environmental Impact

Production of carbon materials is known for its associated environmental impacts of which graphene is not an exception. Figure 24.8 shows the LCA modelling of graphene using the "cradle-to-gate" approach. The results obtained from the analysis of the modelling are shown in Figs. 24.9 and 24.10.

Figure 24.9 shows that graphene production leads to high emissions into the atmosphere including CO_2 and dust particles. These are reported to be harmful to life and the environment at large. Furthermore, other emissions such as emissions into fresh water and sea water occur during graphene production from its feedstock and these directly contribute to environmental burdens when graphene ink is produced in commercial scale. The reduction or prevention of these emissions requires more energy for their treatment which contribute directly to high energy consumption during graphene ink production.

However, Fig. 24.10 indicates that serious non-lethal accident internally leads to the health and safety result during graphene ink production. This implies that the production of graphene ink has low risk of internal accident that may lead to loss of life.

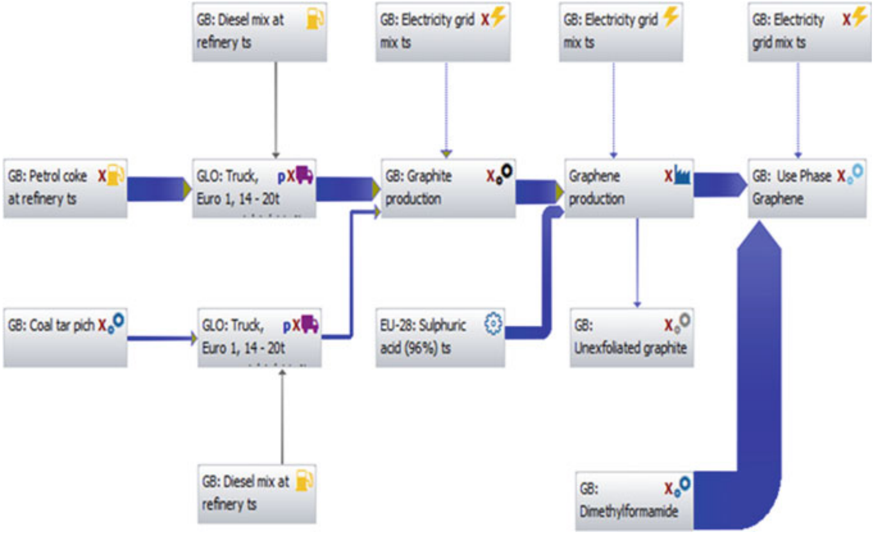

Fig. 24.8 LCA model of graphene capturing the cradle-to-gate approach

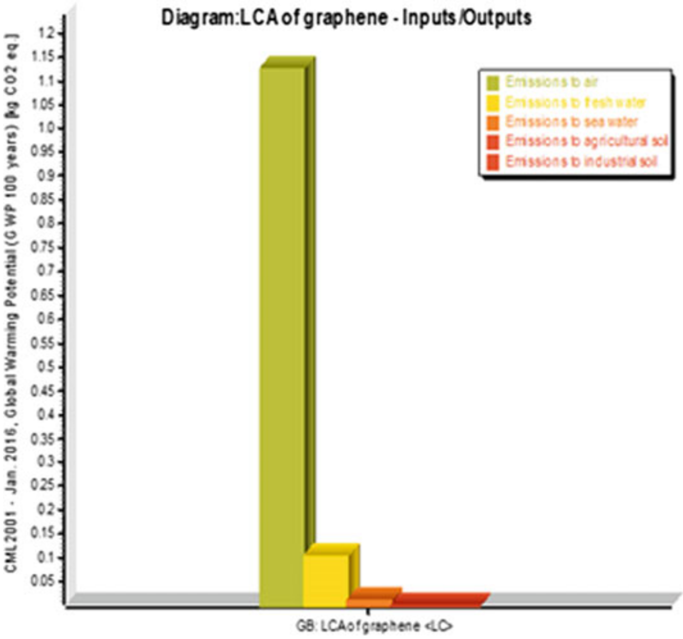

Fig. 24.9 Emissions associated with graphene ink production

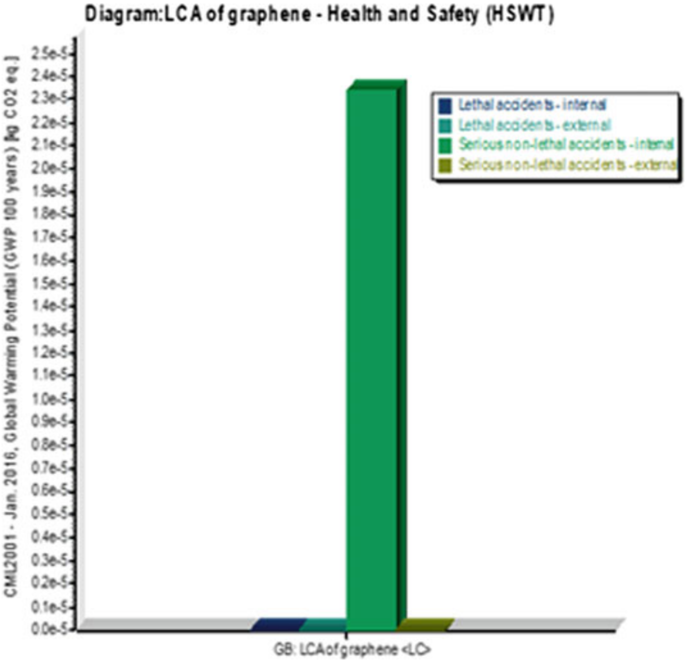

Fig. 24.10 Health and safety issues associated with graphene ink synthesis

24.5 Conclusion

The application of LCA to evaluate the energy utilisation and environmental impact associated with graphene heating element has been fully assessed by capturing all relevant production processes, the quantity of raw materials and their associated energy requirements. The aim of this research has been achieved because the process map, material flow and energy flow represent the LCA model of graphene as heating element. The results that were obtained from the analysis can be summarised below.

The result from the analysis shows that every 1 kg of graphene produced requires an embodied energy of 264–304 MJ.

Again, the result from the analysis indicates that 454–492 MJ of energy is utilised for the production of 3.2 kg of graphene ink. This shows that for every 1 kg of graphene ink produced about 142–154 MJ of energy is consumed. Based on this, it can be deduced that, 1 kg of graphene produced uses 52% more energy than the same quantity of 1 kg of graphene ink produced. It can be concluded that there is possibility of reduction in energy consumption of graphene towards the use phase which must be confirmed by further investigations.

Furthermore, the result from the LCA of graphene modelling indicates that emissions to air lead to all emissions associated with graphene production. These emissions show the environmental impact associated with graphene ink production from its ore. Although these emissions are harmful to life, the safety result shows that there is no serious internal accident associated with graphene ink production.

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Chapter 25
A Zero Energy Prefabricated ADU for New Zealand

Milad Moradibistouni, Brenda Vale and Nigel Isaacs

Abstract Human activities threaten the sustainability of energy and environmental resources. One route to alleviate this is that all buildings need to be zero energy in operation. This paper discusses the results of simulating the energy use of a prefabricated accessory dwelling unit (ADU) for different construction scenarios in Wellington, New Zealand. The aim is to see whether it is possible given the construction constraints to achieve zero energy for space conditioning. The simulation was first done using ALF 3.2 software, developed specifically for New Zealand conditions. Changes in each scenario relate to using different thicknesses of Structural Insulated Panels (SIPs) for walls and roof and considering different types of floor, together with different heating regimes. Using ALF 3.2 a total of 36 different scenarios were simulated to see how much energy the ADU needs during a year and where the main sources of energy loss and gain occur. The next stage was running the simulations while adding different degrees of thermal mass to selected designs to see the effect of mass on the ADU energy consumption. The last stage was amending the size of windows in the best performing designs in order to find the best balance between gains and losses through them. Simulation results showed that heating the whole ADU to 16 °C all day and using 165 and 215 mm SIPs panels for walls and roof, respectively, with the ADU sitting on a 150 mm insulated concrete slab delivers the best result, being very close to zero energy for space conditioning.

25.1 Introduction

Currently, humanity is using the earth's resources at a rate equivalent to 1.6 planets, and without change, it will be 2.0 planets by 2050 [1]. "By 2040, close to 65% of the world's population will live in cities, up from under 55%," and this is predicted to cause a 25% increase in demand for energy [2]. In 2016, over 81% of world energy and more than 99% of world CO_2 came from coal, oil, and natural gas, which

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all are non-renewable fossil fuels [3]. In 2015, the average concentration of CO_2 (399 ppm) was a 40% increase in comparison with that of the mid-1800s and was also the highest level in the last 800,000 years [4]. This CO_2 concentration is one of the main reasons behind global warming, which is predicted to rise by approximately 0.3 °C per decade (with an uncertainty range of 0.2–0.5 °C) in the next century [5]. Significant improvements in the building sector could help overcome the shortage of non-renewable sources of energy and reduce greenhouse gas (GHG) emissions as buildings and the activities inside them (embodied and operating energy) are responsible for over one-third of global final energy demand [6].

The story is same in New Zealand, where in 2017 the residential sector was responsible for the third highest energy demand of 11% after transport and industries at 39 and 37%, respectively. The building and construction industry was responsible for 4% of the industrial sector demand or just over 1% of the total [7]. So, in 2017, the construction industry and residential sector in New Zealand were responsible for over 12% of the total national delivered energy, which is equal to 71.54 PJ. The same report also showed that in the residential sector, electricity, fossil fuels, and renewable sources were responsible for 69, 17, and 14% of sector energy, respectively. However, just over 18% of this electricity was generated from fossil fuels, in this case gas, coal, and oil [7]. The Business New Zealand Energy Council developed two energy scenarios they named Kayak and Waka. In both scenarios, the residential and commercial sectors are predicted to have the biggest growth in demand for electricity [8]. This data shows the importance of having zero energy houses now to reduce total energy use and consequent environmental impacts in the future. This paper thus presents the results of three series of energy simulations using ALF 3.2 to see if it is possible to build a zero space heating energy, prefabricated ADU by making the best decisions in terms of choice of materials and construction types.

25.2 The Prefabricated ADU

Prefabrication is a method of construction where the whole building or parts of it are manufactured away from the final location, transported to site and attached to the foundation [9]. This method has the potential to use the resources of energy, water, and raw materials approximately 50% more efficiently than conventional construction, while also having 30–70% fewer environmental impacts and 35% fewer CO_2 emissions [10–13]. Most of these benefits come from having more control over the production process in the factory compared to on site. ADUs are secondary dwellings constructed on an existing house lot that provides full living facilities for the occupants independent of the primary house [14]. ADUs can provide more houses without the need for new infrastructure and with the least change to the local environment. Combining the advantages of prefabrication with the concept of ADUs could provide more energy efficient and environmentally friendly houses in a relatively short time.

25.3 Methodology

The prefabricated ADU was designed as part of a larger PhD project. The design was affected by considering New Zealand ADU-related council rules, transport limitations, and accessibility considerations for older people, as this sector of the population is growing fast and could form a market for smaller dwellings in existing communities that are easy to keep warm. This paper focuses on simulating the energy efficiency of the selected design (Fig. 25.1), using a deductive approach. In this approach, three series of simulations (over 50 in total) were run to eliminate the less energy efficient scenarios at each stage and narrow the available options to the one nearest to zero energy at the end. In this study, zero energy only refers to the delivered energy needed to space condition the dwelling. It excludes other operational energies, such as those for lights and appliances, and at this stage does not consider embodied energy. It also excludes possible energy generation on site by using photovoltaic panels.

From the available simulation software, ALF 3.2, which was developed by the Building Research Association of New Zealand (BRANZ), was selected to evaluate the operating energy [15]. ALF was designed for calculating the energy performance of conventional houses in New Zealand and determining the Building Performance Index (BPI). The BPI shows the compliance of the house with the Energy Efficiency Clause H1 of the New Zealand Building Code. Clause H1 monitors temperature, humidity, and uncontrollable airflow in houses with the aim of keeping the BPI below 1.55 [16]. ALF provides a context for comparing the energy efficiency of different designs to see the effects of different insulation levels, window types, building orientation, and degrees of thermal mass. ALF collects data under the six main categories of climate and heating level, floors, roof/skylights, walls and windows, mass, ventilation, and moisture. The word "roof" represents the ceiling of the ADU made

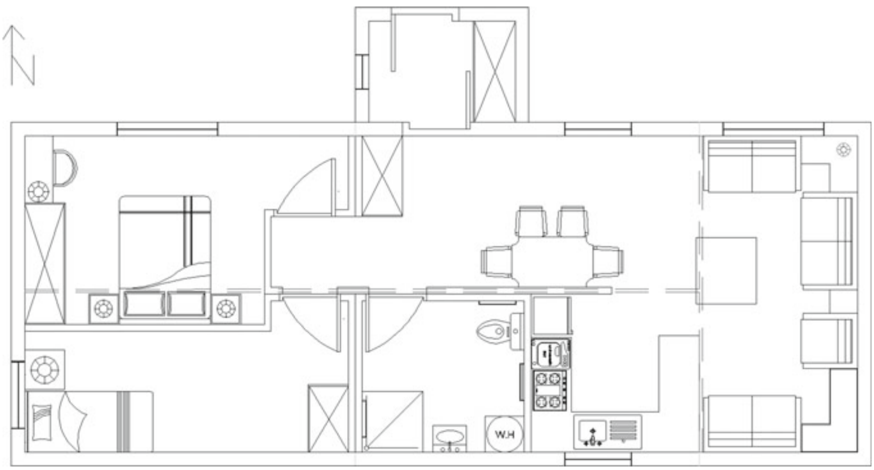

Fig. 25.1 The ADU plan

Table 25.1 Variable items used for simulations

Category	Variables	Variable values
Climate and heating	Heating level	16 °C
		18 °C
Suspended floor	Thickness—*R*-values	115 mm–2.6 m^2 °C/W
		165 mm–4.0 m^2 °C/W
Roof	Thickness—*R*-values	115 mm–2.8 m^2 °C/W
		165 mm–5.2 m^2 °C/W
		215 mm–6.9 m^2 °C/W
Wall	Thickness—*R*-values	115 mm–3.3 m^2 °C/W
		165 mm–5.3 m^2 °C/W

of Structural Insulated Panels (SIPs). A SIPs panel is a thick layer of rigid insulation sandwiched between two skins of plywood or oriented strand board. When joined together, these panels form the structure of the wall, and in this case the ceiling, which is then covered with a trussed rafter roof as the waterproof covering. Moisture analysis of the ADU is not included in this paper.

Each of the ALF categories consists of subcategories, which can be classified into fixed and variable items (Table 25.1). Fixed items were consistent during all simulations, while one variable item was changed in each simulation, to discover its effect on the required space conditioning of the ADU. Out of 36 initial simulations, two designs with the lowest requirement for energy, one with a suspended floor, and one with a concrete slab were selected for the next stage of simulations. These two scenarios were then simulated with different degrees of concrete as thermal mass. This led to a further four simulations. The most energy efficient scenario in this second round was then simulated with different window areas to find the most efficient window to floor plan area ratio.

25.4 Fixed and Variable Items

The ADU is made of five main prefabricated modules each 5.1 m × 2.55 m × 2.4 m. It has two bedrooms, a living room, a kitchen, a bathroom, and a prefabricated entrance module of 2.1 m × 1.9 m × 2.4 m. The size of each module was based on the maximum allowed size of loads before needing to apply for oversize load permissions. The maximum dimensions are 2.55 and 20 m, respectively, for width and length of loads, while the height can be a maximum of 4.30 m, including the truck height [17]. The ADU was designed with two types of window of 2 m × 1.2 m and 0.8 m× 1.2 m (Fig. 25.1).

In terms of the fixed items in ALF, the ADU is located in Wellington on a plot with a medium level of shelter, with 2 occupants, and is heated 24 h. The suspended floor version had a continuous perimeter wall with a height of 0.15 m, sheltered from the wind. In the concrete slab version, the slab is fully insulated with an *R*-value of 5.2 m^2 °C/W. The soil conductivity was equal to 1.2 W/m °C. Windows were PVC or timber frames with clear Insulated Glass Units (IGU)/Low E + Argon fill. The ADU was classed as airtight, being a post-1960 simple shape. In all scenarios, the kitchen had a window mounted extract, working 1 h/day. and the bathroom had an extract humidistat or light controlled extractor. There is no chimney, metal fluid heater, or thermal mass in the walls. The three groups of variable items are the heating level, the thickness of walls and roof, and the floor type and thickness (Table 25.1). The ADU Structural Insulated Panels (SIPs) are made of 12 mm oriented strand board on each side with different thicknesses of polyurethane in between. The resultant different *R*-values formed the variable items in the first series of simulations (Table 25.1).

25.5 First Series of Simulations: Evaluating the Effects of Variables

Changing the variable items in the first series of simulations produced 36 different scenarios. Table 25.2 shows the details of scenarios 31 and 35, which had the least required heating for a slab and a suspended floor. There was no need for cooling. It was not possible to include all scenarios in the table due to lack of space.

Scenarios with a heating level set at 16 °C and with a 150 mm slab consume less energy than those set at 18 °C with a suspended floor, although these differences could have been predicted. Figure 25.2 shows the level of difference between the required heating for scenarios set at 16 and 18 °C has an inverse relationship with the *R*-value of the roof and walls. The difference between the required heating of scenarios 1 and 2, with 115 mm SIPs panels in both walls and ceiling, was 495 kWh, while for scenarios 35 and 36, with 165 mm panels for walls and floors and 215 mm panels for the ceiling, was 252 kWh. The average difference between scenarios set at 16 and 18 °C was 344 kWh (Fig. 25.2). Similar relationships were found when comparing scenarios with a suspended floor with those with a slab, although here the levels of difference are smaller than for the comparison of scenarios with different heating level settings.

Table 25.2 Variations in scenarios with least required heating

Scenario	Heating level	The thickness of the floor		Wall thickness	Roof thickness	Required heating (kWh)
	16 °C	Suspended floor 165 mm	150 mm concrete slab	165 mm	215 mm	
31	∨		∨	∨	∨	1361
35	∨	∨		∨	∨	1391

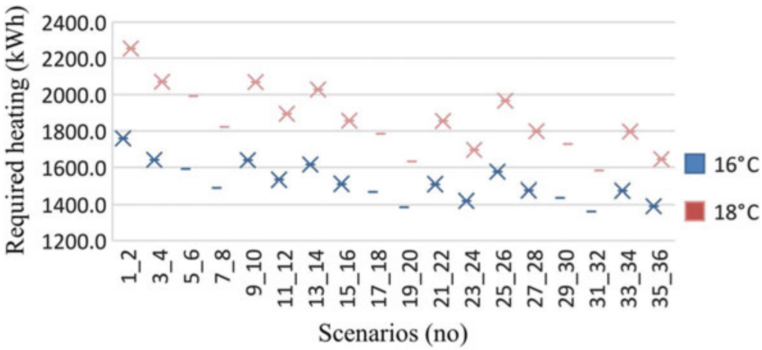

Fig. 25.2 Annual energy requirements of different heating settings (a line indicates scenarios with a slab and a cross with a line through those with a suspended floor)

At this stage scenario 31, with the lowest heating energy consumption of all versions with a slab, and scenario 35, with the lowest for all versions on a suspended floor, were selected for the next series of simulations. Scenario 19 with a concrete slab with 165 mm wall and ceiling SIPs was the next lowest at 1385 kWh and thus slightly higher than scenario 31 at 1361 kWh.

25.6 Second Series of Simulations: Evaluating the Effects of Adding Thermal Mass

Table 25.3 shows the effect of different degrees of mass on the required heating for scenarios 31 and 35, which was the only variable in this round of simulations. ALF 3.2 has a specific tab for adding layers of mass, which means the floor is made of concrete but is not inserted in this table, and the software does not consider it as thermal mass. Doing this, the area of mass was 64 m^2 with no mass in the walls.

Table 25.3 confirms that having higher degrees of thermal mass can decrease the energy consumption of the building by storing heat in the mass and thus making use

Table 25.3 Effect of thermal mass on the heating requirements of the ADU

Scenarios	Degree of mass	Required heating (kWh)	
		No mass	With mass
31	50 mm slab with full insulation	1361	597
	100 mm slab with full insulation	1361	464
	150 mm slab with full insulation	1361	448
35	50 mm concrete block on suspended floor	1391	629

of both solar and peak incidental gains [18, 19]. Table 25.3 shows having a 50 mm concrete slab, which is too thin for general use, and a layer of 50 mm concrete blocks on a suspended floor can decrease the required heating by approximately 56% in scenarios 31 and 35. Doubling and tripling the thickness of concrete in scenario 31 increases the reduction from 56 to 66 and 67%, respectively. This shows a diminishing return in energy reduction for the level of mass [20]. Despite this, at this stage, scenario 31 with its fully insulated 150 mm slab was selected as the most energy efficient scenario for use in the last series of simulation

25.7 Third Series of Simulations: Optimizing the Windows Sizes

The aim of this series of simulations was to modify the area of windows to achieve the best energy balance between losses and gains. Before modification, there were three windows in the north facing wall, each 2.0 m × 1.2 m, two in south-facing wall and one in west side of the ADU, each 0.8 m × 1.2 m giving a total of 10.0 m^2 of windows. After modification, there were still three windows in the north facing wall, two of 1.5 m × 1.2 m and one of 1.0 m × 1.2 m, one in the south-facing wall and one in the west wall of the ADU, each 1.0 m × 1.2 m, giving a total of 7.2 m^2 of windows. This final number and area of windows followed after 20 simulations testing the effect of different window areas and windows facing in different directions on the required heating for the ADU. Decreasing the area of the windows from 10.0 to 7.2 m^2 can reduce the required heating of the ADU from 448 to 423 kWh which is approximately a 6% reduction.

25.8 Final Simulation of the Most Efficient Scenario

Figure 25.3 shows the results of the final simulation of scenario 31 with 150 mm slab and the modified windows.

Based on Fig. 25.3, air leakage and the external walls are the main sources of energy loss in the ADU, being responsible for respectively 30 and 21% of annual energy loss. After this, windows and slab floor each account for 18% and the roof for 13%. When it comes to the gains, there are two main sources of solar and internal gains. The latter includes the heat produced by the ADU occupants, appliances, and the production and usage of hot water. ALF calculated the internal gains as equal to 1614 kWh (64% of all gains), and the solar energy gain was 901 kWh. However, it should be noted that all of these gains are not useful, and the total useful gain was 1149 kWh or just over 45% of total gains. This means the total annual energy balance of the ADU is −423 kWh, which represents the total annual heating requirement. Additionally, the ADU BPI is 0.61, which is less than half the upper

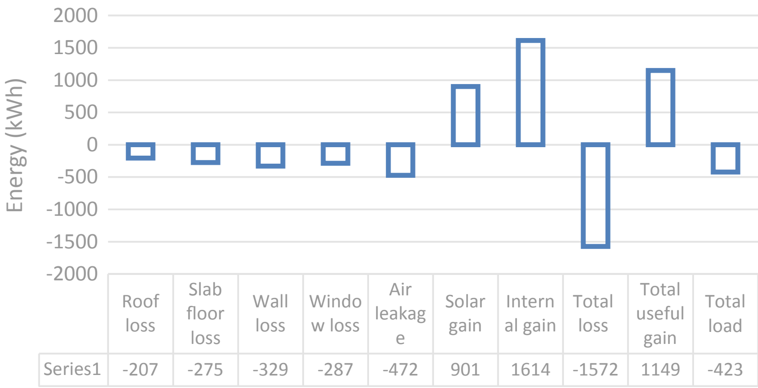

Fig. 25.3 Scenario 31, the final simulation result

limit of 1.5. Another issue is that the various versions of ALF were designed based on conventional New Zealand house building methods and materials, while the ADU is prefabricated and made of SIPs panels, which potentially should give an up to five times more airtight construction than conventional materials [21]. This means that the air leakage from the ADU would be less than 472 kWh. However, as there is no tab for making these changes on ALF, this amount was accepted as the final air leakage.

At this stage, to make the ADU closer to being zero energy, a heat recovery system was selected as a design option. A heat recovery system can reduce both air leakage and the heating/cooling energy load [22, 23]. These systems are available in different efficiencies, although the majority of documents accept 80% [24–26]. Accepting the ADU is very well sealed this means the heat lost through the ventilation air, which is assumed to be the same as the air infiltration heat loss, could be reduced by 80%. This would give a ventilation heat loss of 94 kWh, reducing the final energy requirement to 43 kWh/year. This amount could be generated by using photovoltaic panels on the roof of the ADU [27].

25.9 Discussion and Conclusion

Running over 50 different energy simulations of the prefabricated ADU showed there are many factors affecting the energy needed to keep the house within the comfort zone. Although a 16 °C set level sounds low, this was for whole house heating. Given the highly insulated nature of the SIPs panels, the radiative heat loss from the occupants will be less than for a less well-insulated building, and they will feel comfortable at lower air temperatures. Using this lower setting was useful, as setting the heating level to 18 °C increased the annual energy requirement by 496 kWh.

The next factor was the effect of changing the R-value on the annual energy needs of the ADU. With the heating level at 16 °C, the simulation results showed that increasing the *R*-value of the walls from 3.3 to 5.3 m^2 °C/W decreased the required annual heating by over 100 kWh (scenarios 1 and 3). Improving the *R*-value of the roof, first from 2.8 to 5.2 m^2 °C/W and then to 6.9 m^2 °C/W, respectively, cut approximately 145 and 184 kWh from the required energy. Despite the positive effects of higher *R*-values, the subsequent impact of these changes on the thickness of panels should be considered carefully, especially in prefabricated ADUs, as it can affect their transportability. Table 25.1 shows that adding 2 m^2 °C/W to the *R*-value of the walls increases their thickness from 115 to 165 mm. Similarly, adding 2.4 and 4.1 m^2 °C/W to the ceiling *R*-value increases the thicknesses of panels from 115 to 165 and 215 mm. This can make each module 100 mm bigger in all directions.

Next was the type of floor, which could be suspended or a concrete slab. Increasing the thickness of the suspended floor from 115 to 165 mm by adding more insulation can reduce the required heating by 120 kWh a year. Replacing a 165 mm suspended floor with a 150 mm insulated concrete slab on the ground decreased the required heating of the ADU by 48 kWh a year. The advantage of a suspended floor is that the SIPs floor panels can be attached to the walls in the factory, while with a concrete slab the walls have to be attached to the slab on site. Attaching the walls to the floor in the factory means more control over joints and better continuous insulation while attaching the walls to the slab on site means more time on site and the possibility of more defects. However, transport limitations should be considered for a factory made insulated suspended floor, so the height of the modules is not too great. The other differences between the suspended floor and concrete slab are the fact the latter includes 150 mm of thermal mass, which the suspended floor lacks, and adding some degrees of mass could affect the transportability of the ADU. This is crucial because Table 25.3 showed the importance of having a degree of thermal mass in the ADU.

Modifying the windows was conducted considering the direction of the ADU, which was fixed, and also the characteristics of the site in Wellington. Different simulations showed that the solar gain, mostly from the windows was always more than windows losses, by up to over three times. However, Fig. 25.3 showed that air leakage is the main source of loss in the building, so it is essential that windows and doors with good seals are specified so the ADU is as airtight as possible, leaving the heat recovery systems to bring in the fresh air. Having smaller windows also reduces the risk of infiltration and the simulations showed by reducing the area of windows the reduction in losses is more than the reduction in gains. As a result of this specific project and location, smaller windows can improve the energy efficiency of the ADU. However, the amount of natural light inside the ADU is another factor to be considered as this also depends on the area of windows. Moreover, the direction of windows can affect the energy efficiency of the ADU, and rotating the ADU may lead to different final energy requirements. This remains to be explored further.

Finding the best scenario by adding thermal mass and modifying the area of windows ended with an annual ADU energy use of 423 kWh. At this stage, a heat recovery system was used to cut the air leakage loss by 80%, ending with 43 kWh/year as the annual energy space conditioning requirement of the ADU, which is near to being zero energy. What this shows is that making the right technical decisions can potentially reduce the heating load of the ADU by over 90% (compared with scenario 31 in Table 25.2).

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Chapter 26
A Survey on Energy Efficiency in Metal Wire Deposition Processes

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Abstract Additive manufacturing (AM), which includes different technologies, allows free-form parts to be produced flexibly by selectively depositing material layer after layer. Among the various AM processes, metal wire deposition (MWD), which uses a metal wire melted by a high-energy source as feedstock, has been found to be suitable for the manufacturing of low-complexity, medium-to-large components at relatively high deposition rates. Some industrial applications have been identified, despite the quality of the as-deposited surfaces, which usually require further finishing operations. Several researches have been focused on process optimization. However, there is still a lack of consolidated knowledge concerning the environmental impact and the energy efficiency of MWD, aspects that are critically surveyed in this paper. First, the unit process level is considered, and an analysis of the needed specific energy input, while the wire flow rate and the deposited materials are varied, is carried out. Second, a framework is proposed to assess the energy requirements under a cradle-to-gate perspective.

26.1 Introduction to Metal Wire Deposition

Metal wire deposition (MWD) defines the additive manufacturing processes, whereby a metal wire is melted through a heat source and deposited onto a layer-wise structure with the purpose of creating or repairing parts [1, 2]. MWD-based

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processes are generally characterized by high deposition rates, as well as material and equipment cost-effectiveness [3], and are able to generate high-density parts that show good structural integrity [4, 5]. MWD, which is one of the direct deposition processes, represents a potential solution to the production of medium-to-large products [5, 6], whose dimensions would otherwise encounter limits if manufactured by means of powder-bed (PB) technologies [7]. Another difference between direct deposition processes and PB ones is the opportunity MWD offers to create functionally graded materials (i.e., structures with different properties in specific locations) [8, 9]. Moreover, MWD has been shown to be flexible and to have an open architecture. During manufacturing, rotation and translation motions can be driven by exploiting robots or CNC gantries [4]. However, the use of wire instead of powder as feedstock material also involves significant effects on the process. The beads created during MWD (e.g., WAAM) are characterized by a width of 1–2 mm, whereas the beads deriving from powder-bed processes range from a few micrometers to 1 mm at most. This difference enables a higher (even up to 16-fold) deposition rate (DR) [2, 10], thus allowing large parts to be produced in a short time [4]. The typical deposition rate values are of the order of some kg per hour (e.g., 2–10 kg/h) [4, 11], depending on the combination of heat source and deposited material. Moreover, DR values can be doubled, if the use of a tandem torch is exploited [12]. Higher DRs can be reached, but the higher they are, the lower the feature resolution [4]. Too high DRs could thus be counterproductive, since more post-AM machining operations would be needed [10]. Parts manufactured, starting from a wire feedstock, are characterized by high quality and full density. The risk of contamination of the material feedstock is lowered with wire [13], since the surface area is less than that of the equivalent mass amount of powder [14], especially for such reactive materials as Ti and Al [7] and for the materials required in aerospace applications [13]. Moreover, wire-deposited parts might show lower porosities than parts obtained from PB processes [15], as well as satisfactory structural integrity [9].

The main challenges of MWD regard the residual stresses and the surface finish (in the same way as for other AM processes), which is notoriously lower than in PB processes [11, 16]. Residual stresses and distortion can be traced back to the lack of uniformity in the heat history of the component and solved or avoided through (i) the partial clamping of the part [9], (ii) the use of rollers, or (iii) the adoption of thermo-mechanical post-processes [17, 18]. Not only is the choice of the correct heat source for a certain material fundamental, but the identification of the optimum set of process parameters also plays a crucial role in the microstructure and, thus, in the mechanical properties of a part [8]. The importance of in-process monitoring should be underlined [6], as well as the use of non-destructive techniques, such as iterative learning control, laser vision sensing, and others [19] to avoid the risk of generating defects and to ensure an acceptable quality of the part [5].

Different heat sources are available for wire deposition: laser beam, electron beam, and electric arc (WAAM). Three main variants exist for the generation of an arc: gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW) [20, and references therein]. Moreover, sub-variants of these processes have been developed over the years, such as cold metal transfer

(CMT), which is also available in variable polarity deposition mode (VP-CMT [2]), or double electrode GMAW (DE-GMAW), which uses a GTAW torch to provide the bypass current [21]. These processes primarily differ according to their material supply modality, since GMAW and CMT exploit consumable electrodes, and adopt a coaxial wire torch configuration. Instead, in PAW and GTAW, the wire is fed separately off-axis. Despite this, a TopTIG technique has been tuned, on the basis of a TIG welding technique, but with coaxial wire [22].

Different topics related to metal wire deposition have been investigated over the years: design (e.g., deposition paths, adaptive path generation, and cross-structures), process variations (e.g., hybrid manufacturing and twin-wire deposition), residual stresses (distortion control and microstructure), and forming appearance (e.g., bead overlapping and arc state control) [10]. Some researchers have recently (2018) focused on such themes as an accurate selection of the parameters that affect the thermal history of the components, together with microstructure control, non-destructive testing applications, and new wire deposition techniques [23–31]. Only a few studies have addressed the cost-related aspects or environmental impact assessments [32–34], and the literature lacks information concerning the process efficiency of wire-based additive manufacturing techniques. The present paper aims to discuss the energy efficiency of MWD processes. The energy requirements, at both the unit process level and in a cradle-to-gate scenario (including the material production and the post-AM phases), are herein surveyed on the basis of the existing literature.

26.2 Energy Efficiency at the Unit Process Level

Several papers that have analyzed the influence of variations in the main parameters on the performance of the MWD process are available in the literature. Some of the studied parameters are: (i) the laser output power, (ii) the travel speed, (iii) the wire feed rate, (iv) the wire diameter, (v) the wire material, and (vi) the idle time, and (vii) the deposition path. Most of the existing studies were aimed at understanding the effects of these parameters on the quality of the deposition process. Table 26.1 lists the variation ranges of the factors used in the assessment of laser-MWD (L-MWD) processes, which are here considered for the sake of brevity. These studies were generally carried out on the basis of factorial plans, defined by means of the design of experiment techniques, and were targeted at understanding the effect of individual factors and their interactions. Laser output power can be generated by fiber or diode lasers [14, 29, 35–45], CO_2 lasers [46], and Nd:YAG lasers [13, 47, 48]. Different materials have been considered, with wire diameters ranging from 0.8 to 1.6 mm. The wire feed rate is usually kept between 6 and 60 mm/min; however, this value must be chosen according to the laser output power and the travel speed. In fact, Froend et al. [14], who adopted a travel speed of 1 m/min and a laser output power of around 3.5–4.5 kW, found higher values (Table 26.1). Combinations of factors that have led to a stable and qualitatively satisfactory process as well as unattainable process combinations have been identified within the ranges proposed in Table 26.1. Output

Table 26.1 Investigated parameter variation ranges for laser-MWD processes

Material	Wire diameter (mm)	Input power (W)	Travel speed (mm/min)	Wire speed (mm/s)	References
ER308 Si	1.2	2400–3000	1100–1250	8.3–50.8	[46]
ER70-6	1.0	2700–3000	900–1250	15.0–57.2	[46]
AISI 316L	0.8	1600–3200	180–540	26.6–53.3	[35]
AISI 316L	0.8	1000–1300	n.a., 240	12.5–43.7	[36, 37]
AISI 308	1.0	1000	1000	20.0	[29]
AISI 308L Si	1.2	1250–2000	150–500	10.0–50.0	[38]
AISI 308L Si	1.2	1600–2000	175–250	13.3–30.0	[39]
AISI H11	1.2	845–945	400–600	6.7–12.0	[40]
Ti–6Al–4V	1.2	3500	600	40.0	[48]
Ti–6Al–4V	1.2	1200–2060	50–400	14.3–55.5	[41]
Ti-6Al-4V	1.2	2625–3500	450–600	30.0–40.0	[13]
Ti–6Al–4V	1.0	1000–2000	600–750	10.0–31.3	[42]
AA5087	1.0	3500–4500	1000	16.6–166.6	[14]
AA5087	1.0	4500	5000	166.6	[43]
Inconel 625	1.2	1000–1800	102–510	6.7–23.3	[44]
Waspaloy	1.2	2000	102	25.0	[45]
ZE41A-T5	1.6	2250–2750	2000–3000	50.0–83.3	[47]

Some values have been deduced by the authors from the original publications

variables such as (i) the absence of defects, (ii) microstructural homogeneity, (iii) vibrations that are created in the feed system, (iv) the thermal cooling rate of the flow, (v) porosity, (vi) the lack of filling, and (vii) the geometrical response were assumed as metrics for the quality assessment. Once the type of laser has been chosen, the first parameter that needs to be identified is the laser spot [38], which is chosen according to the targeted melt pool size. The melt pool has to maintain a certain width in order to keep on melting the continuously fed-in wire [39]. Consequently, only a careful setup of the wire, in relation to the melt pool [49], and of the process parameters can prevent the generation of defects in the part, thus leading to the best condition while depositing material. Next, the three main parameters that drive MWD in this phase are the laser output power, the travel speed, and the wire feed rate. Their combination is responsible for the amount of the mass that is deposited and the energy delivered for the melting. Consequently, when the laser power and the traverse speed are kept constant, (i) if the wire is fed into the melt pool too rapidly, the melting will be incomplete or lacking, while (ii) if the wire is fed too slowly, droplet-wise deposition will occur [41]. The power is instead directly responsible for the energy delivered to the melt pool; hence by fixing the travel speed and wire rate, the higher it is, the lower the height of the beads [38]. The same effect is obtained by decreasing the traverse speed and maintaining the same power and the same wire rate. On the other hand, high power can lead to macro-porosities [14, 42]. Other parameters that can affect the generated heat flow are the geometry of the workpiece and its temperature [6]. The preheating of samples has shown a decrease in the needed energy input [14].

The choice of the process parameters obviously influences the energy efficiency performance. By referring to the data available in the literature, and per each experimental test, it has been possible to compute the here-defined ‘specific energy input’ (SEI), that is, the ratio between the laser output power and the material flow rate (which, in turn, can be obtained by multiplying the cross-sectional area of the wire by the wire feed speed and the material density). This indicator, which is plotted as a function of the material flow rate in Fig. 26.1, allows the energy input to the material (in MJ), provided by the laser source, necessary to deposit a unit mass of material (in kg), to be quantified. It is worth remarking that only the SEI values corresponding

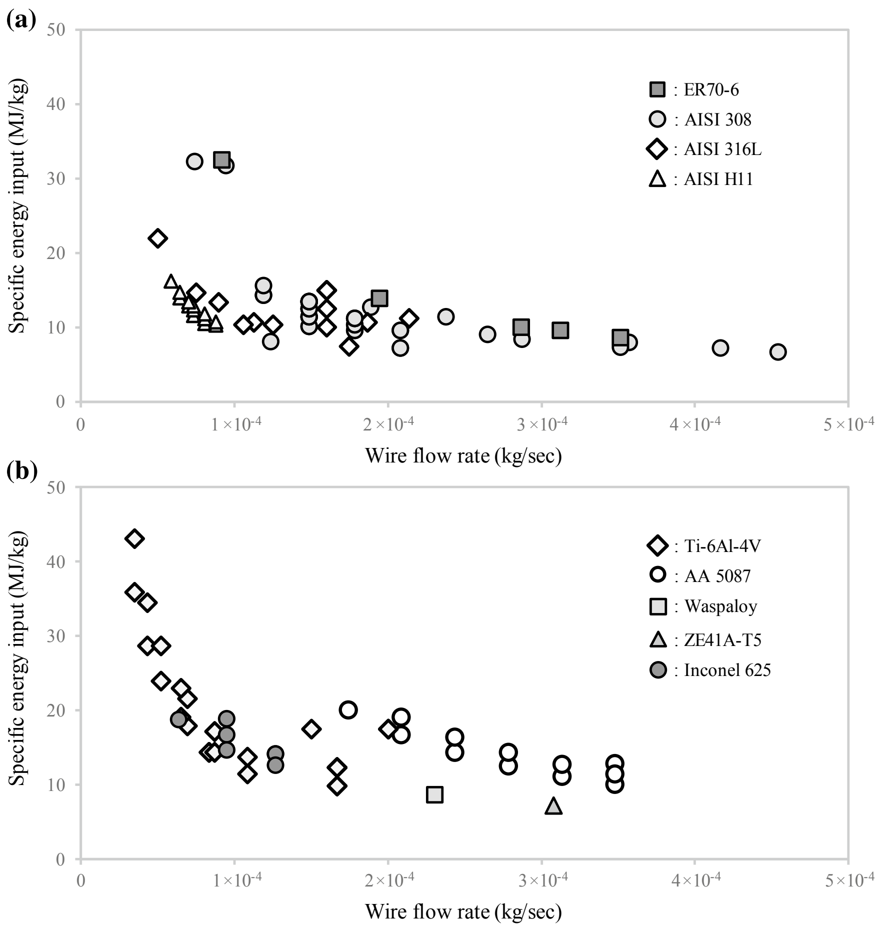

Fig. 26.1 Specific energy input (SEI) for steel (**a**) and other materials (**b**)

to the combinations of process parameters that lead to satisfactory quality and stable process conditions are plotted in Fig. 26.1. Variations in the combination of process parameters could also lead to comparable SEI values and wire flow rates, but the quality of the part might be unacceptable.

The specific energy input does not correspond to the specific energy consumption (SEC) defined in Kara et al. [50], because the SEI parameter does not consider all the energy losses in the laser delivery fiber, in the laser source or, more in general, in the entire machine architecture. In other words, the SEI value represents only a partial contribution to the total electric energy consumption of the L-MWD system. In fact, the total electric energy consumption of an MWD system should also include (i) the efficiency of the laser system, (ii) the energy consumption during non-productive times (such as the setup and dwell times), (iii) the consumption of all the auxiliary equipment, and (iv) the usage of the consumables (such as shielding gases).

26.2.1 Energy Consumption During Non-productive Times

The idle energy consumed by a machine when operating in standby mode (i.e., during the setup or such post-processing operations as substrate loading, part unloading, programming) should be added to the energy consumption during deposition. Moreover, wire-based AM techniques transfer a large amount of heat to the existing structure. The introduction of dwell times between the deposition of subsequent layers is necessary, and this has to be accounted for when quantifying the energy efficiency of the process. These times allow the base to be cooled and the as-deposed material to be consolidated [25]. Some authors have shown that it can be useful to add a rolling pass or a machining pass during these pauses. For instance, Gu et al. [23] studied the microstructural deformation and the strengthening mechanisms of a wire arc additively manufactured Al–Mg 4.5 Mn alloy, caused by an inter-layer rolling process carried out on the top surface of each layer. These rolling passes improved the micro-hardness of the samples and also reduced the grain size, with a consequent improvement in the yield strength. Hönnige et al. [24] used two different rolling techniques to control the residual stresses on samples made of ER2319 (an aluminum alloy) by WAAM. Inter-pass vertical rolling was applied to the top of the samples. Side rolling was instead applied to the side surface of the samples, after they had been completed. The first technique reduced the out-of-plane distortion, but produced a particular residual stress profile. Side rolling was even more effective and inverted the distortion. Karunakaran et al. [9] applied a machining pass after each deposited layer by integrating CNC machining and GMAW for the creation of a near-net-shape part. A face-milling pass along the growth direction prevents the oxides and the scallops from affecting the surface quality, due to a cumulative error effect.

26.2.2 *Energy Consumption of Auxiliaries and Consumables*

Focusing on the AM stage, it is possible to make a list of some common equipment: (i) CNC or robot systems to move the heat source and/or the part, (ii) gas and fume extractors, (iii) cooling systems (such as impinging air jets [26], or water-cooled workpiece tanks [51], and (iv) computers. This equipment all contributes to the total energy consumption of the process and also affects the energy efficiency. Moreover, all the MWD techniques share the need of a shielding gas to protect the melt pool. The most frequently employed are pure argon, pure helium (or a mix of the two), and other blends of argon + CO_2 or argon + H_2. The selection of the shielding gas depends on the adopted process [22]. The energy necessary to produce the shielding gas (i.e., its embodied energy) should also be included in the total energy balance.

26.3 A Cradle-to-Gate Energy Efficiency Assessment

An LCA-based energy efficiency assessment of metal wire deposition should not only be limited to the manufacturing process, but should also include the raw material production, the pre-manufacturing and the post-AM finishing phases [52, 53], as proposed in Fig. 26.2 (adapted from [54]).

26.3.1 *Material Production and Pre-manufacturing*

The material-related impacts assume a crucial role in the assessment of the environmental performance, particularly when AM-based approaches are compared with conventional manufacturing [55]. All the material and resource flows can be translated directly into primary energy flows; therefore, material usage contributes to the

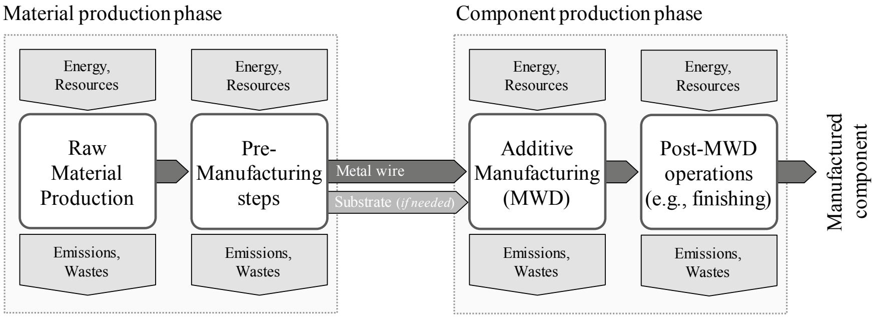

Fig. 26.2 A framework for assessing the environmental impact of an MWD-based process considering cradle-to-grave system boundaries

efficiency analysis as far as the cumulated energy of a given manufacturing approach is concerned. Raw materials have to be extracted and refined in order to obtain the in-stock materials. These raw materials then have to be further processed (e.g., by means of hot rolling and wire drawing [34]) in order to produce the metal wire. Each additional unit process suffers from its own material losses and has its own resource/energy demand and carbon dioxide emissions.

26.3.2 Material Losses and Material Savings

The mass of the wire generally has to compensate for the mass of the finished part, the mass of the imposed machining allowance for the finishing operations, and the mass of the in-MWD process material losses. Moreover, a substrate on which the part is built is needed in some approaches, and this unit process (if present) has to be included in the assessment, as detailed in Campatelli et al. [33]. The in-process material losses are lowered through the use of wire-based AM processes [56], as the wire melts completely during manufacturing [4, 57], and the material usage efficiency is almost 100% [41, 58]. Vice versa, powders are susceptible to being partially blown outside the melt pool [41]. When enabling significant material savings, an AM-based approach also appears to be highly beneficial from the environmental point of view. Williams et al. [4] reported two cases of WAAM parts which enabled a huge amount of material saving to be achieved. One such case was that of an aluminum wing rib, originally machined from a solid piece of 670 kg to reach a final weight of 18 kg, with a buy-to-fly (BTF) ratio of approximately 37. The same geometry simultaneously deposited by two robots in an open chamber led to a BTF ratio of 12, with a material saving of 216 kg. A 28.8-kg titanium external landing gear assembly decreased from 10.4 to a BTF of 1.2. The material and cost savings are evident, because of the reduction in the needed machining, as well as in the use of expensive dies [6]. Thus, MWD appears to be an encouraging manufacturing route for aerospace and defense industries, where BTF ratios are generally high [8, 59].

26.3.3 Post-MWD Operations

Machining operations are usually mandatory on parts realized by means of wire deposition [4, 8, 60], since the as-deposited surfaces are characterized by poor roughness and evident stair steps [16], which makes wire deposition suitable for near-net-shape parts but not for net-shape parts. For this reason, realizing components with a low level of complexity is preferable, e.g., by completely avoiding internal cavities [59]. Therefore, it is possible, through MWD, to create preforms [22] that are subsequently machined, thus saving the costs of billets and dies [4]. MWD processes (as others AM technologies) are not intended to supersede conventional manufacturing processes, but they can coexist complementarily [21]. Moreover, different heat treatments can be considered. Bermingham et al. [61] applied different post-heating processes: (i) stress relief, (ii) hot isostatic pressure, (iii) vacuum annealing, and (iv) solution treatment plus aging, to Ti–6AI–4V components produced by WAAM. Even a preheating treatment can be applied to reduce porosity, as shown in [14]. Thermo-mechanical surface post-treatments (i.e., laser shock peening) are also possible [17].

26.4 Conclusions and Outlooks

Metal wire deposition-based technologies are direct energy deposition processes that are suitable to additively manufacture three-dimensional, low-complexity, medium-to-large components at relatively high deposition rates and starting from a metal wire as a feedstock. The here-proposed survey of the literature has shown that considerable efforts have been made to optimize the process parameters, in order to minimize the defects that may occur during material melting. However, energy efficiency and environmental impacts are issues that have not yet been dealt with. At the process level, the specific energy input during the pure deposition phase is only a part of the total energy demand, as the consumption derived from the standby phases and all the auxiliary equipment/consumables should also be added. Moreover, when the spectrum of analysis is extended, the (typically mechanical) finishing processes, which are mandatory to achieve a compatible surface finish with more traditional manufacturing approaches, should also be included. An interesting scenario arises when material production is accounted for in the calculation of the cumulated energy demand. In fact, the reduction in material waste and the achievable buy-to-fly ratios can make these processes extremely competitive, from the environmental impact perspective. However, further analyses are needed in this direction.

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Chapter 27
A Case Study Analysis of Energy Savings Achieved Through Behavioural Change and Social Feedback on Manufacturing Machines

John Cosgrove, Frank Doyle and Bart van den Broek

Abstract Energy consumption in industry, particularly in manufacturing SMEs, continues to be inefficient with identifiable waste electrical consumption in machines and associated technical services. Holistic approaches to energy management that engage both the owners and the operators of a process are needed to drive progress. This research shows that there is value in energy and resource optimisation and productivity to be gained in a manufacturing company through engaging with machine operators, providing live performance feedback and authorising local control of machine operations. This research investigated visible feedback mechanisms, including factual and social displays, in a limited industrial experiment in a manufacturing SME to demonstrate potential energy savings from changes in practice. Factual feedback on a set of milling machines is shown to provide savings of 2.9% of total energy consumption, and social feedback based on machine threshold levels is shown to deliver savings of 5.1% of total energy consumption. An additional non-energy benefit (NEB) of a 7.9% improvement in productivity was also observed. The research highlights the importance of identifying auxiliary (non-value added) energy use within production, such as idle energy consumption in machines, as an area with potential for significant reductions through low-cost changes in operational behaviour and procedures.

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27.1 Introduction

27.1.1 Research Context

According to the European Energy Agency [1], industry remains the largest electricity-consuming sector in the European Union in 2014, accounting for 37% of all electricity consumption. The World Energy Outlook [2] states that the industry sector is very complex, and a detailed understanding of the various processes or product types is necessary to monitor energy efficiency. Previous research [3] estimates that only approximately 40% of the potential for improving the efficiency of energy use in industry is exploited. Latif et al. [4] describe how current efforts have failed to provide a rigorous index for examining the sustainability of manufacturing processes. Litos et al. [5] state that very few studies address eco-efficiency through a holistic approach that can guide practitioners in achieving better control over their manufacturing practices.

In a policy guide, the European Council for an Energy Efficient Economy [6] identifies that successful energy management requires a strategic commitment to change by senior management to tackle the company's energy and carbon emissions. Existing literature highlights the important role that business leaders (owners) and shop-floor workers (operators) have in achieving energy efficiency savings in manufacturing companies; however, few studies explicitly incorporate these roles, nor address what practical actions they should implement. Thomas et al. [7] identify that effective worker empowerment was the key factor to the successful implementation of a business sustainability framework. Walsh [8] describes the importance of empowering people and how technicians on the line have the ability to influence the energy consumption. Salonitis and Ball [9] identify that the success of campaigns to change individual behaviour depends primarily on the ability of the organisation to first assess current energy consumption, develop goals and objectives and finally share them with stakeholders. ECEEE [6] identifies behavioural change as being much harder to implement and maintain than technical change and that initiatives such as employee awareness schemes and training programmes can lose impact very quickly. Vinkhuyzen and Karlsson-Vinkhuyze [10] identify that there is still a considerable gap between knowledge and action in delivering sustainable consumption in production.

27.1.2 Implementation of Energy Savings in Production

A common characteristic of part manufacturing is that even when the machine is idle, it is still consuming more than 50% of its maximum power [9, 11]. Müller et al. [12]

demonstrate in laboratory tests that only 8% of the energy consumption in a milling machine was used for the value-adding activity of material removal. Vikhorev et al. [13] show that one of the main energy losses relates to production machine idling, accounting for 23% of the line's annual energy consumption, and state that the idling energy losses are usually caused by inefficient operation by line personnel. Schmidt et al. [14] identify that measurement of parameters at the machine tool level could enable a more detailed assessment of the energy consumption and costs per manufacturing step; however, they describe that data availability is generally insufficient. Smith and Ball [15] identify the potential for savings from machines that could be shut down or switched to the emergency stop (e-stop) state after a defined period of time at the end of a cycle. Mousavi et al. [16] demonstrate a correlation at machine tool level between wasted time identified through overall equipment effectiveness (OEE) calculations and wasted energy where machines are kept running and consuming energy even when the machines are not contributing positively to production (non-value-added). A gap in the research is identified where approaches to energy efficiency in machine tools have not sufficiently considered the potential for social feedback in order to achieve reduced energy consumption through behavioural change.

27.2 Energy Management Framework

27.2.1 Research Context

Cosgrove et al. [17] propose a conceptual framework which operates from the top down, ensuring alignment with the motivation of senior management and incremental improvement in a company's environmental performance. As shown in Fig. 27.1, the framework is made up of two connected cycles, the initial specification phase and the implementation phase which consist of iterations of owner/operator engagement and persistent energy savings.

In general terms, the 'Operators' of the process are defined as the people whose actions directly impact on the efficient operation of the process. The two key steps in the process involving the authoritative voice of the 'Owner' and the contextual knowledge of the 'Operators' are vital in achieving successful implementation of the framework. The researchers worked closely with key informants and champions in an empirical case study to introduce new concepts and approaches to energy management that have delivered considerable impact in the company.

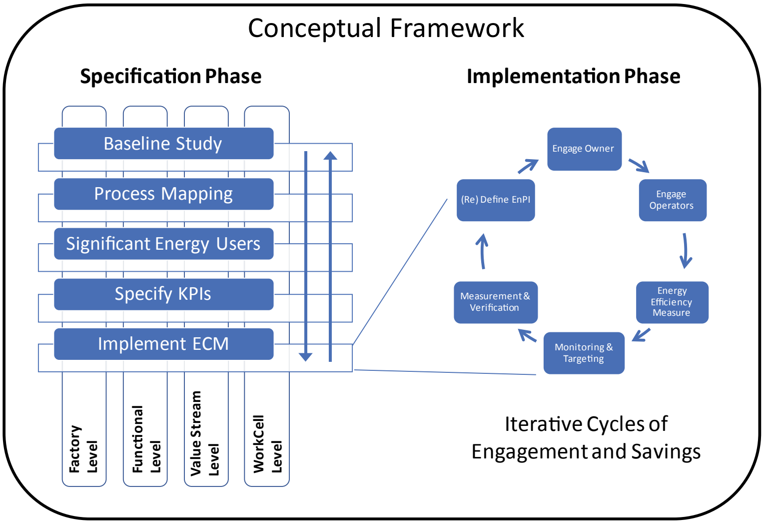


Fig. 27.1 Conceptual framework [17]

27.3 Empirical Case Study—Manufacturing SME

27.3.1 Manufacturing SME—Case Study

The case study for the research is a precision engineering company employing 60 people in Limerick, Ireland. The company manufactures components in steel, aluminium and plastics to supply the medical devices, aerospace, automotive and pharmaceutical sectors and normally operates over two shifts, days and evenings, Monday to Friday with some limited production over the weekend. The factory covers an area of 2050 m^2 and in 2017 consumed roughly 918,000 kWh of electrical energy with an electricity utility bill of €147,150. Production consists of fifteen computer numerical control (CNC) vertical machining centres (milling machines), nine CNC lathes of various configuration (turning centre, sliding head and twin spindle), four CNC electrical discharge machining (EDM) machines, four coordinate measuring machines (CMM) and associated technical services.

Non-participant observation and discussions with the machine operators initially highlighted that they did not have the authority and/or required knowledge to turn off idling machines. The main priority of the machine operators was to produce the target number of products for their shift and to maintain their machine in good order. The practice in the company was to load long-run jobs into the machine at the end of the shift and to leave the machines processing after the operators had left. In addition, there was reluctance to shut the machines down due to perceptions of machine misalignments or increased set-up time necessary at the start of the next

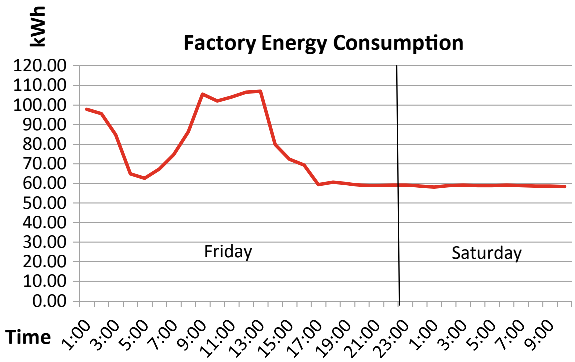


Fig. 27.2 Factory auxiliary energy in kilowatt hours (kWh) on a Friday/Saturday

shift. In general, the machine operators welcomed the research and were enthusiastic to save energy and to contribute to reducing unnecessary costs to the business.

27.3.2 Factory Level Analysis

Temporary electricity consumption data were gathered using electricity meters/loggers to show the baseline auxiliary power consumption of the factory. A typical power profile is shown in Fig. 27.2 where the auxiliary idle energy can be clearly seen after 17:00 on a Friday after which there is typically no production or other activities running in the factory.

This auxiliary energy was recorded at 60 kW per hour and stayed constant from Friday evening until Saturday morning. The average weekly energy consumption over the year (2015) was 19,125 kWh, so the non-production energy use accounts for a minimum of 30% of weekly electricity (KWh) consumption and approximately 28% of the total annual electricity utility bill [18]. The identification of this significant energy reduction opportunity (SERO) was presented to the company management who agreed to carry out a more detailed level of analysis and to engage with the researchers on further energy efficiency measures.

Based on the approach proposed by Wising et al. [19] to promote a culture of effective energy management in manufacturing companies, the researchers provided informal training to all employees on energy awareness and simple energy reduction techniques. This involved short (5–10 min) workshops with groups of machine operators and engineering staff and highlighted the need to get engagement and input from the machine operators in order to achieve the company's goals of:

- Reducing energy use, making the company a more environmentally friendly.
- Reducing energy costs, making the company more economically viable.
- Preventing unnecessary waste, in-line with other 'Lean' and 5S projects.

One part of the research thus set out to investigate if energy consumption can be significantly reduced by providing workers with feedback (e.g. on their screens, especially with social feedback). According to Arroyo [20], providing feedback is an effective way to change someone's behaviour in energy-related tasks, and this feedback can naturally be provided through various types of technology. Fogg (2009) argued that the best way to make technology persuasive is to make something small, simple and understandable. Therefore, in this research, it was understood that feedback would have to be given through easily understandable technology in order to change the behaviour needed to achieve energy reductions.

27.3.3 Machine Level Analysis

For maximum savings, manufacturing machines should be turned off right after each manufacturing process, when power (in particular direct energy) is no longer for production. A typical power consumption profile showing the power consumption for two parts is shown in Fig. 27.3. The approach used was to implement real-time monitoring of the machine energy consumption and to provide the operator with a visual display showing him when the machine has completed a part cycle and was idle and waiting for a manual operator intervention. The potential for energy saving lies in the machine being switched to zero consumption during the idle time. The threshold levels shown were used to provide the feedback triggers to the operator display. During this experiment, the dependent variable 'Energy Saved' was calculated by multiplying the time, between when the button was pushed and the start times of a new product, with the measured idle energy usage.

The monitoring system consisted of a push button and three current transformers (CTs) that measured the inputs and connected to a programmable logic controller (PLC), as developed by Doyle et al. [21]. In order to process the inputs (the measurement of power and the push button actions) and to enable the output (feedback and recorded data), the researchers developed specific programmes and algorithms for the PLC (written in Structured Text code) and developed database software for the computer (written in Java code). The monitoring systems ran on two machines (Miyano CNC milling machine and Doosan CNC milling machine) for three weeks. For the first week, there was no operator intervention and a baseline operation was recorded. In week two and three, alternative feedback screen was used on each machine and operator intervention was required. Throughout the experiment, the machine's consumed energy was recorded, as well as the date and time stamp in order to complete the analysis of the 'Energy Intensity' per product cycle.

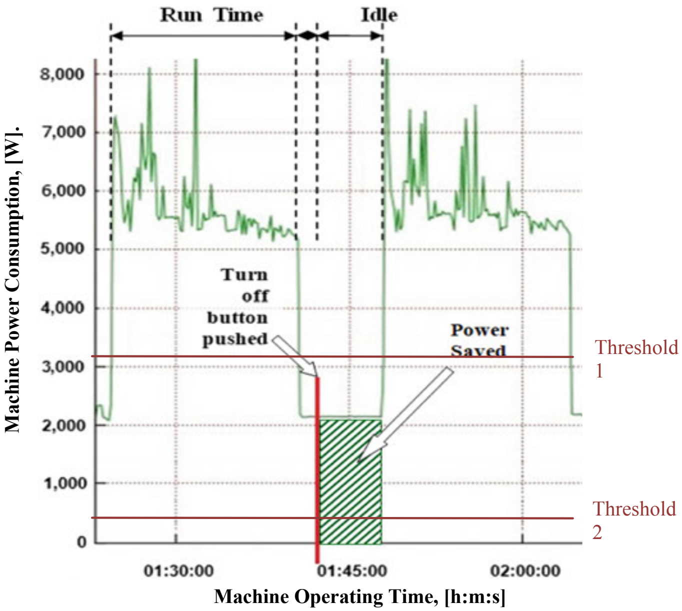


Fig. 27.3 Indication of potential energy saving

27.3.4 Industrial Experiment

In order to secure the maximum cooperation of the participants, the study was set up in three parts: firstly, because the participants' engagement is very important, there was a pre-experiment questionnaire held concerning the preferences, with regard to this experiment, of the factory floor employees. During this questionnaire, nine different factual and social feedback types were presented. Results indicated the most preferred social and factual feedback types that would be used in the energy engagement experiment later on. Secondly, an energy engagement experiment with the selected feedback on energy use per produced product was conducted. Throughout this experiment, the influences of social and factual feedback on the energy efficient behaviour of the machine operators were investigated. Lastly, a post-experiment study was conducted to gain further insight into the participants' thoughts and ideas for future development and implementation of the feedback method in this manufacturing environment. The combined approach provided empirical results to investigate the use of social feedback for energy efficiency behavioural change in manufacturing SMEs.

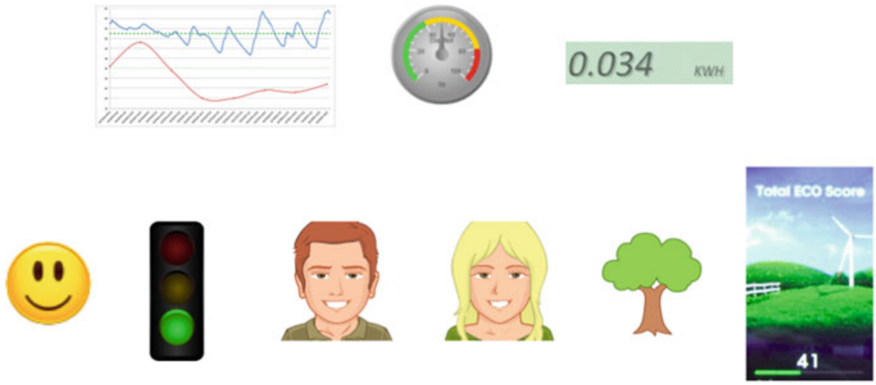


Fig. 27.4 Feedback figures. Graph, power gauge, digital indicator, emoticon, traffic light, male avatar, female avatar, growing trees, eco score

27.3.5 Pre-experiment Questionnaire

Seventeen employees (aged 24–52, $M = 38.65$, SD $= 9.39$) at a precision engineering company, of which 16 were male and of which 1 was female, completed the questionnaire. Eleven out of 17 employees work in the manufacturing environment of the company. Six out of the 11 manufacturing employees hold a leadership function (two engineers, three production team leaders and one operations manager); the other five are operators. Apart from general demographics, the survey contained questions, for instance; whether they are aware that a machine, when it is running idle, still consumes energy and that it can be turned off. Furthermore, it contained questions on their awareness, and their willingness, to turn off a machine at a given time and questions were asked on whether the employees had the authority to do so.

According to Midden and Ham (2008), factual feedback can be given to employees by displaying a digital sign with numeric kWh information, whereas social feedback can be given as positive or negative pictorial expressions or views shown on a computer screen. The participants were asked to rank the type of feedback graphics that they would prefer to be used and have displayed on the machine screens from the selection shown below in Fig. 27.4.

The results indicated a very strong preference for the power gauge in the category of factual feedback and in the category of social feedback, a preference for the emoticon. By providing energy consumption indicators for the machines, like a graph, a gauge or a digital energy meter, any machine operator could easily recognise when the machine is still running in productive mode or when it is in idle state, and judge whether to turn off the machine or not. The chosen factual display (power gauge) in Fig. 27.5 shows the real-time current consumption of energy by the machine.

Fig. 27.5 Factual feedback being displayed on a screen

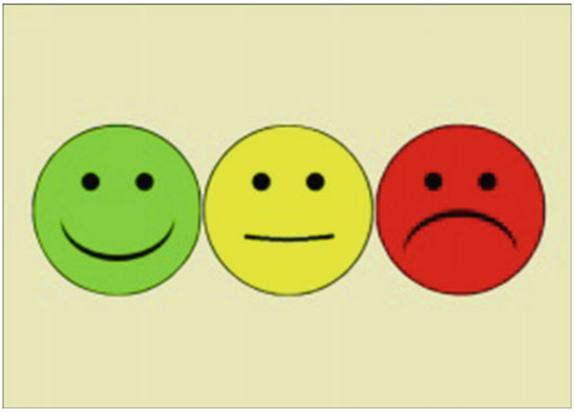


Fig. 27.6 Social feedback displayed on a screen

Following research completed by Ham and Midden (2014), in which participants receive on-screen social feedback, the researchers developed the on-screen social feedback through the use of emoticons with diverse emotional expressions, as shown in Fig. 27.6.

27.3.6 Energy Engagement Experiment

Considering there were only two machines available for the research, a maximum of five participants were involved in the study, as these participants were the only employees that were operating the two milling machines. The participants were enabled to perform diverse trial experiments to counterbalance the relatively low number of participants. A statistical power analysis showed that, with five participants, a minimum of nine trial experiments per participant (thus forty-five in total) were required, which would give a power value of 0.804. In any event, the participants complete 457 trials (parts manufactured) in total resulting in a power value of 1. However, with only five participants, the potential for bias in any individual employee means that the statistical reliability of the experiment is not fully robust. Further trials to repeat the experiment on a larger scale would provide better data.

27.4 Results and Feedback

After the trials had been finalised in the second week, the participants completed a questionnaire, following which the participants were debriefed and thanked for their participation. Due to the poor statistical power, the results are used for differentiating purposes only (Fig. 27.7).

The machine operators appreciated the presence of feedback in their work environment, with the social feedback being a little more popular than the factual feedback. Furthermore, the participants supported the assumption that the feedback has improved the energy efficiency of the manufacturing process. Notably, the operators would like to continue using the feedback during their future manufacturing work.

As shown in Fig. 27.8, the energy saved during the social feedback condition was significantly higher than the energy saved during the factual feedback condition. The difference ($M = 90.53$, $SD = 24.35$) confirms the hypothesis that the machine operators, who received social feedback, would reduce the machine's idle time more than machine operators who just received factual feedback (Fig. 27.9).

The results above pertain to the productive periods (i.e. normal working hours during the day and the night shift). If the non-productive periods during the week (i.e. lunch, coffee breaks, moments between shifts and even weekends) are considered, then significant further savings can be extrapolated (Table 27.1).

A typical week at the company comprised of 69 h of parts production and 99 h without any production. During these productive hours, as previously has been concluded, 2.9% energy could be saved by providing factual feedback, and 5.1% of total energy could be reduced by giving social feedback. In addition, where the machines were left in the off-state for the duration of the non-productive hours, additional savings of 20% were achieved.

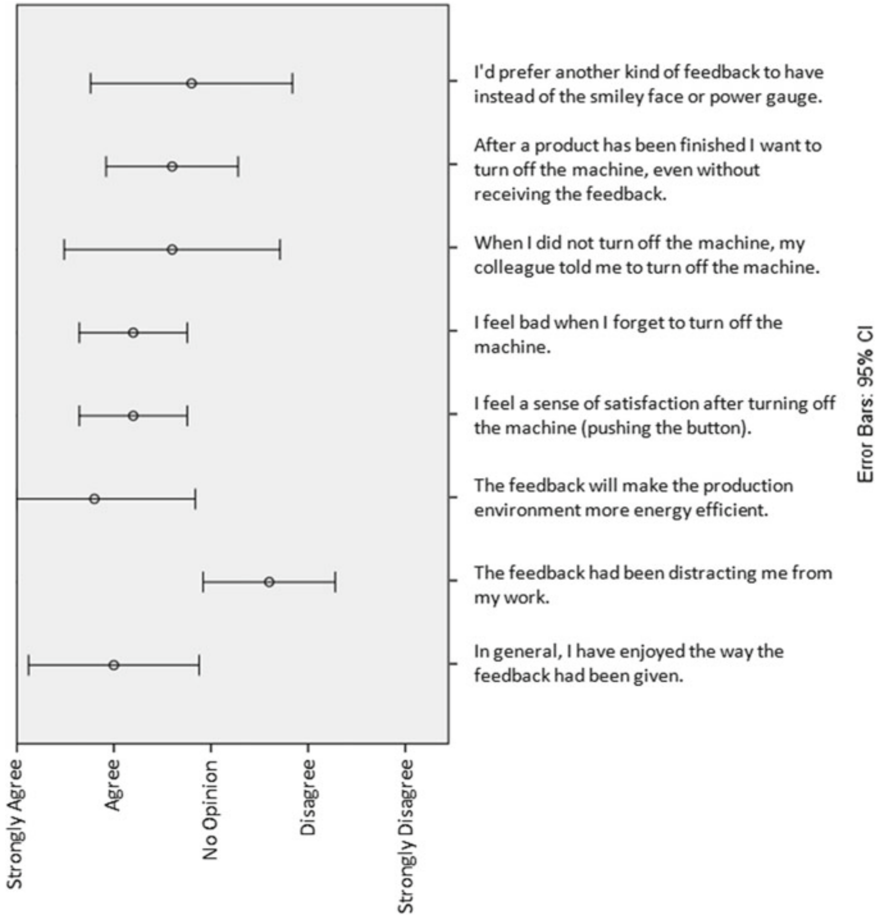


Fig. 27.7 Survey study: general questions

Table 27.1 Weekly work schedule

	Mon	Tue	Wed	Thur	Fri	Sat	Sun	Total
Working hours (day shift)	8	8	8	8	5	n/a	n/a	
Working hours (night shift)	8	8	8	8	n/a	n/a	n/a	
Productive hours	16	16	16	16	5	0	0	**69**
Non-productive hours	8	8	8	8	19	24	24	**99**

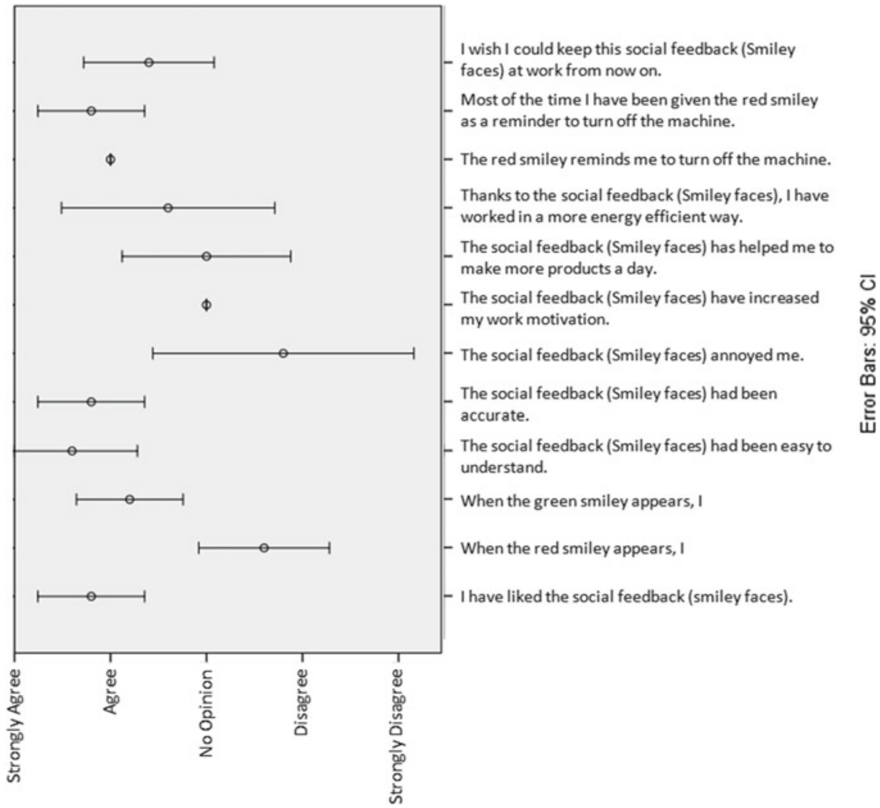
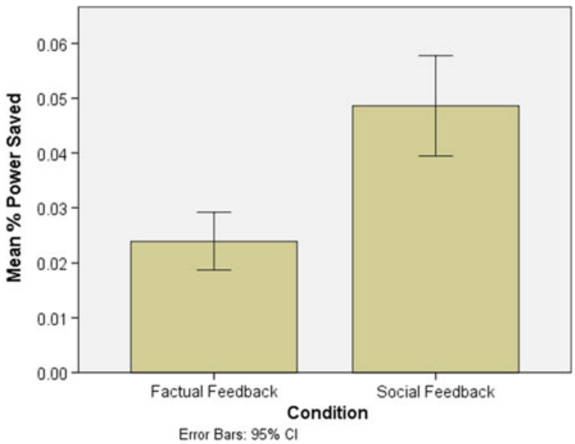


Fig. 27.8 Survey study: social feedback

Fig. 27.9 Percentages of the energy that is saved when a machine is turned off



An additional non-energy benefit (NEB) of improved productivity was observed as the products were unloaded and loaded earlier into the machine, which in its turn decreased the non-productive time. The machine operators reduced the milling machine's non-productive time (turned off time + idle time) from 31.3% ($M = 0.313$, SD = 0.026) of the total time while receiving no feedback to 23.4% ($M = 0.234$, SD = 0.023) while receiving feedback on the machine operation, giving an increase in productivity of +7.9%.

27.5 Discussion and Conclusions

There is value in resource optimisation and productivity to be gained in a manufacturing company through engaging with machine operators, providing live performance feedback and authorising local control of machine operations. Visible feedback mechanisms can be factual or social, with the limited industrial experiment in a manufacturing SME demonstrating a greater response to the social feedback displays.

By displaying factual feedback on the milling machines, 2.9% of the total energy was saved during production time. However, by displaying social feedback, instead of factual feedback, 5.1% of energy was shown to be saved. Practitioners of energy management in industry (energy engineers/production engineers) need to align initiatives with the company goals and to provide the right information on energy usage to the personnel who can influence change in behaviour and practice in their production operations. The quantification of the cost of auxiliary energy or waste has been shown to be a motivational factor for company management to engage with energy efficiency measures and to address the actions necessary to drive interventions and employee awareness.

The research highlighted the importance of identifying auxiliary (non-value added) energy use within production, such as idle energy consumption in machines, as an area with potential for significant reductions through low-cost changes in operational behaviour and procedures.

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Part VI
Sustainability-Oriented Industrial Technologies in the Domain of Industry 4.0

Chapter 28
Safe By Design in 3D Printing

Katja Nau and Steffen G. Scholz

Abstract This paper presents a safe-by-design approach developed for enhanced inks containing nanomaterials for 3D inkjet printing. Manufactured nanomaterials, like aluminium oxides and zirconium dioxide, are increasingly used for additive manufacturing today. However, the impact and interaction of nanomaterials on human health and the environment are widely discussed today. Our approach aims to describe the safe and sustainable use of nanomaterials for 3D inks. We rely on well-characterised non-toxic nanomaterials; their properties are documented in safety data sheets. In order to identify possible exposure to humans and the environment, we investigate the development of inks and their application in the 3D printing process.

28.1 Introduction

Nanotechnology is considered one of the key technologies of the twenty-first century. It rightly bears this name, because almost all branches of science and industry are already affected by it today. Manufactured nanomaterials have become an integral part of our everyday life. They can be found in numerous products on the market, from electronics and products for the automotive and construction industries to cosmetics and medical products [see also 1]. The success of this fascinating technology is based on its versatility. It will also bring about fundamental changes in basic research. Manufactured nanomaterials offer a great innovative potential and they are assumed to be beneficial to mankind and the environment by reducing material usage and energy consumption. But new chemicals and materials also raise concern, because

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they may pose unknown risks to the environment and/or to the health of humans and animals. These possible risks and safety aspects are discussed since the early 2000s [2–5].

Nanomaterials are chemical substances or materials that are manufactured and used on a very small scale. Nanoscale structures, defined as nano-objects, range from approximately 1 to 100 nm in at least one dimension [6]. Nanomaterials have unique and more pronounced properties compared to the same bulk material. Therefore, the physicochemical properties of nanomaterials may differ from those of the bulk substance or particles of a larger size. In order to develop sustainable products, it is important to monitor and control processes right from the beginning.

Additive manufacturing (AM) enables a new manufacturing paradigm, such as the rapid, distributive manufacture of complex 3D objects. It is a technique for preparing 3D objects by layered material construction. The commonly used term 3D printing is one of the several AM processes. 3D printing was developed in the 1980s [7]. One type of 3D printing is the 3D inkjet printing. The layering process allows materials with different aesthetic, haptic and physical properties to be processed in the printing process, stable in shape and without adhesive joints. Various materials with different properties can be used for this purpose, e.g. high stiffness, transparency, conductivity or elasticity. AM processes have some important advantages over traditional manufacturing techniques; for example, the design of products is more flexible due to the additive approach. Various nanomaterials are especially suitable for ink formulation of novel 3D inkjet inks to obtain functionalities embedded in objects [8, 9]. Selecting safe nanomaterials and looking at them over their life cycle in 3D printing were the subject of our research. Here, we focus on the safe-by-design aspect.

28.2 Method

Safe by design (SbD), also known as prevention through design (PtD), is a concept that is well established in fields like building, nuclear technology, water treatment, health facilities, and occupational health and safety in the context of nanotechnology. Generally, SbD is not new and has been used for years in industry [10]. Various fields have adopted and developed different but related concepts that are first of all based on the idea to design products or processes that bear an intrinsically low risk potential, instead of confining this potential by application of protective systems. SbD has to integrate the anticipated safety impacts of materials or products into the design and production phases. In the context of nanotechnology, SbD is a rather novel concept, aiming at the development of functional as well as safe nanomaterials and nano-enabled products [11]. The approach implicates three aspects: a safe design, a safe production and a safe use. SbD is a concept, in which methods for minimising work hazards are applied at an early stage of development, e.g. materials, with an emphasis on optimising the health and safety of employees over the entire life cycle of materials and processes [12]. This approach of SbD was applied for the first time to nanomaterials in 3D printing.

28.3 Results

28.3.1 Safe by Design for Nanomaterials in 3D Inkjet Printing

Using manufactured nanomaterials in inks for 3D printing, nanosafety aspects of the potential toxicity of these materials are becoming increasingly important. In our research, nanosafety aspects accompanied the 3D printing processes in safety issues on various developed nanomaterial-containing inks, possible exposure hotspots during development, occupational health and safety and environmental aspects. The process chain of the nano-ink development starting with the nanomaterials including entry points for nanosafety approaches until the end of life of a product developed in the project DIMAP (Digital Materials for 3D Printing) is shown in Fig. 28.1.

The goal of this research project was to establish ceramic-enhanced, light-weight polymeric, electrically conductive and high-strength polymeric compositions for inkjet printing. New inks with various components have been developed. Among the important ingredients that have been used are diverse nanomaterials: aluminium

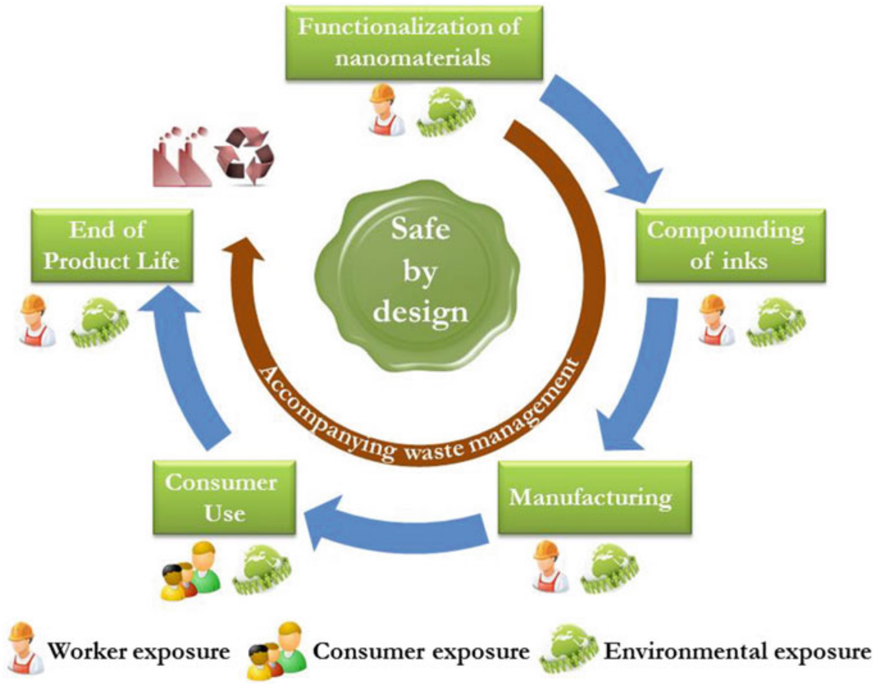


Fig. 28.1 Process chain of nano-ink development including entry points for nanosafety approaches (*Source* DIMAP)

oxide, aluminium nitrate, silver or zirconium dioxide. The SbD accompanying measure should ensure a safely carried out development process and a safe production of nano-inks. Safe by design assumes the knowledge of the used chemicals/nanomaterials. This knowledge served as the starting point for the entire concept. As a basis for our SbD approach, we analysed and described mandatory physicochemical properties of individually manufactured nanomaterials in detail. The substance name is essential, at best with CAS-No and form of delivery (as a powder or suspension). Also, the information about the chemical composition: purity and potential contaminations, is vital. Particle size and/or size distribution in suspensions (including dispersion medium) must be specified, also the specific surface area of powders (e.g. BET surface). The knowledge about the surface chemistry (functionalisation, coatings, modifications) and also morphology (shape) is mandatory aspect to be fulfilled.

Desirable assessment criteria are information about crystallography of the nanomaterial, surface reactivity and/or surface charge (zeta potential, isoelectric point), the formation of potential radicals, porosity, defect density and magnetic properties [see 13]. This information then was used as the basis for understanding the toxicity of nanomaterials. The above-mentioned nanomaterials were selected because they are per se non-toxic.

Within our research project, it was very important that every newly manufactured or used nanomaterial (ceramics, ink components, etc.) or chemical product is well characterised as part of a workplace risk assessment with the help of the above criteria and that the data are summarised within with a safety data sheet (SDS). A SDS, also known as material safety data sheet (MSDS) or product safety data sheet (PSDS), is an important component of product stewardship and occupational safety and health. Safety data sheets are a well-accepted and effective method for the provision of information to recipients of substances and mixtures in the EU. These have been made an integral part of the system of regulation [14]. It is intended to provide workers and emergency personnel with procedures for handling or working with that substance in a safe manner.

28.3.2 Development of the DIMAP SDS Template

An important aim of our accompanying nanosafety research was to communicate this information about material properties in the best possible way and make it available to everyone. In order to have a uniform basis for all partners from both research and industry, a SDS template was developed, which was used by project partners from universities, research centres and industry. Thus, every newly developed ink and every modification could be documented, and this information was available to everyone.

The SDS follows a 16-section format, which is internationally agreed and for substances especially, as shown in Fig. 28.2.

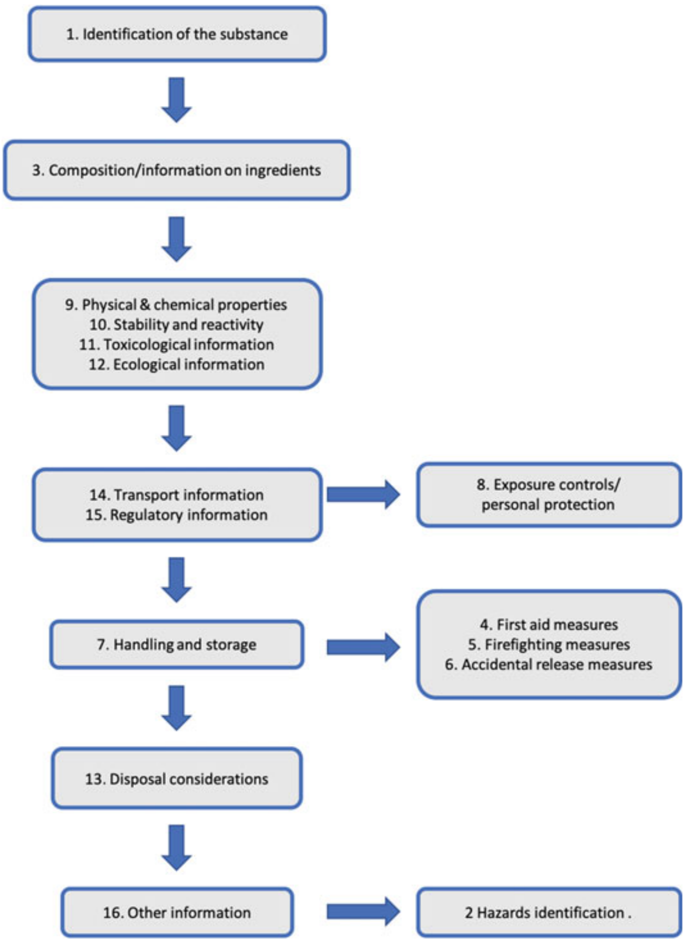
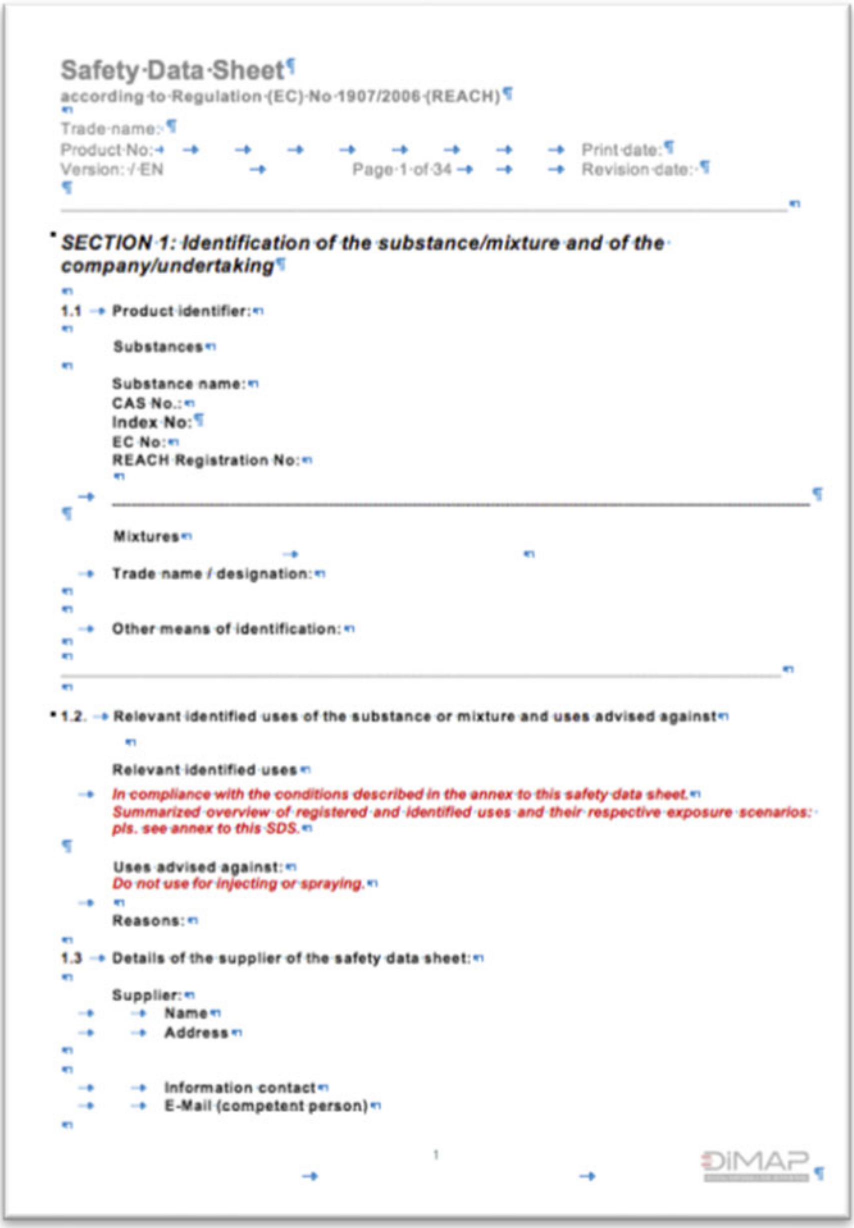


Fig. 28.2 Example sequence for compiling an SDS (adopted to [15])

Figure 28.2 shows a proposed step-by-step approach to establishing an SDS to ensure its internal consistency (the figures refer to the sections of the SDS). The approach starts with the identification of the substance and shows a linear process to emphasise that, for example, the final identification of hazards in Sect. 28.2 of the SDS is unlikely to be possible until inputs have been made to other sections. In reality, the process is likely to be an iterative process in which some aspects in different sequences must be considered as the one presented or even parallel. Following these indications, we developed a template with a fill-in guide, shown in Fig. 28.3.

In addition to existing SDS from purchased products, data sheets were created and communicated for all new materials and intermediate products, so that every user had knowledge about them.


Safety Data Sheet
according to Regulation (EC) No 1907/2006 (REACH)

Trade name:
Product No: Print date:
Version: / EN Page 1 of 34 Revision date:

SECTION 1: Identification of the substance/mixture and of the company/undertaking

1.1 Product identifier:

Substances

Substance name:
CAS No.:
Index No:
EC No:
REACH Registration No:

Mixtures

Trade name / designation:

Other means of identification:

1.2. Relevant identified uses of the substance or mixture and uses advised against

Relevant identified uses

In compliance with the conditions described in the annex to this safety data sheet.
Summarized overview of registered and identified uses and their respective exposure scenarios: pls. see annex to this SDS.

Uses advised against:
Do not use for injecting or spraying.

Reasons:

1.3 Details of the supplier of the safety data sheet:

Supplier:
Name
Address

Information contact
E-Mail (competent person)

1

DIMAP

Fig. 28.3 First page of the SDS template (*Source* DIMAP)

28.3.3 Identification of Possible Exposure Hotspots Within the Framework of the Development of Inks for 3D Printing

The development of novel chemicals or materials requires new knowledge about the potential biological effects and health hazards associated with them. Before such materials are launched for different uses, they must be tested for safety without any risks to health according to the legal requirements in different countries. This also applies to the development of inks for 3D printing.

To prevent any risk, we focused on the identification of possible exposure hotspots during the development of nano-inks and 3D printing.

In general, an exposure to nanoparticles of people and the environment with possible incorporation and impacts can only occur when nanoparticles are released. Consequently, nanoparticles cause no effects when they are firmly embedded, e.g. in plastics. Nevertheless, during the lifetime of nanomaterials, nanoparticles can be set free by various processes, e.g. during production, application or after use. Nanomaterials, which are embedded in a composite material, e.g. in inks or plastics, can be released into the environment by mechanical, thermal or chemical processes. Mechanical processes can be drilling, grinding or sawing. Combustion is a typical example of a thermal process, in which nanoparticles could be set free. The application of corrosive chemicals on surfaces is an example of a chemical process. The different processes of release can apply alone or in combination with each other. For example, grinding of a composite material with embedded nanomaterials can lead to a nanoparticle release by mechanical abrasion and additionally by the heat.

Usually, no single nanoparticles are released from the raw material. They normally enter the environment linked to other particles (as agglomerates or aggregates) or embedded in matrix materials (e.g. fragments of plastics).

Within the DIMAP project, we identified possible exposure hotspots for nanomaterials release in the work packages dealing with ink development. Various chemicals and nanomaterials, especially during the development of ceramic-enhanced inks and electrically conductive inks, are used. When nanomaterials are manufactured and used, mainly from powdery feedstocks, laboratory personnel and the environment may be exposed if particles are released during handling. During the process development workmen and environment, may be exposed too, when test structures are printed and optimisation processes are carried out. An exposure of “test consumers” is also possible when the design studies and demonstrators are printed for the first time. Identifying these potential exposures and pointing out possible hazards were part of our SbD approach.

28.4 Discussion

A risk is defined differently depending on the (scientific) discipline. In general, the term “risk” denotes the potential loss of something of value, e.g. health or an intact environment or simply your purse. A risk exists only if hazard and exposure occur together. For a risk assessment of manufactured nanomaterials, the hazard potential of each material has to be evaluated in detail: toxic or non-toxic. Also, the various forms have to be considered individually: for example, nanoparticles from dry powder (typically highest potential for exposure), nanoparticles in dilutions or suspensions or physically bound or encapsulated (e.g. inks or plastics, typically lowest potential for exposure).

With the DIMAP approach, we want to ensure a safe use of nanomaterials at the workplace. Exposure to nanomaterials also depends on the process, on the technical control measures implemented and, where these are not sufficient, on the use of personal protective equipment. Employers should reduce exposure to dangerous substances to levels that are not considered harmful to workers’ health.

Our analysis shows that used particles, as well as chemicals, have to be handled with care. However, exposure measurements did not show a significant release of particles in the air, and the selected nanomaterials are classified as non-toxic. The measurements clearly indicate that all particles are firmly embedded in the resign and finally in the printed products.

Thus, the workflow and the established procedures during all process steps in the project are following the guidelines in accordance with Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) specifications. The REACH directive states: “…the most important instrument for communication in the supply chain is the safety data sheet”. As per part of the DIMAP project, safety data sheets were prepared for new components (e.g. ceramic inks) and always requested for the standard materials. These information sheets were sent together with the materials within the project. Project partners were informed where a potential release of nanomaterials could be expected and how to establish approved procedure in order to minimise the impact. In addition, various workplace measurements were carried out to determine potentially released nanomaterials and their quantity. No significant amounts (mostly below even measurement thresholds) of nanomaterials were detected, so no further precautions were necessary. Thus, it can be concluded that the nanoparticle inks under investigation in this research study are inherently safe.

However, since inhalation at the workplace appears to be the most important route of exposure to nanomaterials, the production of any airborne nanomaterials at the workplace should be minimised. This can be achieved through the use of enclosed working environments and wet processes. Dust-generating process steps such as grinding and abrasion should be avoided as far as possible. If nanoparticles are present in the air at the workplace, appropriate ventilation measures should be provided. As a last resort, workers may be trained in the use of breathing apparatus, protective clothing, gloves and goggles.

28.5 Conclusion

Finally, it is worth emphasising that a complete risk assessment of new nanoparticle inks is mandatory for all future inks. In particular, for newly produced (nano)materials, it is inevitable to identify and examine a potential hazard of the material under controlled conditions, e.g. in the lab, and to quantify exposure, i.e. the amount of material, which may come into contact with humans, animals or the environment, respectively.

About DIMAP

The EU H2020 project DIMAP (Novel nanoparticle enhanced Digital Materials for 3D Printing and their application shown for the robotic and electronic industry, duration 2015–2018) focused on the development of novel ink materials for 3D multi-material printing by PolyJet technology. The project has advanced the state of the art of AM through modifications of their fundamental material properties by mainly using nanoscale material enhanced inks. The project targeted at the following objectives: additive manufactured joints and luminaires, ceramic-enhanced, electrically conducting, light-weight polymeric and high-strength polymeric materials, novel multi-material 3D-printer. Further focus pointed out during the nanomaterial and printer development has been a safe-by-design approach, workplace safety, risk assessment and a life cycle assessment [overview: 16].

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Disclaimer

Any opinions in this publication are those of the authors only.

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Chapter 29
Total Cost of Ownership for Different State of the Art FDM Machines (3D Printers)

Janin Fauth, Ahmed Elkaseer and Steffen G. Scholz

Abstract Total Cost of Ownership (TCO) analysis is an important tool to estimate total costs incurred for Additive Manufacturing (AM) over the time of the useful life from the purchaser's perspective. Thus, the paper on hand describes the application of the TCO model to different state of the art Fused Deposition Modelling (FDM) machines. The application of the TCO model to AM aims at uncovering and integrating cost savings and sustainability benefits into procurement decisions. A generic TCO model for AM was developed and applied to three selected FDM printers. The true costs were identified with the help of historical costs, vendor data and results from measurements on material and energy consumption. The cost calculations showed that the value and distribution of TCO cost components highly depend on the type of FDM printer as well as on identified influencing factors. The study resulted in recommendations towards sustainability improvement and concurrent cost reduction in AM, such as the reduction of material waste. To unleash cost and sustainability advantages, it is recommended to optimise procurement decisions while disclosing all true costs and properties of the 3D printers at the time of the product selection.

29.1 Introduction

Additive Manufacturing (AM) is an evolving manufacturing technology that allows producing 3D parts from a CAD model by adding material in layers, opposite to tra-

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ditional manufacturing techniques, where layers are removed from the base material. AM comprises several technologies, whereat the technology relevant for this study is Fused Deposition Modelling (FDM), where filament form material is inserted into the print head and then thermally melted and extruded onto a printing platform by movements of the print head in *X*, *Y* and *Z* coordinates [1–3].

AM has become a key enabler for modern industry and has been implemented worldwide in several sectors. AM enables enhancements in production technologies, automation of processes and real-time evaluation of data. AM opens new opportunities and provides several advantages over conventional manufacturing techniques. Besides its unlimited design freedom, AM has shown great advantages for decentralised manufacturing, on-demand manufacturing, quality improvement, small volume manufacturing and mass customisation. Despite these opportunities, AM still faces many challenges such as size restrictions, relatively slow production times, barriers to market acceptance and penetration due to commercial impacts, i.e. costs of printing equipment and running costs [4].

The adoption of AM seems not to be appropriate for all sectors and thus, organisations must decide whether it is more beneficial to adopt advanced technologies or to stick to conventional process flows. A literature review shows that cost-effectiveness and sustainability of AM have not been examined sufficiently yet, it seems questionable how cost-effective and sustainable AM really is. However, the growth of advanced manufacturing technologies like AM is driven by the enthusiastic demand for a more sustainable, competitive and cost-effective economy and it is thus relevant to unleash the full potential of advanced manufacturing technologies.

The motivation of this paper is to examine AM, focusing on FDM printing, from a cost perspective by considering true costs of 3D printers over the time of the entire useful life. While uncovering potential hidden costs from the purchaser's standpoint, at the same time, sustainability aspects in terms of material and energy consumption in AM will be considered within this study. The approach used as a framework for the assessment is the Total Cost of Ownership (TCO) concept. TCO is an approach to consider all costs that are associated with a product over the time of its useful life and includes costs from the acquisition, ownership, usage to the subsequent disposal of a good or a service [5]. Total Cost of Ownership distinguishes between pre-transaction, transaction and post-transaction costs. Pre-transaction costs are defined as costs that incur before the actual purchase (e.g. costs for the identification of needs), transaction costs occur during the purchase (e.g. delivery costs), and post-transaction costs are costs that incur after the purchase (e.g. costs for maintenance) [6]. Within the application of the TCO concept to AM, the study has three objectives: (1) development of a generic TCO model for AM for the identification of true cost components, (2) application of the model to exemplary FDM printers for comparison and (3) identification of influencing factors on the cost components and on sustainability achievement.

29.2 Related Work

To the best of the authors' knowledge, there is a lack of studies that examine the TCO of AM while concurrently considering sustainability aspects. However, some of the below-described investigations focused on analysing AM either from a cost or from a sustainability perspective.

Saccani et al. developed a general TCO model for durable consumer goods, with the possibility to be extended to cover a wider range of machines, e.g. 3D printers, as they are not being completely consumed in one use. Saccani et al. calculated the costs based on the type of investment activities that accrue for durable consumer goods, which were classified into five focal processes: decision-making, ownership, training, usage and product support. The TCO computation in the paper of Saccani et al. is demonstrated through the example of washing machines while considering various application modes. The investigation shows that only four out of many activities make up 95% of TCO in the washing machine application, which mainly refers to the product price and consumables or required resources [7].

A study on costs and cost-effectiveness of AM by Douglas and Stanley found that machine costs and material costs are among the most significant cost factors in AM. However, in the course of technological development, this might have changed, as more and more FDM printers are available at lower prices. In addition, compared to traditional manufacturing methods, energy consumption seems to be a significant cost component for AM such as further cost components that might accrue [8].

Looking at AM from a sustainability perspective, a study by Hegab et al. focused on the assessment of sustainability of machining processes through the development of an algorithm, which is based on quality characteristics and sustainable machining metrics to find optimal process parameter levels by using five major sustainable metrics. These metrics are environmental impact, energy consumption, machining costs, waste management, personnel health and operational safety, which are identified as the pillars for the achievement of sustainability in machining processes [9].

Ford and Despeisse conducted exploratory case studies to regard sustainability benefits and sustainability challenges intently. In contrast to the findings by Douglas and Stanley, Ford and Despeisse identified resource efficiency benefits, reduced energy intensity and reduced material waste generation as sustainability benefits of AM. Some sustainability challenges of AM address the potential to improve cost-effectiveness and energy efficiency at higher production volumes, the lack of knowledge on environmental performance of AM technologies and the limited or non-recyclability of plastics or multi-material goods [10].

This literature review shows some dubieties towards sustainability advantages and challenges as well as cost-effectiveness of AM and a lack of studies that examine true costs of AM with the help of TCO and concurrently consider sustainability aspects. In this context, the study on hand aims at covering this research gap.

29.3 Methodology

The TCO study focused on the investigation and cost calculation for three selected FDM printers, which are: Stratasys uPrint SE Plus (printer 1), Leapfrog Bolt (printer 2), MakerBot Replicator 2X (printer 3) [11–13]. The investigated printers are used for research purposes in the respective organisation.

The first step of the study was to identify all activities and corresponding cost components, which are relevant for AM, by developing a TCO model for AM based on the structure of the five principal processes for durable consumer goods by Saccani et al. [7]. This approach considered all activities associated with the investment in a 3D printer over the time of the useful life, from the acquisition until the disposal of a 3D printer. The activities were allocated to the corresponding monetary, non-monetary or opportunity costs, while opportunity costs for a loss in alternative business activities were included in the form of labour costs, whenever it was not possible to compute the true costs. The listed costs include value-added tax when applicable and all recurring costs over the time of the useful life. Resulting cost components were classified according to the TCO categories pre-transaction, transaction and post-transaction costs and the developed generic TCO model for AM was then applied to the three above described FDM machines. To identify true costs of every investigated 3D printer, different approaches were applied. To identify the purchase price and other transaction costs, material costs, equipment costs and historical costs were used for the calculations. Vendor data was gathered to determine costs for maintenance, repair and training. Within the process of data collection, emphasis was given to the measurement of resource consumption, meaning energy and material consumption. This allowed to calculate true costs for resource consumption and to verify manufacturer's data on predicted energy and material consumption. To measure true energy and material consumption, test prints were conducted using a standardised model of a small traffic cone ($h = 50$ mm, $R = 17$ mm, $r = 8$ mm, $V = 26\ \text{cm}^3$) for all printers. The investigated printers and printed test structures are represented in Fig. 29.1.

Energy consumption was measured with the help of the energy metre Voltcraft Energy Check 3000, which was mounted to the printers. Energy measurements were made at several points of time during the printing process for each test structure and printer. The formulas used for the calculation of material and energy costs are:

$$C_{\text{material}} = p_{\text{material}} * w_{\text{average}} * n_{\text{prints}} * t_{\text{useful}}$$

C_{material} Material costs in €
p_{material} Price of material in €/g
t_{useful} Useful life in a
w_{average} Average weight of cone in g
n_{prints} Number of prints per year

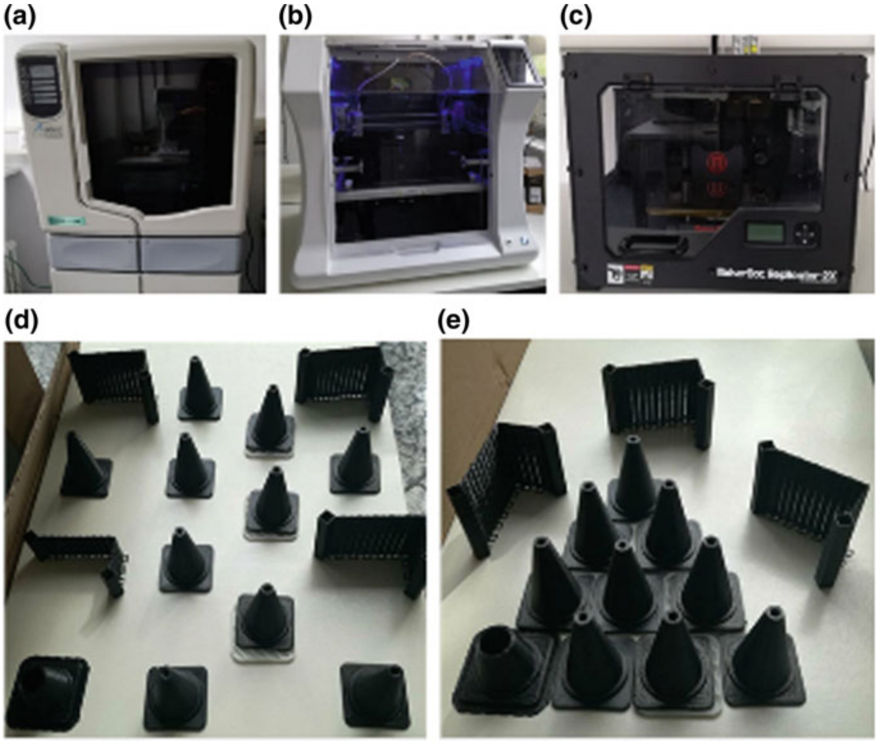

Fig. 29.1 Experimental setup. **a** Printer 1. **b** Printer 2. **c** Printer 3. **d**, **e** Printed test pieces

$$C_{\text{electricity}} = W_{\text{average}} * p_{\text{electricity}} * n_{\text{prints}} * t_{\text{useful}}$$

$C_{\text{electricity}}$ Electricity costs in €/kWh
$p_{\text{electricity}}$ Electricity costs in €/kWh
W_{average} Average energy consumption in kWh

The test prints were conducted under default settings to ensure comparability among the printers. Material used for the test prints was ABS material. Since the aim of this cost analysis was to calculate the cost components under real conditions, the assumption of a daily operating grade of six hours held. Important to note is that the selected printers are not used for manufacturing purposes in the respective organisation, but for research purposes. To obtain the costs over the total life span of a 3D printer, a useful life span of five years [14] with 248 working days each was estimated. This daily operating grade generated a different number of contingent prints per day for each printer, because the average build time of one traffic cone differentiated between the printers. The analysis section focuses on computing the costs for each printer, assuming its maximum number of possible prints within the six hours operating grade. Since the number of potential prints differs a lot among the printers, which makes the variable cost components less comparable, a recalculation assuming a uniform number of prints for all investigated printers was considered.

29.4 Results and Discussion

29.4.1 Generic TCO Model for FDM Machines

On the basis of the previously described approach (Chap. 3), a generic TCO model for the application to AM (FDM machines) was developed. Figure 29.2 graphically illustrates this model and shows that pre-transaction, transaction and post-transaction cost components of AM add up to Total Cost of Ownership of AM. Pre-transaction components for a 3D printer are costs for product selection, identification of needs and supplier selection and supplier integration. Transaction costs for the FDM printers are the purchase price, costs for delivery, return, correction of parts, installation and for attachments purchase (e.g. software). Post-transaction costs are costs for training, material, equipment and energy, waste of resources, maintenance, repair or damage payments (spare parts), technical support and disposal of the printer.

29.4.2 TCO Comparison for Different FDM Machines

Based on the developed model in Fig. 29.2 (Sect. 29.4.1), the TCO for each of the three selected FDM printers were calculated. The results of the cost calculations are presented in Table 29.1.

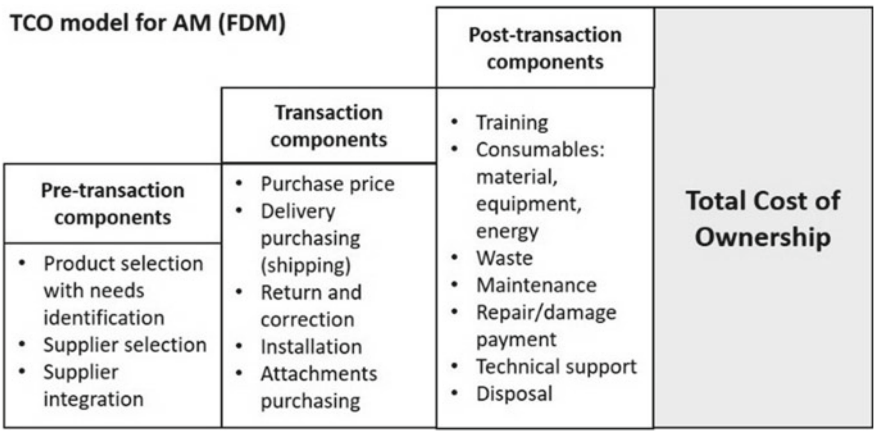

Fig. 29.2 Total cost of ownership model for AM

Table 29.1 Overview total costs of investigated FDM machines

TCO type	Cost components	Costs printer 1 (in €)	Costs printer 2 (in €)	Costs printer 3 (in €)
Pre-transaction costs	Product selection	924.72	924.72	924.72
Total pre-transaction costs		924.72	924.72	924.72
Transaction costs	Purchase price	15,423.00	7319.04	2805.13
	plus shipping	Included	99.00	14.90
	Return	106.60	Included	29.80
	Installation	1644.12	308.24	154.12
	Attachments	Included	151.25	Included
Total transaction costs		17,173.72	7877.53	3003.95
Post-transaction costs	Training			
	External training	1130.50	1500.00	Not provided
	Self-training	154.12	154.12	308.24
	Material	21,789.51	1105.36	2022.38
	(Thereof material waste)	(8173.67)	(129.68)	(864.53)
	plus shipping	122.50	49.00	98.00
	Equipment	5188.71	1140.30	1550.00
	plus shipping	44.10	74.20	104.30
	Energy	913.14	29.39	301.88
	Maintenance	641.52	288.98	321.73
	Repair	2625.50	119.00	309.11
	Plus shipping	10.20	20.07	14.90
	Disposal	163.03	156.03	126.05
Total post-transaction costs		32,782.83	4636.45	5156.59
Total costs		50,881.27	13,438.70	9085.26

The results in Table 29.1 show that printer 1 distinctly incurs the highest total costs, followed by printer 2, which can be justified with the comparatively high capacity in terms of number of potential prints within the operating grade and good quality of test structures and low number of faulty prints. Printer 3 has the lowest total costs in the investigation, but quality of the test structures is relatively worse and number of misprints high. The segmentation of total costs into the three TCO categories showed that pre-transaction costs are the lowest TCO cost category and are alike for all investigated printers, because time spent on identifying and selecting new printers does not differentiate in the case of application. Costs for supplier selection and integration were not considered in the sample calculation as suppliers were

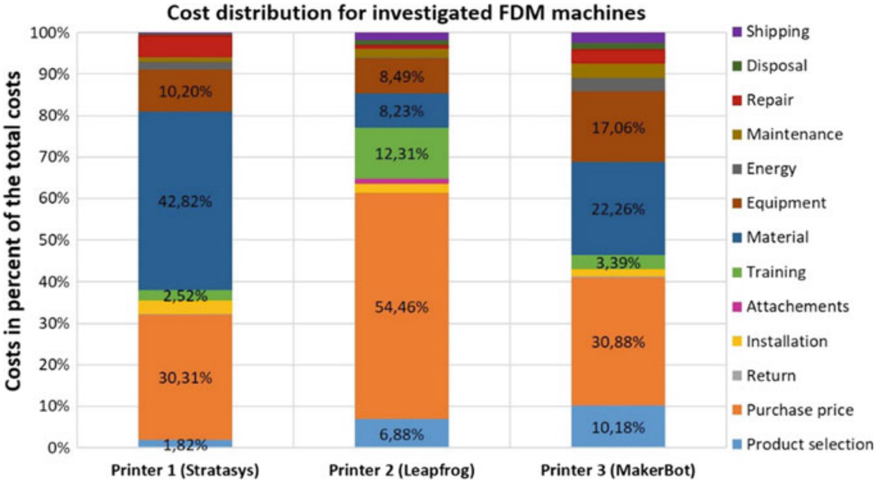

Fig. 29.3 Cost distribution for investigated FDM machines

already integrated in the respective organisation. Also, costs for technical support did not incur for the investigated printers.

To enable a detailed results analysis and discussion, Fig. 29.3 illustrates the distribution of the included cost components. The bar graph includes all cost components, which were considered in the cost calculation for the selected FDM printers, and shows the costs in per cent of the total costs for each printer.

The in-depth results analysis with the help of Table 29.1, and Fig. 29.3 shows that material costs are the highest cost component for printer 1, which was justified with the fact that only supplier-original filaments are compatible with the printer and a support structure is required. Support structure is required according to the printer properties and default settings of some of the investigated printers (printer 1 and 3). Waste was considered in terms of material waste and as part of material costs for all printers. The test prints found that printer 1 produces an approximate rate of 38% material waste, which is mostly caused by required, non-valuable support structure but also by material rejections during the print. However, not only material costs cause relatively high post-transaction costs, but also costs for all consumables, namely equipment and electricity as well as the previously named material, are higher under any tested capacity utilisation for printer 1 than for printer 2 or 3. Remarkable in matters of energy consumption is that printer 1 exhibits the highest average energy consumption and thus costs per print, even though the build time is the shortest. This is probably attributable to the high level of energy consumption during the heating and cooling period. Altogether, post-transaction costs are the highest TCO unit for printer 1.

Looking at printer 2, transaction cost is the highest TCO unit, because the purchase price is very high in relation to other cost components. Compared to printer 1, material costs are considerably lower by reason that the material can be purchased cheaply from resellers, and no material is spent on printing a support structure. Material is therefore not wasted in the form of support structure, but a certain proportion of the material costs are attributable to material waste, more precisely to rejected material during the print. Printer 2 has a considerably low level of energy consumption and thus low electricity costs. Besides the electricity costs, also the costs for spare parts (repair) are comparatively low. Among all three investigated printers, printer 2 incurs the lowest costs for equipment and energy of all investigated printers, which results from the calculations with a unified number of prints. However, it is remarkable that costs for training are relatively high for printer 2.

The highest cost component among total costs for printer 3 is the purchase price. Correlating with the results of the literature research, the second most significant cost component is material costs, followed by costs for equipment. Remarkable in the results from the measurements on material usage is that about 43% of the expended material are spent on support structure and thus wasted. Compared to printer 1 and 2, printer 3 incurs the highest costs for energy consumption. Similar to the results for printer 1, post-transaction costs amount to the highest TCO unit of printer 3.

The findings from this study seem to be in accordance with outcomes from related work, stating that machine and material costs are the most significant cost components. Depending on the type of printer within this investigation, machine and material costs together add up to between 52 and 73% of the total costs.

29.4.3 Influencing Factors on Costs and Sustainability of AM

In accordance with expectations prior to the calculations, influencing factors on the costs of the FDM printers mostly refer to effects on variable costs, as they change with the reference value. Variable costs in the case of AM refer to consumables like energy, material and equipment. The same applies to the impact on sustainability achievement. As waste management is one pillar for achieving sustainability, the high amount of material waste, caused mostly by support structure and/or rejected material, shows some negative impact on sustainability achievement. In addition to the amount of wasted material, a preliminary study identified the impact of software and parameter selection on total material consumption, which also effects material costs and sustainability in terms of resource exploitation. However, all test prints included in this study were conducted under default settings, e.g. the filling levels were reset to default settings, to disregard potential impacts that parameter changes could have on costs to ensure comparability among the printers.

In the case of all printers, energy costs incur only a relatively small fraction of the total TCO costs, but the costs still differentiate between the investigated printers. Taking printer 1 as example, some potential was identified to improve sustainability in terms of reduced energy consumption during heating and cooling periods. Like material and energy costs, the costs for printing equipment seem to vary significantly between different FDM printers, depending on the specifications and requirements of the machine. Printers that do not require printing equipment contribute to lean manufacturing through the reduction in costs and materials (plastics) used, which benefits sustainability achievement. All in all, the potential for improvement towards sustainable AM and concurrent cost reduction mostly refers to reduced material waste (for printer 1 and 3), optimised energy consumption during non-printing periods (for printer 1) and reduced amount of required printing equipment (especially printer 1). In addition to potential influencing factors on variable cost components, the costs for equipment, software and spare parts strongly depend on the specifications, while costs for training and maintenance depend on supplier specifications. An in-depth analysis of the printer and supplier properties is therefore recommended.

29.5 Conclusion

This paper reports on the development of a general TCO model for the application to AM, in this case to three selected FDM printers. Using three selected FDM printers as objects of research, the study facilitated to uncover relevant cost components and true costs of AM, which helped to derive explanations on the significance and variation of cost components and to draw the following conclusions. The in-depth analysis of printer properties and the uncovering of true costs offered insights into the achievement of sustainability in AM. Especially variable costs, meaning costs for consumables like material, energy and printing equipment, seem to have a direct impact on sustainability achievement. The study found some recommendations towards sustainability improvement and concurrent cost reduction in AM. This refers to the optimisation of software and parameter selection towards the reduction of material consumption, investment in printers with lowest possible amount of material waste through the avoidance of reject material and non-necessary support structures, inclusion of material recycling into the AM lifecycle, avoidance of investing in printers that require printing equipment and investment in printers with lowest possible level of energy consumption. This presupposes an in-depth analysis of relevant cost components and printer properties prior to the purchase of a 3D printer for the optimisation of procurement decision. In particular, this can be approached with the application and enhancement of the developed TCO model, which proved to provide an appropriate framework for the assessment of total costs together with sustainability in AM.

The research was limited to the investigation of three FDM printers, used for research purposes. In this case of application, total costs and especially variable costs seem to keep within reasonable limits, due to small manufacturing volumes and low operating grade. However, the results are estimated to deviate widely for printers, which are used for commercial manufacturing in enterprises. In this latter case, the adoption of FDM printers might be less beneficial than traditional manufacturing until improvements in cost-effectiveness and sustainability in AM are reached. The suggestion for the future is to further investigate in studies on TCO and sustainability assessment for FDM machines while considering different application modes, operating grades and solutions for improvement.

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Chapter 30
On the Assessment of Thermo-mechanical Degradability of Multi-recycled ABS Polymer for 3D Printing Applications

Amal Charles, Pedro Matiotti Bassan, Tobias Mueller, Ahmed Elkaseer and Steffen G. Scholz

Abstract Although additive manufacturing (AM) has offered proven ability to reduce waste when compared with traditional manufacturing techniques, however, AM processes such as fused filament fabrication (FFF) still poses some negative environmental and economic aspects in terms of generated waste. This waste comes from rafts, supports, or bases that are parts of the supporting structure necessary in the construction of proper 3D-printed parts. In addition, another source of waste comes from jobs that failed due to a variety of reasons as is common with 3D printing. One possible way to minimize the negative effect is to recycle this waste material. Through the usage of commercially available cutting mills and extruder equipment that are easily procurable, it is possible to recycle the waste and reuse it as a filament. In this context, this paper aims to experimentally investigate the feasibility of recycling 3D printing waste material, namely of ABS material which is a popular 3D printing material and to evaluate changes in the mechanical behaviour after each recycling cycle, while taking the performance of the virgin material as a reference point. The mechanical behaviour of the recycled materials was assessed as a function of obtainable tensile strength, toughness and thermal transition. The results show that the ABS filament shows great promise for recycling at least once and could lead to significant material and cost savings. In this work, it is possible to observe how many times ABS can be recycled and used as filament, without adding virgin material.

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30.1 Introduction

The fused filament fabrication (FFF) technique was first introduced in 1991, but the first 3D printer that actually produced parts out of acrylonitrile–butadiene–styrene (ABS) polymer filament was released in 2000. These 3D printers, which were known as 'new-generation machines' would indicate the start of the 3D printing revolution. Late 2001 saw the commercial shipment of the first FFF printer capable to produce parts in ABS [1].

As the FFF technology sees many innovative developments and improvements, the machine tools become more popular, widely available and affordable. Therefore, it is imperative now to also consider and evaluate the sustainability of the process and its long-term impacts.

The fact that 60% of all plastic ever produced was not properly discarded and is in landfills or in the natural environment [2] and shows the importance of recycling the waste generated by additive manufacture processes using polymers. Many research attempts are being made to investigate material savings by the early detection of printing errors and by creating highly efficient printing systems [3–5]. FFF printing generates a considerable amount of waste, which occurs primarily due to failed builds as well as secondary structures such as supports, brims and bases that are subsequently removed during the post-processing step. This waste usually goes straight into the disposal, although ABS, being a thermoplastic polymer, is a prime candidate for reusing. Using a cutting mill and an extruder, equipment that easily can be found in research centres and laboratories, it is possible to recycle the waste and reuse it as a filament. In general, the processes to reduce waste can be classified as: reuse, mechanical recycling and chemical recycling [6].

- when the parts are cleaned and reused without other processes [6].
- Mechanical recycling: process used in this work, the part is milled, reprocessed and then reused, without changing the chemical structure [7, 8].
- Chemical recycling: convert the polymer into low-molecular structures and can be used for the production of chemical products [9].

Nowadays using a small extruder, it is possible to recycle filament and household plastics at home and save over 90% off the cost with it [10].

One important issue that needs to be considered when recycling filaments is that polymers suffer chemical and physical degradation during the process. This problem affects some properties such as: tensile strength, impact strength, flexural strength, melt flow index (MFI), thermal behaviour and rheology [8, 11–17].

The aim of this research work is to experimentally investigate the degradation that occurs while recycling 3D printing ABS filament as well as the influence of the extrusion process on mechanical and thermal properties.

The parameters measured to evaluate the degradation are:

- Visual examination
- Differential scanning calorimetry

- Tensile test
- Charpy impact test

30.2 Filament and ABS Recycling Background

ABS is a popular thermoplastic polymer, which over the past few years has gained popularity for usage in the FFF technique. It has excellent roughness, good dimensional stability, good processability, and chemical resistance and stability. All these advantages allied with good price turned ABS into the largest selling engineering thermoplastic [10]. ABS is highly suitable for injection moulding and is therefore used in a wide variety of manufactured products which includes automotive components, sports equipment, electrical enclosures as well as toys such as Lego bricks. And when extruded as a filament, ABS is a common material used for 3D printing.

ABS has two phases: amorphous styrene–acrylonitrile copolymer (SAN) phase and a rubber polybutadiene (PB) phase. The PB phase degrades before, during the initial stages, consuming the unsaturated groups and formatting oxidized halves. PB contains tertiary carbons that can be oxidized during the degradation and breaking PB/SAN bonds [15]. This degradation is represented in Fig. 30.1.

Previous research attempts to characterize the degradation of 3D printing filament have concentrated on other popular filaments such as Polylactic acid (PLA). Cruz Sanchez et al. processed PLA filament for FFF 3D printers and recycled five times. Their tensile test results showed decreased tensile strength values with each successive recycling cycle, showing a bigger difference between cycle one and two [18].

Rahimi et al. recycled ABS five times while producing the parts using an injection-moulding machine. They then used impact and tensile tests in order to analyse the mechanical behaviour. Their results show that the increase in the number of reprocess cycles increases in stress strength. They also observed a drastic decrease in impact strength, a property which ABS is known to have high values [16].

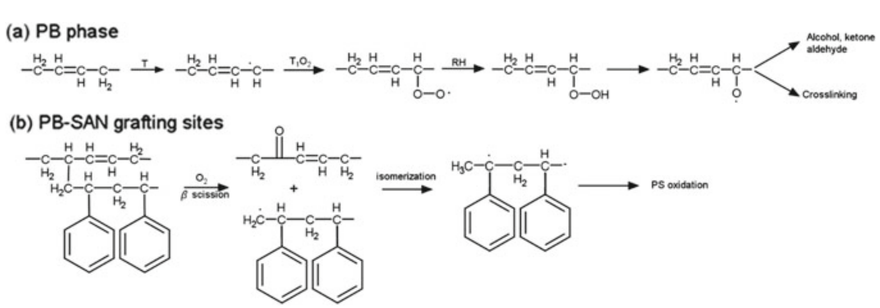

Fig. 30.1 Degradation mechanism of ABS (Adapted from [12])

Scaffaro et al. did tensile tests on virgin ABS (v-ABS) and post-consumer ABS (pc-ABS) blends up to three recycles and changing the percentage (0–100% of pc-ABS). It is possible to observe a bigger decrease of tensile strength between the 100% v-ABS to 100% pc-ABS on the first recycling [15].

Arostegui et al. recycled ABS by dissolution, up to four cycles and then injection moulded. They tested every cycle with DSC. From their results, it is possible to observe that virgin ABS decreased from about 112 to 107 °C the glass transition temperature (T_g) while the dissolved and injected material decreased to 95 °C.

For impact, Arostegui et al. tested v-ABS and four recycles specimens where it is possible to observe bigger difference between v-ABS and first recycling. The yield stress tests show a very similar result where the v-ABS had higher results and recycled ABS close results but lower than v-ABS [11].

Looking at the literature, there has been no experimental study looking at the influence of the degradation by recycling 3D-printed ABS. Although, there has been important reported studies with recycled ABS/HIPS blends [17], re-ABS nanocomposites [19], PBT/PC/ABS blends [12], accelerated weathering on ABS [13], fracture analysis of ABS and ABS-based materials [14], tensile strength on different filaments [20] and recycling polymers waste [6, 8].

30.3 Methodology

30.3.1 Printing

The process parameters used to print the tensile and impact tests specimen can be seen in Table 30.1.

Table 30.1 Process parameters

Parameters	Value
Filament diameter	1.75 mm
Nozzle diameter	0.40 mm
Layer height	0.16 mm
Retraction height	0.30 mm
Retraction amount	4.00 mm
Path width	0.40 mm
Print speed	40 mm/s
Travel speed	120 mm/s
Infill	100%
Printing angle	−45°/45°
Nozzle temperature	230 °C
Bed temperature	100 °C
Outlines	3

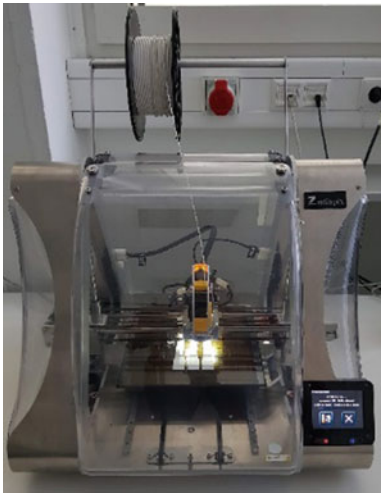

Fig. 30.2 ZMorph SX 3D printer

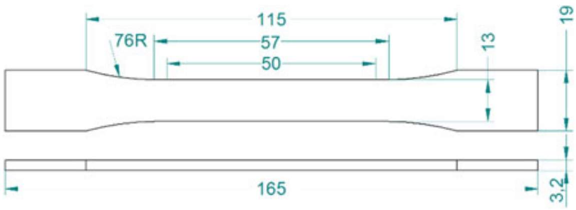

Fig. 30.3 Specimen type I from ASTM D638-14 standard (all values in millimetres)

The printer used is a ZMorph SX (see Fig. 30.2) using a white ABS filament from Makerbot with a diameter of 1.75 mm as the starting point. The printer is equipped with interchangeable tool heads. For this work, a single extruder with a direct drive unit was chosen. To avoid delamination of the parts from the printing platform and adhesive spray was used to allow for maximum adhesion.

30.3.2 Tensile Test

The tensile test specimen was built following ASTM D638-14 standard [21] choosing the type I geometry (as shown in Fig. 30.3). The parameters being measured include:

- Elastic modulus E (MPa): ratio of stress (nominal) to corresponding strain below the proportional limit of the material.
- Tensile strength (σ_m) (MPa): Maximum stress sustained by the test specimen.

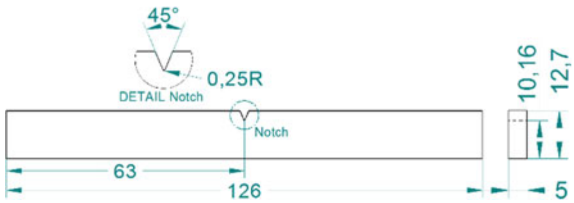

Fig. 30.4 Charpy impact specimen from ASTM D6110-18 (all values in millimetres)

30.3.3 Charpy Impact Test

A Charpy impact test is a standardized test used to determine the amount of energy absorbed by a material during fracture. This acts as a tool to study temperature-dependent ductile–brittle transition. For the impact tests, the parameters from ASTM D6110-18 standard [22] were followed. The size of the specimen is shown in Fig. 30.4. As was the case with the tensile test, five specimens were impact tested within each cycle too.

30.3.4 Differential Scanning Calorimetry (DSC)

A DSC test is conducted to determine the glass transition temperature (T_g) of a polymer. It depicts the temperature range where a polymer transitions from a hard, relatively brittle, glass-like material to a soft rubbery material. A Netzsch DSC 204 instrument was used from −20 to 300 °C at a heat rate of 10 °C/min.

30.3.5 Milling and Extruding

Both the virgin filament as well as the recycled filament were broken down in a grinding machine into small ABS particles where the size distribution was observed to be between 1 and 5 mm. This size distribution was suitable for conducting the subsequent filament extrusion of ABS in the desktop extruder from FilaFab, model PRO 350 EX (Fig. 30.3).

In the extruder process, plastic goes into the feed hopper in small pieces or pellets, which is pushed through by the turning screw until the heated zone where it is heated and passes through the nozzle as a filament (Fig. 30.5).

The material was milled and extruded three times, based on the literature review, and this number was deemed enough to show the difference in the mechanical behaviour when comparing with the original material.

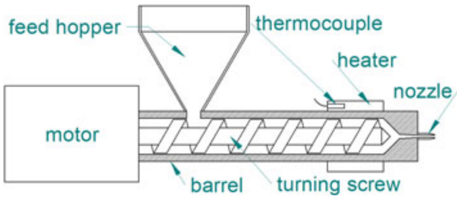

Fig. 30.5 Extrusion mechanism of PRO 350 EX filament extruder

Fig. 30.6 Visual examination

30.4 Results and Discussion

30.4.1 Visual Examination

From visual inspection of the specimens, it was possible to observe that as the number of cycles increased, the printed part showed a noticeable degradation in colour. This can be attributed to the loss of certain additives during the extrusion process leading to the darkening of the filament as shown in Fig. 30.6.

30.4.2 DSC

In order to evaluate the influence of the recycling process on the polymer and to identify possible degradation effects, DSC was used to measure the glass transition temperature (T_g). As can be seen in Fig. 30.6, there is a small difference between the T_g values on each cycle. For standard ABS polymers, the measured T_g value is given at 105 °C. The recycled filaments all measured at almost exactly 105 °C. This demonstrates that the temperature range at which the recycled filaments transition from a hard brittle substance to a soft rubbery polymer remains same and the recycling process chosen for the experiments has no substantial effects on the polymer within

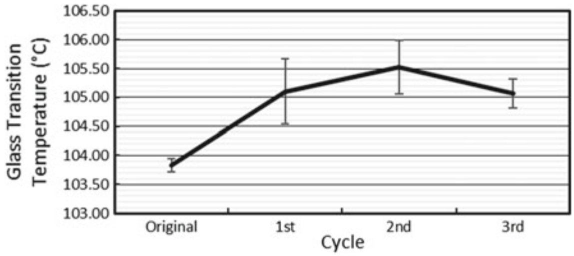

Fig. 30.7 Glass transition temperature on all cycles

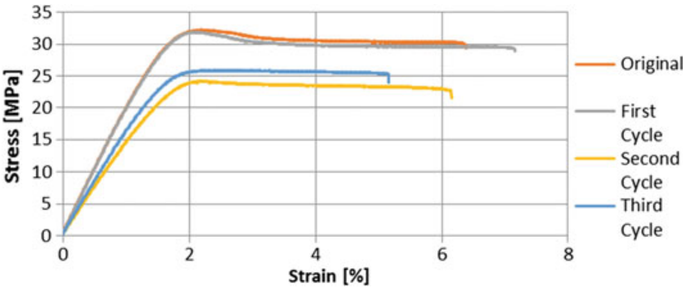

Fig. 30.8 Tensile stress

three loops of regrinding and extruding new filament as can be judged from the thermal behaviour (Fig. 30.7).

30.4.3 Tensile Test

The results from the universal testing machine show that there is a progressive decrease in maximum tensile stress and elastic modulus through each recycling step. The decrease in tensile stress is minimal between the original filament and once recycled filament. However, both the second and third cycle showed greater reductions. Young's modulus for the second cycle was measured to be 25% lesser than the virgin material while the third cycle showed a reduction of 16% when compared to the virgin material (Fig. 30.8).

30.4.4 Charpy Impact Test

There is an increase in the amount of impact energy required to fracture the recycled filaments when compared to the original filament. However, the increase is only slightly higher considering the error margins and still quite comparable to the original

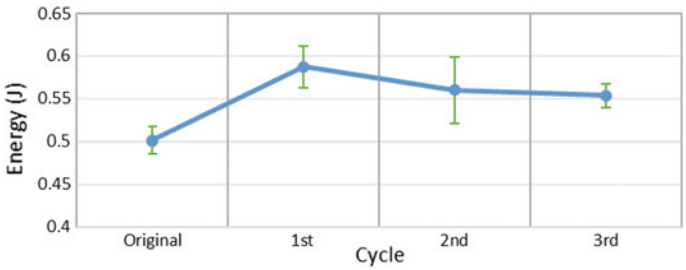

Fig. 30.9 Charpy impact test results

specimen. Therefore, it can be concluded that the impact strength of the recycled polymers tends to remain constant within the three recycling cycles conducted in this work (Fig. 30.9).

30.5 Conclusions

The intent of this work was to investigate the influence of a recycling process on ABS processed by FFF and, if possible, establish rules on the amount of recycled material that can be used in mixture with fresh material for producing new filament. Based on the experimental results, it can be concluded that the suggested method of recycling ABS polymer filament from failed builds and other printing wastes can indeed increase the lifetime of printing with ABS polymers without too much mechanical or thermal degrading. The results of tensile test show that there is only a minimal decrease in tensile strength between the original and first cycle but a drop in maximum tensile strength after the second recycling round. Results of impact test on notched samples showed no significant loss of impact strength, even a slight increase could be observed. This may be resulting from slight changes in polymer viscosity and therefore small improvements in printing quality, which should have a higher influence on the impact behaviour than the tensile strength. Concerning polymer degradation, the measurement of the glass transition temperature (T_g) showed almost no variation at all, therefore it can be concluded that the chosen recycling process is very subtle and does not lead to a significant variation in the chemical composition of the ABS. In fact, the T_g of the recycled polymers (in contrast to the original filament) showed exactly the T_g of native ABS found in literature, which could be due to the fact that some of the additive added to the virgin Makerbot ABS filament may have been lost during the extrusion process leading to a more homogenous recycled ABS filament. A constant T_g depicts that the same process parameters in terms of temperature can be used for the printing of recycled ABS as applied to virgin ABS filament.

In summary, it can be concluded that recycling of ABS filament at least once is highly recommended and could lead to substantial material as well as cost savings, if the aesthetics of the printed part are not the main issue since discolouring of the original material is possible. When considering only the mechanical and thermal properties, mixing recycled and virgin material is another way to increase the recycling rate of additive manufacturing materials.

Further work will be conducted on further characterizing the recycled ABS filament in order to understand all chemical changes that happen during the material extrusion process, including measuring the viscosity, as this will have an effect on the extrusion behaviour during the printing process. Also, additional effort will be put in closely examining the print quality, since it has a strong effect on the mechanical behaviour, especially in the impact test.

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Chapter 31
A Study on the Modeling and Simulation of Bio-inspired Hedgehog Spines Structures for More Efficient Use Digital Manufacturing Processes

R. O'Sullivan, A. Rees, C. A. Griffiths and J. Wadlinger

Abstract Direct digital manufacture and additive manufacture have allowed designers the ability to design components without the design limitations witnessed in subtractive manufacturing process routes. In particular, designers can now design parts that fully utilize material usage resulting in a more sustainable and environmentally friendly application of manufacturing technology. Within this context, designing and manufacturing bio-inspired components have the potential to increase both component functionality and optimize material usage. One such area of biomimicry with advantageous strength-to-weight ratio can be found in hedgehog spines. Within this study, hedgehog spines were redesigned to facilitate production through additive manufacture. In addition, with the use of finite element analysis to quantify the resulting compressive characteristics, the optimal internal geometry and septa spacing were determined. Also, a design of experiments study was conducted to determine which design features have the greatest influence on the resulting stress in the spine. The analysis concluded that the combination of longitudinal stiffeners and equally spaced septa give the spine its superior compressive strength.

31.1 Introduction

The term 'biomimetics' was first used in the 1950s by Otto Smith, a biophysicist and bioengineer who attempted to produce a device that mimicked the electrical impulse of a nerve [1]. However, the concept of biomimicry has been around for centuries; for example, Leonardo Da Vinci's design for a 'flying machine' mimicked the flight of winged animals such as bats and birds in the fifteenth century. Examples of how biomimicry is being used today include; Velcro® which replicates the tiny hooks of burdock seeds, honeycomb structures are used to maintain the strength of a material

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while reducing the amount of material used, swimsuits that mimic the aerodynamic properties of sharkskin and needles comprising a central straight needle and two outer jagged ones that mimic mosquito mouths to glide painlessly into the skin [2]. There is a large amount of diversity in natural structures, from the tensile strength displayed by spiders' silk and an abalone shells ability to absorb large impacts to the superhydrophobicity of lotus leaves [3].

Some of the properties displayed in nature come from chemical or biological processes. However, this study will focus purely on the physical properties of biological structures. Hedgehog spines have a high strength-to-weight ratio with their main function most likely being shock absorption, as they can resist buckling up to 200 times their critical load [4]. The unique internal structure of these spines is thought to be the key to their strength and bio-mimicking it has many potential shock-absorbing applications.

31.2 Biomimetic

31.2.1 Hedgehog Spines

In the study by Vincent, it was concluded that both hedgehog spines and porcupine quills both consist of pointed tubes made from the fibrous alpha protein keratin [5]. In the case of porcupine quills, they differ in length across the body and are relatively easy to remove. Hedgehog spines are typically embedded into the skin and slightly curved in geometry. The porcupine's quills main function is defense, while in comparison with the hedgehog spines main functions are shock absorbing, as hedgehogs bounce when they fall [5].

Hedgehog spine structures consist of an outer tube-shaped wall with orthogonal longitudinal and circumferential stiffeners in a 'square honeycomb structure.' There is a foam-like structure located down the center to support the outer walls from local buckling. This structure means that compared to hollow tubes, the spines are three times better at resisting buckling under axial load [5].

When designing hedgehog spines for a given bending stiffness, the mass of the tube could be reduced by increasing the relative radius, giving the tube a higher second moment of area, and therefore greater flexural rigidity. However, the tube would undergo Brazier ovalization at the point of highest force, but the longitudinal and circumferential stiffeners provide reinforcement, and if they were increased in size, the foam core could be removed. The material in the center of the core had a low second moment of area and provides very little support in proportion to its mass, meaning it can safely be omitted from the structure [5].

Figure 31.1 displays the spines from a female African Pygmy Hedgehog [6]. The air pockets along the core of hedgehog spines, separated by regularly spaced septa and other internal structures, delay the onset of buckling under axial loads, enabling the spines to absorb large amounts of mechanical energy [7]. The septa delay the

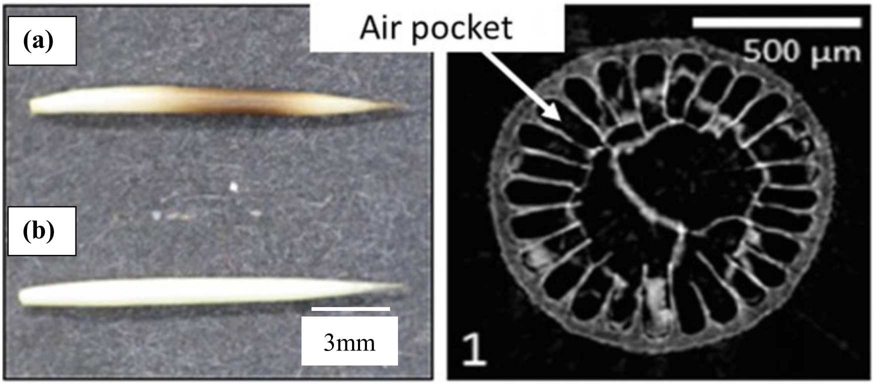


Fig. 31.1 **a** Spines and **b** microscopic view of spines from a female African Pygmy Hedgehog [6]

onset of local buckling by retaining the cross section, making the second moment of area higher. In addition, the septa resist tension rather than compression, as they are thin enough to buckle in compression. Once the load is large enough to cause a section of the spine to become oval, the effect of the second moment of inertia is reduced, and the spine fails due to local buckling or compression failure [7].

In a study by Kennedy et al., it was concluded that hedgehog spines are gram for gram stronger than certain grades of stainless steel for rods of the same diameter (1 mm) and as pliable as styrene rods of a slightly larger diameter. This combination of strength and elasticity as well as being lightweight and material efficient makes hedgehog spines good shock absorbers, with biomimetic potential [6].

The research in this paper is a starting point for the creation of a knowledge repository with focus on the applicability of bio-inspired structures to aid design functionality and deliver more sustainable products due to optimized material usage. The paper is organized as follows. Section 31.3 discusses the model configuration and finite element analysis (FEA) setup. In Sect. 31.4, the results are discussed. Finally, in Sect. 31.5, the main conclusions from the conducted study are presented.

31.3 Experimental Setup

31.3.1 Model Development

SolidWorks was used to both 3D model and perform the subsequent FEA simulation. The initial model was based on the diagram in Fig. 31.2. To simplify its geometry, the dimensions were taken from indicative values from previous research studies [4–7]. The dimensions are presented in Table 31.1. Initially, FEA was attempted on the simplified replica design; however, the model was unable to mesh due to length

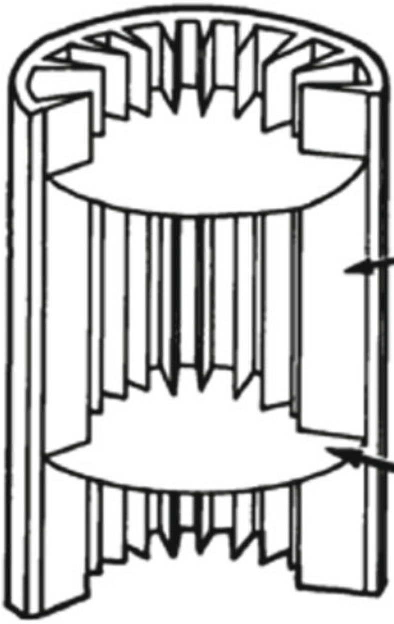


Fig. 31.2 Simplified spine diagram [9]

Table 31.1 Hedgehog spine dimensions (African Pygmy) [4]

Spine length (mm)	Spine outer diameter (mm)	Wall thick-ness (mm)	Longitudinal stiffener length (mm)	Longitudinal stiffener width (mm)	Septum thick-ness (mm)	Septum spacing (mm)	Number of longi-tudinal stiffen-ers
20	1	0.045	0.184	0.015	0.020	0.217	25

scale integration challenges in the simulation software. Therefore, the initial model was scaled-up by a factor of 100 to facilitate meshing. The model also contained fillets between the intersection of the septa and the tube wall to reduce stress raisers and to more accurately replicate real hedgehog spines. The material used for the simulations was PLA, and the properties are presented in Table 31.2.

For the FEA, a static simulation was set up with one end of the spine fixed in all directions and a compressive force applied at the other end. The compressive force was increased in regular intervals from 1 to 100 kN. This test was then repeated

Table 31.2 Material properties of PLA

Material	UTS (MPa)	Strain at failure	E (MPa)
PLA	47.66	0.04	3414

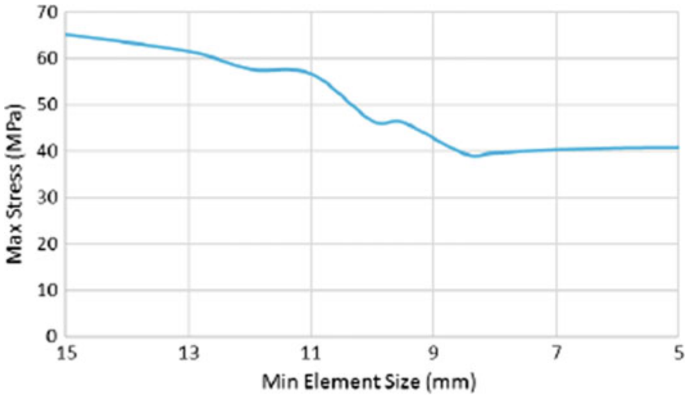


Fig. 31.3 Mesh refinement

with the longitudinal stiffeners and the evenly spaced septa removed individually and together, so that their isolated effects on the spine could be assessed.

The FEA studies were also repeated on standard tubing geometries for benchmarking study purposes.

31.3.2 Mesh Refinement

To ensure the FEA on the spine was not mesh dependent, the optimum mesh was found through mesh refinement. This was done by running multiple simulations and reducing mesh size each time, until the difference in the maximum stress was negligible between runs. The graph in Fig. 31.3 illustrates the results of curvature-based meshes ranging from 15 to 5 mm. The results begin to plateau around a minimum element size of 7 mm; therefore, this mesh size was chosen for the study.

31.3.3 Factorial Analysis

A full factorial design of experiment (DOE) was conducted to determine which factors/interaction of factors has the greatest influence on the mechanical properties of the spine. Table 31.3 displays the factors and levels of the parameters analyzed in the study. The model was set up with a compressive force of 425 kN.

Table 31.3 Factors used for full factorial analysis

Factor	Level	
	−1	1
A. Wall thickness (mm)	4.5	6.5
B. Number of stiffeners	15	20
C. Stiffener thickness (mm)	16.8	25
D. Septum spacing (mm)	60	100

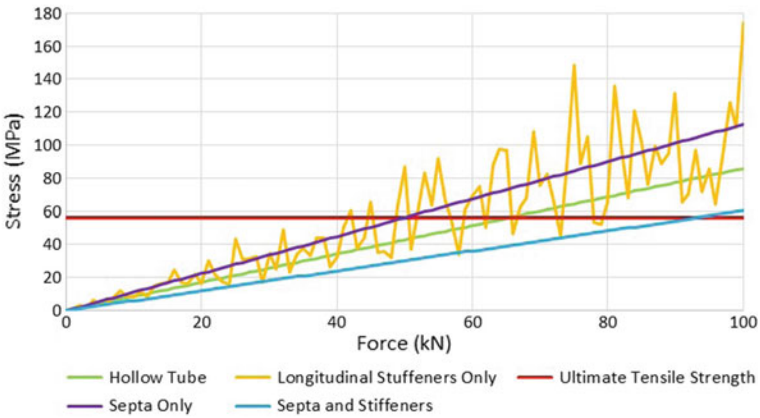


Fig. 31.4 Resulting stress profiles

31.4 Results and Discussion

31.4.1 Initial FEA

Figure 31.4 shows the results from the initial simulations. In this study, the resulting maximum stress was analyzed to evaluate the effect of adding a septa and longitudinal stiffeners to a hollow tube design. It can be seen that when compared to a hollow tube of the same thickness, the addition of the septa increases the maximum stress in the spine, meaning it reaches its ultimate tensile stress (UTS) at a lower force. The addition of the longitudinal stiffeners on their own also increases the maximum stress in the spine, but unlike the smooth line of the septa, the results oscillate erratically. However, Fig. 31.4 shows that when combined the longitudinal stiffeners and septa collectively decrease the maximum stress in the spine and increase the force required for the spine to reach its UTS from 62 to 92 kN.

Table 31.4 Factors used for full factorial analysis

Run	Factor				Maximum stress (MPa)
	A	B	C	D	
1	−1	−1	−1	−1	55.16
2	1	−1	−1	−1	36.08
3	−1	1	−1	−1	30.65
4	1	1	−1	−1	26.69
5	−1	−1	1	−1	30.50
6	1	−1	1	−1	28.25
7	−1	1	1	−1	20.84
8	1	1	1	−1	19.22
9	−1	−1	−1	1	39.88
10	1	−1	−1	1	40.24
11	−1	1	−1	1	32.13
12	1	1	−1	1	25.26
13	−1	−1	1	1	30.50
14	1	−1	1	1	28.25
15	−1	1	1	1	20.84
16	1	1	1	1	19.22

Table 31.5 Optimum factor levels

Factor	Level	Value
A. Wall thickness (mm)	−1	6.5
B. Number of stiffeners	−1	20
C. Stiffener thickness (mm)	−1	25
D. Septum spacing (mm)	1	60

31.4.2 Full Factorial Analysis

A full factorial design of experiment (DOE) was conducted (Table 31.4) to determine the optimum design parameters. Also, a Pareto analysis (Fig. 31.5) was conducted to determine the effect that each design factor has on the resulting maximum stress. The analysis concludes that factors B (number of stiffeners) and C (stiffener thickness) have the highest influence over the maximum stress.

The normal probability plot shown in Fig. 31.6 verified the distribution of the data used in the experiments. The results fit the line well suggesting the data is reliable and error free. Figure 31.7 gives the main effects plot for stress, with the optimum factors given in Table 31.5. A confirmation run was carried out to ensure the results were correct. The model was then subjected to increasing forces, so that the force at failure could be determined. The results are displayed in Fig. 31.8, and it can be seen that the spine reached its UTS at approximately 1250 kN.

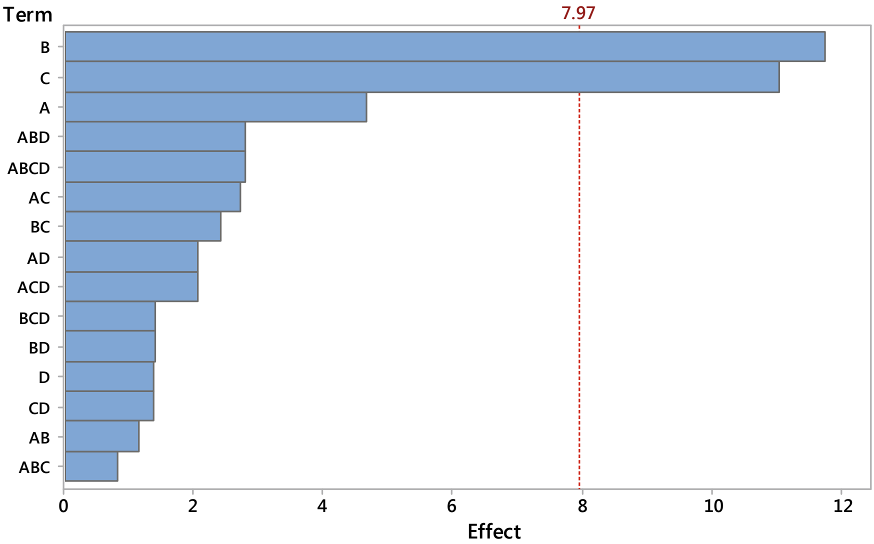


Fig. 31.5 Pareto chart of the effects

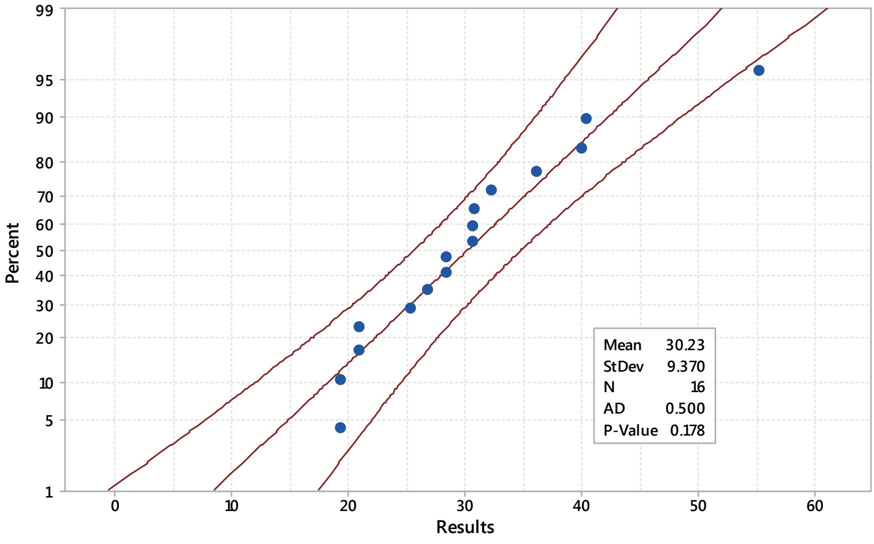


Fig. 31.6 Normal probability plot

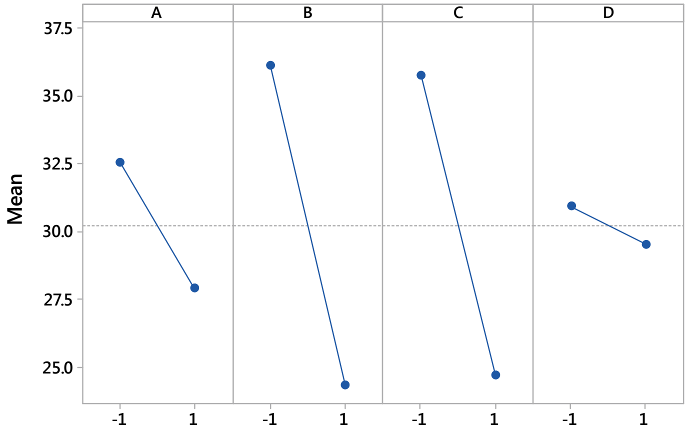
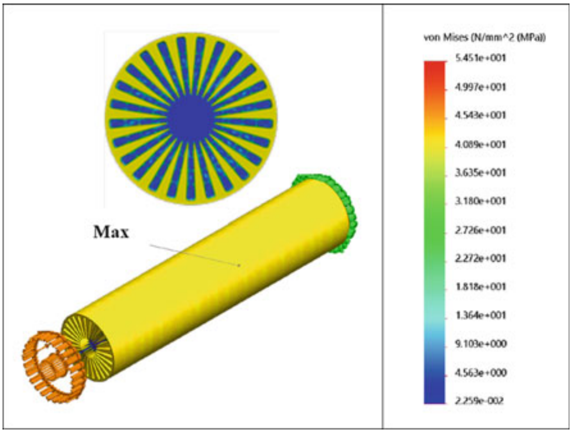


Fig. 31.7 Main effects plot for stress

Fig. 31.8 Stress distribution in the models at maximum force



31.5 Comparison to Steel

To gain an understanding of the benefits that producing bio-inspired components through digital manufacturing can provide, the resulting mechanical properties were compared against alternative materials. In particular, the PLA hedge spines developed within this research were compared against tubular steel sections in 201 stainless steel AISI 1010 and AISI 1018. Table 31.6 displays the material properties. It can be concluded the results from the PLA samples are comparable to those obtained from metal with regard to maximum compressive force and strength-to-weight ratio. This demonstrates the potential to use the design of the hedgehog spines for applications such as crash structures.

Table 31.6 Steel tubing properties

	201 stainless steel [8]	AISI 1010 cold drawn [9]	AISI 1018 cold drawn [10]	PLA hedgehog spine
Volume (m^3)	0.009	0.009	0.009	0.0502
Density (kg/m^3)	6800	7870	7870	1240
Max compressive force (kN)	1150	1500	1860	1250
Strength-to-weight ratio	1918	2161	2680	2200

31.6 Conclusion

The aim of this paper was to demonstrate the benefits that digital and additive manufacture provides designers with regard to delivering more sustainable and environmentally friendly manufacturing platforms. In particular, this study analyzed the benefits that mimicking hedgehog spines deliver. This was achieved through computational modeling of an individual spine and optimizing through a DOE full factorial study.

The main findings from this paper were:

- The initial testing showed that the strength provided by the unique internal structure of the spine comes from a combination of longitudinal stiffeners and equally spaced septa. However, separately these components act as stress raisers.
- The DOE analysis further proved that cross-sectional area was the governing factor of stress in the spine. In particular, the thickness of the longitudinal stiffeners had the greatest effect on the stress, closely followed by the number of stiffeners.
- The research in this paper is a starting point for the creation of a knowledge repository with focus on the applicability of bio-inspired structures to aid design functionality and deliver more sustainable products due to optimized material usage.

31.7 Future Work

The main conclusions from this work offer the potential to broaden the knowledge base of both the application of bio-inspired components and how inherent variation within digital manufacturing platforms will affect the resulting mechanical properties. Additional future work can also investigate the validation of the simulation results through different methods of digital manufacturing platforms.

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Chapter 32
Internet of Things Solution for Non-invasive Vital Data Acquisition: A Step Towards Smart Healthcare System

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Abstract The advent and subsequent explosive growth of hi-tech medical industry is one of the main features of the modern era. It is driven by the legitimate plea to apply smart healthcare environment for a broad range of working systems, entailing hospitals, schools, workshops, etc. In particular, smart healthcare offers a unique opportunity to optimise the interaction between the human and the medical system (equipment/tools and doctors) for diagnosis, monitoring and treatment measures, which certainly will decrease infections and disease's transmissions. However, developing a reliable Internet of Things solution, to facilitate a seamless and flawless data transmission among smart assets, is an indispensable task to fully implement. Accordingly, the motivation for this paper is to develop an IoT technique for a non-invasive healthcare system to enable vast collecting and analysis of human vital data via a computer vision technique in order to reduce infections. In particular, concurrent IoT communication was designed for a mesh of three nodes, entailing a sensing node for heartbeat measurement, a vital data visualising node and a broker node. This was developed to guarantee a real-time visualisation of the vital data of the human/patient and it was enriched by an offline visualisation and online cloud visualisation via the broker node. Furthermore, an embedded software architecture was developed that offers a reliable solution to minimise communication latency and provides real-time response to acquired information. Also, the software design is applicable to easily interface with newly added nodes in the future to increase the scale of IoT mesh.

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32.1 Introduction

According to the US Census Bureau, a rapidly growing population of the elderly is in continuous increase and the number of adults will double by 2025. Also, it is expected that healthcare costs will reach nearly 20% of the gross domestic product (GDP) of the USA [1]. The rapid increase in population necessitates further development in the healthcare system. Healthcare systems have been introduced to recognise a patient's vital data and to document and visualise the medical investigation and to suggest the optimal responses to be taken. Nevertheless, due to the high-risk nature of the medical environment, these systems face real challenges such as infection transfer and trouble of managing the data among sub-systems. Also, missing medical histories and vital data features due to inconsistent follow-up of the patient is an issue that still needs addressing for further development of the healthcare system.

In this context, addressing these challenges is the motivation for this research. The aim of this paper is to develop a usable, safe, scalable, sustainable and affordable healthcare solution based on integration of computer vision and IoT technologies. The proposed solution enables real-time monitoring of the health of adults at home, kids in schools, employees/engineers in corporate/manufacturing environments and to thereafter facilitate the early recognition/prediction of diseases.

In recent years, researchers have focussed on developing non-invasive sensing techniques for vital data such as heart rate, blood pressure, body temperature and respiration. Non-invasive heartbeat recognition is one of modern healthcare solution objectives. The sensing of heartbeats based on non-invasive data acquisition was developed using integration photoplethysmography concept using a digital camera. The digital camera captured the blood from a hand finger and analysed the frame into its three basic colour components (red, green, blue); then, the heart rate estimation result is calculated based on the analysis of the 3D component of colours [2]. However, this solution is still not fully non-invasive because the patient has to put his finger over the LED, which could lead to diseases and infection. The non-invasive concept is developed to be fully separated from the patient's body by developing an image processing algorithm for pulse reading of heart rate and respiratory based on CCD camera capture. This algorithm applied on a human face with dimensions (3 cm $\times$ 4 cm). The algorithm detected the brightness changing using spectral analysis in order to get vital data [3]. Nevertheless, the environment could affect the brightness and illumination factors which cloud change the results.

In addition to computer vision, the non-invasive sensing of vital data can be implemented via radio frequency. Vital-radio algorithm is developed to detect the heart rate within a range of 8 m [4]. The sensing of heartbeats was performed by a photosensor via infrared LEDs and a phototransistor embedded in an earphone. The phototransistor sensed the reflection of the infrared LED. The amount of infrared reflection changed corresponding to the changes in the amount of blood which is relative to heartbeats [5].

All previous computer vision algorithms for vital data acquiring is limited to detected small changes which could cause inaccuracy. Eulerian video magnification has introduced methods to detect small changes which cannot be seen by the naked eye [6]. The magnification is introduced by applying some temporal filtering to the frames of the video in order to visualise hidden information. In this paper, the proposed heart rate estimation algorithm is developed based on Eulerian video magnification concepts. Also, the proposed algorithm integrates with the IoT algorithm to manage the healthcare solution.

Internet of Things (IoT) is enabled by the modern design of radio frequency identification (RFID), wireless sensor network (WSN) and communication techniques with Internet protocols integration. The core foundation is to have smart sensors and algorithms that cooperate autonomously without human responsibility; then, the algorithms process the sensing data to produce information. This information is exchanged between IoT nodes via the established communication technique. The communication session enables physical objects to talk with each other. Also, it provides a physical object to talk with Internet (cloud computing) [7].

In the literature, IoT architecture has been designed on 5 layers (object layer, object abstraction layer, service management layer, application layer and business layer). Object layer refers to the sensors of the physical system. Its objective is collecting the information of the physical world by digitalising physical behaviour and sending it to the object abstract layer. The objects produce information which will be received by the object abstraction layer which sends it to the service management layer using communication protocols such as RFID, BLE, Zigbee, Wi-Fi and LoRa. Service management layer (Middleware) enables IoT approach to work with heterogeneous specs/behaviours without decency on hardware features. The decision/response occurs in this layer. The application layer provides the services' deployment based on request or not. The significance of this IoT is the ability for providing high-quality services that the interface customer requires. Finally, the business layer aims to manage all IoT sub-system and produce the data visualisation after analysis of the process. Furthermore, it is responsible for the evaluation and monitoring of the output. The big data analytics cloud is enabled by this layer [7, 8].

This research introduces healthcare solution based on vital data acquisition using non-invasive sensing algorithms in order to prevent infections and contaminations. This data acquisition consists of a human heartbeat estimation algorithm based on a computer vision approach. The algorithm developed based on low-cost machine in order to minimise the cost of the healthcare solution set-up. Also, the data acquisition is integrated within the IoT algorithm, which consists of three nodes in order to visualise the vital data in local and cloud computing side. Furthermore, the IoT algorithm design is capable of an increase in the scale of interfacing with other vital data acquisition. Furthermore, the IoT run based on low power-consuming platform. The IoT algorithm introduces many features of data exchange due to the selection of heterogeneous physical layer. This healthcare solution offers minimum interface with patient in a usable way. Also, it introduces fully documentation and visualisation of vital data versus time.

32.2 Proposed Architecture

The proposed solution is designed via a non-invasive data acquisition technique, which uses computer vision algorithms to estimate the heartbeat. This data acquisition interfaces with the IoT algorithm as its object layers. The IoT mesh is developed based on three nodes (sensing node, visualisation node, broker node). The sensing node works to acquire the vital data from the data acquisition. The visualisation node works to visualise the vital data using local connection (without Internet service). The broker is developed based on two different RF technologies that are a LoRa and Wi-Fi, which enable changing of vital data with other nodes and cloud computing concurrently. The vital data visualisation is introduced using the ThingSpeak cloud. The block diagram for the proposed healthcare solution is shown in Fig. 32.1.

32.2.1 Non-invasive Data Acquisition for Heartbeats

The heartbeat estimation is accomplished based on a computer vision algorithm using C++ programming language, OpenCV library and Qt Creator IDE. The algorithm is designed to work in real time, for the acquiring of vital data with continuous streaming from the 30-fps camera. The software was developed and runs on an affordable machine (PC) with specs (Core i3rd generation, 4 GB RAM and web camera). The Eulerian video magnification conducts the magnification of imperceptible changes in the video frames. The algorithm decomposes the frames form the camera and apply the detected image of a human face into various spatial frequency bands. The algorithm applies the identical temporal filter to all bands. After that, the filtered spatial bands enlarge the frame with 100× magnification factor and added back to the original frame and collapsed to produce the output frames (video). The selection

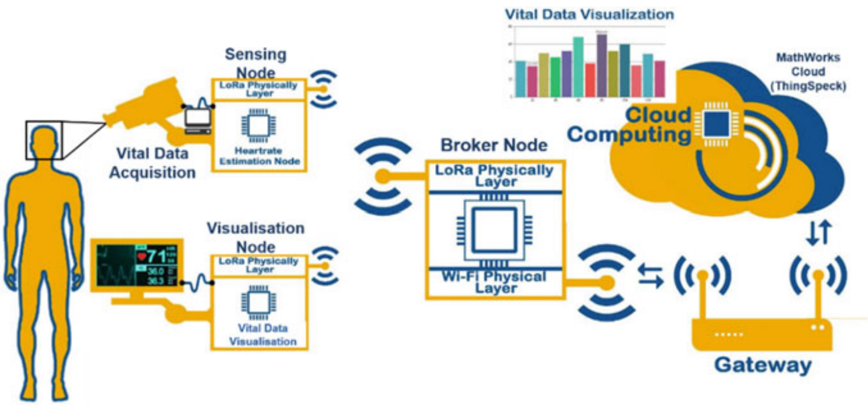


Fig. 32.1 Architecture of the proposed healthcare solution

of temporal filter and amplification factors has to be within the frequency range of the heart rate. The amplification is applied with temporal frequencies 0.83–1 Hz is referring to 50–60 bpm. The processed frame will change the colour of skin in video (frames) and influence the spatial motion in the video (frames) that occurs due to the change of heart rate. Finally, the heartbeat estimation is calculated by the resultant changes of the processed frame.

32.2.2 Proposed IoT Algorithm

In real time, the proposed algorithm exchanges the vital data of the developed IoT nodes. Also, the proposed algorithm is capable of increasing the number of nodes without issues. The structure of broker is designed based on the integration of LoRa SX1276/1277 modules with ESP32 Module in one node using STM32. Although, the sensing and visualisation nodes were developed based on LoRa SX1276/1277. For architecture, LoRa is responsible for the exchange of data with the sensing, visualisation and broker nodes. However, ESP32 is responsible for the exchange of data through the cloud over an Internet connection based on Wi-Fi technology.

The IoT algorithm is designed to reduce power consumption and keep data exchange stable. In this context, the algorithm is developed based on specific features of IoT platforms. LoRa modem works on 137 MHz to 1.02 GHz with maximum link budget 168 dB. Firstly, LoRa performs data exchange based on a programmable bit rate up to 300 kbps. The module has a built-in fully integrated synthesiser with a resolution of 61 Hz. The current is 9.9 mA for physical layer and 200 nA for register retention. Also, the module has a sensitivity down to −148 dBm. The algorithm is performed based on FSK/LoRaTM modulation. Furthermore, the LoRa has excellent blocking immunity. Secondly, ESP32 is IoT platform based on Wi-Fi and BLE (Bluetooth low energy) technologies. ESP32 performs IEEE 802.11 n based on the frequency 2.4 GHz with speed up to 150 Mbps. Also, ESP32 introduces a good memory management because is enable heap memory fragmentation. The previous features enable the designed algorithm to use two physical layers (LoRa and Wi-Fi). Thus, it minimises the power consumption and time of sending/receiving the data.

The proposed IoT solution is based on 3 nodes: one sensing nodes, an IoT broker node and a vital data visualisation node. All nodes circuits were designed based on Eagle Electronic Design Automation (EDA) program as shown in Fig. 32.2. The schematic for sensing node, broker node and visualisation node is shown in Fig. 32.2a–c, respectively. The implementation of the proposed IoT solution is as follows: the sensing node is designed via a LoRa module, TTL (transistor–transistor-level interface) module and STM32 microcontroller. This TTL interface manages the voltage changing between the microcontroller and computer voltage level, as shown in Fig. 32.2a. The sensing node reads the vital data from the (data acquisition) computer vision software using TTL converter on universal serial bus (USB) port. The visualisation node is designed as follows: LCD, LoRa module interfaces with STM32 microcontroller to perform the visualisation of vital data in local connection,

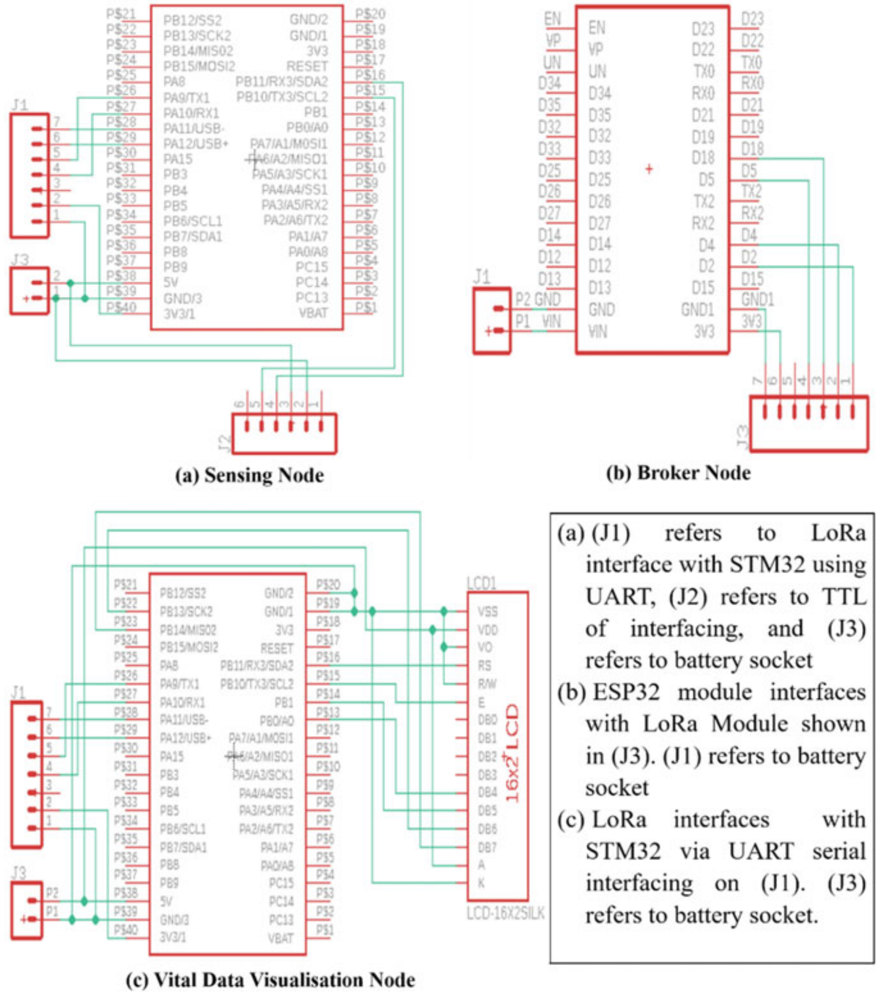


Fig. 32.2 Schematic of nodes design via Eagle EDA

as shown in Fig. 32.2c. The broker node is designed by ESP32 with LoRa module interfacing to exchange the data via two different radio frequency (RF) platforms (LoRa, Wi-Fi), as shown in Fig. 32.2b. The integration of ESP32 with LoRa module is developed to enable communication with cloud via Wi-Fi module of ESP32.

The activity diagram of the IoT algorithm is shown in Fig. 32.3. The vital data exchanging scenario is performed as follows: the sensing node is concatenating the sensing data from the data acquisition (PC) into the frame and sends it to the vital data visualisation node. In parallel, the vital data is sent to the broker node in order to minimise the time of IoT algorithm execution. After that, the visualisation node

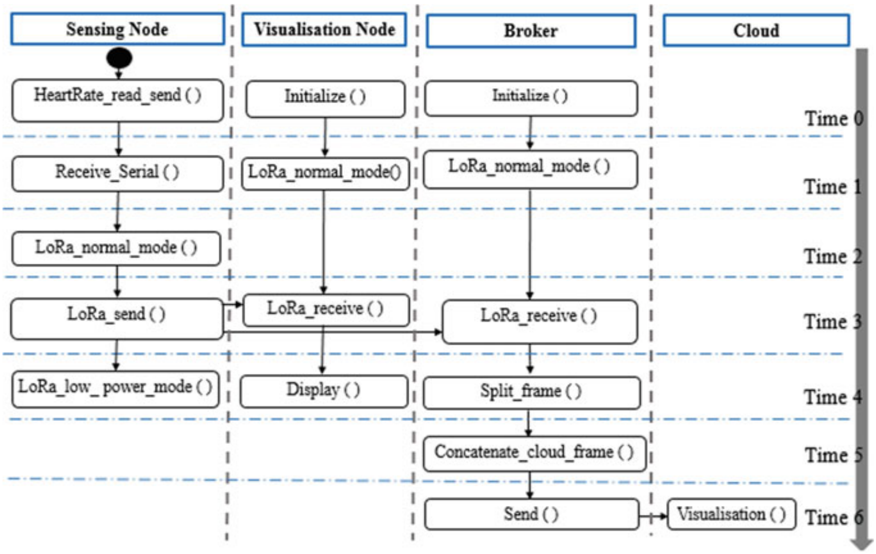


Fig. 32.3 Activity diagram of IoT nodes communication

displays the vital data. In parallel, the broker concatenates the vital data frame and sends it to the cloud. After that, the cloud visualises the vital data verses time.

The software is written using C programming language for STM32 microcontroller based on ARM cortex. Every node has its interfaces with the LoRa module. LoRa module has many modes (sending, receiving, sleeping, configuration). These S/W algorithms use the sleep mode to reduce the usage of power as much possible. Also the ARM microcontroller consumes less power than other microcontrollers due to the variety of frequency bus selections on ARM architecture. All node software starts with clock setting (frequency) to control the speed of program execution. Sensing node software uses two UART buses with 9600 baud rate. UART 0 for interface with the data acquisition (PC) and the UART 1 form interfacing with the LoRa module. The software works to read the heartbeats (BPM) from the data acquisition. After that, the node extracts the 10 elements of frame in order to send it to the other nodes (broker node and visualisation node) via LoRa module. The frame consists as follows: ID_of_node, heart_rate_(PBM), vital_alarm_flag and size_of_array (elements), as shown in Fig. 32.4a. Visualisation node software works to receive/listen the vital data from the sensing node via LoRa and visualise the (BPM) value on the LCD, as shown in Fig. 32.4c. IoT broker node works to receive vital data from sensing node and extracts the frame to get vital data (BPM, Alarm). Alarm refers to emergency state, which is equal to 1 (activated) if the BPM value is over then 100; otherwise, it equals zero. After that, broker concatenates a new frame with vital data features and sends it to the cloud computing, as shown in Fig. 32.4b. Moreover, the solution is capable to increasing the scale of acquired vital data. In order to test the scalability, the broker is set to measure human body temperature as an additional

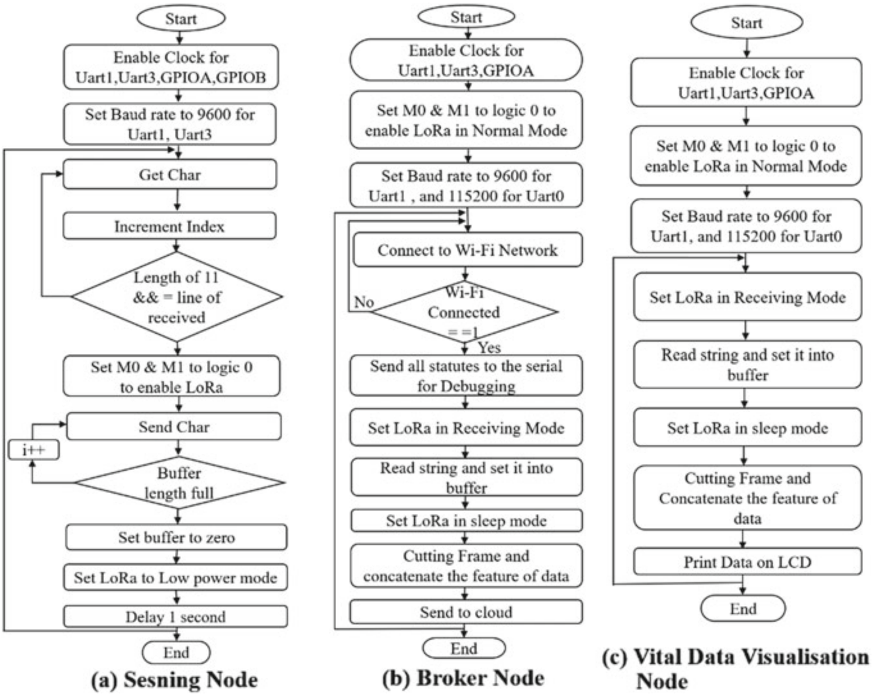


Fig. 32.4 Proposed software flow charts of IoT nodes

vital data for testing purpose. Furthermore, the broker state is debugged by serial mentoring to get full monitoring to the functionality of the solution.

32.3 Results and Discussion

Figure 32.5 presents the output of computer vision software, where the results are printed on the console of Qt creator IDE. Printed results contain heart rate (BPM) and the buffer of vital data console. The sensed BPM is equal 52.3055, which is highlighted using red colour. The buffer is the frame of vital data which is sent to the sensing node. Buffer elements are highlighted in blue, which contains (ID_of_node = S, heart_rate_(BPM) = 52, vital_alarm_flag = 0 and size_of_array = 10). For instance, in our example, the heart rate alarm is zero because the heartbeats are less than 240, which indicates the feasibility of the vital data acquisition solution to accurately recognise the emergency case of the patient early. Figure 32.6 shows the data transfer throughput to the sensing node, which is printed in the console for debugging purpose. The BPM value for the highlighted buffer is (S,52,0,10), which

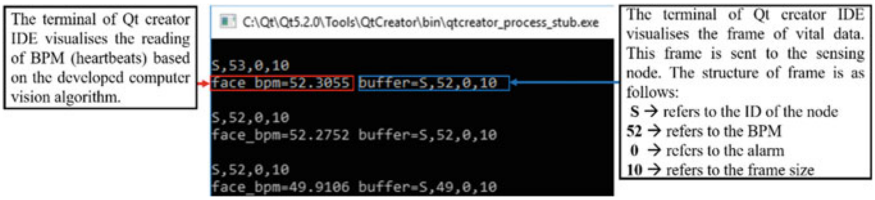


Fig. 32.5 Console output (results of heartbeats) of non-invasive data acquisition solution

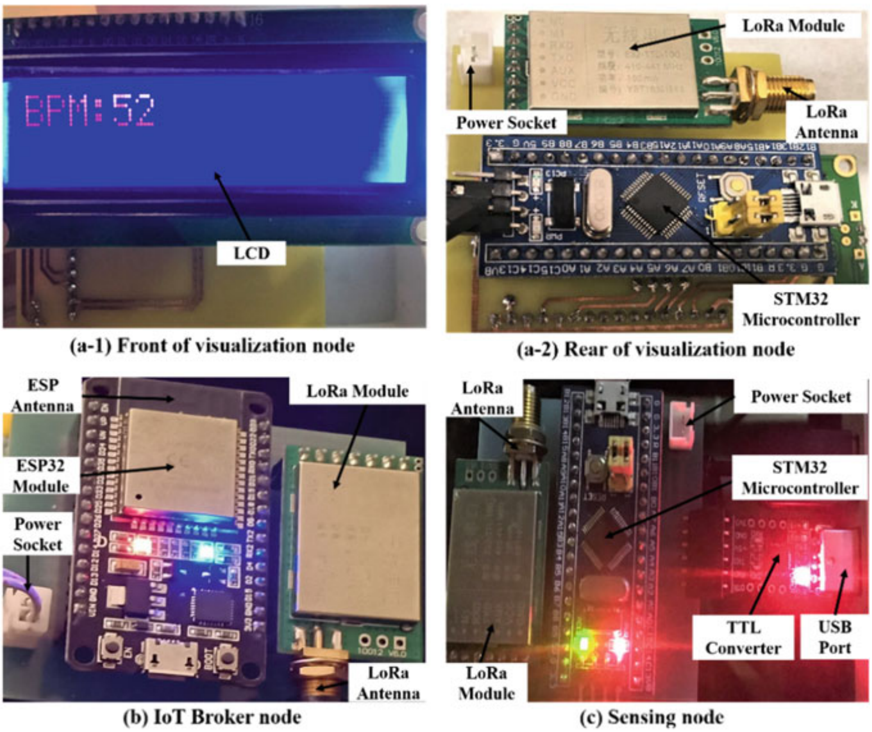


Fig. 32.6 Developed IoT nodes

presents the integer value of the bpm (52) and neglects the fraction (0.3055) in order to reduce the throughput.

Figure 32.6a–c presents the developed IoT nodes. Figure 32.6c presents the interfacing of sensing node with interfacing with the computer USB socket via TTL. Figure 32.6a presents the vital data visualisation on LCD (see a-1), which printed 52 bpm after listened to the sensing node. The vital data updates every 2 s. This visualisation verifies the communication session with the sensing node. Figure 32.6b shows the broker node with variant physical layers (LoRa and Wi-Fi). The serial monitoring of the IoT broker is debugged to visualise the cloud communication, as

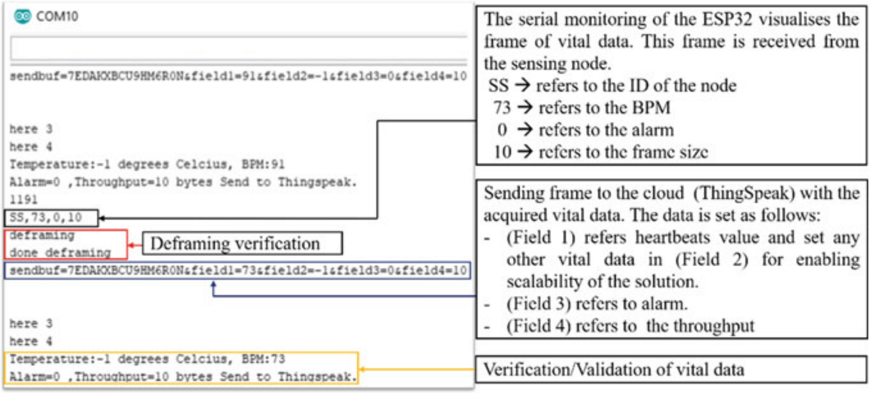
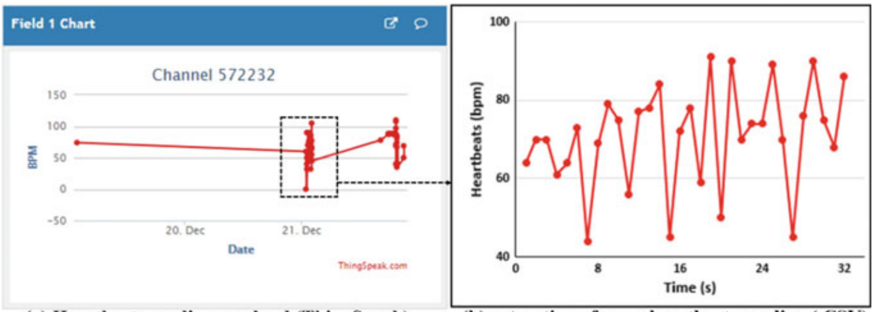


Fig. 32.7 Serial monitoring of IoT broker node



(a) Heartbeats reading on cloud (ThingSpeak) **(b) extraction of some heartbeats reading (.CSV) from cloud and visualise its features**

Fig. 32.8 Vital data visualisation and documentation via cloud

shown in Fig. 32.7. Figure 32.8a, b visualises the BPM on the cloud (ThingSpeak), where the results are plotted versus time. Figure 32.8b presents heartbeats versus time with seamless reading.

32.4 Conclusion

In this research, a safe, inexpensive and scalable healthcare solution was developed. With the aim of visualising the real-time vital data of patients, kids and employees in various environments. The developed solution reduces the chances of infection and cross-contamination as the data acquisition is conducted using a non-invasive approach via computer vision. Also, it predicts diseases early, thanks to the real-time monitoring and vital data history of user. A doctor can use this vital data for investigation of the health case of a human to provide full analytics of the diseases early. The vital data is visualised and analysed via developed IoT approach based on two different physical layer structures, which enable exchange of the data with IoT nodes and cloud computing. Finally, one can be concluded that the proposed healthcare system offers a safe and environmentally sustainable solution.

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Chapter 33
Industrial Assistance as an I4.0 Topic—MMAssist: Assistance in Production in the Context of Human–Machine Cooperation

Christian Wögerer, Matthias Plasch, Manfred Tscheligi and Sebastian Egger Lampl

Abstract In this paper, MMAssist_II, a national Austrian flagship project for research, development and establishment of assistance systems is presented. The Assistance Units could be used as a toolbox for different applications. Besides a fundamental understanding of demands for such Assistance Units, also a demonstration in industrial production settings is part of the project. An extensive evaluation will describe the usability of the units. Therefore, a large group of 9 scientific partners and 16 industrial partners join the consortium. Assistance in production as an I4.0 topic is becoming increasingly important in connection with the ever-increasing demands on production (variety of variants and mass customization) and the continuously growing demand for qualified workers in Europe.

33.1 Introduction

33.1.1 Initial Situation

Austrian production companies manufacture goods of high quality and have a staff of well-trained employees. However, companies currently face technological and societal challenges to which they have to react to in order to continually provide competitive goods on an international level. These challenges include the demand of customers for individualized products, which leads to smaller lot sizes and faster production cycles. At the same time, production machines are more and more connected and equipped with sensors. This leads to an increased information density and more complexity for the workers, which induces a higher workload and stress.

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Furthermore, Austria is experiencing a demographic change. As Austrian citizens get older, they stay longer in employment. All of these trends, as well as the goal to keep up the high quality of produced goods, lead to an increased need of optimized assistance for the worker in the factory.

In Sect. 33.2, this paper is presenting the general aspects of the project followed by Sect. 33.3 describing the technical concept of MMAssist_II. In Sect. 33.4, the available basic technologies are presented. Section 33.5 shows the most relevant research concept of automatic recognition of assistance needs. The paper ends with Sect. 33.6 presenting the first results after a 6-month project duration.

33.2 The Project MMassist_II

33.2.1 General Project Description

The lighthouse project MMAssist_II [1] will form a national research network with an international scientific board in order to find recognition and acceptance within the Austrian economy.

Goals and innovation: The goal of the project partners in MMAssist_II is to research and implement modular, reusable assistance systems for employees in production companies. Therefore, the project partners will work on the exemplary use cases: maintenance and service, arming of machines and simultaneous handling of multiple machines and assembly to analyze the technical and socio-economic requirements for assistance systems in these areas. Based on a strongly context-oriented requirement analysis, the partners will implement the so-called Assistance Units, which are modular components for assistance systems. Assistance Units are defined in a way that they can be applied to different application contexts. The partners will implement a software framework to enable a dynamic configuration and interaction of Assistance Units, thus forming an assistance system for a given application. To configure an Assistance Unit, different input and output modalities, as well as modules for context generation, are needed, which will also be developed in the project. In order to measure and evaluate the efficiency and feasibility of the project's approach, the partners will implement laboratory-based prototypes of defined Assistance Units and evaluate them in real production environments.

Expected results: The project partners expect to gain a profound empirical and socio-technical understanding of the demands and requirements for assistance systems in the production context. These systems will consist of reusable, scientifically grounded Assistance Units that are thoroughly evaluated. The implemented assistance systems will be evaluated, by workers of production companies, in real production environments. This will lead to findings about the acceptance and user experience of workers who use assistance systems and a measurable reduced workload of the workers.

33.2.2 Key Facts

MMAssist_II was launched in May 2017 and will run until April 2020. The project involves 25 different partners from research and industry, which are key players for research and manufacturing in Austria [2]. The partners' expertise covers the whole manufacturing value chain from basic research to industrial manufacturing of high-tech products and services. This consortium was set up to have all necessary competences without any overlap in research, and besides technical capacities there is also social-economic knowledge available. The industrial partners cover a wide range of different technical branches and provide real use cases to demonstrate the results in a production near environment. Key facts are shown in Fig. 33.1.

33.2.3 Objectives

The goal of the project partners in MMAssist_II is to explore assistance systems for employees in production environments and to develop these systems. This is necessary to overcome future technical and socio-technical challenges for production, by setting new paradigms of industrial assistance. Figure 33.2 shows challenges for future.

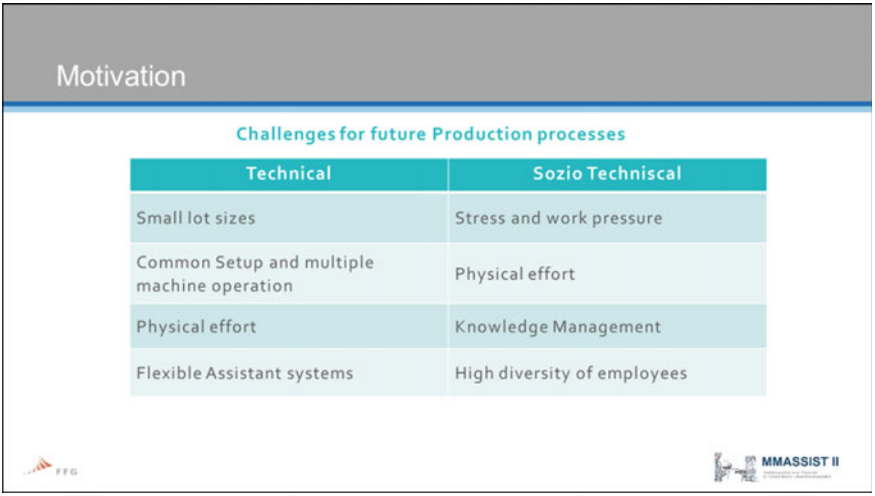
These assistance systems should be tailored to the needs of employees for their special context. It is also the goal of the project partners, to develop more than only specialized solutions and assistance systems. Moreover, the assistance systems being developed are relevant to Austrian production companies in general. Therefore, the project partners have defined the following objectives.

Project- Facts

FFG Number.:	**858623**
Titel:	**Assistenzsysteme in der Produktion im Kontext Mensch – Maschine Kooperation**
Acronym:	**MMAssist_II (www.mmassist.at)**
Coordination:	**PROFACTOR GmbH/ University Salzburg**
Start:	**01.05.2017**
Duration:	**36 months**
Funding:	**3 912 568 €**
Total Costs:	**6 131 405 €**
Partner:	**25 (10 scientific Partner, 15 Company partner)**

FFG MMASSIST II

Fig. 33.1 Key facts of the MMAssist_II project



Technical	Sozio Techniscal
Small lot sizes	Stress and work pressure
Common Setup and multiple machine operation	Physical effort
Physical effort	Knowledge Management
Flexible Assistant systems	High diversity of employees

Fig. 33.2 Challenges for future production processes

OBJECTIVE 1: Exploration of modular, reusable assistance systems. The project partners will develop assistance systems that can be used not only for the specific individual case, but are applicable in different contexts and for different applications. The purpose is to establish a general approach for implementing assistance systems for employees in manufacturing companies. This system should be open and able to motivate other companies to include their products and developments into the system later on.

OBJECTIVE 2: Context-oriented detection of assistance needs. Methods are developed, to enable the identification of the assistance needs of people in the vicinity of the machines from machine point of view. The purpose is to explore intelligent assistance systems, which offer targeted assistance only if it is needed. An important point is the acceptance by the workers, and therefore a neutralized information exchange has to be implemented.

OBJECTIVE 3: Improve the work and assistance experience. As a major goal, the project partners will implement assistance systems that increase positive factors of work and assistance experience while they are used, and reduce negative factors. Thus, it will be achieved that the systems are accepted by users and contribute to an improvement in their daily work.

OBJECTIVE 4: Applicability in real production environments. The project partner aims to use the implemented assistance system application at the industrial partner's production facilities and to evaluate in terms of productivity, acceptance through the staff and ergonomics. This evaluation should prove that the assistance systems are also usable in real production environments and beyond the project. For this reason, leading companies are included in the project development from the beginning to secure a real industrial relevance and industrial standards of the developed assistance systems.

33.3 Project Concept

The goal of MMAssist_II is to fundamentally research and characterize assistance in a production context. Based on this, optimized assistance systems for future working places focused on the human worker ("human-centered workplace") will be developed, implemented and evaluated in an industrial environment. Basis for the implementation are the so-called Assistance Units—which are modular components for assistance systems. Assistance Units are defined in a way that they can be applied to different application contexts. The partners will implement a software framework to enable a dynamic configuration and interaction of Assistance Units, thus forming an assistance system for a given application.

33.3.1 Motivation

The central motivation shown in Fig. 33.3 is the development of Assistance Units (Unit $1 \ldots n$) based on available and adapted basic technologies (e.g., mixed reality methods, visualization of complex data, object recognition, scene interpretation and others). These Assistance Units are implemented in a software framework, and the best fitting Assistance Units for an application are composed of an assistance system that is tailored for the given production context. The Assistance Units and the assistance systems are implemented, tested and evaluated in different use cases, first in the laboratories of the partners and then in "semi"-real production environment. Also, some tests in a real environment are planned.

33.3.2 Assistance Units

A generalized description of an Assistance Unit is shown in Fig. 33.4 considering the example of an Assistance Unit for assembly. Any assistance has, in addition to a clear title and a short description of the unit, primarily a definition which knowledge source is needed by the Assistance Unit to work correctly. These sources of knowledge can be, for example, information about the condition of the employee that is available on the machine, or process data, such as installation instructions. Among the needed data, also the information, when the Assistance Unit must be activated, based on the context information of the employee and the process, is required. A second central element of an Assistance Unit is a description of "how and by which equipment" the employee can make submissions to the Assistance Unit, and also the output

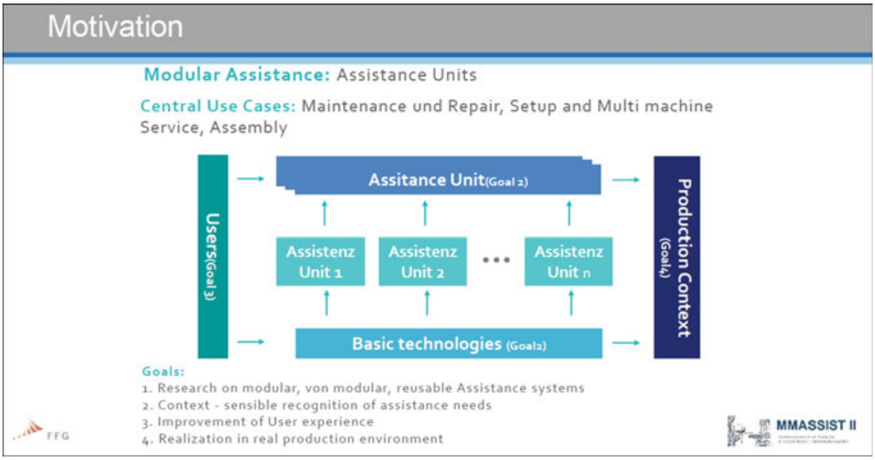


Fig. 33.3 MMAssist_II motivation

Defined Assistance Units after recommendation Phase

	Assistance Unit	Use Case		
		Assembly	Service and maintenance	Setup and multi machine service
1	Digital instructions	X	X	X
2	Annotation of artifacts	X	X	X
3	Physical Assitence - Ergonomics	X		
4	Documentation		X	X
5	Communication with experts		X	
6	Display status information			X
7	Collaborative Robotics	x		

Fig. 33.4 Defined Assistance Units

form, in which way the information of the machine is given to employees. So, the main components of an Assistance Unit are name, assistance/assistant task (type), knowledge source, input form, input device, output form and output device.

33.3.3 Work Package Structure

The work package structure for MMAssist_II in context with the aim of the project is shown in Fig. 33.5. Ten different work packages including the project management and led by experienced project managers are the key for a successful project implementation. Work packages are on different technology readiness level (TRLs) and are well connected to each other. The detailed structure of the work packages is shown in Fig. 33.5.

Work package (WP) 1 summarizes the tasks of the project related to the management of the project and the dissemination of project results. AP2 parses the requests of Assistance Units and assistance systems in the context of production from the point of view of the users and from a technical perspective. A planning model for the identification of assistance needs will be developed in WP3. Moreover, a model for structured preparation of work content and an employee model will be designed. Based on the theoretical results of WP2 and WP3, Assistance Units are explored in WP4. With these units, assistance can be detected automatically. WP5 develops basic algorithms for Assistance Units. In WP6, partners develop approaches for the dynamic configuration of Assistant Units for specified use cases. A software framework is developed to implement the dynamically configured assistance systems in AP7. This framework is basis for WP8, in which assistance is prototypically implemented in laboratory environments. The assistance systems in a real environment are implemented in WP9 at the facilities of the industry partners. Finally, the implemented assistance systems are evaluated in WP10.

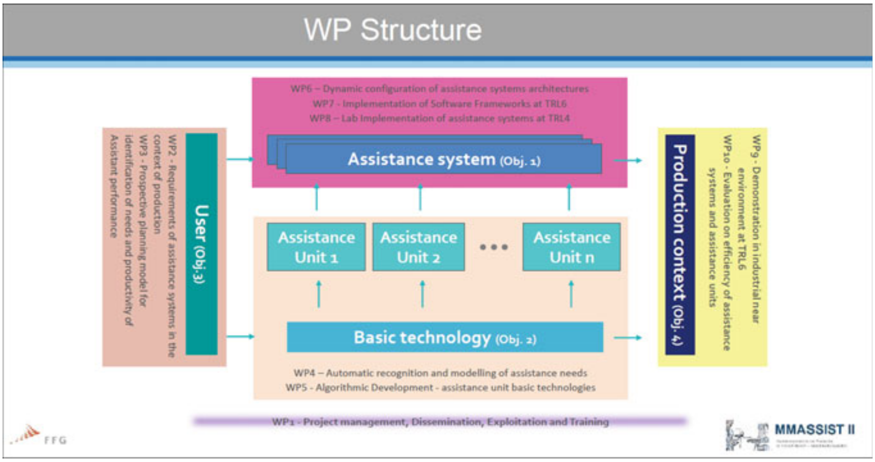


Fig. 33.5 Work package structure

33.3.4 System Architecture

Core unit of the technical system architecture shown in Fig. 33.6 is the single "Assistance Units" which are integrated into an overall assistance system via the software framework. The assistance system has interfaces to sensors that allow, together with a direct user input a context recognition for the identification of assistance needs. Derived cognitive or physical assistance is provided via the respective Assistance Units. The overall system also has interfaces to external legacy systems (especially ERP and MES), which can retrieve, for example, job information and machine structural analysis.

Task management module manages the orders that can be adopted or entered directly via the administration interface from external systems, and informs the users about a specific job and corresponding support performance. The user management module enables central management of user master data and roles of all Assistance Units and interacts with a skill database that stores relevant skills of employees for the respective tasks. In the asset database, resources or appropriate references are stored, which can be consumed by the Assistance Units. The content management system has the purpose to take care of digital resources that need to be imported in an appropriate form, edited, saved, updated, illustrated and re-exported.

A knowledge database provides process knowledge from and also knowledge about the relevance and quality of certain assets. Here, employees can assess for a specific resource, which was offered by the assistance system in one specific step, how helpful it was, or correct a proposed sequence by the system.

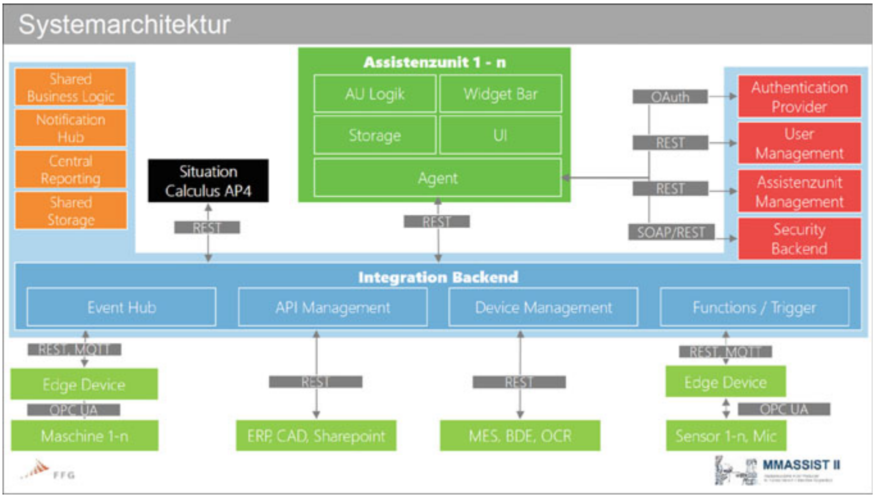


Fig. 33.6 System architecture

33.4 Basic Technologies

In the MMAssist_II project, nine scientific partners from Austria provide different basic technologies shown in Fig. 33.7 for various Assistance Units. Either these technologies are ready for implementation or they were developed ready for use. Most challenging problem is the interface between these basic technologies and the software framework. Main basic technologies are:

Object recognition, event recognition and scene interpretation by Technical University Vienna [3]: A system to generate hypotheses on the current state and events happening in human–robot collaborative (HRC) scenarios is being developed. The software modules will be based on existing approaches and software libraries for object modeling and object pose recognition, concepts to describe events in HRC scenes and fusion of data streams including action recognition, robot states and object recognition.

Mixed reality methods by Evolaris [4]: Focus of this work is to develop methods to augment visual information using head-mounted displays (HMDs) and modes for the user to interact with the HMD (data input). A major challenge is given through the requirement of selecting appropriate information given the current context and individual needs of the user.

Visualization of complex data by Fraunhofer Austria [5]: The main focus is developing approaches to enable real-time visualization of a large amount of data, e.g., complex CAD models, on thin clients (data glasses). Moreover, a model-based tracking approach based on CAD data is developed, to facilitate position-stable augmentation of data in industrial environments.

Interaction for robot-based assembly processes by PROFACTOR [6]: Within this technology package, concepts to enable intuitive interaction in HRC scenarios will be

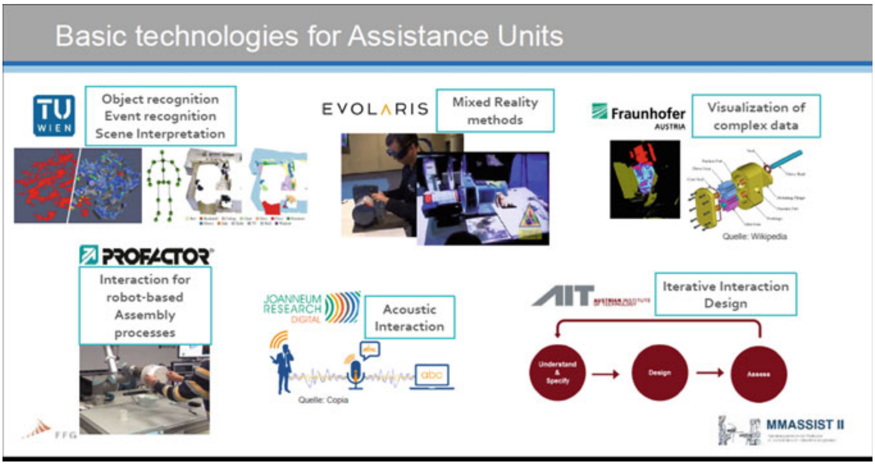


Fig. 33.7 Basic technologies available for MMAssist_II

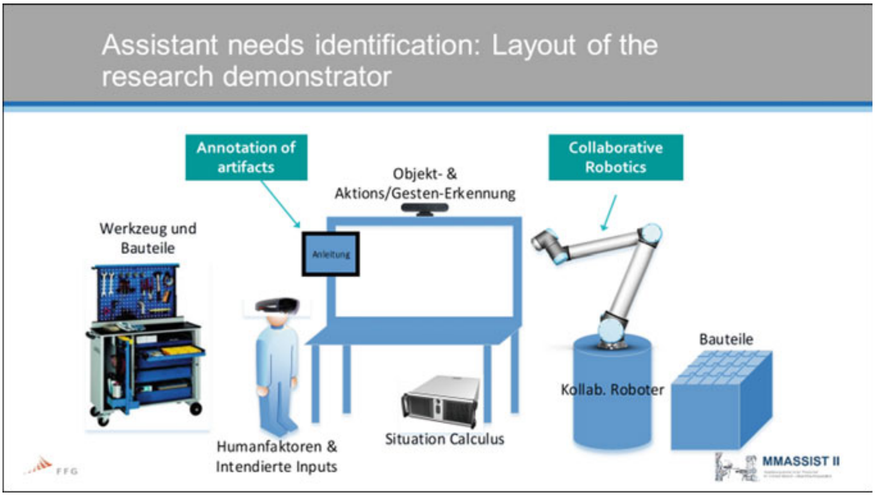


Fig. 33.8 Test rig for automatic recognition of assistance needs

developed. Major challenges include the implementation of flexible models to enable fast adaptation of process knowledge and adaptation of the human–robot interaction (user-specific needs), avoiding explicit programming.

Acoustic interaction by Joanneum research [7]: The main goal is to develop speech interfaces to enable intuitive interaction with assistance systems in an industrial setting. In order to maximize user-friendliness, the interfaces are not restricted to a collection of commands and can cope with different dialects and languages. Acoustic feedback is used to inform the user about the states of the assistance system.

Iterative interaction design by AIT [8] and PLUS [9]: The goal is to implement a research through design (RtD)-based process, where prototypes for current and present interaction models/modes are developed by potential end users. This generated valuable feedback serves as input to an iterative development process for assistance system interaction design (Fig. 33.8).

33.5 Automatic Recognition of Assistance Needs

The most important research topic in the project is the automatic recognition of assistance needs. It enables the system to recognize where and which assistance is needed in the current status. Therefore, a demonstrator including the basic technologies and selected Assistance Units is built up (Fig. 33.9).

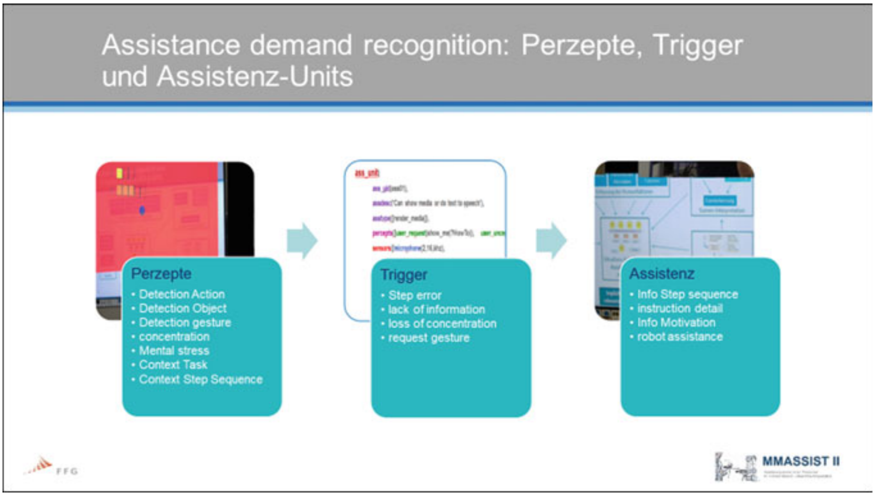


Fig. 33.9 Procedure of demand recognition

33.6 First Results

As the project has started in May 2017, the work performed in the first 6 months was focused on requirements and finding a set of basic technologies as described in Chap. IV. Also, a more detailed definition of the use cases and the Assistance Units, which will be implemented, was done. This led to three different use cases with seven Assistance Units in total.

- Service and maintenance (use case 1)
- Notification of maintenance protocols (Assistance Unit 1)
- Communication with experts (Assistance Unit 2)
- Setup and multi-machine service (use case 2)
- Guiding through setup process (Assistance Unit 3)
- Multi-machine service (Assistance Unit 4)
- Assembly (use case 3)
- Notification of assembly instructions (Assistance Unit 5)
- Part delivery (Assistance Unit 6)
- Assembly instruction review (Assistance Unit 7).

A requirement analysis based on the needs of users of the assistance systems in the context of production was done. The goal was to capture the requirements from a technical and a socio-economic view. First steps were done so far:

- Determine the requirements for Assistance Units: Data collection is almost completed, and currently data will be analyzed and interpreted.
- Conceptual design and modeling of Assistance Units to the subsequent implementation: An adequate conceptual base model for the taxonomy of Assistance Units

and situation patterns was identified and is now further developed for the project problems.
- Investigation of job satisfaction and acceptance by the use of Assistance Units: An existing framework for the project was adopted. A data collection tool to raise job satisfaction was developed.
- Analysis of relevant safety and security factors within the use of Assistant Units: Data collection was carried out, and a knowledge base was developed.

33.7 Conclusion and Outlook

The main expected result is a software framework which connects all main basic technologies to Assistance Units which could be used to create a use case-sensitive assistance system adapted to the needs of the workers. This is an open system which could be enlarged by contributing (and other interested) companies.

The main challenge is to find a software solution and architecture which is able to handle the interface problematic between the single subsystems.

Besides the first promising results, it is a challenge to manage a research project with 24 partners and to find a common solution for a lot of different companies.

The topic of assistance in production is extremely important in connection with Industry 4.0, since cognitive assistance is currently much more in demand from industry than physical assistance. For the sustainable effect of assistance technologies, however, it is also very important to consider physical assistance, especially in connection with work ergonomics.

Acknowledgements This work has been supported by the Austrian Research Promotion Agency [10] in the program "Production of the Future"-funded project MMAssist II (FFG No.: 858623) and the Austrian Ministry for Transport, Innovation and Technology (bmvit) [11].

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Part VII
Green Manufacturing with an Industrial Metabolism and Smart Access Perspective

Chapter 34
A Knowledge Sharing Framework for Green Supply Chain Management Based on Blockchain and Edge Computing

Hua Zhang, Shengqiang Li, Wei Yan, Zhigang Jiang and Weijie Wei

Abstract Aiming at the problem of knowledge asymmetry in supply chain enterprises in green supply chain management, this paper proposes a decentralized knowledge sharing framework based on blockchain and edge computing technologies. The security and reliability of the knowledge sharing framework are guaranteed by the security encryption, non-tamperability of the blockchain. Edge computing that provides edge intelligence services is integrated into the framework to meet the needs of the blockchain for distributed networks. Firstly, the concept of open green supply chain is introduced, and the model of knowledge creation processes of green supply chain enterprises. Then, the application prospects of blockchain and edge computing technologies in green supply chain management are illustrated, and a green supply chain management knowledge sharing framework based on these two technologies is proposed. Finally, an automotive enterprise is taken as an example to verify the effectiveness and feasibility of the proposed green supply management knowledge sharing framework.

34.1 Introduction

At present, due to the rapid development of the manufacturing industry, it has stimulated the economic growth momentum and provided rich products for human soci-

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ety, but meanwhile it has also caused a series of problems such as resource shortage and environmental pollution, which makes more prominent contradiction among the economy, environment, and society. Green supply chain management, which comprehensively considers the impact of various links in the supply chain on the environment, emphasizes the protection of the environment and promotes the coordinated development of the economy, environment, and society. However, in today's knowledge explosion, knowledge-based market economy, knowledge asymmetry is increasingly becoming an important factor restricting the overall operational efficiency of green supply chains. The knowledge sharing of green supply chain management among supply chain enterprises is conducive to improving the knowledge level of enterprises in the entire green supply chain, thereby improving the overall competitive advantage of the green supply chain.

For the field of knowledge sharing in green supply chain, scholars at home and abroad have conducted extensive research. Based on the perspective of green supply chain management, Zhang and Yang [1] researched the risks of knowledge sharing in green supply chain management. Cao and Zhao [2] analyzed the influencing factors of knowledge sharing in green supply chain through the perspective of chain integration, and the results show that innovation, green cultural competitiveness and trust between enterprises can promote knowledge sharing among green supply chain enterprises. Chung et al. [3] studied the relationship between trust and the factors affecting knowledge sharing in green supply chains, and the results show that trust is crucial for knowledge sharing.

However, the above research mainly studies the knowledge sharing of green supply chain management from the perspectives of the risk and factors of knowledge sharing in green supply chain management and rarely proposes specific ways to solve the risks problems existing in knowledge sharing in green supply chain management from a technical point of view. In this paper, aiming at this problem, we proposed a proposes a framework for knowledge sharing of green supply chain management based on blockchain and edge computing techniques, which provides a more secure and reliable approach to share knowledge in green supply chain. In turn, the concerns of enterprise knowledge sharing in the green supply chain will be eliminated, and the overall operation quality and efficiency of the green supply chain will be improved, and the development of the manufacturing industry will be developed in a direction of lower carbon, environmental protection, and sustainability.

34.2 Open Green Supply Chain and Knowledge Creation Model

34.2.1 The Concept of Open Green Supply Chain

With the rapid development of Internet technology and the application of cutting-edge technologies such as Internet of Things, artificial intelligence and big data

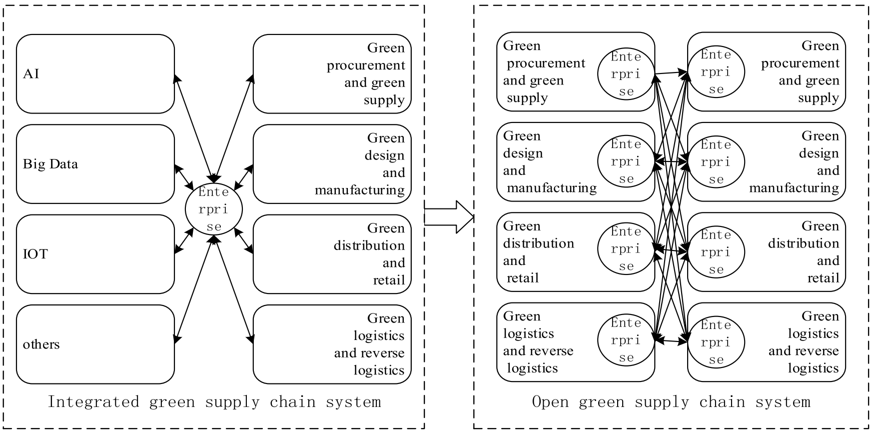

Fig. 34.1 Integrated green supply chain system and open green supply chain system

in manufacturing, the future green supply chain ecosystem should be interrelated and open to each other. As shown in Fig. 34.1, it will be converted from the current integrated green supply chain system to an open green supply chain system, in which not only do each green supply chain node need to be linked to each other within the enterprise, but green supply chain companies should also be connected to each other. Therefore, we define an open green supply chain as a new phase of the green supply chain ecosystem, which uses open, distributed, and decentralized manufacturing networks to support knowledge sharing among green supply chain companies in manufacturing.

34.2.2 The Knowledge Creation Model of Green Supply Chain Enterprises

The process of knowledge creation in green supply chain enterprises mainly includes stages of knowledge acquisition, analysis, adaptation, and application. The knowledge acquisition stage mainly collects data, information and internal and external knowledge sources. The internal knowledge sources are mainly the relationships among the workers in the green supply chain nodes, the organization database, and the nodes in the green supply chain. The external knowledge sources are mainly market information, green supply chain node workers and technical information. The knowledge analysis stage mainly analyzes the collected data, information and knowledge through different analysis tools and methods. After the analysis process, the knowledge content will be extracted and transformed into specific forms for internalization and absorption between the nodes of the green supply chain. The knowledge adaptation stage is mainly to adapt the extracted knowledge to meet the

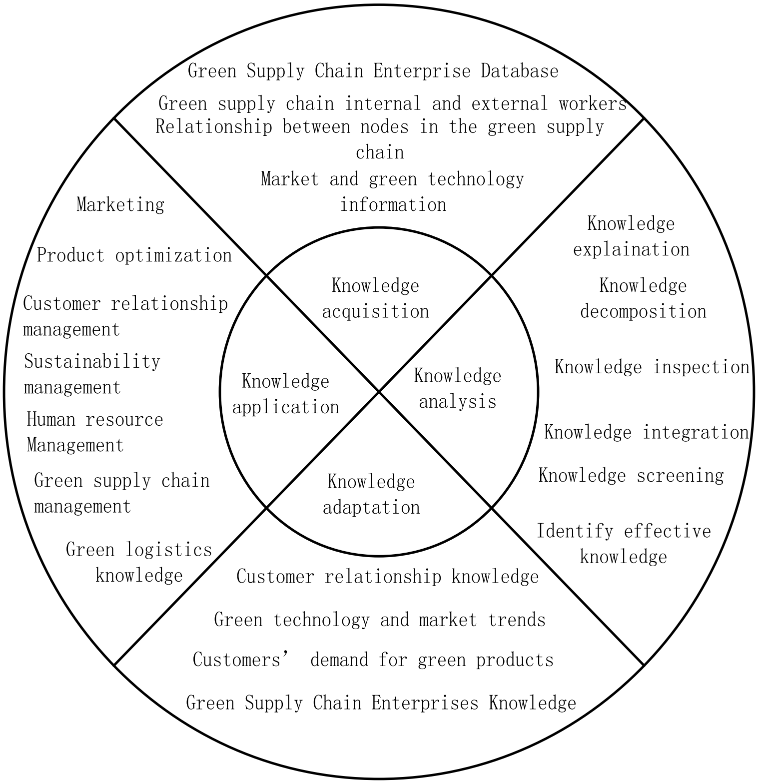

Fig. 34.2 Knowledge creation process model of green supply chain enterprises

specific needs of the market and green supply chain enterprises. The adapted knowledge should be more specific and flexible in order to facilitate the retrieval and reuse of knowledge. The knowledge application stage is to apply the adapted knowledge to a specific link of green supply chain management. The green supply chain enterprise knowledge creation process model proposed in this paper, as shown in Fig. 34.2, can achieve continuous learning and spiraling and knowledge exchange can occur in all stages of knowledge acquisition, analysis, adaptation, and application. It helps to enrich the core knowledge of each node in the green supply chain and thereby improve the overall efficiency of the supply chain.

34.3 Blockchain, Edge Computing and Green Supply Chain Management

34.3.1 Application Prospects of Blockchain and Edge Computing

Blockchain is a distributed data storage technology that uses cryptographic algorithms and chained association structures to organize data blocks, which are jointly maintained by participating nodes to ensure that data is almost impossible to be modified, and ultimately ensure data consistency. In view of the nature of the blockchain, it is particularly suitable for solving some problems such as promoting secure transactions between decentralized parties, enhancing security and mutual trust, reducing fraud as well as promoting transparency and efficiency in multi-party transactions. At present, blockchain is mainly used in the financial sector, such as the application of blockchain in the insurance and banking industries. At the same time, it is also expanding to the real economy outside the financial sector, such as blockchain technology in supply chain management, real estate industry, medical, international trade and other aspects of the application. Edge computing is an open platform that integrates network, computing, storage, and application core capabilities. It provides near-end services near the side of the object or data source to meet the industry's basic needs in real-time business, application intelligence, security and privacy protection. Based on the advantages of edge computing, it is mainly used in smart home, smart factory, health care, logistics, insurance and traffic monitoring.

34.3.2 Green Supply Chain Management Knowledge Sharing Framework

Although edge computing has many advantages, it also faces security threats such as identity authentication, network security, and privacy security. However, blockchain data encryption mechanisms can address these security threats, ensuring that data is exchanged securely in an untrusted environment. On the other hand, the distributed network required for blockchain operation can be provided by edge computing. Finally, as shown in Fig. 34.3, this paper proposes a green supply chain management knowledge sharing framework based on blockchain and edge computing. The framework mainly includes the knowledge layer, intelligent layer, application layer, green supply chain enterprise layer and market trend layer. The details of each layer are as follows:

1. The infrastructure layer supports the establishment of a green supply chain knowledge sharing framework by providing basic software and hardware structures. It mainly consists of blockchain and edge computing two technologies in which blockchain ensures the security, reliability and decentralization of knowledge

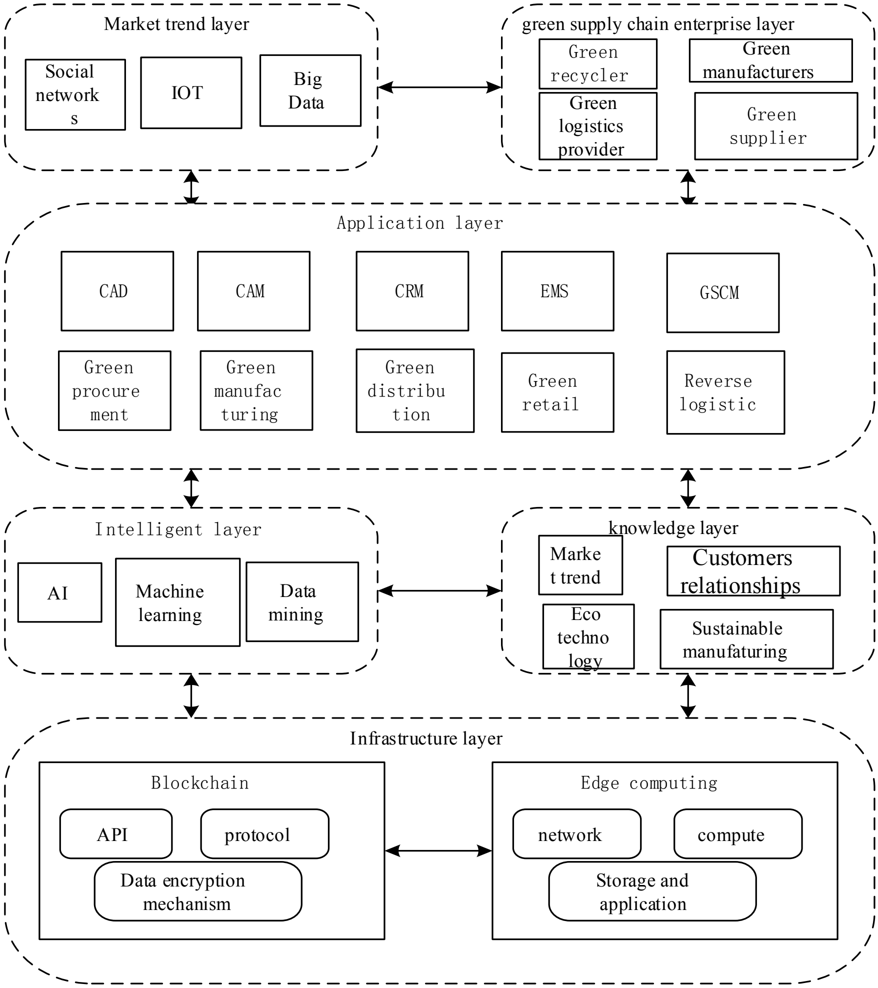

Fig. 34.3 Green supply chain management knowledge sharing framework

sharing by providing application network interfaces, protocols and data encryption mechanisms, and edge computing provides a near-end service and a distributed network for knowledge sharing through its integrated network, computing, and storage platforms.

2. The knowledge layer, which contains data and information gathered from the market trend layer and application layer, as well as data analysis and processing results from the enterprise and application layers of the green supply chain. It consists of a knowledge base of database and storage market trends, customer relationships, processing techniques, environmental technologies, and sustainable manufacturing.

3. The intelligence layer provides processing power for the data analysis and reasoning process at the application layer. It mimics human thinking to achieve different cognitive functions by using different artificial intelligence tools and statistical methods such as big data and machine learning and data mining.
4. The application layer is mainly composed of a series of management systems, services, and software products provided by the company on the green supply chain enterprise level. They include customer relationship management, corporate management, green supply chain management, green procurement and green supply systems, green distribution, green retail and green reverse green logistics services, computer-aided design and technical machine-aided manufacturing software.
5. The green supply chain enterprise layer contains stakeholders in all aspects of the green supply chain. It mainly includes green suppliers, green manufacturers, green logistics companies, green recyclers, distributors, retailers, etc.
6. The market trend layer is a vital source of data and information throughout the framework. It is mainly composed of social networks of various entities in the market, big data from various Internet applications and Internet of Things devices, and market dynamic information obtained through various market research methods. The various market data and information provided by the market trend layer will be collected and analyzed by the enterprise and application layers to extract the knowledge they need.

34.4 Case Study

In this section, the proposed knowledge sharing framework of green supply chain management is illustrated with a case of knowledge sharing in the automotive green supply chain management. This case study is based on the knowledge sharing between the automotive manufactures and its components' suppliers. In the real scenario of manufacturing automobiles, because manufacturing a automobile need a great variety of components and in particular different kinds of automobile all have different components, it is quite difficult for automotive manufactures to choose the most suitable components for different automotive products to achieve the reduce the costs of manufacturing the automobiles. Consequently, it is critical for manufacturers to conduct knowledge sharing with the component's supplier.

34.5 Conclusions

The green supply chain management ecosystem is transforming from integrated and centralized system to the open and distributed system. In the open green supply management system, the node enterprises in green supply chain can conduct knowledge sharing with each other, so they can have more can focus their attention on enhancing their core knowledge to improve the competitive ability of them and finally to dramatically improve the efficiency and effectiveness of the whole green supply chain.

This paper is targeted to solve the trust and risks problems in green supply chain management knowledge supply. In order to solve this problem, we propose a knowledge sharing framework by incorporating the blockchain and edge computing technologies. The proposed framework is decentralized, secured, and reliable, so it can dispel green supply chain enterprises' concern about risks and trust problems to boost the knowledge sharing among green supply chain corporations.

The future work is to apply the proposed framework to the green supply chain management in manufacturing so as to help the manufacturing enterprises achieve sustainable development.

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Chapter 35
Industrial Metabolic Pathway Analysis and Flux Control for the Metallurgical System

Gang Zhao, Junwen Chen, Hua Zhang and Zhigang Jiang

Abstract The scientific theories of industrial metabolism (IM) and engineering evolution for manufacturing system play a fundamental role in the analysis, computation, and control of the flows of mass and energy in a manner of transparent accuracy and dynamic efficiency. Therefore, the systemic characteristics and evolutionary regulations of the industrial metabolism are analyzed and discovered through a new approach based on the bio-metabolic engineering. The new approach is to start with the pathway analysis (IMP) and the network building (IMN) of industrial metabolism. This research carries out fundamental and theoretical innovation in the science of industrial metabolism and engineering evolution for manufacturing, which acts as technical precondition and lays scientific foundation for establishing the green and smart manufacturing system.

35.1 Introduction

In order to realize the analysis, calculation, dynamic regulation, and optimal control of industrial metabolism in manufacturing system, it is necessary to have a complete and accurate grasp of the complex material energy flow law of manufacturing system. The current research method in the field of industrial metabolism and industrial ecology is still the analysis of material energy flow [1–4]. There are many studies on the characteristics of material energy flow, and there are three main types of methods

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summed up: full lifecycle analysis and evaluation method, input and output inventory analysis method, material flow analysis method.

Lu Zhongwu, a Fellow of the Academy of Engineering and a professor of Northeastern University in China, was the earliest pioneer in the study of system energy saving and industrial ecology by using lifecycle theory. In his monograph, "Fundamentals of System Energy Conservation", he first elaborated the basic concepts of energy saving in carrier body and system [5], established the lifecycle benchmark logistics diagram of iron and steel products [6], and analyzed the environmental load problem of typical process of steel production in China [7]. Professor Liu Fei of Chongqing University first elucidated the scientific connotation of green manufacturing in China [8] and carried out a great deal of research on the modeling of material energy flow in machine tools and processes [9, 10]. Professor Liu Zhifeng of Hefei University of Technology discussed the design criteria for the whole lifecycle structure of products that take into account energy optimization and functional realization [11].

The improved input and output process model (IOPM) of MIT Karen is a representative method of input and output inventory analysis. By studying energy efficiency and pollution emission, three typical coking processes existing in iron and steel enterprises in Shanxi Province of China were analyzed. The IPCC provides a method of calculating carbon emissions based on emission factors and is essentially an analysis of input and output inventories based on carbon-containing fuels. The common problem of Io inventory method is that the manufacturing system is treated as a black box, which only considers the statistical law between input and output and ignores the law of material energy operation inside the manufacturing system.

Most of the above methods are based on mathematical statistics, and there are some shortcomings in explaining the law of material energy operation based on physical and chemical processes within the manufacturing system. Most of its research objects are specific industries, industrial parks, regional countries and other macroscopic manufacturing systems; the discussion is also often focused on the macro-level.

In order to solve the problem of material energy flow research from large into small difficulties, Mr. Metallurgy Yin Ruiyu, academician of the Chinese Academy of Engineering and professor of the General Institute of Iron and Steel research, put forward the important idea of metallurgical process system analysis-integration-optimization and advocated the reduction of macroscopic engineering effect through analytic microscopic system. He established the branch of metallurgical process, summed up a number of engineering effects in the steel manufacturing process, and constructed the material energy flow network of the steel manufacturing process. The purpose of analytic integrated optimization is to promote the emergence of macroscopic laws through microscopic behavior, the essence of which is engineering evolution. On the basis of metallurgical process engineering, Metallurgy, Yin Ruiyu discusses the concept and method of engineering evolution theory and puts forward the dynamic model of engineering evolution, but does not give the mathematical model that can be applied.

Based on the above ideas, taking into account the industrial metabolic process of manufacturing system and the process of organism cell metabolism, the feasibility of high similarity in material energy exchange form and engineering application field, drawing on the basic theory of biological metabolic engineering, using the improved industrial metabolic flux balance analysis method, the structure of industrial metabolic network. It is helpful to establish a bridge between the microscopic mechanism (physicochemical) and macroscopic law (statistics) to understand and master the industrial metabolic mechanism of manufacturing system (Fig. 35.1).

Two important papers published by California Institute of Technology and Massachusetts Institute of Technology Bailey and Stephanopoulos in "Science" mark the birth of the discipline of metabolic engineering. The core problem to be solved in metabolic engineering is to regulate metabolic behavior by means of metabolic flux balance analysis, which requires the establishment of chemical metrology, reaction kinetics and thermodynamic models of each reaction in complex metabolic pathways to provide balanced metabolic flux data throughout the metabolic network. The quantitative relationship between the interaction between coupled reactions and metabolic pathways was clearly demonstrated. The mathematical essence of the principle of metabolic flux balance (metabolic flux balance) is a group of differential equations of reactive dynamics based on chemometrics, which is restricted by the thermodynamic conditions of metabolic processes. The metabolic flux equilibrium equation group is listed by the metabolic flux equilibrium network after formal expression, and the equation constant of independent flux in the linear equations constitutes the flux coefficient matrix. Using this method, the flux equilibrium model was constructed for most metabolic pathways of Haemophilus influenzae and Helicobacter pylori, Schilling and Covert, respectively, and the most suitable metabolic flux model was calculated. Metabolic flux equilibrium equations are often ultra-static and have no unique solution, but allow for full solution space.

The flux coefficient of cell metabolism is usually dominated by biological law, while the flux coefficient of industrial metabolism is determined by the physicochemical law and process principle of manufacturing system (manufacturing equipment or reaction container), which involves a special number of variables and complex equation structure. Numerical evolution models are usually considered to solve the structural parameters of differential equations in continuous systems, including the solution of flux coefficient matrices.

Literature studies show that industrial metabolism and cell life metabolism in manufacturing system are highly similar in form and mathematical description, by introducing flux balance principle and metabolic regulation method in biological metabolism engineering and by using MAS-based evolution algorithm, a more in-depth method of material energy flow analysis and calculation can be developed. It can not only describe the microscopic mechanism of industrial metabolism but also reflects the macroscopic law and helps to realize the dynamic prediction and optimal regulation of industrial metabolic flux.

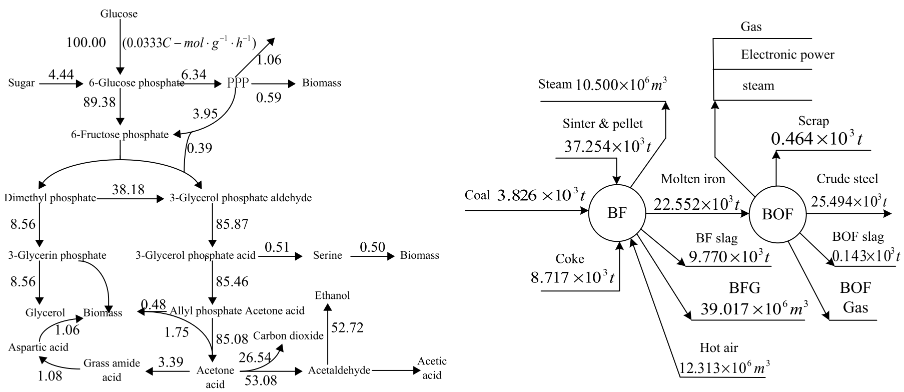

Fig. 35.1 High similarity between cell metabolism and industrial metabolism in the form of material energy exchange

35.2 The Primary Principle and Method

35.2.1 *The Principle of Industrial Metabolic Flux Balance (IMFB) Based on the Dynamic Differential Equations*

35.2.1.1 Establish the Dynamic Differential Equations to Indicate the IMFB Process

The metabolic substrates input and flow through the manufacturing nodes. Subsequently, the metabolic product output after synthesis or decomposition processes is operated by the manufacturing nodes. The output rate of the metabolic product in a steady-state is known as the industrial metabolic flux (IMF). The principle of industrial metabolic flux balance (IMFB) is established on a set of dynamic differential equations, that is, the industrial metabolic flux equilibrium equation, the equilibrium relationship between the change rate of node metabolite intensity with time and all metabolic flux in industrial metabolic network is described, as shown in formula (35.1).

$$\frac{\mathrm{d}X}{\mathrm{d}t} = N \cdot V \tag{35.1}$$

In which, N—flux coefficient matrix; V—industrial metabolic flux matrix; industrial metabolic strength of X—node metabolites.

When N is constructed and solved, the industrial metabolic flux V can be solved based on formula (35.1), the flux value flowing through all nodes is calculated accurately, and the transparent, accurate, real-time and efficient flux analysis and calculation method are established.

35.2.1.2 The Structure and Reconciliation of the Flux Coefficient Matrix *N* Are Calculated

Constructing flux coefficient matrix N is the premise of solving flux Matrix V. The industrial metabolic pathway shown in Fig. 35.2 constructs its flux coefficient matrix N, as shown in formula (35.2).

$$N = \begin{array}{c} \begin{array}{cccccccc} v_1 & v_2 & v_3 & v_4 & v_5 & v_6 & v_7 & v_8 \end{array} \\ \begin{bmatrix} n_{11} & n_{12} & n_{13} & n_{14} & n_{15} & n_{16} & n_{17} & n_{18} \\ n_{21} & n_{22} & n_{23} & n_{24} & n_{25} & n_{26} & n_{27} & n_{28} \\ n_{31} & n_{32} & n_{33} & n_{34} & n_{35} & n_{36} & n_{37} & n_{38} \\ n_{41} & n_{42} & n_{43} & n_{44} & n_{45} & n_{46} & n_{47} & n_{48} \\ n_{51} & n_{52} & n_{53} & n_{54} & n_{55} & n_{56} & n_{57} & n_{58} \\ n_{61} & n_{62} & n_{63} & n_{64} & n_{65} & n_{66} & n_{67} & n_{68} \end{bmatrix} \end{array} \begin{array}{|c} \\ X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \end{array} \tag{35.2}$$

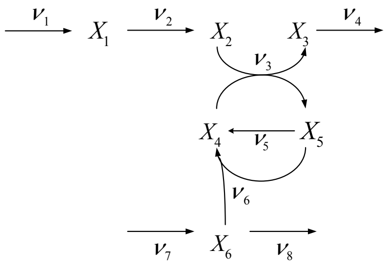

Fig. 35.2 Examples of industrial metabolic pathways

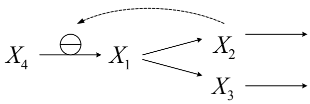

Fig. 35.3 Industrial metabolic pathways with flux feedback

In the formula: the n_{ij}-flux coefficient, the metabolite intensity at the X_i-node, and the metabolic flux of the V_j-flowing through the node.

In order to reflect the process principle and physicochemical law on the metabolic node, the flux coefficient can be a more complex form, such as a function of time between the substrate strength and the product strength. The flux coefficient and its function structure parameters can be solved by differential equations or by numerical iterations of evolutionary algorithms.

Establishment of industrial metabolic flux balance (IMFB) analysis and calculation method is based on kinetic differential equations

The metabolic pathway shown in Fig. 35.3, formulated by formula (35.12), is transformed into a group of kinetic differential equations on industrial metabolic flux, such as formula (35.3).

$$\begin{cases} \dot{X}_1 = a_1 X_2^{g_{12}} X_4^{g_{14}} - \beta_1 X_1^{h_{11}}, & X_1(0) = \text{the initial of } X_1 \\ \dot{X}_2 = a_2 X_1^{g_{21}} - \beta_2 X_2^{h_{22}}, & X_2(0) = \text{the initial of } X_2 \\ \dot{X}_3 = a_3 X_1^{g_{31}} - \beta_3 X_3^{h_{33}}, & X_3(0) = \text{the initial of } X_3 \\ X_4 = \text{coefficient} \end{cases} \tag{35.3}$$

in which$\dot{X}_1, \dot{X}_2, \dot{X}_3$—due variables; X_4—independent variables; X_1, X_2, X_3—related variables; a_1, a_2, a_3, $\beta_1, \beta_2, \beta_3$—velocity constants; g_{12}, g_{21}, g_{31}, $g_{41}, h_{11}, h_{22}, h_{33}$—dynamic series;

The structural differences of dynamic system equations are mathematically processed, transformed into linear equations, and the improved industrial metabolic flux coefficient matrix N is established.

When the system is in steady state, it is known by formula (35.12).

$$a_i \prod_{j=1}^{n+m} X_j^{gij} - \beta_i \prod_{j=1}^{n+m} X_j^{hij} = 0 \tag{35.4}$$

Logarithmic transform,

$$\ln\left(\beta_i \prod_{j=1}^{n+m} X_j^{h_{ij}}\right) = \ln\left(\alpha_i \prod_{j=1}^{n+m} X_j^{g_{ij}}\right) \tag{35.5}$$

The linear equations were further collated as

$$a_{i1}y_1 + a_{i2}y_2 + \cdots + a_{i,n}y_n + a_{i,n+1}y_{n+1} + \cdots + a_{i,n+m}y_{n+m} = b_i \tag{35.6}$$

in which: $a_{ij} = g_{ij} - h_{ij}$; $b_i = \ln(\beta_i) - \ln(\alpha_i) = \ln(\beta_i/\alpha_i)$; g_{ij}, h_{ij}—dynamic series $y_i = \ln(X_i)$; β_i, α_i—velocity coefficients.

The linear formula (35.6) is simply written as the below matrix form,

$$A_D \cdot \overrightarrow{y_D} + A_I \cdot \overrightarrow{y_I} = \vec{b} \tag{35.7}$$

Ignoring the effect of independent variables on flux balance, the formula (35.7) is further simplified as the following,

$$A_D \cdot \overrightarrow{y_D} = \vec{b} \tag{35.8}$$

in which A_D—the improved flux coefficient matrix N reflects the dynamic functional relationship between metabolic flux, substrate and product strength between metabolic nodes over time.

Combined with the case of the manufacturing system, the flux coefficient matrix is solved and the metabolic flux is calculated. The flux values were calibrated on the metabolic pathway and the industrial metabolic network diagrams of different scales were plotted.

35.2.2 Establishment and Solution for the Matrix N of Flux Coefficients

Cell metabolic flux calculation follows Michaelis–Menten velocity law, metabolic flux.

$$v = v(X) = \frac{v_{\max} X}{K_m + X} \tag{35.9}$$

In the formula: the maximum flux of the $v_{\max}$; the K_m—M constant.

By logarithmic transformation and Taylor series expansion, the equation is obtained:

$$\omega \approx \ln(\alpha) + g \cdot Y \tag{35.10}$$

In formula: The natural logarithm of omega metabolic flux; $Y = \ln(X)$; g—kinetic series; Alpha Velocity constant.

By Descartes transform, obtained:

$$v \approx \alpha \cdot X^{g} \tag{35.11}$$

The formula (35.11) is substituting (35.1), and the tectonic kinetic differential equations are as follows:

$$\dot{X}_i = a_i \prod_{j=1}^{n+m} X_j^{gij} - \beta_i \prod_{j=1}^{n+m} X_j^{hij} \tag{35.12}$$

In the formula: $\dot{X}_i$—variables; $X_1, \ldots, X_n$—n related variables; $X_{n+1}, \ldots, X_{n+m}$—m independent variables; α_i, β_i—Velocity constants; g_{ij}, h_{ij}—Dynamics series;

In particular, when the industrial metabolic nodes of the manufacturing system have specific process principles and physical and chemical laws, industrial metabolic flux V does not fully comply with the law of Michaelis–Menten velocity, at this time the flux equation needs to be reconstructed, and the structural structure of the flux coefficient matrix n is very important. For example, considering the effect of time, the Michaelis–Menten flux equation will be replaced by the following formula:

$$P(t) = \frac{k_1 k_2 E_t X_t}{k_1 + k_2 + k_1 X_t} + \frac{k_1 k_2 E_t X_t}{(k_1 + k_2 + k_1 X_t)^2}\left[e^{-(k_1+k_2+k_1 X_t)t} - 1\right] \tag{35.13}$$

In the formula: k_1, k_2—constant; k_{-1}—reversible process constant; E_t—regulatory strength; X_t—metabolic substrate strength; $P(t)$—metabolic product strength.

It can be seen that in logarithmic coordinates, the kinetic series can also constitute the flux coefficient matrix n. The flux coefficient matrix N and the kinetic series must be able to reflect the functional relationship between the metabolic substrate intensity X_t and the metabolic product Strength $P(t)$ flowing through the metabolic node, that is, the process principle and physicochemical law on the metabolic node.

Therefore, in order to determine N and reflect the physical and chemical laws observed by node flux, two approaches are resolved:

According to the conservation of matter and energy and the principle of process, the differential equations of all metabolic nodes are listed directly, and the flux coefficient matrix n is obtained by using mathematical transformation into linear equations. However, the regulatory behavior, environmental constraints, and human will that are independent of the actual physical and chemical state in the industrial metabolic network cannot be described by differential equations.

35.3 Cases Study

An industrial metabolic pathway analysis of manufacturing system is developed on the structure of industrial metabolic network.

The manufacturing system is called the industrial metabolism node (Imnode) by the abstract discrete controllable manufacturing unit. Taking the process section and equipment system as the unit, the industrial metabolic nodes are obtained, and the process and physicochemical process of each metabolic node are calibrated. The general structure of industrial metabolic nodes is shown in Fig. 35.4;

The industrial metabolic pathway (metabolic pathway, IMP) refers to the flow path of the material energy formed by the input and output metabolites flowing through the industrial metabolic nodes. The IMP is analyzed, and the metabolic flux symbol and flow direction on each imp are calibrated. The expression of industrial metabolic pathway is shown in Fig. 35.5.

The industrial metabolic pathway that calibrates metabolic flux forms an intricate network of links, known as the industrial metabolic network (IMN). According to the manufacturing process, follow the flux controllable principle, merge the metabolic nodes and pathways with uncertain process mechanism, and structure the industrial metabolic network. Figure 35.6 is an industrial metabolic network of crude steel manufacturing systems.

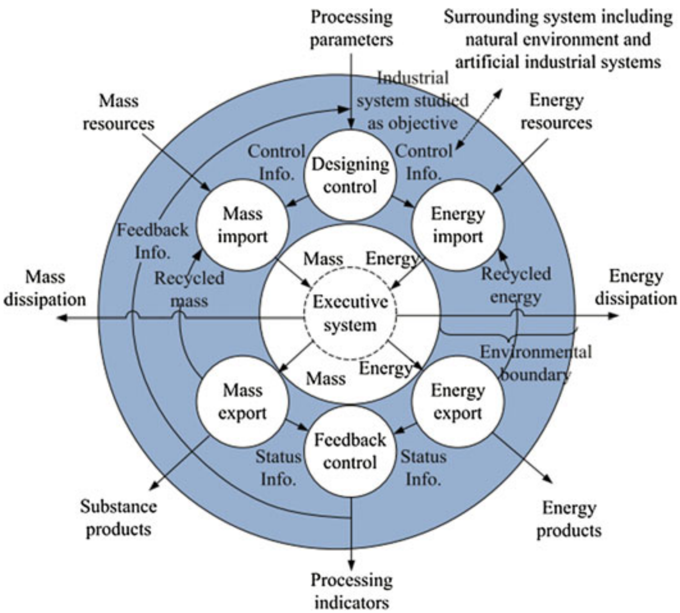

Fig. 35.4 General structure of industrial metabolic nodes

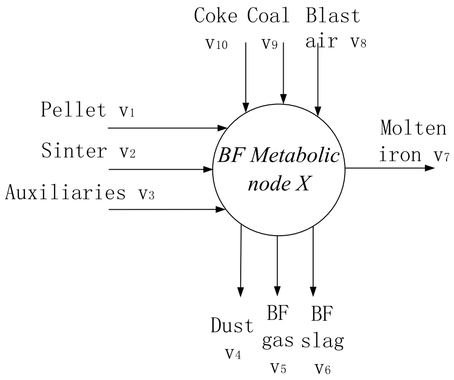

Fig. 35.5 Model for metabolic pathway

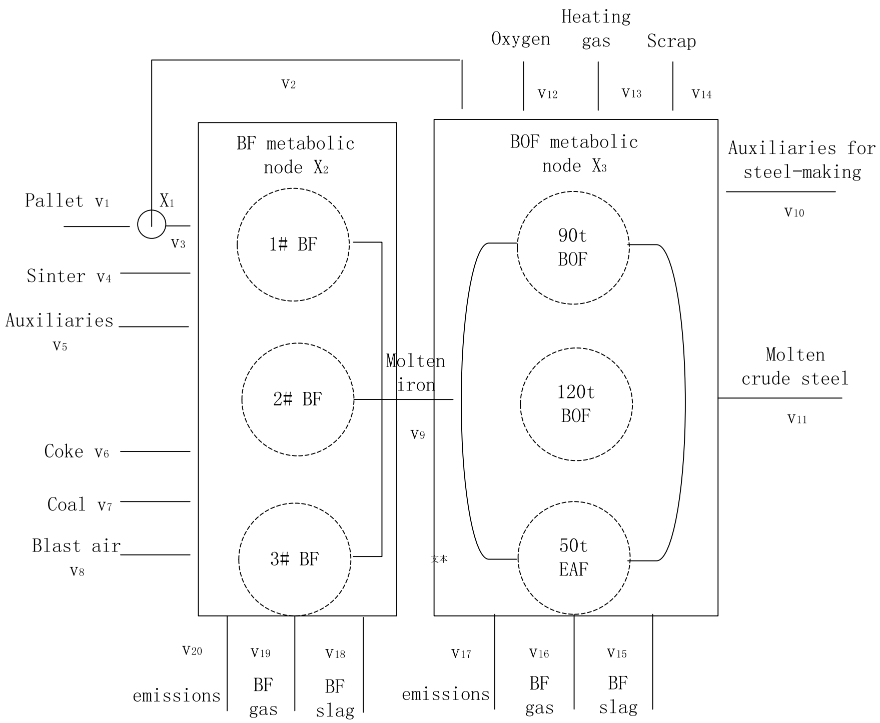

Fig. 35.6 Metabolic network of the crude steel making system

35.4 Conclusions

(1) The kinetic modeling method used in cell metabolism flux balance and regulation technology can be used mathematically to analyze the industrial metabolic network of manufacturing system with high similarity. Therefore, the theoretical basis and mathematical methods of this study are feasible.

(2) Using the method of big data fusion and feature extraction, the IMFB analysis calculation data and FCM monitoring data are processed and compared to complete the validity confirmation of IMFB model.

(3) Combined with metal material integrated manufacturing cases, high-precision calculation and monitoring of industrial metabolic flux based on carbon emissions, development of industrial metabolic flux optimization and control technology for integrated 3D printing integrated manufacturing systems for metal material preparation and micro-casting forging and milling, improving manufacturing energy efficiency and reducing carbon emissions, explore green intelligent manufacturing technology for integrated metal material preparation and integrated 3D printing.

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Chapter 36
Evolution of Carbon Emission Mechanism of Blast Furnace Iron-Making Based on Metabolic Flux Balance

Junwen Chen, Gang Zhao, Hua Zhang and Xing Gao

Abstract Aiming at the complexity of carbon emission in blast furnace iron-making production process, the method of bio-metabolism flux balance is used to analyze the carbon flow calculation method, construct a metabolic flux network, solve the metabolic flux matrix, and carry out the evolution analysis of blast furnace iron-like biological metabolism. The results show that the metabolic flux evolution of the blast furnace iron-making system is completely feasible, which will help to establish a bridge between the microscopic mechanism and the macroscopic law, and understand and master the industrial metabolic mechanism of the manufacturing system.

36.1 Introduction

Climate change is the most complex global environmental issue today, and it is also a huge challenge for mankind. In human actual production activities, CO_2 emissions caused by energy consumption are the main source of global CO_2 emissions. As an important area of China's industry, the steel industry is a resource- and energy-intensive industry and is also a major emitter of CO_2 and various pollutants.

The production, transmission, conversion, and dissipation of material energy in the production of steel manufacturing systems simultaneously produce intermediate products, by-products, and emissions, which have an impact on the environment. In order to realize the analysis, calculation, dynamic adjustment, and optimization

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control of the steel manufacturing system, it is necessary to have a complete and accurate grasp of the complex material energy flow law of the manufacturing system. Lu Zhongwu first expounded the basic concept of energy-saving body and system energy conservation [1], established a steel product life cycle benchmark logistics map [2], and analyzed the environmental load problem of China's steel production typical process [3]. Polenske et al. [4] input and output process model inventory analysis methods, through the study of energy efficiency and pollution emissions, three typical coking processes in Shanxi Province, China steel industry analysis [4]. The IPCC provides an emission factor-based carbon emission calculation method, which is also an input–output inventory analysis based on carbon-containing fuels [5]. Ku, Harn Wei the microalgae hydroponic technology developed according to metabolic engineering technology is used to absorb CO_2 emitted from power plants [6], and L. Cheng et al. of Zhejiang University used the microalgae cultured in the photomembrane reactor for atmospheric CO_2 absorption [7]. The whole life cycle method mainly analyzes the flow characteristics of the manufacturing resources of the product and pays less attention to the influence of the manufacturing system and the equipment itself on the material energy. The inventory analysis only considers the statistical law between input and output but ignores the internal manufacturing system. Based on a systematic analysis of the intracellular metabolic pathway network, the cellular metabolic processes are targeted and purposefully engineered at the cellular and molecular levels to achieve more efficient biochemical transformation, energy transfer, and supramolecular assembly, and to enhance metabolites. Production speed and production capacity [8], there are also completely similar application requirements in the field of manufacturing engineering.

In view of the above problems, the industrial system metabolism and cell life metabolism of manufacturing system are highly similar in form and mathematical description. By introducing the flux balance principle and metabolic regulation method in bio-metabolism engineering, a deeper analysis of material energy flow can be developed. The method can not only describe the microscopic mechanism of industrial metabolism but also reflect the macroscopic law and help to realize the dynamic prediction and optimal regulation of industrial metabolic flux, improve utilization and productivity, and reduce by-products and pollution emissions.

36.2 Principle of Flux Balance in Blast Furnace Iron-Making

36.2.1 Principle of Metabolic Flux Balance

Two important papers published by California Institute of Technology and Massachusetts Institute of Technology Bailey and Stephanopoulos in "Science" mark the birth of the discipline of metabolic engineering [9, 10]. Metabolic engineering is a fusion of molecular biology and reaction engineering techniques. Based on a systematic analysis of intracellular metabolic pathway networks, the cellular metabolic processes are targeted and purposefully engineered at the cellular and molecular levels to achieve more efficient biochemical transformation, energy transfer, and supramolecular assembly. Its application areas mainly include: improving raw material utilization rate; producing new substances, new drugs; degrading pollutants; blocking or reducing the formation of by-products; increasing the production speed and production capacity of metabolites. There are also similar applications in the manufacturing engineering arena, such as increased utilization and productivity, reduced by-products and pollution emissions. Therefore, metabolic engineering technology is increasingly used in the field of green manufacturing.

The core problem that metabolic engineering needs to address is the regulation of metabolic behavior by means of metabolic flux balance analysis, which requires the establishment of stoichiometry, reaction kinetics, and thermodynamic models of individual reactions in complex metabolic pathways to provide equilibrium across the metabolic network. Metabolic flux data, and clearly show the quantitative relationship between interactions between metabolic reactions and metabolic pathways [11]. The mathematical essence of the metabolic flux balance principle is the set of reaction dynamics differential equations based on chemometrics, which is also governed by the thermodynamic conditions of the metabolic process [12]. The metabolic flux balance equations are listed by the metabolic flux balance network after formal expression, and the independent flux equation constants in the linear equations constitute the flux coefficient matrix.

The input metabolic bottom stream passes through the node, and the steady state rate of the metabolite output after synthesis or decomposition process is called industrial metabolic flux. The principle of industrial metabolic flux balance describes the equilibrium relationship between the rate of change of metabolite strength over time and all metabolic fluxes in industrial metabolic networks by establishing a set of dynamic differential equations, namely the industrial metabolic flux balance Eq. (36.1) shown.

$$\frac{\mathrm{d}S}{\mathrm{d}t} = N \cdot V \tag{36.1}$$

where: N-flux coefficient matrix; V-industrial metabolic flux matrix; industrial metabolic intensity of S-node metabolites. When N is constructed and solved, the industrial metabolic flux V can be solved based on Eq. (36.1), and the flux values flowing through all nodes can be accurately calculated to establish a transparent, accurate, real-time, and efficient flux analysis and calculation method.

If a reaction produces a metabolite, the corresponding element is 1, and if the reaction uses a metabolite as a substrate, the matrix element is -1. If the metabolite is not related to the reaction, the corresponding matrix element is zero. Matrix elements also represent a one-to-one stoichiometry. For example, two substrate molecules are used to form a product molecule and the loss of substrate is noted as -2.

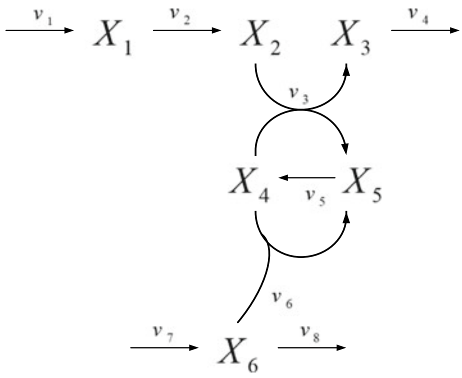

Fig. 36.1 Example of an industrial metabolic pathway

Constructing a flux coefficient matrix N is a prerequisite for solving the flux matrix V. The industrial metabolic pathway shown in Fig. 36.1 is constructed with a matrix of flux coefficients N, as shown in Eq. (36.2).

$$\begin{array}{cccccccc|c} v_1 & v_2 & v_3 & v_4 & v_5 & v_6 & v_7 & v_8 & \\ \hline \left(\begin{matrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix}\right. & \begin{matrix} -1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix} & \begin{matrix} 0 \\ -1 \\ 1 \\ -1 \\ 1 \\ 0 \end{matrix} & \begin{matrix} 0 \\ 0 \\ -1 \\ 0 \\ 0 \\ 0 \end{matrix} & \begin{matrix} 0 \\ 0 \\ 0 \\ 1 \\ -1 \\ 0 \end{matrix} & \begin{matrix} 0 \\ 0 \\ 0 \\ 2 \\ -1 \\ -1 \end{matrix} & \begin{matrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{matrix} & \left.\begin{matrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -1 \end{matrix}\right) & \begin{matrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_n \end{matrix} \end{array} \quad (36.2)$$

36.2.2 Evolution Process of Blast Furnace Iron-Making

The process of producing molten iron in blast furnace is a complex iron–coal chemical system. During the smelting process, a series of material exchange reactions occur between the blast furnace and the outside world. The complex blast furnace iron-making system is mainly composed of three major systems: raw fuel production, hot-metal production and auxiliary production. As shown in Fig. 36.2, the blast furnace iron-making production is to charge iron-containing materials such as sinter and coke into the blast furnace from the top of the furnace, and to blast and pass the temperature rise and reduction reaction through the tuyere to form a liquid-reduced carbon-containing iron liquid and slag. The production process of blast furnace gas containing CO_2, CO, and the like is excluded. Its main purpose is to obtain the liquid pig iron with the desired temperature and composition in an economical and efficient manner using iron ore.

Consistent with the metabolism of cells, the blast furnace iron-making system also has its own unique metabolic and operational modes. Exploring its energy prevalence

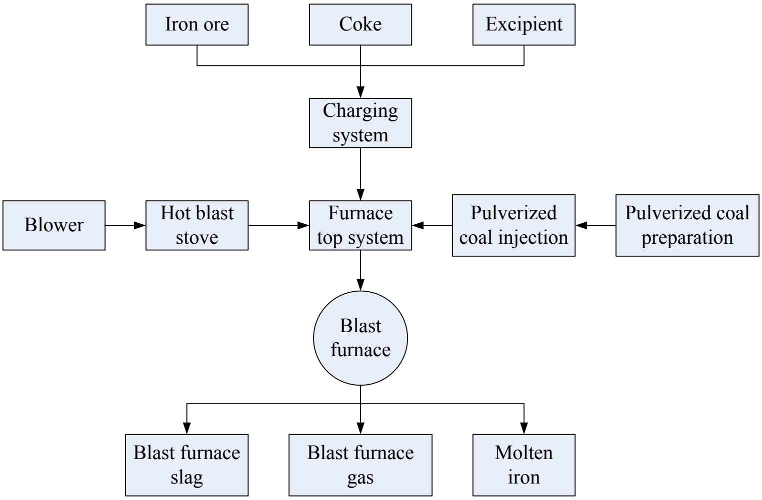

Fig. 36.2 Schematic diagram of blast furnace iron-making process

essentially regulates metabolic behavior by means of metabolic flux balance analysis, requiring the establishment of stoichiometry, reaction kinetics, and thermodynamic models of individual reactions in complex metabolic pathways to provide equilibrium in the entire metabolic network of the blast furnace. Metabolic flux data clearly show the quantitative relationship between interactions and metabolic pathways. The mathematical essence of the metabolic flux balance [1] principle is the set of reaction dynamics differential equations based on chemometrics, which is governed by the thermodynamic conditions of the metabolic process. Therefore, it is first necessary to comprehensively analyze the energy flow network of the blast furnace iron-making system.

Based on the above ideas, taking into account the feasibility of manufacturing system industrial metabolic processes and organism cell metabolism processes, the high degree of similarity in the form of material energy exchange and engineering applications, using the basic theory of bio-metabolism engineering, using improved industrial metabolism Flux balance analysis method, the construction of industrial metabolic network, helps to establish a bridge between microscopic mechanism (physical chemistry) and macroscopic law (statistics), understand and master the industrial metabolic mechanism of manufacturing systems.

36.3 Case Study and Discussion

36.3.1 Based on MAS Carbon Emission Metabolic Flux Evolution Case

The experimental data of No. 1 blast furnace of a steel mill in Wuhan was selected. Due to the complex reaction mechanism inside the blast furnace, in order to accurately describe the carbon flow direction, the typical characteristics are extracted. According to the internal temperature distribution characteristics of the blast furnace, the high is divided into three areas from top to bottom: preheating zone, hot storage zone, and high-temperature zone [13]. The input iron-making raw material iron ore and coke are injected into the preheating zone from the top of the furnace, and the air is blown in the high-temperature zone of the furnace bottom and the fuel is input to rapidly increase the temperature inside the furnace and generate a reducing gas. The iron in the iron ore is separated in the isothermal zone by the action of coke and a reducing agent and is output as molten iron, accompanied by slag and blast furnace gas. The reaction conditions between the various materials are mainly temperature, so the division of the furnace area is mainly based on this (Table 36.1).

The data report comes from the actual data of No. 1 blast furnace in June 2015, including the input raw material quantity, output product quantity, and other parameters. The effective capacity of the blast furnace is 1436 m^3, the diameter of the furnace waist is 9500 mm, the diameter of the hearth is 8400 mm, and the cross-sectional area of the hearth is 55.5 m^2. In the MAS system, the input material has to be converted to a dimensionless value, which is converted by the interface. Since the

Table 36.1 Reaction rules and conditions

Reaction zone	Reaction formula	Condition (°C)
Preheating zone	$Fe_2O_3 + CO \rightarrow 2FeO + CO_2, \quad +37,112$ kJ	>570
	$Fe_2O_3 + H_2 \rightarrow 2FeO + H_2O, \quad -63,555$ kJ	>570
Hot storage area	$FeO + CO \rightarrow Fe + CO_2, \quad +13,598$ kJ	>570
	$FeO + H_2 \rightarrow Fe + H_2O, \quad -27,698$ kJ	>500
	$CO + H_2O \rightarrow CO_2 + H_2, \quad -124,390$ kJ	>810
High temperature zone	$FeO + C \rightarrow Fe + CO, \quad -152,088$ kJ	>1200
	$SiO_2 + 2C \rightarrow Si + 2CO, \quad -162,761$ kJ	>1000
	$MnO + C \rightarrow Mn + CO, \quad -261,291$ kJ	>1450
	$P_2O_5 + 5C \rightarrow 2P + 5CO, \quad -1,921,293$ kJ	>900
	$FeS + CaO + C \rightarrow CaS + Fe + CO, \quad -145,358$ kJ	>1000
	$2C + O_2 \rightarrow 2CO, \quad +2,564,872$ kJ	>300
	$CO_2 + C \rightarrow 2CO, \quad -165,686$ kJ	>1000
	$C + H_2O \rightarrow CO + H_2, \quad -124,390$ kJ	>1000

Table 36.2 Enter the number of material populations (unit: 10^2)

Date	Materials				
	Fe_2O_3	C	C/min	H_2O	O_2/min
06-01	2166.82	555.52	34.59	7.34	1108
06-02	2295.94	554.67	34.48	8.84	1059
06-03	2110.74	563.07	36.32	7.11	1103
06-04	2147.87	545.70	36.32	8.27	1119
06-05	2117.6	554.32	37.87	7.52	1127
06-06	2162.62	565.77	39.45	8.60	1149
06-07	2162.62	558.67	40.67	7.97	1178
06-08	2279.99	581.65	41.23	8.60	1191
06-09	2229.56	575.87	39.34	7.10	1071
06-10	2203.43	567.56	38.53	8.21	1125
06-11	2149.29	566.57	37.34	7.38	1197
06-12	2123.63	575.87	39.33	8.9	1117
06-13	2109.32	568.34	38.35	7.70	1155
06-14	2133.57	583.05	37.34	8.95	1070
06-15	2198.38	555.43	36.21	8.70	1112

blast furnace iron-making input material usually contains a plurality of components, the data in the report is sorted and converted into the population of each substance as shown in Table 36.2.

36.3.2 Results and Discussion

The blast furnace iron production process has a cycle of about 120 min and is divided into four time periods, each of which is 30 min. The input coke and the pulverized coal as fuel are mainly presented in the blast furnace with CO_2 and CO in the blast furnace gas, and some of the carburizing reaction occurs in the blast furnace into the crude iron in the form of Fe3L, and a very small part is present in the gas dust. The image of the CO_2 and CO values in the blast furnace gas is actually collected on June 1 and the mass of the carbon-containing material according to the change of time is shown in Fig. 36.3.

As can be seen from Fig. 36.3, the input coke and the pulverized coal as fuel are mainly present in the blast furnace in the blast furnace gas with CO_2 and CO, and some of the carburizing reaction occurs in the blast furnace and enters the crude iron in the form of Fe3L. Part of it is in the gas dust. According to the carbon input of the blast furnace iron-making on June 1, and the three reaction zones divided by the blast furnace, the metabolic network distribution is constructed by the carbon flow. According to the above, the metabolic flux matrix is obtained.

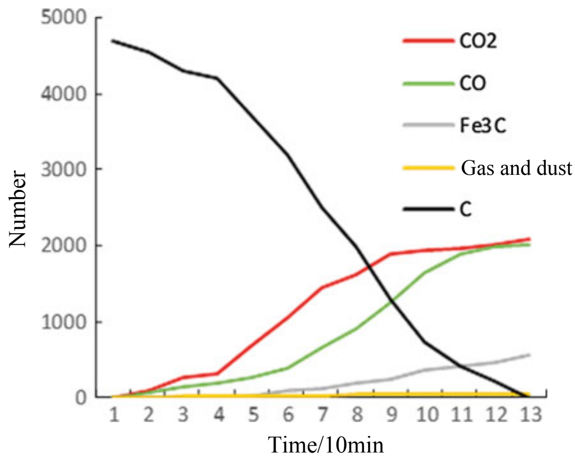

Fig. 36.3 Carbon flow distribution curve

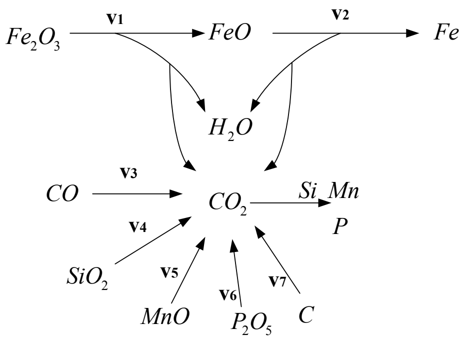

Fig. 36.4 Metabolic network

According to the three reaction intervals of the blast furnace iron-making, Fig. 36.4 shows the carbon flow metabolism network of the chemical reaction of the three reaction zones in the blast furnace iron-making process. Whether it is a substrate or a reactant, each carbon flow path is clearly visible. According to the principle of cellular metabolic flux, the flux metabolic coefficient matrix is shown in Fig. 36.5. It can be seen that the principle of cellular metabolic flux is equally applicable to the blast furnace iron-making system, and the evolution of the metabolic pathway of the blast furnace iron-making system is a completely new method.

36.4 Conclusions

Through the introduction of bio-metabolism engineering in the blast furnace iron-making system, the carbon dioxide is produced in the blast furnace iron-making process to simulate the evolution of cell metabolism, and the metabolic flux analysis

Fig. 36.5 Flux matrix

V_1	V_2	V_3	V_4	V_5	V_6	V_7	
1	-1	0	0	0	0	0	X_1
0	1	-1	0	0	0	0	X_2
0	0	2	-2	0	0	0	X_3
0	0	0	1	-1	0	0	X_4
0	0	0	0	1	-1	0	X_5
0	0	0	0	0	1	-1	X_6
0	0	0	0	0	0	-2	X_7
0	0	0	0	0	0	-2	X_8

method is used to construct a carbon flux metabolic flux network to obtain metabolic flux. The coefficient matrix, the method of bio-metabolism engineering, is fully applicable to blast furnace iron-making.

The work that needs to be done in the future can be carried out in the following two aspects. First, study the blast furnace iron-making metabolic node and calibrate the process and physical and chemical processes of each metabolic node. Second, analyze the metabolic pathways of blast furnace iron-making and calibrate the metabolic flux symbols and flow directions on each pathway.

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Chapter 37
Manufacturing Process-Oriented Quantitative Evaluation of Green Performance for Iron and Steel Enterprise

Gang Zhao, Minchao Xie, Xing Gao and Dan Ruan

Abstract In order to objective evaluation of resources efficiency and environmental impact of an iron and steel enterprise, it is necessary to carry out overall assessment about its green performance, and to analyze related indictors differences, so that more specifically to improve green performance of iron and steel enterprise. On the basis of constructing a quantifiable multi-level green evaluation indicators system, firstly, after processing of actual production data in iron and steel enterprises can obtain the judging value of green evaluation indicators, through compared the judging value with the industry basic values, it concluded the scores of every green indicators and reflected on the radar-graph, and then through the area and perimeter of two evaluation vector quantitative evaluated green performance of iron and steel enterprise and its indicators difference. Lastly, using radar-graph method can to carry on graphics intuitive evaluation and numerical comprehensive evaluation for the green evaluation indicators of three iron and steel enterprise, so that the iron and steel enterprises to clarify its position in the industry, and analyze the advantages and disadvantages of its own existence. For the first time applying radar-graph to the evaluation of green performance of iron and steel enterprise and its indicators difference, it has more intuitive visibility and more accurate quantitative evaluation.

37.1 Introduction

Iron and steel enterprises are key industries with multiple inputs and outputs, and it has long production cycle processes. From the coking, pelletizing, sintering to iron making, steel making, steel rolling, and other processes, it takes a lot of resources

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and energy. At the same time, it will also be accompanied by the emission of waste and high pollutants. With natural resources are limited and environmental issues attract much attention, iron and steel companies have made the comprehensive utilization of resources and reduction of pollutant emissions as their corporate mission. In connection with the steel manufacturing process of the company and study, its greenness is essentially a study of the production process indicators of the iron and steel enterprises. Many scholars have built a steel enterprise environmental performance evaluation system [1–3] and an iron and steel industry planning environmental assessment index system [4] based on environmental protection. But starting from the manufacturing process of steel companies, there are few literature about the evaluation system based on comprehensive consideration of the negative effects of the environment and the recycling of resources. Based on this perspective, this paper combines the academic viewpoints of Ma [5], He [6], and Zhao [7] to construct a green evaluation index system for steel companies.

The evaluation index system for steel enterprises is mainly based on traditional evaluation methods with subjective judgments, and numerical analysis is mainly used [1–6]. In view of the characteristics of iron and steel enterprises, the index system is characterized by a large number of indicators and distinct levels. This paper proposes the application of radar chart method to the green evaluation system of steel enterprises for the first time based on the evaluation methods used in the literature in other fields. A comprehensive evaluation of a large number of green indicators is carried out by using the method of radar drawing combined with graphics and numeric values to determine the degree of rational utilization of resources and the reduction of the negative impact of the environment.

37.2 Construction of Green Evaluation Index System

The green evaluation index of iron and steel enterprises contains many factors. It is necessary to consider not only the improvement of resource utilization in the production process but also the reduction of energy consumption and the minimization of negative impact on the environment. Starting from the characteristics of the production process for iron and steel enterprises, analyze two different phases about source resource input and terminal by-product emissions of iron and steel companies to establish a green evaluation index system for iron and steel enterprises. The source technical indicators and terminal technical indicators are considered as the first-level indicators of the green evaluation index system for steel companies, and the degree of utilization of corporate resources and energy and the impact of polluting wastes discharged on the ecological environment are reflected by specific indicators [8].

37.3 Comprehensive Evaluation of Radar Chart Method

37.3.1 Treatment of Green Evaluation Indexes of Iron and Steel Enterprises

In order to evaluate the overall greenness of iron and steel enterprises, various green evaluation indicators need to be processed. From the production report of the enterprise, the relevant data of the calculation of the index value are obtained. The two data of the production and consumption of steel products in the enterprise reports can be obtained by the example of the consumption of the new water quantity in tons of steel, which is used in the production of steel products in the enterprise reports. Because the daily consumption of water and steel output of steel enterprises is dynamic, the index of new water consumption per ton steel is also in dynamic change. The index value of these dynamic changes is processed to get the judgement value of the index, and the green degree of each index can be judged by comparison between the judgment value and the industry benchmark value.

These green evaluation indexes can be roughly classified into two categories, one is that the higher the value is, the higher the green level is, the other is that the smaller the value is, the higher the green level is. In the actual production process of iron and steel enterprises, these dynamic changes are mostly Fluctuating on the basis of a certain value. Taking the new water quantity per ton steel as an example, through the two sets of data of daily steel production and new water consumption in the production report, the dynamic change data of the new water consumption per ton steel per day can be calculated. After fitting this set of data to MATLAB for curve fitting, a fitting curve $f(x)$ for the indicator of fresh water consumption per ton of steel in the steel production process can be obtained. In some cases, the value of a single index will reach the advanced level of the domestic green, but in some cases, the actual fitting curve of the single index of the iron and steel enterprises is complex and changeable. In order to evaluate the actual green degree of a single index, the principle of the fixed integral is used to solve the problem.

According to the principle of definite integral, the fitting curve $f(x)$ is used as the integrand, and the transverse coordinates (days) corresponding to the two ends of the curve are the lower and upper limit of the integral, and the result is the area of the fitting curve. The value obtained by dividing the area by the length of the abscissa called A, which is used as a judgement value for evaluating the greenness level of a single indicator of a steel enterprise.

$$\frac{\int_{x_0}^{x_1} f(x)\mathrm{d}x}{x_1 - x_0} = A \tag{37.1}$$

Formula: $f(x)$ is the fitting curve, and $x_1 - x_0$ is the corresponding number of days. A is used to evaluate the green level of the single index in iron and steel enterprises.

The green level of each index can be obtained by comparing the judgment value A of the single index green level of iron and steel enterprises with the benchmark value of the index. The industry benchmark value obtained is compared with the enterprise judgment value, and the control result is divided into four grades. Take the positive index as an example:

(1) the judgment value is lower than the minimum standard value: 1 point;
(2) the judgement value is between the lowest reference value and the intermediate reference value: 2 points;
(3) the judgement value is between the intermediate reference value and the highest benchmark value: 3 points;
(4) the judgement value is higher than the highest standard value: 4 points.

Similarly, the rating of the reverse indicator is the opposite of the positive indicator. With regard to the determination of the number of grades to be divided, the more the number of documents, the more accurate the evaluation result, so that it is divided into four grades for the sake of simple calculation. The higher the score of the green evaluation indicator, the higher the level of greening of steel companies.

37.3.2 Difference of Green Index and Quantitative Evaluation of Green Character of Iron and Steel Enterprises

The green level of iron and steel enterprises can be determined by the comprehensive evaluation value (Y) and the computation of the comprehensive evaluation value (Y) is derived from the two-dimensional eigenvalue (V) constructed by the area evaluation vector ($\overline{V_1}$) of the radar chart and the circumference evaluation vector ($\overline{V_2}$). The value of the area evaluation vector directly reflects the green overall superiority of the iron and steel enterprises, while the perimeter evaluation vector directly reflects the difference of the green index. Therefore, the area characteristics and circumference characteristics are the keys to evaluate the difference between green level and green index of iron and steel enterprises. However, in the actual evaluation process, the shape, area, and perimeter of the radar map vary with the ranking of the evaluation index, but the average area and average perimeter of the radar map are unchanged, so the average area and average circumference of the radar map can be used as the two characteristics. In order to comprehensively evaluate the green level of iron and steel enterprises [9].

(1) the calculation of the average area characteristic quantity and the average perimeter characteristic quantity. The calculation of the average area characteristic quantity ($\overline{A}$) and the average circumference characteristic quantity ($\overline{P}$) is based on the mathematical calculation method. First, the area and the circumference of each small triangle in the radar map are calculated, and then the average area and the evaluation perimeter are calculated.

$$\overline{A} = \frac{m \sum_{i=1}^{m-1} \sum_{i<j}^{m} \frac{1}{2} R_i R_j \sin \theta_{ij}}{C_m^2} \tag{37.2}$$

$$\overline{P} = \frac{m \sum_{i=1}^{m-1} \sum_{i<j}^{m} \sqrt{R_i^2 + R_j^2 - 2R_i R_j \cos \theta_{ij}}}{C_m^2} \tag{37.3}$$

In the formula: $\overline{A}$ is the average area of the green evaluation index radar map of iron and steel enterprises. $\overline{P}$ is the average circumference of the green evaluation index radar chart of steel enterprises, M is the number of green evaluation indexes, R is the score of the index, i and j are the i and j index in the green evaluation index, θ is the two edge angle, which represents the weight of the index. Because the number of indexes studied in this paper is too much, in order to simplify the influence of the subjective factor of calculating and eliminating the weight, we take θ as the fixed value, i.e. $\theta = \frac{2\pi}{m}$.

(2) The construction of a two-dimensional characteristic quantity (V). The construction of two-dimensional eigenvalues is based on the average area characteristic ($\overline{A}$) and the mean perimeter characteristic ($\overline{P}$).

$$V = \left(\overline{V_1}, \overline{V_2}\right) \tag{37.4}$$

In the formula: $\overline{V_1}$ is the area evaluation vector. The larger the value of the steel enterprise, the higher the overall advantage of the green level of the iron and steel enterprise; the $\overline{V_2}$ is a perimeter evaluation vector, which reflects the difference between the green evaluation indexes, the larger the value is, the smaller the difference is, and vice versa.

$$\overline{V_1} = \frac{\overline{A}}{A_{\max}} \tag{37.5}$$

In the formula: $A_{\max}$ is the largest score in iron and steel enterprises for the area of the inscribed m edge of the circle of the radius. $A_{\max} = mR_{\max}^2 \sin \frac{\pi}{m} \cos \frac{\pi}{m}$. The value of $\overline{V_1}$ is between 0 and 1.

$$\overline{V_2} = \frac{\overline{P}}{P_{\max}} \tag{37.6}$$

In the formula: $P_{\max}$ is the circumference of the inscribed positive m edge of the circle with the largest index score in the iron and steel enterprise, $P_{\max} = 2mR_{\max} \cos \frac{\pi}{m}$, and the value of $\overline{V_2}$ is between 0 and 1.

(3) Comprehensive green evaluation of iron and steel enterprises. The synthetic evaluation function is constructed by using the geometric mean number of two characteristic quantities. The final evaluation value (Y) is the comprehensive evaluation result of the green level of steel enterprises.

$$Y = \sqrt{\overline{V_1} \times \overline{V_2}} \tag{37.7}$$

Formula: Y is a comprehensive evaluation value for calculating the green property of iron and steel enterprises.

37.4 Case Analysis

Three representative iron and steel enterprises were selected for trial calculation. First, the actual data of its production are selected, and then the actual data are processed to get a comparison between the judgement value of the green index and the datum value, and the score of the green evaluation index is obtained. The specific score is as shown in Table 37.1.

According to the score of green evaluation index of three enterprises, we can draw out the green evaluation index radar chart of three iron and steel enterprises, respectively. In order to simplify the complexity of the radar chart, take $y1 \ldots y25$ represents each green evaluation index, $R1 \ldots R25$ represents the scores of each index. The drawn radar chart is shown in Fig. 37.1.

It can be clearly seen from Fig. 37.1 that the total area of radar chart of *B* iron and steel enterprise is larger, and its overall greening level is higher than that of the other two iron and steel enterprises. In terms of the single green evaluation index, the *B* steel enterprise is closer to the outer circle in the respects of the utilization rate of blast furnace gas, the utilization rate of coke oven gas, the recovery and utilization of iron dust (mud), the utilization rate of blast furnace slag and the utilization rate of converter slag, and its green evaluation index is better than the other two iron and steel enterprises. *C* steel enterprises are superior to the other two iron and steel enterprises in terms of energy consumption, energy consumption per ton steel process, energy consumption of steelmaking process of ton steel converter and fuel ratio of blast furnace. In general, the scoring of *A* iron and steel enterprises is more balanced, and the recovery and utilization of resources are higher in *B* steel enterprises, while *C* steel enterprises are lower than the other two iron and steel enterprises in the process of energy consumption. By reading the radar map, the advantages and disadvantages of three iron and steel enterprises in green evaluation index can be judged intuitively, and a new idea is provided to improve the green level of iron and steel enterprises.

According to the above radar chart calculation formula and the MATLAB software can be used to calculate the relevant parameters of the comprehensive evaluation of the radar chart method. The result of the calculation is shown in Table 37.2.

It can be seen from the results of the comprehensive evaluation of the relevant parameters of three iron and steel enterprises that the overall green property of *B* iron and steel enterprises is the highest ($\overline{V_1} = 0.0463$), but its equilibrium degree is not high ($\overline{V_1} = 0.0122$), which may be influenced by the higher energy consumption

Table 37.1 Green evaluation indictors score of three iron and steel enterprises

Index term	*A* iron and steel enterprises		*B* iron and steel enterprises		*C* iron and steel enterprises	
	Score	Index score	Score	Index score	Score	Index score
(y_1) new amount of water per ton of steel	3.63	3	3.77	3	3.98	2
(y_2) energy consumption in coking process of ton steel	123.31	3	108	4	120.23	3
(y_3) energy consumption in sintering process of ton steel	54.18	2	55.54	2	51.87	3
(y_4) energy consumption in pelletizing process of ton steel	30.75	2	25	3	20.02	4
(y_5) energy consumption in iron smelting process per ton steel	417.51	2	430.32	2	387.45	4
(y_6) energy consumption in steelmaking process of ton steel converter	−0.29	2	−0.87	2	−20.09	4
(y_7) fuel ratio of blast furnace	500	3	508	3	487	4
(y_8) blast furnace coke ratio	294.39	3	321.41	3	348.09	3
(y_9) coal ratio of blast furnace	160.63	3	166.08	3	158.99	3

(continued)

Table 37.1 (continued)

Index term	*A* iron and steel enterprises		*B* iron and steel enterprises		*C* iron and steel enterprises	
	Score	Index score	Score	Index score	Score	Index score
(y_{10}) the ratio of two energy generation to total electricity consumption.	36.18	3	45.09	4	41.87	3
(y_{11}) tons of iron ore consumption	2.54	2	2.84	2	1.87	3
(y_{12}) coefficient of scrap steel	10	2	15.3	2	42.74	4
(y_{13}) discharge of wastewater per ton of steel	1.51	3	1.49	3	1.71	2
(y_{14}) reutilization rate of production water	97.4	4	97.6	4	96.8	3
(y_{15}) COD emissions per ton of steel	0.041	4	0.073	3	0.088	2
(y_{16}) ammonia nitrogen emissions per ton of steel	0.008	3	0.007	3	0.012	2
(y_{17}) SO_2 emissions per ton of steel	1.41	2	1.72	1	0.97	3
(y_{18}) NO_x (NO_2) emission per ton steel	1.1	3	1.5	2	0.76	4
(y_{19}) CO_2 emissions per ton of steel	1.91	2	2.03	1	1.89	2

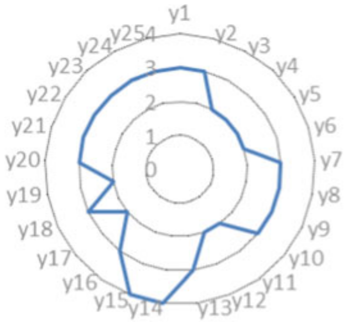
(continued)

Table 37.1 (continued)

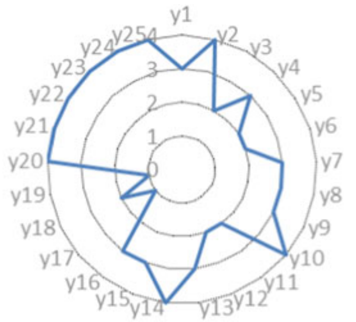
Index term	*A* iron and steel enterprises		*B* iron and steel enterprises		*C* iron and steel enterprises	
	Score	Index score	Score	Index score	Score	Index score
(y_{20}) utilization rate of blast furnace gas	97.9	3	98.3	4	97.2	3
(y_{21}) utilization ratio of coke oven gas	97.11	3	99.30	4	95.61	2
(y_{22}) heat recovery of converter gas in ton steel	25	3	29	4	19	2
(y_{23}) recovery and utilization of iron dust (mud)	99	3	100	4	100	4
(y_{24}) utilization rate of blast furnace slag	99	3	100	4	99	3
(y_{25}) utilization ratio of converter slag	98	3	100	4	92	2

Table 37.2 Comprehensive evaluation-related parameters about radar-graph of three iron and steel enterprises

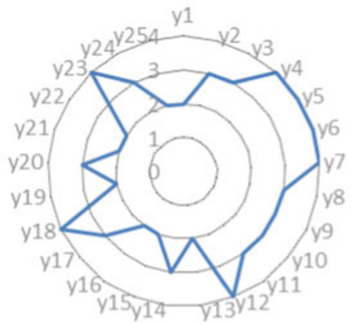
Index value	*A* iron and steel enterprises	*B* iron and steel enterprises	*C* iron and steel enterprises
Average area of $\overline{A}$	2.1450	2.3004	1.5336
Average circumference $\overline{P}$	1.9430	2.4224	2.5499
Area evaluation vector $\overline{V_1}$	0.0431	0.0463	0.0308
Perimeter evaluation vector $\overline{V_2}$	0.0098	0.0122	0.0129
Comprehensive evaluation value Y	0.0206	0.0238	0.0214
Sorting result	3	1	2



（a）Radar chart of A iron and steel enterprises



（b） Radar chart of B iron and steel enterprises



（c）Radar chart of C iron and steel enterprises

Fig. 37.1 Green evaluation indictors radar-graph of three iron and steel enterprises

in the process. According to the comparison of the comprehensive evaluation value *Y* of three iron and steel enterprises, it is clear that the green level of three iron and steel enterprises is ranked as: *B* enterprise > *C* enterprise > *A* enterprise.

37.5 Conclusion

The comprehensive evaluation of three iron and steel enterprises is carried out by using the radar chart method. From the analysis of the evaluation results, the ranking of the green level of the three iron and steel enterprises and the relative advantages and disadvantages of each enterprise on each index are known. Accordingly, the following suggestions are made for the three steel enterprises to achieve the goal of Greening:

(1) the green level of *A* iron and steel enterprises is low, but the green evaluation indexes are relatively balanced, and the difference is small. Therefore, the green level of each evaluation index should be improved on the whole.
(2) the green level of *B* iron and steel enterprises is high, especially the green evaluation index of resource recovery and utilization, but it is obvious that the green evaluation index of energy consumption is relatively inferior. Therefore, the green level of enterprises can be improved from energy saving and consumption reduction.
(3) *C* iron and steel enterprises, although the energy consumption is low, but the recycling rate of resources is generally not high, enterprises can strive to improve the recycling of resources, so as to achieve the green target of energy saving and emission reduction.

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Chapter 38 The Nondestructive Disassembly Method of Interference Fit of Sleeve-Base Structure in the Case of Cooling Excitation

Fulin Wang, Shuai Zhang, Shuaifei Hao and Hongbai Shu

Abstract Sleeve-base structure interference fits are widely applied as a prominent role in mechanical products. The sleeve parts are very vulnerable, so they are disassembled and repaired frequently. Unfortunately, the existing disassembly methods have great damage to those parts. How to achieve nondestructive disassembly for those components is a difficult problem in the field of remanufacturing. This research puts forward a dismantling method of interference fit of sleeve-base structure in the case of cooling excitation. Using liquid nitrogen to cool the contained part, cooling deformation is occurred and the interference fit is weakened, so that nondestructive disassembly is implemented. Taking the sleeve-base model as research objects, the transient heat transfer differential equations under liquid nitrogen cooling excitation are established, and transient temperature field is solved by Laplace transformation and numerical inversion; based on thermoelasticity, disassembly force equation is derived, and theoretical model of cooling excitation disassembly method is developed. A finite element simulation is done with the brass sleeve and 45# steel base model, and a comparison between it and the theoretical analysis is carried out. The results show that: (1) The simulation result of the temperature field has a good inosculation with the calculation of analytical model, and the error of disassembly force between finite element model and theoretical model is only 3.9%. (2) The curves function with disassembly force and cooling time of different interference connection models is obtained by the simulation analysis, which shows that interference fit is obviously weakened and the disassemble force is greatly reduced.

38.1 Introduction

Disassembly is an indispensable step of maintaining or remanufacturing in product life cycle. As a primary process of remanufacturing, disassembly has a significant

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influence on recyclability rate of used parts, as well as the efficiency and costs of the followed repair process. Interference fits of the sleeve-base structure are widely used as a prominent role in mechanical products. The sleeve parts are very vulnerable, so they are disassembled and repaired frequently. The research of interference fit mainly focuses on stress and deformation. Niu [1] investigated the stress and deformation of the sleeve and shaft after interference fit by finite element model and studied effects of interference and sleeve's thickness on the stress and deformation of the sleeve. Unfortunately, the existing disassembly methods have great damage to those parts. So how to achieve nondestructive disassembly for those components is a difficult problem in the field of remanufacturing.

At present, conventional disassembly methods of interference fit of sleeve-base structure like drawing, knocking, and dismounting by press machine and so on, which waste time and energy, and may cause the damage to the components. Vongbunyong and Chen [2] introduced a lot of disassembly process and automation, which can be taken for the disassembly of interference fit. In order to realize the nondestructive disassembly, hydraulic dismantling and temperature difference dismantling methods have aroused wide concern in recent years. Hydraulic disassembly method is weak the interference fit and increase the lubrication effect to realize rapid disassembly by injecting hydraulic oil of certain pressure and viscosity to the interference fit surface with oil bath. Shen [3] focused on the theoretical analysis and finite element simulation of hydraulic disassembly. The research showed that the magnitude of interference was decreased after injecting the hydraulic oil; what's more, the contact interface would be in the state of boundary lubrication and fluid lubrication, so nondestructive disassembly was realized. But hydraulic disassembly owns some shortcomings. Too high oil pressure may lead to fissure expanding and high costs. Furthermore, the oil bath which is built in advance would have an effect on the structural strength of the parts, and the cost is increased.

Li and Xiao [4, 5] presented an approach to disassemble the bearings by using induction heating and did researches on the electromagnetic vortex field and temperature field. Li [6] designed a bearing puller based on power frequency induction heating technology. The magnetic field intensity and temperature distribution were studied through the finite element simulation analysis.

Shen and Zhang [7] established fractal contact model between an equivalent rough surface and a rigid flat plane to simulate the contact of the compressor wheel with the shaft interference fit. Shen [8] analyzed the relationship among the disassembly force, interference, friction factor, the coefficient of thermal expansion, and the heating temperature and then compared the disassembly results of different heating mode. Shen and Yang [9] concentrated on the study of the loose volume mathematical model of the interference fit impeller and shaft in the process of heating.

The disassembly methods above own their advantages, but also have some limitations. For example, when the internal component of interference fit of sleeve-base structure is a thin-walled sleeve, and the containing component is a large part such as the hinged support of engineering machinery, the heating disassembly method of temperature difference has little effect because of the obvious thickness difference. The hydraulic disassembly method is also not good for the thin-walled sleeve.

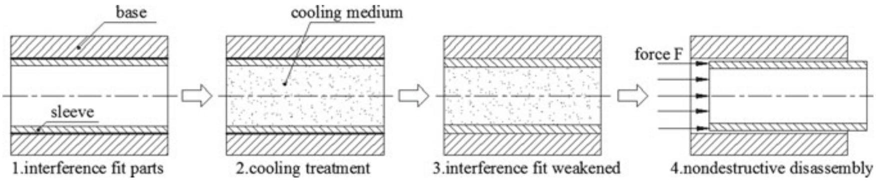


Fig. 38.1 Sketch map of disassembly method with cooling excitation

Based on the heating disassembly method of temperature difference and the liquid nitrogen's application to assembly, a dismantling method of interference fit of sleeve-base structures in the case of cooling excitation is put forward, and the fundamental of the method is expounded. Through theoretical analysis and finite element simulation, the effect of the disassembly method is studied.

38.2 The Fundamental of Cooling Excitation Disassembly Method

The fundamental of cooling excitation disassembly method is shown in Fig. 38.1. Put liquid nitrogen into inner hole surface of the thin-walled sleeve to cool the interference fit components. Due to the differences in parts size, thermal conductivity, and deformation character between the two parts, the sleeve will have a clear radial shrinkage deformation, while the base radial condensation is not obvious, so the interference fit is weakened, resulting in the reduction of disassembly force and disassembly damage.

38.3 The Disassembly Model of Sleeve-Base Structure with Cooling Excitation

38.3.1 The Transient Heat Transfer Analysis with Liquid Nitrogen Cooling Excitation

For interference fit of sleeve-base structures, the transient heat transfer problem is simplified as one-dimensional radial heat transfer model, and the thermal contact resistance is ignored, as shown in Fig. 38.2. Because the amount of interference is micrometer scale, when doing transient heat transfer analysis, the contact position of sleeve and base is thought as nominal diameter. Geometric parameters of interference fit of sleeve-base structures are shown in Table 38.1, and the material thermodynamic properties are shown in Table 38.2.

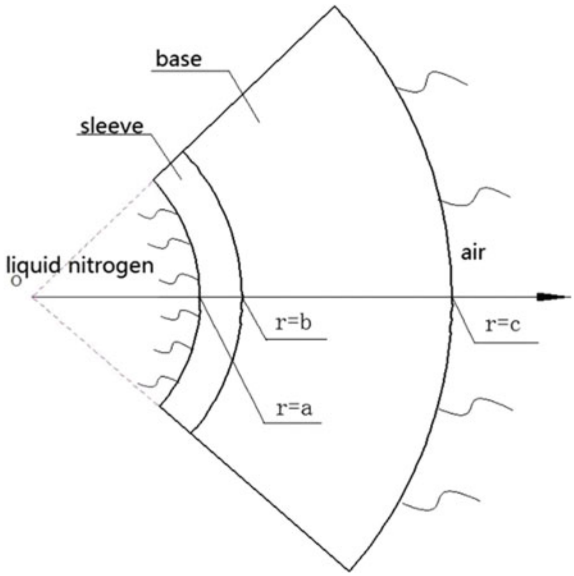


Fig. 38.2 Simplified one-dimensional radial heat transfer model

Table 38.1 Material geometry parameter

Geometric parameters	Parameters values
Inner diameter of the sleeve	$2a$
External diameter of the base	$2c$
Matching diameter	$2b$
Matched length	l
Amount of interference	δ

Table 38.2 Material thermodynamic properties

Properties	The sleeve	The seat
Elastic modulus	E_1	E_2
Poisson's ratios	ν_1	ν_2
Thermal conductivity	λ_1	λ_2
Density	ρ_1	ρ_2
Specific heat coefficient	c_1	c_2
Linear expansibility	α_1	α_2
Coefficient of friction of contact interface	μ	

When contacting with the inner wall of the sleeve, the liquid nitrogen will boil. Suppose the boiling temperature is tf_1, and the heat transfer coefficient is h_1, the outside surface of base has a convection heat transfer with the air, the convection heat transfer coefficient is h_2, and the reference temperature of air is tf_2. The initial temperature of the model is t_0.

The temperature of the parts during the transient heat transfer is a function of the radial position r and the cooling time τ. The temperature field function of the sleeve is $t_1(r, \tau)$, where $a \le r \le b$. The temperature field function of the base is $t_2(r, \tau)$, where $b \le r \le c$.

According to the theory of heat transfer, the differential equation of transient heat transfer of the inner wall of the sleeve with liquid nitrogen excitation is

$$\begin{cases} \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial t_1}{\partial r}\right) = \frac{\rho_1 C_1}{\lambda_1}\frac{\partial t_1}{\partial \tau} \\ \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial t_2}{\partial r}\right) = \frac{\rho_2 C_2}{\lambda_2}\frac{\partial t_2}{\partial \tau} \end{cases} \tag{38.1}$$

The inner wall of the sleeve is in contact with the liquid nitrogen, and the outer wall of the base is in contact with the air. And the heat flux and the temperature at the contact point are always equal. Therefore, the boundary condition of heat transfer is determined:

$$\begin{cases} \lambda_1 \frac{\partial t_1}{\partial r}\Big|_{r=a} = h_1(t_1 - tf_1) \\ \lambda_2 \frac{\partial t_2}{\partial r}\Big|_{r=c} = h_2(tf_2 - t_2) \\ \lambda_1 \frac{\partial t_1}{\partial r}\Big|_{r=b} = \lambda_2 \frac{\partial t_2}{\partial r}\Big|_{r=b} \\ t_1(b, \tau) = t_2(b, \tau) \end{cases} \tag{38.2}$$

Assume that the initial temperature of the sleeve and the base is uniform, as same as the room temperature. So the initial condition of the equation is:

$$t_1(r, 0) = t_2(r, 0) = t_0 \tag{38.3}$$

In general, the solution of complex partial differential equations in the Laplace space can be obtained by Laplace transform. Then, the solution of the original partial differential equations is obtained by inverse transformation or numerical inversion. The equation group (38.1) is transformed into:

$$\begin{cases} \frac{\mathrm{d}^2 T_1}{\mathrm{d}r^2} + \frac{1}{r}\frac{\mathrm{d}T_1}{\mathrm{d}r} - \beta_1 s T_1 = -\beta_1 t_0 \\ \frac{\mathrm{d}^2 T_2}{\mathrm{d}r^2} + \frac{1}{r}\frac{\mathrm{d}T_2}{\mathrm{d}r} - \beta_2 s T_2 = -\beta_2 t_0 \end{cases} \tag{38.4}$$

where $\beta_1 = \frac{\rho_1 C_1}{\lambda_1}$, $\beta_2 = \frac{\rho_2 C_2}{\lambda_2}$. This is a group of nonhomogeneous Bessel equations, according to the Ref. [10], and its general solution is

$$\begin{cases} T_1(r, s) = A I_0\left(\sqrt{\beta_1 s}\cdot r\right) + B K_0\left(\sqrt{\beta_1 s}\cdot r\right) + \frac{t_0}{s} \\ T_2(r, s) = C I_0\left(\sqrt{\beta_2 s}\cdot r\right) + D K_0\left(\sqrt{\beta_2 s}\cdot r\right) + \frac{t_0}{s} \end{cases} \tag{38.5}$$

where I_0 is a zero-order first kind of imaginary quantity Bessel function, K_0 is a zero-order second kind of imaginary quantity Bessel function.

According to the reciprocal property of the Bessel function, the Laplace transform of the four boundary conditions in the Eq. (38.2) is obtained, combine them with Eq. (38.5) to obtain the equation group including coefficients *A*, *B*, *C,* and *D*, so the matrix form is:

$$MX = N \tag{38.6}$$

where

$$M = \begin{bmatrix} I_0(\sqrt{\beta_1 s} r_1) & K_0(\sqrt{\beta_1 s} r_1) & -I_0(\sqrt{\beta_2 s} r_1) & -K_0(\sqrt{\beta_2 s} r_1) \\ \lambda_1 \sqrt{\beta_1 s} I_1(\sqrt{\beta_1 s} r_1) & -\lambda_1 \sqrt{\beta_1 s} K_1(\sqrt{\beta_1 s} r_1) & -\lambda_2 \sqrt{\beta_2 s} I_1(\sqrt{\beta_2 s} r_1) & \lambda_2 \sqrt{\beta_2 s} K_1(\sqrt{\beta_2 s} r_1) \\ \lambda_1(\sqrt{\beta_1 s} I_1 - h_1 I_0)(\sqrt{\beta_1 s} r_0) & -\lambda_1(\sqrt{\beta_1 s} K_1 - h_1 K_0)(\sqrt{\beta_1 s} r_0) & 0 & 0 \\ 0 & 0 & \lambda_2(\sqrt{\beta_2 s} I_1 + h_2 I_0)(\sqrt{\beta_2 s} r_2) & -\lambda_2(\sqrt{\beta_2 s} K_1 + h_2 K_0)(\sqrt{\beta_2 s} r_2) \end{bmatrix} \tag{38.7}$$

$$X = \begin{bmatrix} A & B & C & D \end{bmatrix}^{\mathrm{T}} \tag{38.8}$$

$$N = \begin{bmatrix} 0 \; 0 \; \frac{h_1(t_0 - tf_1)}{s} \; \frac{h_2(tf_2 - t_0)}{s} \end{bmatrix}^{\mathrm{T}} \tag{38.9}$$

Solve the matrix equation to get the coefficients *A*, *B*, *C,* and *D*, and thus, the general solutions $T_1(r, s)$ and $T_2(r, s)$ are obtained. Stehfest [11] proposed a numerical inversion method: Assume the Laplace transform of $f(\tau)$ is $\overline{f}(s)$, and then, the numerical inversion method can be described as follows:

$$f(\tau) = \frac{\ln 2}{\tau} \sum_{i=1}^{N} V_i \overline{f}(s) \tag{38.10}$$

$$V_i = \sum_{k=(i+1)/2}^{\min(i,N/2)} \frac{(-1)^{N/2+i} \cdot k^{N/2}(2k)!}{(N/2-k)!k!(k-1)!(i-k)!(2k-i)!} \tag{38.11}$$

$$s = i \; \ln 2/\tau \tag{38.12}$$

where *N* is an even number, Its general value is 6–18 to meet the accuracy requirements.

The temperature value at the time τ and the radius *r* during the heat transfer process can be obtained by substituting $T_1(r, s)$ and $T_2(r, s)$ into this inversion formula which needs a certain value *r* and τ, and then, whole transient temperature field functions $t_1(r, \tau)$ and $t_2(r, \tau)$ are obtained.

38.3.2 The Analysis of Cooling Deformation and Disassembly Force

The deformation of the interference fit of sleeve-base structure at low temperature excitation is the coupled effect result of contact deformation and thermal stress deformation of the contact interface.

Assume the deformation is within elastic range, so the complex coupling effect is simplified as follows: The sleeve and the base firstly have a thermal deformation at nonuniform temperature field corresponding to a certain time, and then, the interference fit is weakened after cooling. Then, the disassembly force is analyzed.

The contact pressure theory of cylindrical interference fit surface is:

$$p = \frac{\delta}{2b}\frac{1}{\frac{1}{E_1}\left(\frac{b^2+a^2}{b^2-a^2} - v_1\right) + \frac{1}{E_2}\left(\frac{c^2+b^2}{c^2-b^2} + v_2\right)} \tag{38.13}$$

To separate the sleeve and the base, the disassembly force F is required to be equal to the friction force f of contact surface at least.

$$F = f = \mu \cdot 2\pi bl \cdot p \tag{38.14}$$

According to Ref. [12], in the nonuniform temperature field, the thermal deformation of the cylindrical parts at any radius can be described as follows:

$$u_r = \frac{1+v}{1-v}\frac{\alpha}{r}\int\limits_a^r \Delta t \cdot r\mathrm{d}r + \frac{\alpha\int_a^b \Delta t \cdot r\mathrm{d}r}{b^2-a^2}\left[\frac{(1+v)(1-2v)}{1-v}r + \frac{1+v}{1-v}\frac{a^2}{r} - 2vr\right] \tag{38.15}$$

In Sect. 38.3.1, the temperature field of the sleeve $t_1(r, \tau_0)$ and the temperature field of the base $t_2(r, \tau_0)$ have been obtained by transient temperature field analysis. The temperature difference of the sleeve after cooling is $\Delta t_1 = |t_1(r, \tau_0) - t_0|$. Then, the temperature difference of the base is $\Delta t_2 = |t_2(r, \tau_0) - t_0|$. According to the Eq. (38.15), suppose the radial shrinkage displacement at the outer diameter of the sleeve is u_1, the amount of shrinkage displacement at the inner diameter of the base is u_2, and then

$$\begin{cases} u_1 = \frac{2b\eta_1\int_a^b \Delta t_1 r\mathrm{d}r}{b^2-a^2} \\ u_2 = \frac{2b\eta_2\int_b^c \Delta t_2 r\mathrm{d}r}{c^2-b^2} \end{cases} \tag{38.16}$$

After the cooling deformation, the amount of interference is reduced, and the final actual amount of interference is

$$\delta' = \delta_0 - 2(u_1 - u_2) \tag{38.17}$$

Table 38.3 Material properties

Material properties	Brass sleeve	45# steel base
Elastic modulus	1.0e+11	2.09e+11
Poisson's ratio	0.33	0.269
Yield strength	2.4e+08	3.55e+08
Vickers microhardness	210	255
Root mean square roughness	2.0	4.0
Average contour slope	0.109	0.156
Thermal conductivity	110	48
Specific heat capacity	390	450
Density	8500	7800
Linear expansivity	1.8e−05	1.17e−05

In summary, after the time τ_0 of the liquid nitrogen cooling the inner wall of the sleeve, the disassembly force can be described as

$$F = \mu \cdot 2\pi bl \cdot \frac{\delta'}{2b} \frac{1}{\frac{1}{E_1}\left(\frac{b^2+a^2}{b^2-a^2} - v_1\right) + \frac{1}{E_2}\left(\frac{c^2+b^2}{c^2-b^2} + v_2\right)} \tag{38.18}$$

38.4 The Finite Element Simulation Analysis with the Cooling Excitation

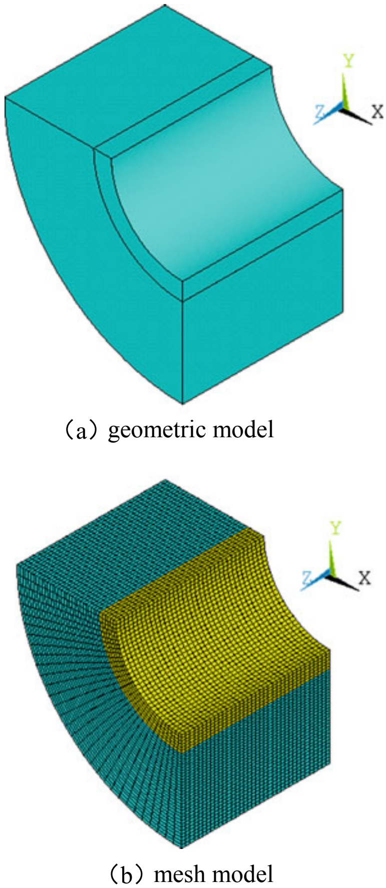
38.4.1 The Simulation Model

Figure 38.3a shows the geometric model of sleeve-base structure. The nominal inner diameter and nominal outside diameter of sleeve are 40 and 50 mm, respectively; the nominal inner diameter and nominal outside diameter of base are 50 and 100 mm, respectively; the matched length is 45 mm. The interference amount is set to three values 0.012, 0.022, and 0.032 mm. The friction coefficient of contact interface is 0.2. The material parameters of the geometric model are shown in Table 38.3. The model is meshed by using thermal element SOLID70 in ANSYS, as shown in Fig. 38.3b.

The interference fit model is analyzed in thermosetting coupling with the sequential coupling method. Because the sleeve-base model is the axisymmetric structure, a quarter of the model is selected to reduce computation cost.

The inner wall of sleeve is in a boundary condition of heat transfer with boiling liquid nitrogen, and the heat transfer coefficient is h_1. The outer surface of base is in a boundary condition of convective heat transfer with air, and the heat transfer coefficient is h_2. Given the thermal contact resistance (TCR) of the contact surfaces, transient heat transfer simulation is conducted. The temperature field distribution at a certain time is obtained, and then, the thermal element is converted into struc-

Fig. 38.3 Simulation model of sleeve-base structure



tural element. By applying the displacement boundary condition to the model, the simulation analysis of contact pressure of interference fit is conducted.

According to the literature [13], for the steam covering the surface of material in film boiling area, the thermal resistance of steam film plays a major role in heat transfer, and the film boiling curve is independent of metal materials. Therefore, based on the experimental research of the literature [14], the heat transfer coefficient of the liquid nitrogen contacting with the surface of brass sleeve is obtained, as shown in Fig. 38.4. The convection heat transfer coefficient of the outer surface of base contacting with room air is $h_2 = 10\ \text{W/(m}^2\text{K)}$.

The reciprocal of thermal contact resistance (TCR) is thermal contact conduction (TCC), and the literature [15] gives the formula for calculating TCC as follows:

$$\text{TCC} = 1.13\left(\frac{\lambda_e m_e}{\sigma_e}\right)\left(\frac{p}{H}\right)^{0.94} \tag{38.19}$$

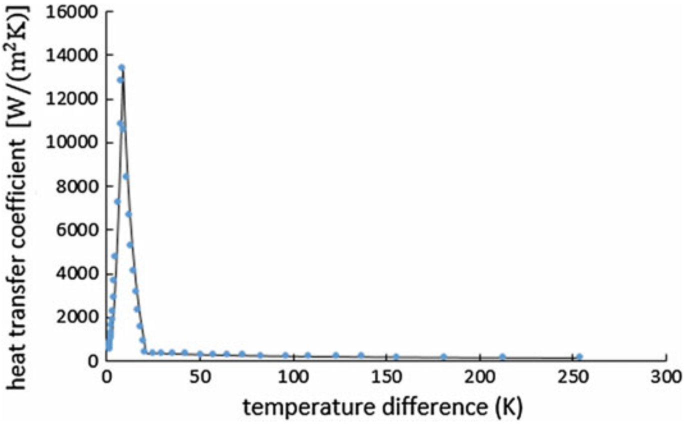


Fig. 38.4 Heat transfer coefficient of the brass contacting with liquid nitrogen

where λ_e is the equivalent thermal conductivity, m_e is equivalent contour slope,σ_e is the equivalent root mean square roughness, p is the contact pressure, H is the microhardness of the soft material in the two contact objects.

38.4.2 Comparison Between Simulation Model and Theoretical Model

Through the inversion algorithm of the semi-analytical model, the temperatures of the inner wall of the sleeve and the outside wall of the base are changing with cooling time, as shown in Fig. 38.4. Then, the comparison of results between the simulation model and the semi-analytical model is carried out.

In Fig. 38.5, during the 200 s cooling time, the node temperature of inner wall of the sleeve calculated by numerical inversion changes from 293 to 251.23 K, while the temperature calculated by simulation model changes from 293 to 251.75 K. Meanwhile, they have the same change rule: The slope of curve is larger at the beginning, which means the temperature declines faster in this period; then, rate of descent becomes smaller and tends to be stable. During the 200 s cooling time, the node temperature of outside wall of the base calculated by numerical inversion changes from 293 to 257.5 K, while the temperature calculated by simulation model changes from 293 to 258.11 K. Meanwhile, they have the same change rule: The slope of curve is smaller at the beginning, which means the temperature declines slower, and then, rate of descent becomes larger and tends to be stable. It is obvious that variation in temperature–time curve calculated by simulation model and by theoretical model is very consistent.

The radial temperature field distribution **with** cooling time 100 s is shown in Fig. 38.6. It is seen that the radial temperature distribution curve calculated by finite

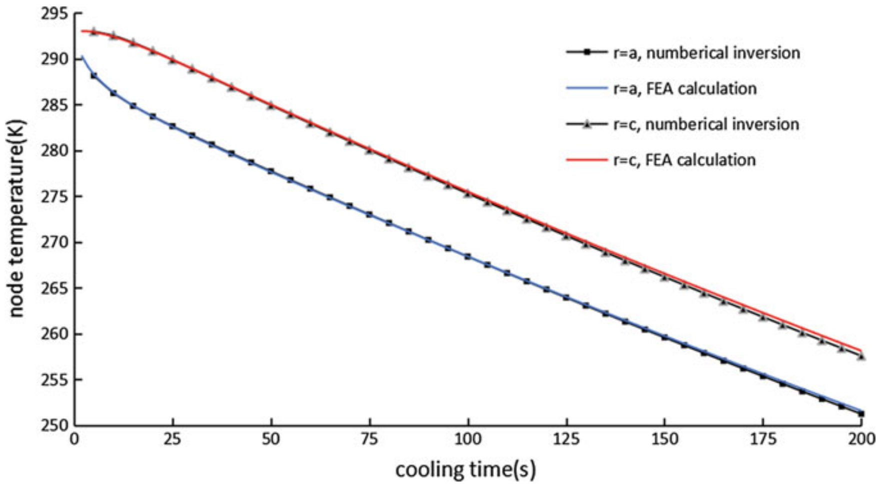


Fig. 38.5 Temperature curve of the inner wall of the sleeve and the outer wall of the base

element simulation is in accordance with the curve calculated by inversion, but the simulation temperature is slightly larger than the inversion value, especially along the radial direction of base. The main reason for this difference is: The contact resistance is neglected by the analytical method, but it plays a part in the finite element simulation. The theoretical analytical method simplifies the heat transfer problem to one-dimensional radial heat transfer, while the simulation uses a three-dimensional model, and the convective heat transfer of the end surface of base is taken into account. So the heat transfer boundary conditions of the simulation model are more practical. In a word, the temperatures calculated by the two kinds of models are very consistent, and the difference is small.

Based on the temperature field as shown in Fig. 38.6, calculate the disassembly force by two methods. The temperature of the sleeve and the base are $t_1(r, 100)$ and $t_2(r, 100)$, respectively. The temperature difference of sleeve and base between their present temperature and initial temperature is Δt_1 and Δt_2, respectively.

According to Eq. (38.16), the radial shrinkage displacement at the outer wall of the sleeve is $u_1 = 0.01075$ mm, the radial shrinkage displacement at the inner wall of the base is $u_2 = 0.0056$ mm, and the actual amount of interference is $\delta = 0.0117$ mm. Thus, by the semi-analytical model, the contact pressure and disassembly force are obtained, $p = 4.54$ MPa and $F = 6415$ N.

When only considering cooling temperature field, the deformation of the two parts with finite element simulation model is shown in Fig. 38.7. The average displacement of the nodes of sleeve outside surface is 0.01075 mm, and the average displacement of the nodes of base inside surface is 0.005565 mm. It is clear that simulation displacement is very consistent with the result by theoretical model.

After the coupled analysis of temperature field and structural stress, the average value of contact pressure obtained is $p = 4.37$ MPa, and the disassembly force is

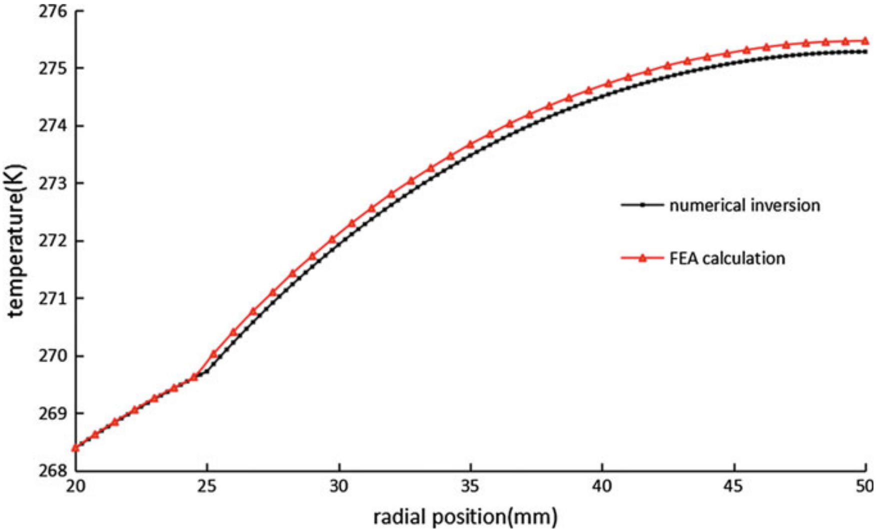


Fig. 38.6 Radial temperature field distribution with the cooling time 100 s

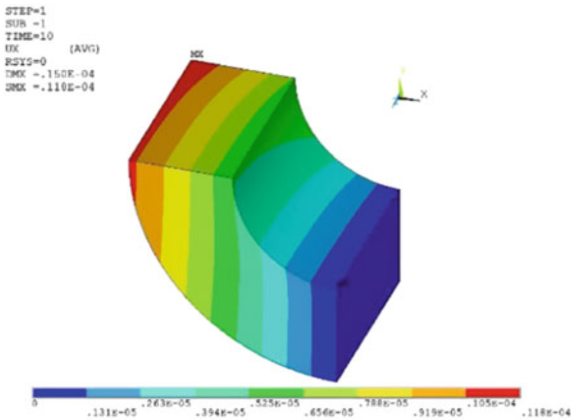
$F = 6175$ N. Compared with the semi-analytical model and the simulation model, the error of the disassembly force is only 3.9%. In summary, the transient temperature field and disassembly force of finite element simulation are basically the same as the calculation results of semi-analytical model, verifying the correctness of the semi-analytical model.

38.4.3 The Comparison of Simulation Results and Experimental Results

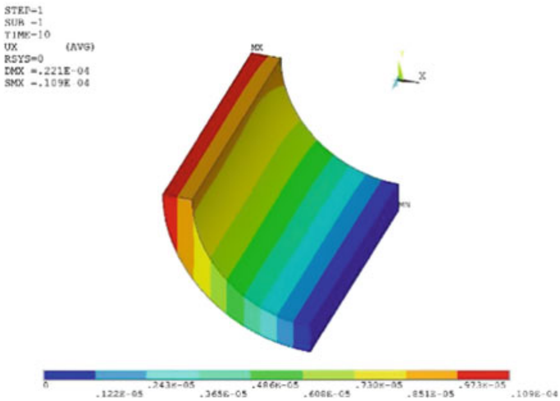
Take the amount of interference 0.012 mm model as an example, Fig. 38.8 shows the relationship between the disassembly force and cooling time, it means disassembly force of the conventional disassembly method when the cooling time is zero. Then, the disassembly force was significantly reduced with the liquid nitrogen cooling. The disassembly force is 6780 N by conventional disassembly method, and the experimental result is 6217 N, while with liquid nitrogen cooling disassembly method, the simulation value is 2281 N and the experimental value is 2100 N after cooling for 50 s, and the simulation value turns to 809 N and the experimental value is 909 N after cooling for 100 s. When the cooling time exceeds 150 s, the interference fit changes to the clearance fit, and the disassembly force is zero.

The trend of the curve shows that the reduction of the disassemble force is quickly at the beginning and then becomes relatively flat. Generally, the disassemble damage is basically proportional to contact pressure between the two contact objects.

Fig. 38.7 Displacement of the parts in *x*-direction



(a)The displacement of base



(b)The displacement of sleeve

Therefore, the liquid nitrogen cooling disassembly method not only helps to reduce the disassembly force, but also to achieve nondestructive parts.

38.5 Conclusion

(1) A new method of disassembling interference fit sleeve-base structure by liquid nitrogen cooling excitation is proposed. Due to the size difference and the thermal sensitivity difference, the cooling deformation occurred and the interference fit is weakened, so that nondestructive disassembly is implemented.

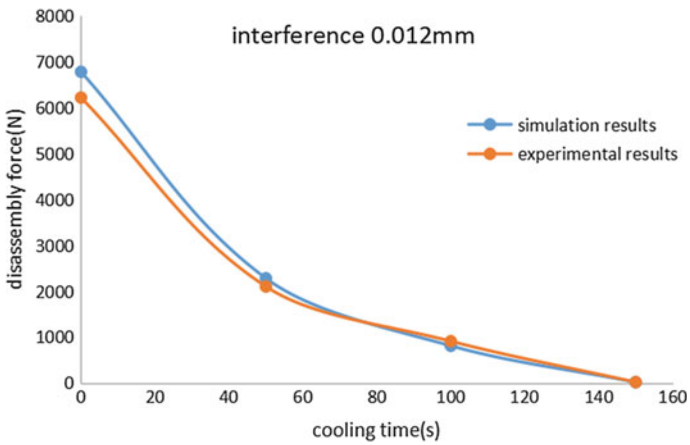


Fig. 38.8 Disassembly force varies with the cooling time

(2) Through theoretical analysis, the transient heat transfer equation and disassembly force equation of sleeve-base model with the liquid nitrogen excitation are established, and the calculation formula is derived, which is related to the part size, material parameters, heat transfer coefficients and cooling time. The error of disassembly force between numerical inversion result and FEA result is only 3.9%, which verifies the coherence of the two models.

(3) The finite element simulation is based on the interference fit model of brass sleeve and 45# steel base. The curves of disassembly force and cooling time of interference fit models are obtained by simulation and experiment. The disassembly method by liquid nitrogen cooling can significantly weaken interference, reduce the disassembly force, and the decay speed is quickly at the beginning, then slowly.

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Part VIII
Sustainable Technologies in Automotive and Transportation Systems

Chapter 39
Gait Recognition: A Challenging Task for MEMS Signal Identification

Sebastian Głowiński, Andrzej Błażejewski, Tomasz Królikowski and Remigiusz Knitter

Abstract The paper discusses the methodology of the research on the kinematics of human gait by using MEMS sensors. The capability of the measurement system is presented. Especially, it is focused on the angular velocity data, which were measured by the gyro sensors and used to estimate the flexion—extension of joint angles of the knees. To describe the gait cycle the series of trigonometric Fourier and the function expressed by the sum of sines were applied. In order to do the synthesis, MATLAB package with CurveFit toolbox was used. The obtained by this means approximation functions were done for healthy people and with impaired locomotion system. The result data were summarized in the form of figures and in the table of significant parameters. Additionally, there is other measurement and analysis presented, which applies more sophisticated method. The example wavelet transform is used considering acceleration signals. Using MEMS sensors also collected these signals. In this particular case, the gait feature in the time domain can be examined. This approach leads to specific gait's feature database creation. It will support the diagnostic of the pathology, by a comparison of gait patterns, which will be related to specific diseases. The patterns will be built by using chosen coefficients obtained by the analysis presented in this work.

39.1 Introduction

Research of kinematics and kinetics of a human's gait plays an essential role in human motion, medicine, rehabilitation, and even sports area [1]. The human body movement examinations involve various tracking systems that allow the researchers to transform physical parameters such as displacements, velocities, and accelerations of limbs to a digital space. The most popular and commonly known are optical

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methods including multicamera system BTS smart or Vicon [2, 3]. It requires locating special markers on anthropometric points, for instance, on lower limbs [4]. The cameras recording a movement of markers and special software allow calculating their position in dedicated coordinate system and visualize it. Using methods, which do not apply markers, requires sophisticated software introducing image processing. There are Simic and Organic Motion among others [5, 6]. The optic systems disadvantageous is the necessity of their application is a laboratory environment.

Modern electronic and mechatronic technologies enable a development, i.e., the creation and the production of microelectromechanical systems (micro-electromechanical systems—MEMS). These miniature devices comprise both mechanical and electronic elements in one functional, portable, and robust unit. The latter makes them possible applying and proper working in almost any environments. Usually, MEMS consist of an accelerometer and gyroscopic and magnetic subsystems. They are of small dimensions that characterize Mini inertia. Simultaneously, MEMS are possible to measure the acceleration of huge values. As well as measurements, the systems are able to record signals related to a human gait. This gives the possibility of further analysis, comparisons, and to extrapolate forward, searching gait pathology and its reason [7]. In this way, one can create the database of gait models, providing the beginnings of a diagnostic and solution to the gait problems.

Patients with chronic low back pain walk with more synchronous horizontal pelvis and thorax rotations than controls [8]. In our study, gait kinematics were compared between healthy and patient with lumbar discopathy during normal gait.

39.2 Tools

In this paper, ProMove Mini Inertia measurement system is applied. It consists of six sensors with dimensions 51 × 46 × 15 mm and mass 20 g and it is presented in Fig. 39.1. In this figure, below the sensors of the hub, Inertia Gateway is shown. In this figure, below the sensors, the hub Inertia Gateway is shown. The hub collects the signals from sensors via wireless and by USB interface send to the computer with dedicated software. The general configuration of the main components is shown in Fig. 39.2. ProMove sensors are capable to record acceleration signals that value can reach ±16 g with sampling rate 1000 Hz and angle variation with rotation speed reaching ±2000°/s of maximal resolution 0.007°/s (for speed ±250°/s). Simultaneously, one can measure: an environmental pressure from 260 to 1260 hPa, a direction of magnetic field with value ±4912 mT.

It is possible to connect up to 39 sensors to diagnostic interface and to record measurements with 200 Hz frequency. The battery capacity allows four hours of constant work. The integral part of the system is Inertia Studio Software running under common computer operating systems, i.e., Windows 10, 8, 7 Vista, Linux and Mac OS. The software provides a useful trigger option, which starts and terminates measurements at the desired moment.

Fig. 39.1 ProMove mini sensors and Inertia Gate hub applied in the experiment

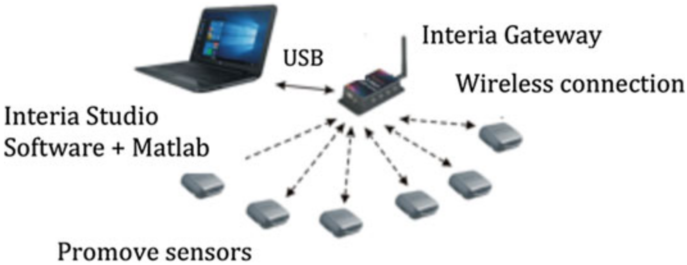

Fig. 39.2 ProMove system configuration

39.3 Experimental Setup

The eight men with no diagnosed diseases and previous orthopedic injuries have been tested (age 23–44 years, mean 28, and the standard deviation 8 years). The average height of patients was 177.3 cm, with a standard deviation of 3.4 cm. The mean mass was 75.4 kg with standard deviation 5.2 s.

Additionally, a person (height 174 cm, weight 72 kg, 42 years old), who complained of left lower limb pain, as an exemplary patent is taken into consideration. The patient was examined at 2016.04.26, and it was shown that this dysfunctionality arose because of the smoothing lumbar lordosis and multilevel changes distorting the intervertebral joints. The symptoms of degenerative disc disease L4/L5/S1 with central protrusion disc m-k L5/S1 entailing root compression and the centre left-sided disc protrusion m-k L4/L5 adjacent to the left L5 nerve root in the spinal canal are confirmed by using the magnetic resonance scan Fig. 39.3.

Taking into consideration technical and medical problems, we focus on the experiment's procedure on the following tasks:

1. The patient's medical history for previous diseases.
2. The basic anthropometric measurements of patients (weight and height).

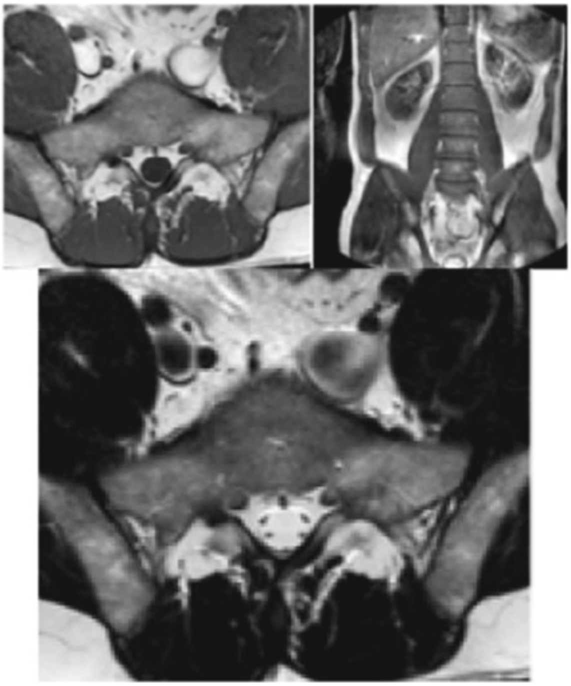

Fig. 39.3 Patient spine magnetic resonance (degenerative discopathy)

3. The correct, the same for each patient, the sensors attachment at characteristic points and signal check.
4. Inertia Gateway connection.
5. The signal level adjusting.
6. Calibration of the sensors and preparing for recording.
7. Measurements and signal recording in the sensors flash memory.
8. Transfer of measured signals to a computer hard drive by wireless or USB.
9. Signal processing—determination of a gait beginning and termination, particular step identification.
10. Further analysis using MATLAB toolboxes (joint angles calculation).
11. Result visualization.
12. Parameter identification using Fourier series and sum of harmonic functions.
13. Comparison with obtained gait samples (gaits database).

The measurements methodology can be described as follows. Via USB connection, the diagnostic interface in form of hub Inertia Gateway is connected to a computer, where Inertia Studio software is installed and running (Fig. 39.2). The sensors are fixed in the proper places on the lower limbs and oriented in the way that is shown in Fig. 39.4. In order to fix the sensors, a band works like Velcro are applied. The active sensors, by wireless, automatically connect to Inertia Studio software running on the computer. The maximal possible range of connection is 10 m. Next, parameters of recording need to be set up. Amongst them the frequency, and in this

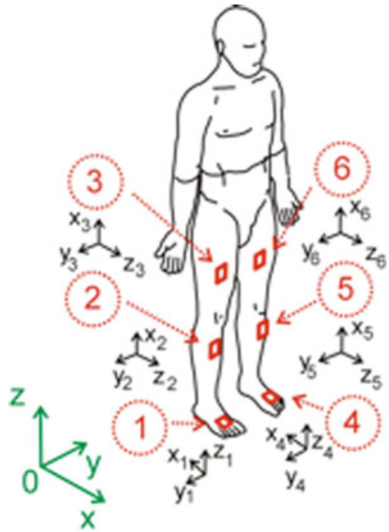

Fig. 39.4 Chosen locations of ProMove mini sensors during examination

way, the sampling rate is essential. During the measurements, the frequency 200 Hz was applied. The software allows automatic calibration and mutual orientation of sensors. It is carried out by reset option.

Thereby, eight sets (eight people) of measurements were realized. Each set consists of 15 steps measured. After each measurement, in the case of one person, the result was recorded on sensors' flash memory. According to the procedure, USB connectors to computer disc drive sent all measurements. The wireless option of data sending was abandoned because it resulted in many samples loss. Software maker guarantees that this inconvenience will be fixed in new software version. After that from each data set, which contained 15 steps, middle 10 steps were chosen. Eventually, using MATLAB packet, a beginning (first sample) and termination (last sample) of each step were identified [9, 10].

39.4 Identification of Parameters

The change of the angle of knees in the sagittal plane as a time function $f(t)$ was described by a function $\theta(t)$ using a sum of sines and trigonometric Fourier series models based on package MATLAB CurveFit [11]. The mean arithmetic knee angle was calculated based on several dozen left and right steps. If we take the period $T =$ 1 step, as consisting of 101 samples ($T = $ <0.100 >), the dependence described knee angles can be written as:

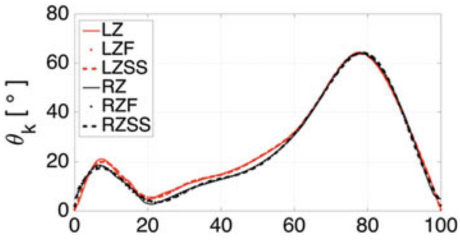

Fig. 39.5 Knee angles during normal gait with interpolation. LZ and RZ represent left and right limb a healthy people, respectively. LZF and RZF are the waveform plots interpolated Fourier series. LZSS and RZSS are the sum of sines

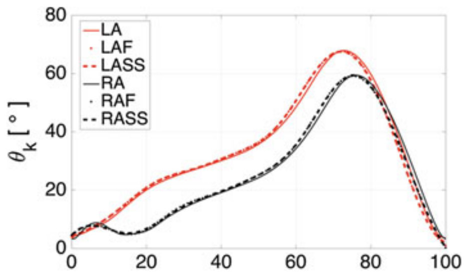

Fig. 39.6 Knee angles during abnormal gait with interpolation. LA and RA represent left and right limb an ill person, respectively. LAF and RAF are the waveform plots interpolated Fourier series. LASS and RASS are the sum of sines

$$\theta_k(t) = \frac{a_0}{2} + \sum_{n-1}^{\infty}\left(a_\mathrm{n}\cos\left(\frac{2\pi nt}{T}\right) + b_\mathrm{n}\sin\left(\frac{2\pi nt}{T}\right)\right) \tag{39.1}$$

Fourier coefficients are determined from the relationship:

$$\begin{aligned} a_\mathrm{n} &= \tfrac{T}{2}\int_0^T f(t)\cos\left(\tfrac{2\pi nt}{T}\right)\mathrm{d}t \\ b_\mathrm{n} &= \tfrac{T}{2}\int_0^T f(t)\sin\left(\tfrac{2\pi nt}{T}\right)\mathrm{d}t \end{aligned} \tag{39.2}$$

The parameters of Fourier series and a sum of sines of the knee angles, characterizing the change in angles, are presented in Table 39.1. Comparison of results and the actual data model is shown in Figs. 39.5 and 39.6. There are knee angles in the function of gait cycle. The sum of sine model fits periodic functions and is given by:

$$\theta_k(t) = \sum_{i=1}^{\infty}(a_i\sin(b_i(t) + c_i)) \tag{39.3}$$

where a is the amplitude, b is the frequency, c is the phase constant for each sine wave term, and n is the number of terms in the series and $1 \le n \le 8$ T.

Studies have confirmed a very good fit of the proposed model; as the coefficient of determination, R^2 can range from 0.9985 to 0.9997. LZ and RZ represent the left and

Table 39.1 Parameters of Fourier series and sum of sine functions

Coefficient	Fourier series—healthy person		Fourier series—person with disease		Coefficient	Sum of sines—healthy person		Sum of sines—person with disease	
Coefficient	Left	Right	Left	Right	Coefficient	Left	Right	Left	Right
a0	0.17	0.126	0.51	0.386	a1	0.968	0.693	0.744	0.679
a1	−0.639	−0.62	−0.421	−0.317	b1	0.044	0.034	0.021	0.028
b1	0.15	0.261	−0.169	−0.251	c1	−0.861	−0.528	0.238	−0.37
a2	0.092	0.257	−0.111	−0.117	a2	0.624	0.748	0.992	0.293
b2	0.529	0.448	0.2	0.157	b2	0.076	0.088	0.144	0.101
a3	0.19	0.139	0.069	0.082	c2	1.22	1.086	−2.026	0.633
b3	0.126	0.043	0.013	0.064	a3	0.131	0.379	0.24	0.146
a4	0.096	0.111	0.006	0.02	b3	0.176	0.093	0.072	0.139
b4	0.095	0.089	−0.016	0.009	c3	−6.369	−2.141	2.952	−3.778
a5	0.07	0.06	0.009	0.005	a4	1.339	0.122	0.864	0.033
b5	0.016	−0.005	−0.004	0.017	b4	0.224	0.173	0.148	0.155
w	0.048	0.045	0.056	0.056	c4	−0.539	0.705	0.999	1.924
					a5	1.306	0.042	0.01	0.016
					b5	0.226	0.231	0.279	0.261
					c5	2.457	0.844	1.318	0.67
Correlation					Correlation				
SSE	0.008322	0.01093	0.003197	0.003793	SSE	0.008015	0.01668	0.002251	0.004693
R2	0.9992	0.999	0.9997	0.9996	R2	0.9992	0.9985	0.9998	0.9995
RMSE	0.00967	0.01108	0.005994	0.006528	RMSE	0.009654	0.01393	0.005117	0.007387

right limb healthy individuals, and LZF RZF waveform plots interpolated Fourier series. The LZSS and RZSS interpolation functions were expressed by the sum of sines. The graph 39.6 illustrated interpolation curve angles of the knee person with discectomy. It notes the lack of extension leg at the knee joint (approximately 20–30% of the duty cycle) people with a discectomy in comparison with healthy subjects. The conclusions of the analyses and evaluations demonstrate the possibility of using gyro sensors for evaluating gait parameters of healthy and impaired movement. The sensors can be used for the preliminary examination and testing patients to determine the type of disease and possible qualification for the next analysis, for example, magnetic resonance imaging (MRI) or computed tomography (CT). The parameters presented in Table 39.1 may function parameters approximating may be used in systems control devices in walk re-education. In the following tests, it is appropriate to compare the results obtained using the gyro sensor of the optical systems [12].

As an alternative identification process and simultaneously verification, the following analysis can be conducted. The different types of parameters have consisted of a set of coefficients. In the case of measurements presented in the paper after the step's identification and separation, a wavelet transform is applied. In order to choose a proper wavelet type and its settings, at the beginning, a range of analysis frequency has to be identified. The basic signals were taken using sensors 2 and 5, placed bellow knee joints (Fig. 39.4). The initial frequency range was chosen to 10 Hz. The precise results were presented in the work [7], but here the only the chosen is shown in Fig. 39.7. The analysed acceleration signal after wavelet transform, in case of the healthy and diseased persons' left leg, is shown in Figs. 39.7 and 39.8, respectively. Continuous wavelet transforms of the signal obtained by using Morlet wavelet of parameter 4 is presented. In Fig. 39.7a, b, modulus and real parts (in the middle figures) and modulus versus pseudo-frequencies (in lower figures) of wavelet coefficients are shown in the case of healthy and abnormal gait.

The results show that a healthy and diseased person gait is different which can be pointed out by these analyses. The healthy people's gait is characterized by a narrow frequency range 2–3 Hz in a whole step cycle. In the case of the wavelets, the lack of a knee joint bending results in the pulling of the leg in the beginning and final phase of the step. It is seen in step periods: first from start to approximately 0.15 s, in a range of frequency from 5 to 10 Hz, and second phase from 0.6 to 0.9 s, for frequency approximately 5 Hz. In both cases Figs. 39.7 and 39.8, the first curves presenting a raw signal (red curve) and so-called wavelet approximation (blue curve) allow to evaluate the main feature of the gait on the one hand and filtering the signals for unwanted components. Here, the influence, i.e., vibration and movement of skin, muscles, and soft tissue, can be removed.

39.5 Conclusions

In the last decades, interest in obtaining in-depth knowledge of human gait mechanisms and functions has increased. Thanks to advances in measuring technologies

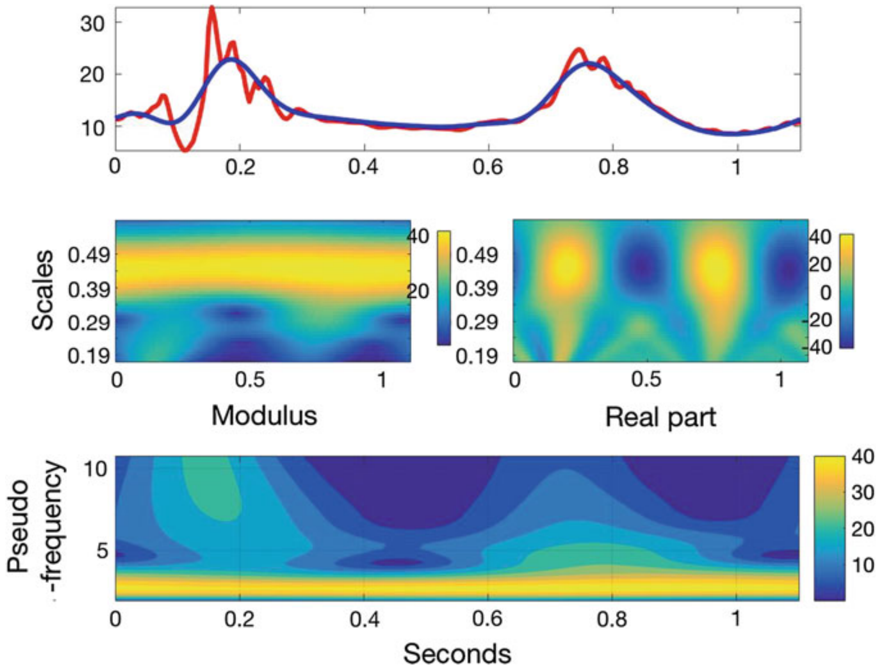

Fig. 39.7 Analyzed signal and reconstructed signal after inverse wavelet transform of the health

that make it possible to analyse a greater number of gait characteristics and the development of more powerful, efficient, and smaller sensors, gait kinematic and dynamic parameters evaluation have improved. MEMS can be used in a preliminary assessment by physiotherapists and doctors. The sensors allow recording parameters such as position, velocity, and acceleration, which can be evaluated in the process of rehabilitation of patients, which will increase the quality of care and safety. It should be noted that in this study only in the kinematic parameters of knee joints are illustrated. The parameters recorded by the acceleration sensors also apply to the individual segments of the limbs. If we know the weight of the patient, the forces acted on joints (hip, knee, ankle) can be calculated. Designated function parameters approximating can be used in control circuit rehabilitation equipment. Moreover, the coefficients, as well as Fourier and wavelet, take specific values to depend on gait feature. Therefore, they can be used during the process of gait patterns creation. The patterns based on these values would be easy to compare, classify, and build classes and categories. Knowing the dynamics of individuals, in a critical situation, the optimization of their evacuation routes can be improved [8, 13].

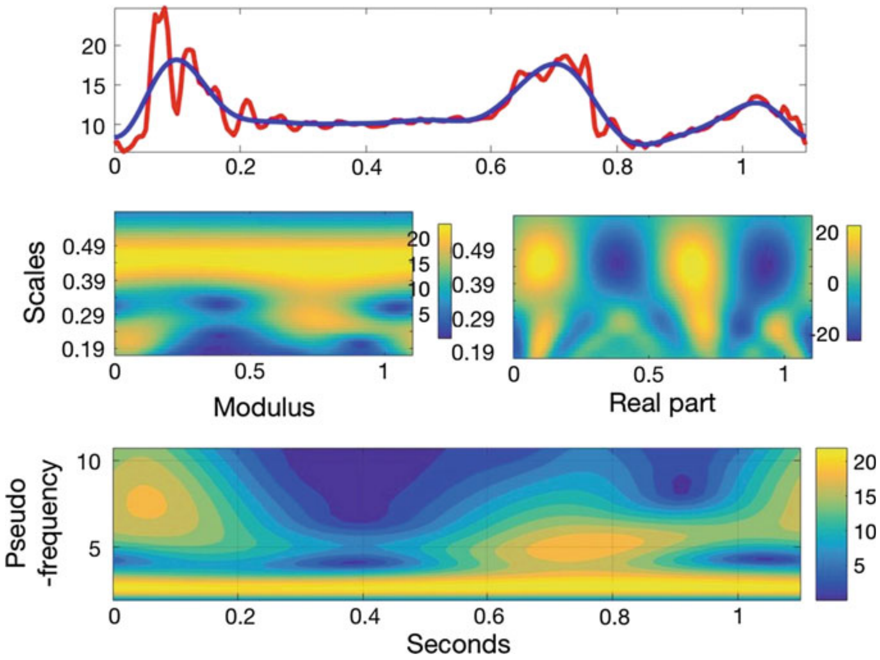

Fig. 39.8 Analyzed signal and reconstructed signal after inverse wavelet transform of the diseased persons' left leg

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Chapter 40
Emission of Particles and VOCs at 3D Printing in Automotive

Królikowski Tomasz, Knitter Remigiusz, Błażejewski Andrzej, Głowiński Sebastian and Kamiński Kazimierz

Abstract 3D printing is one of the fastest grooving technologies, used for parts manufacturing in the automotive industry. There are many printing technologies with different printing filaments ad different printing time. Printing time is correlated with the emission of particles and VOCs (volatile organic compounds). Researchers conducted analysis of VOCs emission during 3D printing. Each 3D printing device should have closed work chamber. The chamber should be constantly ventilated. The extracted air cannot get to the rooms where people are present. The air can be ejected to the atmosphere outside the buildings. The fresh air can be taken from the room where printer is located or directly from outside the building. 3D printing process is accompanied by the release of large amounts of waste heat. Temperature of extracted air is hot enough to apply any heat recovery units.

40.1 Introduction of 3D Printing Technology

3D printing is one of the fastest grooving technologies, and there are trends for printing parts for the automotive industry [1–3]. There are many printing technologies with various printing filaments and different printing time. In March 2015 was presented the CLIP technology (Continuous Liquid Interface Production). Technology bases on the synthetic, light-shielding resin in oxygen warp. The Carbon 3D [4] Company has commissioned printing time analysis for different technologies. The results of tests are shown in Fig. 40.1. The CLIP method is the fastest and generates the lowest emission of harmful substances. The Polyjet technology base on liquid acrylic resin hardened with UV rays. The SLS method (selective laser sintering) base on sintering polyamide powders by high energy pulse laser. The SLA technology (stereolithograpgy) bases on photopolymers resin cured by UV laser. In Fig. 40.1, there is major difference between extreme values of printing time. The CLIP technology is over one hundred times faster than the SLA printing technology.

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Fig. 40.1 Printing time for different printing technology

40.2 Emission of Particles and VOC During 3D Printing

Printing time is correlated with emission of particles and VOCs (volatile organic compounds). The research on 3D printing emission was conducted by Afshar-Mohajer et al. [5]. In Fig. 40.2 is presented the concentration of particles inside the printing chamber as a time function. The experiment was conducted for particles size distributions from a binder jetting 3D printer.

Emission rate changes during printing time. Figure 40.3 presents total VOC emission (TVOC) at the time domain.

As shown in Figs. 40.2 and 40.3, 3D printing generates significant emission of particles and VOCs. For this reason, each 3 printing device should have closed work chamber. The chamber should be constantly ventilated. The air extracted from printing area should be purified from particles and be ejected to the atmosphere outside the buildings. The filtration of extracted air should be considered. The fresh air can be taken from the room where printer is located or directly from outside the building.

40.3 Heat Recovery at the Working Chamber

3D printing process is accompanied by the release of large amounts of waste heat. Printing temperature depends on used filament and expected physical properties of printed object. Temperature can reach up to 250 °C [6, 7]. Temperature of extracted air is hot enough to apply any heat recovery units. The most popular heat recovery unit is cross recuperator, and it transfers heat from hot extracted air to the fresh air taken from outside [8, 9]. 3D printing process can be compared to painting technology. Both of them generate emission of VOCs and particles floating in the air.

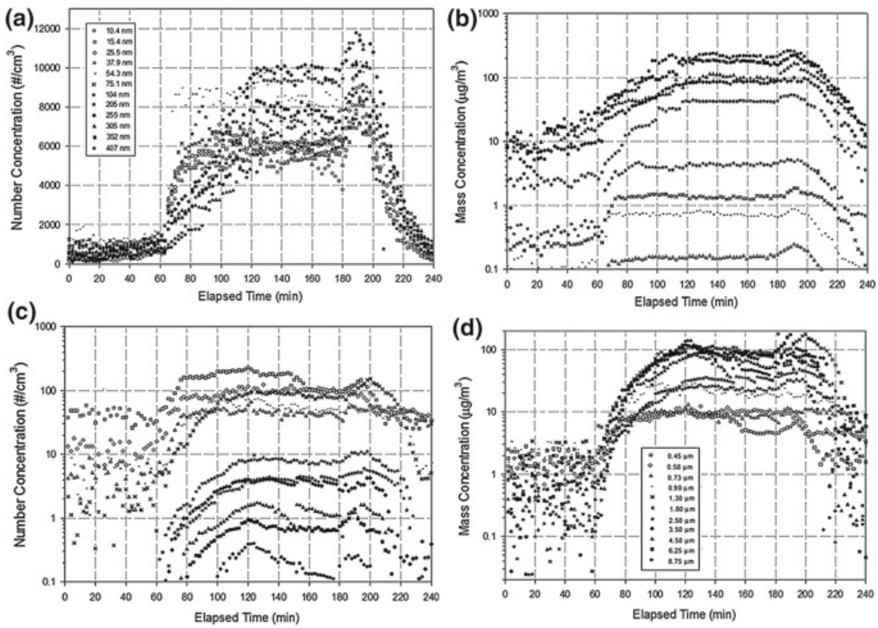


Fig. 40.2 Concentration of the particles as a function of time: **a** number concentration of particles smaller than 407 nm measured by SMPS, **b** number concentration of particles larger than 407 nm measured by OPC, **c** mass concentration of particles smaller than 407 nm measured by SMPS and **d** mass concentration of particles larger than 407 nm measured by OPC [5]

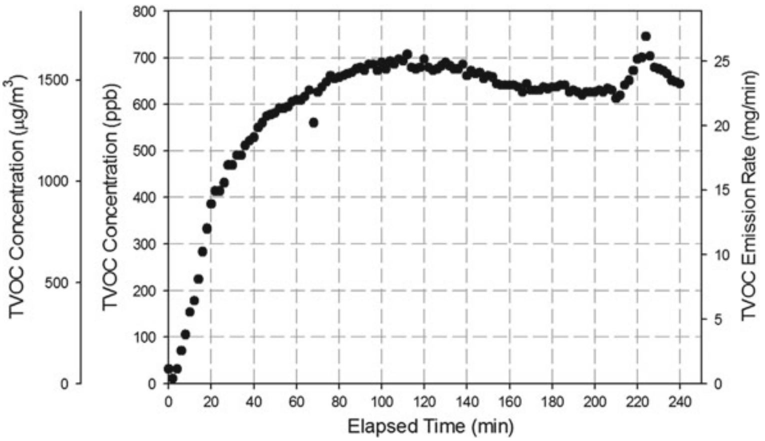


Fig. 40.3 Concentration and emission rate of TVOC as a function of time [5]

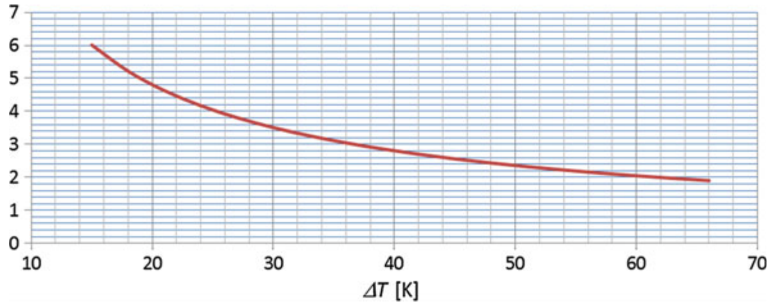


Fig. 40.4 Average COP of heat pumps in function of temperature difference [16]

Table 40.1 Specification of BLIXET B100

Specification	
Print field (mm)	X400 × Y400 × Z1000
Toolhead	2 pieces (1.75 and 2.85 mm filament)
Nozzle size (mm)	0.8 and 1.2

Table 40.2 Specification of Creality CR-5

Specification	
Print field (mm)	X500 × Y500 × Z500
Toolhead	1 (for 1.75 mm filament)
Nozzle size (mm)	0.4

At painting technology, overspray particles cause creation of sediments on internal parts of extraction ducts. Overspray sediments groove on recuperator's thins and finally recuperators are clogged. Increasing thickness of sediments gradually decreases efficiency of heat recovery [10, 11, 12]. The phenomenon of overspray sediments formation is described in [13]; their thermal conductivity qualifies them into a group of thermal insulators [14, 15]. Similar phenomena can be expected for installation for 3D printing.

Another method of low temperature waste heat recovery is the application of heat pump. This solution can help to transfer heat from extracted hot air to the table located under printed object. Energy efficiency of heat pumps is described by COP parameter (coefficient of performance). COP describes how many kilowatts of heat can be transformed using one kilowatt of electric power. Value of COP depends on temperature difference between heat source and heat receiver. High values of COP are reached for low temperature differences. Figure 40.4 shows average COP of heat pumps in function of temperature difference [16] (Figs. 40.5 and 40.6; Tables 40.1 and 40.2).

A hybrid system of heat recovery can be considered. The system consists of recuperators and heat pump. Two-step heat recovery significantly maximizes energy efficiency of printing process, particularly for massive printing of huge objects. There

Fig. 40.5 3D printer BLIXET B100 used for research

are more than 30 FDM printers in The Center of the 3D Printing and Design in the Faculty of Technology and Education currently. Among them is the printer BLIXET B-100 with largest working area of 400 × 400 × 1000 mm and the second one with 500 × 500 × 500 mm working area. In the case of these two printers, the highest heat emission was observed (Figs. 40.7 and 40.8).

Temperature measurements contributed to recognition of problems found in open FDM printer designs. One of the problems in the proper temperature distribution is the lack of specialized tools and programmes optimizing the machine's working movements. Another consideration, apart from the established concepts of a closed room without constant-temperature air flows, is to match the gcode so that it makes movements at designated points depending on the model and its diameters for the use of appropriate print temperatures with negligible shrinkage (Figs. 40.9 and 40.10).

The above picture shows an uneven temperature distribution for the heating table. In subsequent studies and assumptions, it will also have to be eliminated. There is a high probability that this event may have an adverse effect on the quality of the printed model (Figs. 40.11 and 40.12).

The specialized chamber is designed to limit the air flow in the working area. It has to practically improve the quality of manufactured parts and even temperature distribution reducing problems with accurate executions. The proposed solution will be the most advantageous for FDM (fused deposition modelling) printing technology using ABS material. Filament manufacturers recommend a constant chamber

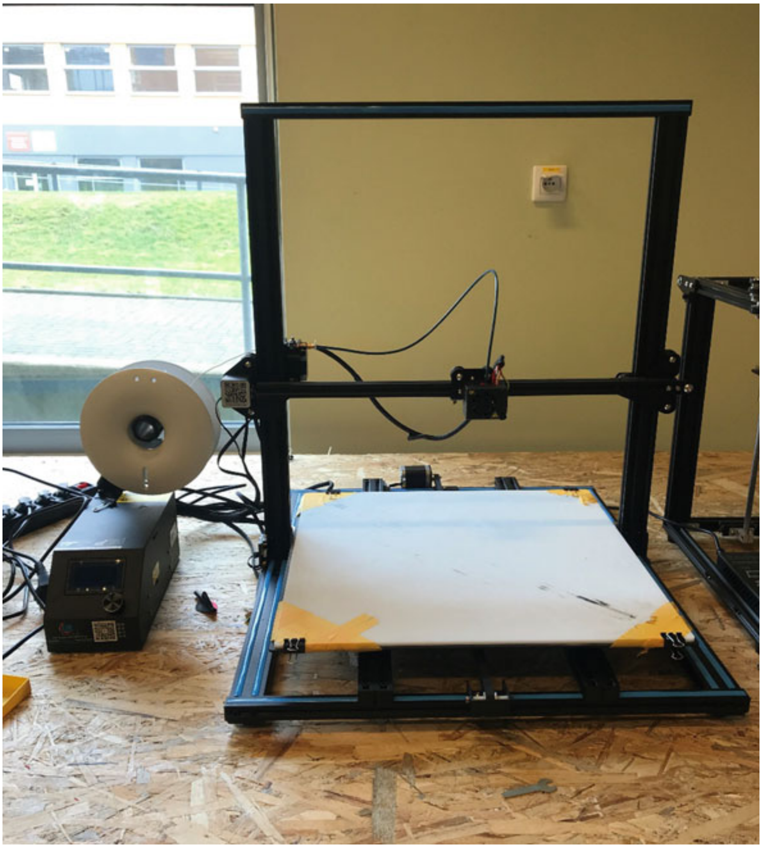


Fig. 40.6 Creality CR-5 Printer used for research

Fig. 40.7 Chamber that maintains a constant temperature

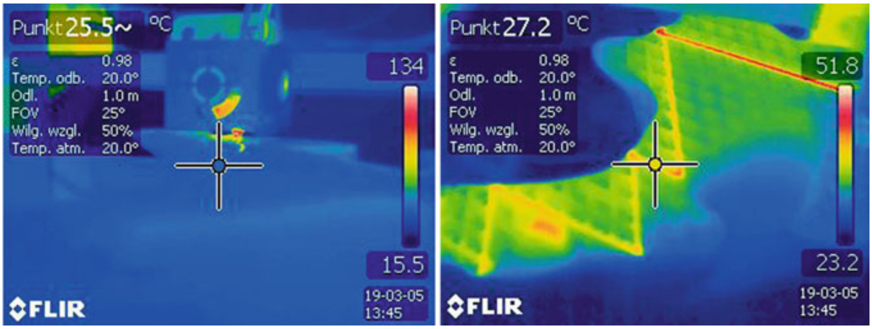


Fig. 40.8 Emissivity of temperatures during 3D printing

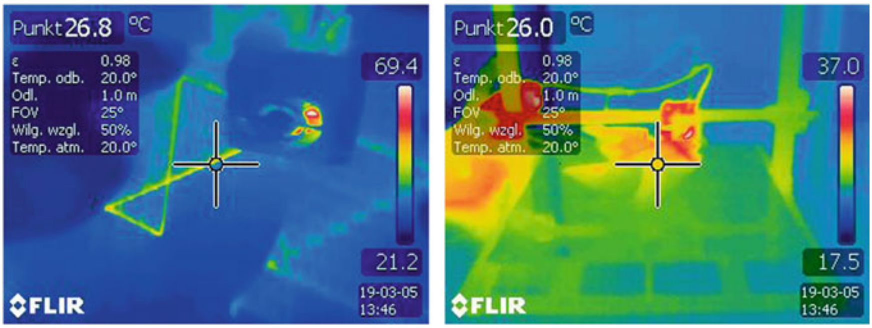
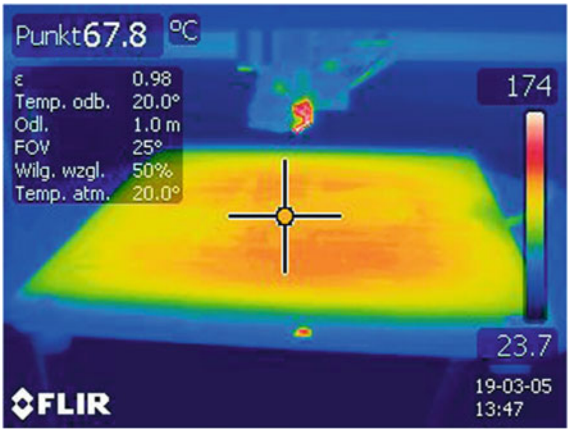


Fig. 40.9 Emissivity of temperatures during 3D printing

Fig. 40.10 Emissivity of the heating bad



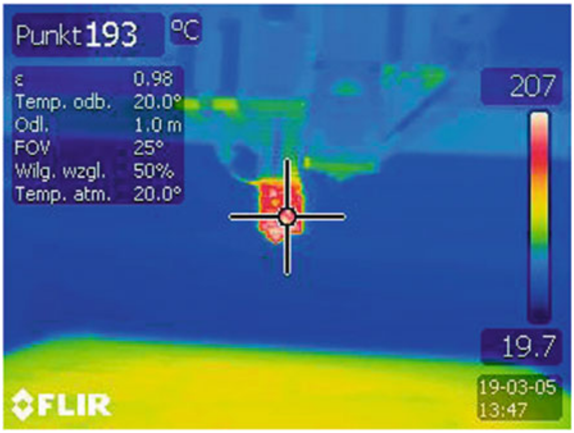


Fig. 40.11 Emissivity of the head with nozzle

temperature and limited airflow. Some manufacturers of 3D printers use heated work areas, while it is for a unitary solution. The used chamber is to perform the task of a fully automated 3D printer farm. In the further stage of the research, the use of a heated chamber and reduction of excessive air movements are considered. This solution will be used to print components from materials requiring much higher temperatures such as PEEK, which is a high-performance thermoplastic with a melting point of 400 °C and an upper continuous operating temperature of 260 °C. Its special chemical structure makes PEEK highly resistant to thermal and chemical damage, and it is also possible to use it inside the body. The features of PEEK material are successfully used in industry, where it more and more often replaces aluminium, steel or even titanium.

40.4 Conclusion

In case of high emission of particles and VOCs, all 3D printers should have a closed work chamber with constant air exchange. Printing in open space causes a health risk. The heat recovery application is justified by high amount of waste heat extracted with exchanged air. Further research on that topic should be done both for desktop and industrial printers.

Fig. 40.12 Built-in chamber that is the basis for measurements

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Chapter 41
Significant Parameters Identification for Optimal Modelling of the Harp-Type Flat-Plate Solar Collector

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Abstract Modern hot water and heating systems are usually supported by energy which comes from the Sun. This additional energy is converted into useful form by solar collectors. The purpose of the work is to present a procedure, which determines the influence of specific design parameters on the solar collector thermal performance. Numerical simulations of the heat transfer process in the collector panel are studied by means of distributed-character modelling method (D-C) and additionally computational fluid dynamics (CFD) calculations. In order to validate the numerical models, experimental investigations are carried out. The thermal efficiency is determined according to EN ISO 9806:2013 and considered as output (effect) of the models. A statistical robustness test is introduced in order to indicate significant parameters (factors), which should be taken into consideration during the modelling, optimization and finally solar collector manufacturing.

41.1 Introduction

The efficiency of the solar thermal collectors is based on their geometrical parameters, materials and manufacturing technology. Modern innovative solar collectors can effectively transform solar energy into useful heat. However, there is still an interest in more effective solutions and design optimizations. Because of a high number of design configuration parameters affecting the collector thermal performance, the number of simulations needed to find the optimal collector design configuration becomes enormously high. Significance analysis is a mathematical tool, which can help to understand the relationships between different input parameters and the system output. It is possible, based on these analysis results, to separate most significant input parameters from all the input parameters scope. In the presented significance

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analysis procedure, the specific model of flat-plate solar collector is used. The solar collector thermal efficiency is strongly correlated with the heat losses from absorber to ambient. Easiest way to reduce heat losses from solar collector is to increase thermal isolation thickness at the backside of collector chassis. However, this kind of modification will reduce only backside heat losses. In order to reduce the overall heat losses from solar collector, the design configuration of absorber assembly should be improved. Several works correlated with this area can be found in the literature. Mintsa Do Ango et al. [1], based on polymer FPSCs, studied the influence of various design and operational parameters on collector thermal performance. It has been shown that air gap between the absorber and glass covers strongly influences the solar collector thermal efficiency. An optimal collector performance was obtained at air gap thickness around 10 mm. Cooper [2] studied the correlation between heat loss coefficient and solar collector inclination angle. It has been shown that overall heat loss will increase with the inclination angle. Furthermore, when the inclination angle is higher than 60°, the heat loss coefficient will increase more rapidly. Eisenmann [3] studied the correlation between collector efficiency factor and material content. The main result of work [4, 5] is given by a monograph, which describes the impact of absorber plate thickness and tubing configuration on the value of solar collector heat removal factor. It has been found that the specific collector design modifications can lead to the material content reduction on about 20–25%, without any noticeable thermal efficiency reduction. In this paper, the structural parameters of FPSCs are tested and analysed in terms of their significance on solar collector performance.

41.2 Solar Flat-Plate Collector Modelling

The modelling methods are based on the well-known Hottel–Whillier–Bliss theory [6], which is suitable for almost every kind of solar collectors. Another group of solar collector modelling approaches, highly developed during the last years, are CFD numerical methods. In order to perform the identification of significant structural parameters, the simplified distributed-character model was built and CFD modelling procedure using *ANSYS Fluent 13* was carried out. The elaborated model consists of M nodes perpendicular to flow direction (e.g. absorber discrete elements, flow channels and working fluid) and N nodes parallel to flow direction. As a result, the $N \times M$ system of ordinary differential equations is obtained and solved with the finite difference method. Detailed description of the solar collector modelling process and model parameters determination were presented in work [7].

The absorber taken into consideration is an assembly of a flat-plate metal sheet with pipes welded into the uninsulated side of plate. The model prepared to use in this paper assumes equal mass flow rate in each pipe of solar absorber, so there is only one fin section of absorber taken into consideration. For each absorber fin component, in this case absorber plate, flow channel and working fluid, energy balance equations are derived.

Energy balance equation which contains fluxes of accumulation, conduction, heat loses and absorbed solar radiation in the absorber plate is formulated as:

$$\rho_a c_a V_a \frac{dT_a}{d\tau} = \left(-\lambda_a g_a \frac{dT_a}{dx}\right)\bigg|_x - \left(-\lambda_a g_a \frac{dT_a}{dx}\right)\bigg|_{x+\Delta x} - \left[\alpha_{amb}(T_a - T_{amb}) + \sigma \varepsilon_a \left(\frac{T_a}{100}\right)^4 - G_{sun}(\tau\alpha)\right]\Delta x \quad (41.1)$$

where τ is time, $\rho_a c_a V_a$ stands for absorber density, specific heat and volume, T_a and T_{amb} represent the temperatures of absorber and ambient, λ_a is absorber heat conduction coefficient, g_a is the absorber plate thickness, α_{amb} is the heat loss to ambient coefficient, σ and ε_a are the Stefan–Boltzmann constant and absorber surface emittance coefficient, G_{sun} is global solar radiation value and $(\tau\alpha)$ represents collector transmittance–absorptance coefficient.

In Eq. (41.1) spatial derivatives $\frac{dT_a}{dx}$ are replaced by forward differential quotients:

$$\frac{dT_a}{dx}\bigg|_{i=0} = \frac{T_i - T_{i+1}}{\Delta x}; \quad \frac{dT_a}{dx}\bigg|_{i=W_a/2} = \frac{T_i - T_p}{\Delta x}$$

Thermal energy generated in the absorber plate is conducted into fluid channels through the homogeneous bonds. The energy balance equation, which consists of the heat fluxes of accumulation in the flow channel, conduction in the flow channel, heat losses to ambient and conduction between the absorber plate and the flow channel, is formulated as:

$$\rho_p c_p V_p \frac{dT_p}{d\tau} = \left(-\lambda_p \pi S_p \frac{dT_p}{dy}\right)\bigg|_y - \left(-\lambda_p \pi S_p \frac{dT_p}{dy}\right)\bigg|_{y+\Delta y} - \left[\alpha_{amb}\pi D_p (T_p - T_{amb}) + \lambda_p g_{a\to p}(T_p - T_a)\right]\Delta y \quad (41.2)$$

where τ is time, $\rho_p c_p V_p$ stands for pipe density, specific heat and volume, T_p and T_{amb} represent the temperatures of pipes and ambient, λ_p is pipe heat conduction coefficient, $g_{a\to p}$ is the absorber–pipe connection linear dimension, D_p is outside pipe diameter, and α_{amb} is the heat loss to ambient coefficient.

This model assumes uniform temperature distribution in the cross section of the flow channel, equal to the temperature of the bond. The energy balance for working fluid was formulated as:

$$\rho_f c_f V_f \frac{dT_f}{d\tau} = (m_f c_f T_f)|_y - (m_f c_f T_f)|_{y+\Delta y} + \alpha_{p\to f}\pi d_p (T_p - T_f)\Delta y \quad (41.3)$$

where τ is time, $\rho_f c_f V_f$ stands for fluid density, specific heat and volume, T_f is the temperatures of working, and $\alpha_{p\to f}$ is the heat transfer coefficient at the boundary between pipes and working fluid, determined on the basis of *Nusselt* number, given by Heaton [5]:

$$\alpha_{\mathrm{p}\to\mathrm{f}} = \frac{Nu_{\mathrm{f}}\lambda_{\mathrm{f}}}{d_{\mathrm{p}}} \tag{41.4}$$

where

$$Nu_{\mathrm{f}} = 4.4 + \frac{0.00172\left(RePr\frac{d_{\mathrm{p}}}{L}\right)^{1.66}}{1 + 0.00281\left(RePr\frac{d_{\mathrm{p}}}{L}\right)^{1.29}} \tag{41.5}$$

41.2.1 CFD Model

The second approach of solar collector simulation methods, often used to determine the efficiency of solar collectors, is CFD models built with CFD simulation software. Fan and others [4] present CFD solar collector model verified with experimental outdoor data. In this paper, the solar collector is modelled with an assumption of uniform energy generation in the absorber tube and considering only a convective heat loss coefficient, calculated using external software SolEffs and set as an input for the CFD calculations. The comparison between calculated results and experimental data shows good agreement, especially in high flow rates. Furthermore, the authors show non-uniformity of the mass flow rate in absorber flow channels and discuss the influence of flow non-uniformity on the collector performance. Turgut and Onur [8] perform a numerical CFD analysis to determine the average heat transfer coefficients for forced convection airflow over a flat-plate solar collector surface. To compare this method with the previously shown distributed-character modelling method, a simplified CFD model was built using code Fluent 13. The domain of the proposed CFD solar collector model consists of the same physical components' representation: an absorber plate, fluid channels and working fluid. However, in this case, all geometrical details of the absorber were taken into consideration. Collector chasing is represented by convective and radiative heat loss from the absorber to ambient. The heat loss coefficient is estimated during thermal experiments of average absorber surface temperature and ambient collector temperature. Using the geometrical absorber model, the unstructured mesh was generated with the ICEM CFD mesh tool. The absorber plate was meshed with hexahedron type of volume elements, and all fluid channels and fluid domain were meshed with tetrahedral type cells. Solar energy absorbed by an absorber was determined as:

$$q_{\mathrm{a}} = G_{\mathrm{sun}}(\tau\alpha) \tag{41.6}$$

where G_{sun} is the global solar radiation (W/m^2) and $(\tau\alpha)$ is effective transmittance–absorption product. In default operation conditions, a solar collector works in laminar flow conditions; therefore, a laminar flow model was used. In this case, FLUENT will solve the governing conservation equations of mass, momentum and energy. The governing equations are represented by a conservation equation for transport of a scalar quantity ϕ, written in an integral form for an arbitrary control volume V, as follows:

$$\oint \rho\phi\vec{v}\cdot \mathrm{d}\vec{A} = \oint \Gamma_\phi \nabla\phi \cdot \mathrm{d}\vec{A} + \int_V S_\phi \mathrm{d}V \tag{41.7}$$

where $\oint \rho\phi\vec{v}\cdot \mathrm{d}\vec{A}$, $\oint \Gamma_\phi \nabla\phi \cdot \mathrm{d}\vec{A}$ and $\int_V S_\phi \mathrm{d}V$ stand for change of parameter ϕ by convection, diffusion and generation, respectively.

In the presented numerical approach, the natural convection flow was taken into account by setting the fluid density ρ as a function of temperature, using the Boussinesq approximation:

$$\rho_\mathrm{f} = \rho_0(1 - \beta\Delta T_\mathrm{f}) \tag{41.8}$$

where β is the fluid thermal expansion coefficient and ρ_0 is constant density of the flow. Calculation was performed in transient mode with pressure staggering option PRESTO and second-order upwind method for discretization of the momentum equations. The semi-implicit method (SIMPLE) was used to treat the pressure–velocity coupling. Calculation was considered converged when the scaled residuals for continuity equation, momentum equations and energy equations fall below 10^{-4} and 10^{-7}, respectively.

41.3 Experimental Work

Thermal efficiency measurements have been carried out with a 2 (m^2) parallel tube flat-plate solar from KOSPEL Inc., Poland. Collector was tested in steady-state conditions with artificial solar radiation. As working fluid, the water was used. The inlet and outlet water temperature and ambient temperature were measured with RTD platinum sensors (PT-100). The circulation of working fluid was forced by pump, and the mass flow rate was measured using ENCO MPP-6 flow meter. Solar irradiance at collector front plane was measured with LP-PYRA 02 pyranometer. The absorber surface temperature was measured during indoor test with thermocouple type "K". The data collection from RTD sensors, pyranometer, flow meter, ambient temperature sensor and surface temperature sensor was executed by NI CompactDAQ data acquisition system and LabView 2012 software. The absorber surface temperature, during an indoor test, was measured with artificial solar radiation. To simulate the solar radiation, a system of 28 metal-halide radiation sources was used. Each time, the power of radiation and distance between collector surface and solar simulator were modified and measured in 80 points.

41.4 Results and Model Verification

Firstly, the thermal efficiency characteristic η in function of reduced temperature difference $T^*\, m$ was determined in a steady-state indoor test. The reduced temperature difference $T^*\, m$ was determined as $(T_m - T_\mathrm{a})/G_\mathrm{sun}$ difference between the middle temperature of working fluid inside the collector T_m and the temperature of collector surrounding air T_a divided by the value of simulated radiation intensity at the collector surface G_sun. According to EN ISO 9806:2017 standard, the second-order efficiency curve was statistically fitted to the values of collector efficiency measured for four different reduced temperature values $T^*\, m$. Each test point, in Fig. 41.1, shown as crosses (x) represents the average value of thermal efficiency from 30-min measurement period, with constant radiation and inlet fluid temperature value. The actual useful power $\dot{Q}_\mathrm{u}$, for each test point, was calculated according to:

$$\dot{Q}_\mathrm{u} = \dot{m} \cdot c_\mathrm{f} \cdot \Delta T_\mathrm{f} \tag{41.9}$$

where mass flow $\dot{m}$ was obtained from volumetric flow rate measurement with density determined for the temperature of fluid in flow meter. Thermal efficiency η for each test point was calculated from:

$$\eta_i = \frac{\dot{Q}_\mathrm{u}}{A_\mathrm{a} \cdot G_\mathrm{sun}} \tag{41.10}$$

Test data were correlated by curve fitting using least square method to obtain the thermal efficiency function of the form:

$$\eta = \eta_0 - a_1\left(T^* m\right) - a_2 G_\mathrm{sun}\left(T^* m\right)^2 \tag{41.11}$$

where η_0—is the optical efficiency, a_1—is the heat loss coefficient and a_2—is the coefficient of heat loss coefficient depending on temperature. The results of numerical calculations from D-C and CFD models compared with experiment are shown in Fig. 41.1. In case of CFD model result, the correlation with the experiment around

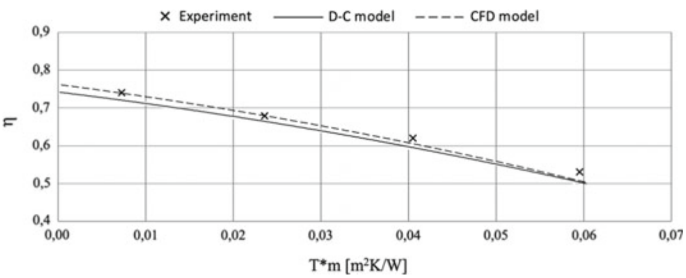

Fig. 41.1 Results of steady-state thermal efficiency measurement and numerical calculations

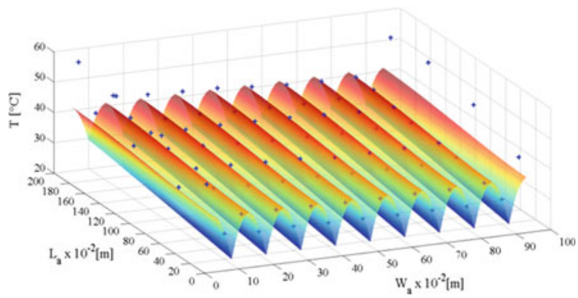

Fig. 41.2 Absorber surface temperature calculated using D-C model, with experimentally measured temperature points

the low values of T^*m is almost perfect. The values of optical efficiency η_0, determined by experiment and CFD calculations, are the same, with accuracy of two decimals. To investigate the relationship between the absorber design and the heat exchange process, the absorber surface temperature was measured experimentally and calculated with D-C and CFD models. As shown in Fig. 41.2, the middle section of the absorber has temperature comparable to calculated values in this region, but the agreement of numerical and experimental results is much lower for the edge zones of the absorber. The reason of results disagreement in the side edge zones of absorber lies in different geometry of marginal fins. In this particular solar collector, the edge fins of absorber are larger than the middle ones. This means that the first and last working channels cooperate with a larger absorption surface than the others.

For the same collector working conditions, the CFD analysis was carried out. As it was mentioned before, all geometrical details of the absorber were considered, and fluid local density was approximated.

The CFD simulation result shows the consequences of geometric irregularity of marginal absorber fins. The observed experimentally high temperature values on the edge of the absorber have been mapped with good agreement with the experiment. The CFD analysis has proved a strong dependency between the geometrical details of absorber design and heat exchanging process. Measurement data are in better agreement in comparison with D-C modelling method.

41.5 Significance Analysis

The models, as a result, give value calculated according to formula (41.9) and subsequently (41.10), which may be represented by the general function Q. Some parameters indicate absorber properties (dimensions, material, construction details) and absorber heating process (heat loss coefficient, thermal conductivity, etc.). The arguments of function Q become the inputs for the significant parameters' assessment calculations. In order to specify the significant and insignificant model inputs (parameters), called the factors (let us call them X), the statistical robustness tests [9] are applied. The function $Q(X_i)$ represents the particular solar collector model. Now, the following methodology has to be introduced [10]:

1. The factors X_i have to be specified precisely. The number of these factors, represented by number i, depends on the model complexity or can be pointed arbitrary in the practical case.
2. The levels of the factors have to be determined. Here, the levels are related to the extreme values of factors X_{imax} maximum, high level (upper + in factor symbol X^+) and X_{imin} minimum, low level (upper − in factor symbol X^-).
3. The factors are examined, evaluated in screening process, on their levels in a correct number of experimental designs (number Nod). The screening means the calculation of the function Q values in the case of the factors taking different levels. The Plackett–Burman design is one of the efficient methods, especially in case a large number F of factors have to be screened.
4. The results of the design i.e. the response of a model, here calculation of the function Q values is used to determine effects for each factor. Because the effect has to be represented by one numerical value, and according to (41.9), the useful power and (41.10) thermal efficiency is determined for each test point, and the root mean square (RMS) is calculated.
5. Eventually, the statistical interpretations are introduced. Statistical interpretations are based on effect comparison to critical effect derived from the t-test statistic.

41.6 Critical Effect Calculation for Statistical Interpretation

The statistical procedure known as the robustness tests can be conducted [9]. The most common method is based on the t-test, which allows comparing the difference between the two data series means, in relation to the variation in the data, measured by standard deviation or standard error. If the data series consist of the model responses, e.g. $Q_i = Q(X_i)f$ or related factor i, which takes high-level values X_i^+ results in Q_i^+ and low-level X-$_i$ results in $Q_i -$, then a mean is calculated according to the formula:

$$E_i = \frac{\left|\sum Q_i^+ - \sum Q_i^-\right|}{F/2} \tag{41.12}$$

E_i can be considered as the effect of the factor i. Now assuming the effects distribution is the student's distribution, one can apply the following statistics:

$$\frac{E_i}{E_{\text{rr}}} < t_{\text{crit}} \tag{41.13}$$

where E_{rr} is a standard error of the E_i effect and t_{crit} is critical value of the t-distribution, which is determined for number of degrees of freedom for E_{rr} and chosen significant level α. If Eq. (41.13) is true, it is assumed that a factor I does not influence useful energy, because its effect E_i is not significantly different from zero. The standard error E_{rr} is calculated using effect values for all factors (E_{crit}) or applies only dummy factors (E_{critD} = margin of error ME).

41.7 Significant Parameters Investigation for Solar Collectors

Five parameters are chosen: X_1—thickness of the absorber's plate, X_2—number of working channels, X_3—inner diameter of working channels, X_4—thickness of the working channels, X_5—absorber–channel connection weld thickness (Fig. 41.3).

The effects E_i are calculated according to Eq. (41.12). In the case of five factors, the number Nod starts from 8 and the next following: 12, 16, 20, 24, 32…. Parameters' levels (high and low) are limited as follows: $X_1^+ = 0.0005$ (m); $X_1^- = 0.0001$ (m); $X_2^+ = 15$; $X_2^- = 7$; $X_3^+ = 0.01$ (m); $X_3^- = 0.005$ (m); $X_4^+ = 0.001$ (m); $X_4^- = 0.0002$ (m); $X_5^+ = 0.004$ (m) and $X_5^- = 0.001$ (m). In this case, the parameters variation results from appropriate technical data for the harp-type collectors, which were used in model validation. The KOSPEL Inc. uses normalized components for production, and in many cases, it can be explained by economic reasons. A significant level is set to $\alpha = 0.05$ and initially number of Plackett–Burman design is Nod = 12. The results are shown in Fig. 41.4 **I** a, b. The red circles with numbers represent parameters and their effects E_i. Rank it represent the expected values of the order statistics of a sample from the standard normal distribution at the same size as the values of each parameter X_i. It is shown in Fig. 41.4 **I**. c, d, the parameters X_4 and X_5 are insignificant in both cases, before and after interactions clearing. In case of the parameter X_2, the significant is on critical level before fold-over process. In order to confirm these results, the number of designs in the next step is increased and equals Nod = 48. The results are shown in Fig. 41.4 **II**. a, b, c, d. and confirm the

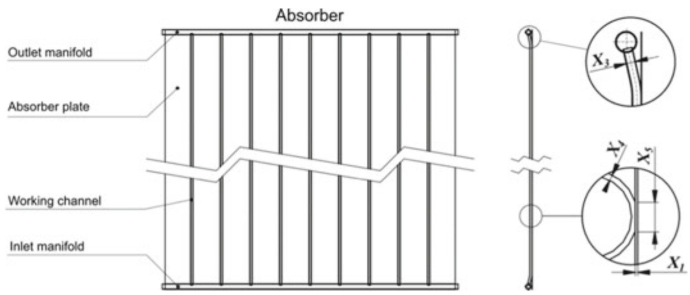

Fig. 41.3 Solar collector structure detailed description and parameters (factors) chosen to significance analysis

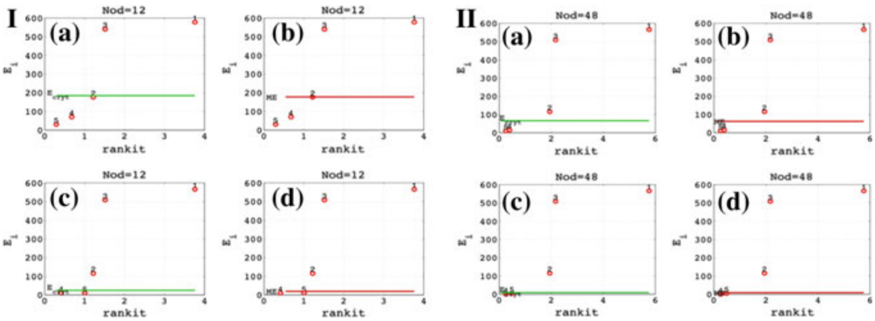

Fig. 41.4 Effects E_i with two-level interaction convolution, obtained by applying Nod= 12 in I; Nod= 48 in II Plackett–Burman design, related to critical values: **a** E_{crit} and **b** *ME before and respectively* **c** E_{crit} and **d** *ME after* fold-over process

insignificant influence of parameters X_4 and X_5 on the chosen result obtained using considered model of the solar collector heat transfer process.

41.8 Conclusion

Two different numerical simulation methods of flat-plate solar collectors' heat exchanging process are presented in this paper. All calculated results were compared with experimental steady-state and transient data. The absorber surface temperature, obtained with numerical models, was verified by contact temperature measurements through the backside of collector housing. The steady-state indoor investigation shows good agreement between calculated and measured results. Determined numerically solar collector efficiency curves were sufficiently similar to EN ISO 9806 standard test result, which means that the basic exploitation parameter scan be found with high accuracy.

The significance investigation shows that farther modification of this type of solar collector should be focused on the thickness of absorber plate X_1 and diameter of the working channels X_3. It is shown in Fig. 41.4 that these parameters are significant and their effects' value is high enough over critical values E_{crit} and ME, contrary to X_4 and X_5. In order to optimize the device construction, these parameters should be considered. Due to obvious and expected high significance of the absorber plate thickness X_1, the applied method of significance parameters assessment should be considered as useful tool for "pre-optimization" procedure. But this analysis does not show "the best" or correct values of model parameters. It has to be done in optimization process in which designated parameters' values are computed.

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Chapter 42
The Concept of Location of Filling Stations and Services of Vehicles Carrying and Running on LNG

Agnieszka Deja, Joanna Harasym, Magdalena Kaup and Dorota Łozowicka

Abstract LNG is a very good energy carrier and can be applied in a great many areas of economy, and its physico-chemical properties allow for using it as engine fuel in road vehicles. LNG infrastructure requires the integrated effort of LNG suppliers, owners and operators of stations, and potential owners of LNG-powered vehicles contrary to infrastructure of the majority of other transport fuels. LNG infrastructure properly implemented aims to minimise costs of LNG delivery chain, gas extraction, liquefaction and distribution, i.e. costs of LNG transport. Fuelling stations and their designs are independent from the LNG infrastructure map, except a liquefaction spot. The article presents the concept of deployment of filling stations and services of vehicles running on liquefied natural gas in Poland. Legal acts concerning exploitation of vehicles carrying LNG and vehicles running on LNG were analysed. An essential aspect of the elaboration includes presentation of variants of routes and locations of infrastructural facilities intended for services of vehicles running on LNG. Motorway rest areas that should be equipped with LNG supply stations were designated based on assumptions and calculations.

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42.1 Introduction

On 22 October 2014, the Directive 2014/94/EU of the European Parliament and of the Council on the deployment of alternative fuels in order to support use of alternative fuels was passed. Liquefied natural gas, LNG, is one of the alternative fuels, which is increasingly significant in transport. LNG as a fuel for fuelling motor vehicles has similar properties to compressed natural gas (CNG) combining ecological and economical advantages. LNG application substantially allows for reducing pollutant emissions, diminishing noise and minimising cost of fuel purchase.

Currently, on the world market the LNG share amounts to over 25% [1]. On the Polish market, LNG became more available after activating a regasification terminal in Świnoujście, the first one in Poland, which allows for transshipment of LNG in a liquid form. So far, a number of vehicles running on the liquefied natural gas, LNG, in Poland have been limited mainly only to buses belonging to the public transport in Olsztyn and Warszawa. There are only three LNG supply stations, in Warszawa, Olsztyn and Matuszewie nearby Poznań, which are not available for the public.

Infrastructure of liquefied natural gas, LNG, requires a rapid development [2]. In case a number of vehicles running on LNG in Poland increase, the road infrastructure will need to be equipped with liquefied natural gas, LNG, supply stations.

The objective of the article is presentation of the concept of location of infrastructural facilities for service of vehicles running on LNG on sections along TEN-T network in Poland.

42.2 Infrastructure and Equipment of Vehicle Service Stations

Road infrastructure condition in Poland is developed not only through modernisation and construction of new sections of expressways and motorways but also via gradual activation of new motorway rest areas (MRAs).

MRA is the place separated from the right of way, equipped with the infrastructure for travellers' rest in a broad sense. MRA predicts to be constructed already in the stage of designing the motorway [3].

While designing MRA, it is vital for the area to be adjusted to volume and structure by type of traffic in the section where there will be a certain MRA. It is recommended to determine the following areas according to MRA categories [4]:

- MRA I—1–2 ha;
- MRA II—2–3 ha;
- MRA III—3–4, 5 ha.

Regardless of the type, the MRA basic function is to provide a comprehensive service for travellers and satisfaction of their necessities. Parking areas are the one of the most crucial MRA equipment components. A number of parking spaces in the parking part are specified each time taking average daily traffic into consideration and predicting the demand for vehicles stopping in a certain parking area. Dependent on needs, stations for overhaul on vehicles are also built as well as parking spaces for vehicles carrying dangerous materials.

While designing, a very important aspect is also a right choice of MRA location in a certain road section. Despite the proper equipment, MRA deployment should be planned in such a way that the areas can be located one from the other in required distances.

Both a number of parking spaces in the MRA parking area and a number of stations at the filling station should be individually specified, with reference to average daily traffic during the year and intensity of motorway development. The MRA parking area, dependent on needs, requires creating a specially labelled station for overhaul on vehicles. A number of parking spaces located in the MRA parking area and a number of stations at the filling station are individually specified, with reference to average daily traffic during the year and intensity of the motorway [5].

MRAs should be located not to cause a threat to road traffic safety or not to have an effect on capacity as well as road efficiency. MRAs are to be separated for each traffic direction. The required distance between adjacent MRAs on A-class roads should not be less than 15 km; however, the distance of MRAs from a border checkpoint should not be less than 3 km. On S-class roads, the distance between MRAs should not exceed 10 km, but the distance from a border checkpoint should not be larger than 1.5 km. Decision on reduction of distances between adjacent vehicle service areas is adopted by the Head of Voivodeship after a prior delivery of authorisation granted by a relevant Minister of Transportation to express the consent to deviate from techniques and construction provisions under the Article 9 of the Act of 7 July 2004, Construction Law (Journal of Laws no. 156, item 1 118 as amended). MRAs are linked with the road on motorways by means of the lane to enter and exit the traffic flow (entrance and exit from vehicle service areas). Lanes to enter and exit the traffic flow cannot be located to endanger road traffic safety, e.g. in poor visible places to enter the roadway, where the road gradient is larger than 4% [5].

Location selected for MRAs is an important aspect already in the stage of construction. Places where they will be erected must comply with many criteria, and additionally, they must be featured with specified parameters. Most of all, vehicle service areas should be in compliance with any terms of safety, traffic, visibility, environment and health. Due to the fact that vehicle service areas cannot negatively influence traffic safety and capacity of roads, they are located separately for each traffic direction [6].

Depending on the area of the site intended for MRA and needs, MRAs can be designed in the combined version or, e.g., MRA I with a small filling station, commercial and catering appliances, stations for vehicle self-service and MRA II with accommodation facilities. The range of the MRA equipment depends on deployment and users' needs [7].

42.3 Legal and Documentary Aspects of LNG Transportation

By virtue of LNG physical properties and qualities, its transportation is included in transportation of dangerous materials. Transportation of goods of this type requires due diligence and compliance with many strict principles.

The basic and most crucial legal act governing transportation of this type is the ADR Agreement prepared in Geneva on 30 September 1957 under the aegis of the Chamber of Commerce of the United Nations, developed and issued by the European Commission of Internal Transport ratified by Poland in 1975. ADR provisions are amended in a two-year cycle.

Other provisions concerning transportation of dangerous materials including LNG are as follows:

- Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on inland transport of dangerous goods;
- The Act of 28 October 2002 on road transport of dangerous goods;
- The Act of 6 September 2001 on road transport.

ADR new structure takes advice and UN model provisions into consideration within transport of dangerous goods. The legally binding agreement is comprised of two attachments A and B. The attachment A includes the breakdown of all the dangerous materials produced worldwide by 13 classes of dangers and includes a detailed classification of these materials in certain classes.

LNG is included in the class no. 2—gases. A basic criterion to be included in this class is the vapour pressure of the substance in the temperature 50 °C larger than 200 kPa (3 atmospheres) or occurrence of gas in gaseous form in the temperature 20 °C under atmospheric pressure 101.3 kPa.

While transportation of dangerous goods, there is a huge risk of spilling liquid on the roadway, allowing gas to escape, which can have negative effects on people, animals and environment. The extent of risk varies depending on properties of certain goods [8].

Fuelling vehicles with liquefied natural gas, LNG, requires installing proper systems in the vehicle. Cryogenic containers are used along with thermal insulation, mostly the foam and powder one in order to store LNG in vehicles. Volume of containers varies between 70 and 300 litres. Pressure occurring in them is 0.15 MPa [9].

Provisions concerning LNG-powered vehicles are defined by the Regulation of the Minister of Infrastructure of 4 May 2011 amending the Regulation on technical conditions of vehicles and range of their necessary equipment (Journal of Laws of 2013, item 951).

Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on development of infrastructure of alternative fuels sets out the framework aiming at a more easier use of LNG, also in the road transport, and provides for the possibility to fill the tanks along main transport corridors of the European Union.

Under the assumptions, by 2025 LNG fuelling stations will have been erected along transit routes of Trans-European Transport Network (TEN-T) [10].

Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on development of infrastructure of alternative fuels set out the objectives, owing to which, by 2025 LNG, fuelling stations will have been built (every 400 km) along transit routes of Trans-European Transport Network (TEN-T).

42.4 Variants of Routes and Locations of Infrastructural Facilities for Service of LNG-Powered Vehicles

Presuming that all the LNG supply stations planned for 2025 will be along TEN-T networks, you should specify how many and which roads in Poland belong to basic TEN-T network. In accordance with the project prepared by the Ministry of Energy "National Framework Policy of Infrastructure for Alternative Fuels" on particular sections of TEN-T network corridors, a number of LNG supply stations for 2025 were proposed. A number of LNG stations for particular routes are presented below [11]:

1. Gdynia–Gdańsk–Katowice/Sławków section—two LNG stations;
2. Gdańsk–Warszawa–Katowice—two LNG stations;
3. Katowice–Ostrava—one LNG station;
4. Szczecin/Świnoujście–Poznań–Wrocław–Ostrava section—two LNG stations;
5. Katowice–Žilina section—one LNG station;
6. Kowno–Warszawa section—one LNG station;
7. Poland/ Belorussia border—Warszawa–Poznań–Frankfurt—two LNG stations.

Three remaining LNG supply stations are those which already exist in Matuszewie, Olsztyn and Warszawa. The drawing 1 shows routes labelled along TEN-T network and LNG supply stations planned. Total LNG supply stations are planned by 2025. Currently, in Poland there are already 3 LNG stations so new 11 stations should be located along TEN-T network: 8 stations along the Baltic–Adriatic corridor and 3 stations along the North Sea–Baltic corridor (Fig. 42.1).

Additionally, LNG stations should be located on existing MRAs, which allows for minimising costs of construction of new stations. MRAs which were designated based on assumptions and provisional calculations can be equipped with liquefied natural gas, LNG, supply stations.

The things taken into consideration while deploying LNG supply stations are as follows:

- Distances between stations;
- Existing LNG supply stations;
- Speed at which a truck runs;
- Drivers' working time.

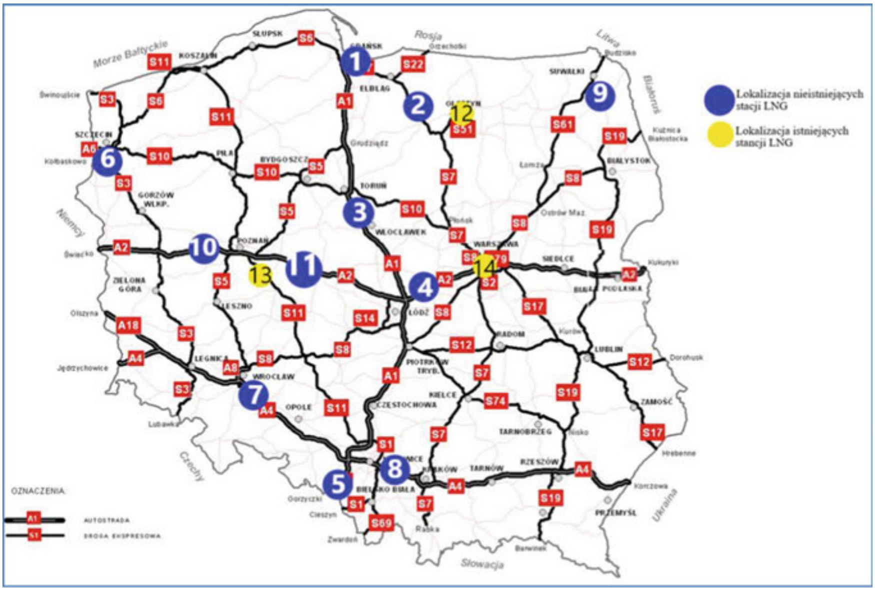

Fig. 42.1 Concepts of locations of LNG supply stations [own elaboration]

The drawing 1 shows location of LNG supply stations, both those existing and planned for 2025. Supply stations were deployed along TEN-T networks, on existing MRAs of minimum II category, as natural gas is dedicated in particular for trucks, and in this case, provisions concerning drivers' working time should be taken into consideration so that they can have relaxation conditions. Furthermore, the distance between one station and the other will be taken into account while deploying stations, and existing supply stations were considered while deploying stations.

A truck driver has to comply with principles included in AETER Agreement which refer to drivers' working time. The driver has to have a break after driving for 4.5 h, and after such a subsequent period they are obliged to have a longer break. The driver's daily working time cannot exceed 9 h.

In accordance with the Rules of the Road, the speed at which a truck can run on the motorway and expressway is 80 km/h. Possible obstacles on the road should be taken into consideration while calculating, which can cause reduction of the speed at which the truck can run, i.e. up to 60 km/h.

The suggested deployment of LNG supply stations on routes along TEN-T networks should satisfy LNG-powered truck drivers. According to MRAs existing on Gdańsk–Warszawa–Katowice route and calculations, the following MRAs were chosen in order to be equipped with LNG supply stations (Table 42.1).

Taking an LGN station located already earlier nearby Gdańsk (Koszwały MRA) and a great number of MRAs on Gdańsk–Katowice route into consideration for the section belonging to the Baltic–Adriatic TEN-T network basic corridor running

Table 42.1 List of locations of LNG supply stations on existing MRAs on Gdańsk–Warszawa–Katowice route [own elaboration]

No.	MRA name	MRA in vicinity	Distance to nearby MRA	Driving time		Commentary
				At $V =$ 80 km/h	At $V =$ 60 km/h	
1.	Koszwały	Sople	123 km	1 h 30 min	2 h	Located nearby Gdańsk, on S7 expressway, which is the beginning of the trans-European road of the Baltic–Adriatic basic corridor, equipped with i.a. parking spaces for trucks, a filling station, a restaurant and toilets
2.	Sople	Koszwały	123 km	1 h 30 min	2 h	Located on the European route E77, between Gdańsk and Warszawa, there are parking spaces for passenger cars, coaches and trucks, a filling station, a restaurant

from Gdynia through Gdańsk to Katowice, the following MRAs were designated to be equipped with LNG supply stations (Table 42.2).

An LNG supply station was located on Katowice–Ostrava section on the MRA existing there (Table 42.3).

Two MRAs were chosen on Szczecin/Świnoujście–Poznań–Wrocław–Ostrava section to be equipped with LNG supply stations (Table 42.4).

Location was designated for one LNG supply station on the section from Katowice to Žilina in the Czech Republic (Table 42.5).

Three locations were collectively designated for LNG supply stations, including the one for Kowno–Warszawa section, for North Sea–Baltic TEN-T network basic corridor; two supply stations were located along entire Poland for the route running from Poland–Belorussia border to Frankfurt (Germany) (Table 42.6).

LNG supply stations were located on existing MRAs in such a way that the distance from one station to the other allows the LNG-powered truck driver to cover the route without worrying about ample uniform time to reach the next point. All the MRAs designated based on calculations have categories II or III; therefore, all of them have a wide range of services rendered. They are equipped with fuelling stations, restaurants, toilets and parking areas. Moreover, the only MARs which were chosen own parking spaces for trucks in order to minimise costs concerning additional equipment of MARs already existing.

42.5 Conclusions

Road infrastructure network in Poland is still developing. New sections of expressways and motorways are built, and old road sections are renovated. There are more and more vehicle service areas along with development of road networks. This is why it is possible to widen a scope of services of existing vehicle service areas to provide them with LNG supply stations.

Analyses and calculations made for existing motorway rest areas along TEN-T networks allowed for elaborating the concept of locations where an LNG supply station could be erected in Poland. Therefore, you can state that:

– By 2025 in Poland, 14 LNG supply stations should be built.
– LNG supply stations should be located along TEN-T networks.
– LNG supply stations should be located on existing MRAs in order to minimise costs of constructing new stations.
– MARs on which LNG supply stations are to be built should have classes II or III.
– Distance between stations should provide a truck driver the opportunity to cover the distance from one station to the other not exceeding accessible working time.

LNG as a fuel dedicated in particular for trucks has a potential to become successful in selected segments of the market for heavy-duty and long-distance vehicles. This is the ideal solution to heavy-duty trucks covering up to 1000 k per day. Such a distance can be covered after filling one tank fully.

Table 42.2 List of locations of LNG supply stations on MRAs existing on Gdańsk–Katowice route [own elaboration]

No.	MRA name	MRA in vicinity	Distance to nearby MRA	Driving time		Commentary
				At $V =$ 80 km/h	At $V =$ 60 km/h	
3.	Otłoczyn	Koszwały	181 km	2 h 15 min	3 h 10 min	Located on the European route E75, crossing near S10 expressway, the best equipped of the nearby MRAs, having parking spaces for i.a. trucks, filling stations, a shop
4.	Nowostawy	Otłoczyn	155 km	1 h 55 min	2 h 35 min	Located at the road node crossing two European routes E30 and E75, at Gdańsk–Katowice route, equipped with filling stations, restaurants, hotel, parking spaces also for trucks

Table 42.3 List of locations of LNG supply stations on existing MRAs on Katowice–Ostrava route [own elaboration]

No.	MRA name	MRA in vicinity	Distance to nearby MRA	Driving time		Commentary
				At $V =$ 80 km/h	At $V =$ 60 km/h	
5.	Mszana Północ	Zastawie	88.3 km	1 h 8 min	1 h 30 min	Located at A1 motorway, near Poland–Czech Republic border where there are parking spaces for passenger cars and trucks, fuelling stations, toilets and a restaurant

Table 42.4 List of locations of LNG supply stations on existing MRAs for Szczecin/Świnoujście–Poznań–Wrocław–Ostrava route [own elaboration]

No.	MRA name	MRA in vicinity	Distance to nearby MRA	Driving time		Commentary
				At $V =$ 80 km/h	At $V =$ 60 km/h	
6.	Wysoka	Sędzinko	222 km	2 h 45 min	3 h 45 min	Located closest to Szczecin, on the European road E65, nearby A6 motorway, equipped with i.a. parking spaces for trucks, fuelling stations, toilets, restaurants
7.	Oleśnica	Sędzinko	221 km	2 h 45 min	3 h 40 min	Located on A4 motorway, the European road E40, between Wrocław and Katowice, where there are a hotel, 24-h restaurant and parking areas

Table 42.5 List of location of LNG supply stations on MRAs existing on Katowice route [own elaboration]

No.	MRA name	MRA in vicinity	Distance to nearby MRA	Driving time		Commentary
				At $V =$ 80 km/h	At $V =$ 60 km/h	
8.	Zastawie	Mszana Północ	88.3 km	1 h 8 min	1 h 30 min	Located on A4 motorway, near Katowice on the route towards the border with Czech Republic where there are a hotel, parking areas, a restaurant and shop

Table 42.6 List of location of LNG supply stations on MRAs existing for Kowno–Warszawa and Belorussia–Germany routes [own elaboration]

No.	MRA name	MRA in vicinity	Distance to nearby MRA	Driving time		Commentary
				At $V =$ 80 km/h	At $V =$ 60 km/h	
9.	Rudniki Południe	Sople	261 km	3 h 10 min	4 h 20 min	The only MRA in Poland located at this route, the European road E67, equipped with parking spaces for trucks, restaurants and fuelling stations
10.	Sędzinko	Oleśnica	221 km	2 h 45 min	3 h 40 min	Located at A4 motorway, at the European road E30, equipped with parking spaces also for trucks, fuelling stations and a restaurant, and parking areas
11.	Police	Sędzinko	153	1 h 55 min	2 h 35 min	Located at A4 motorway, at the European road E30, equipped with parking area for passenger cars, trucks, fuelling stations and a restaurant

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Chapter 43
The Concept of Transport Organization Model in Container Logistics Chains Using Inland Waterway Transport

Agnieszka Deja, Magdalena Kaup and Roma Strulak-Wójcikiewicz

Abstract The growth of container trade at sea and inland ports has necessitated a better integration of water and land transport, which entails the need to expand the hinterland and accessibility from the land side. The infrastructure investment projects completed so far, aimed at improving the efficiency of transport in the hinterland, are the basis for creating new container logistics chains. In many ports of the European Union, the potential of inland waterway transport has been exploited for a long time as an integral component of sustainable transport. In the long run, it will not be possible to efficiently meet the growing demand for container transport in Europe by using only road and rail transport. Therefore, it is important to seek carriage capabilities in environment-friendly modes of transport. Looking into the case of the river-seaport of Szczecin, this author presents a concept of transport organization model involving inland waterway transport in container-based logistics chains. The analysis of the conditions for the functioning of such chains may provide a basis for developing directions to continue to develop the sea and inland ports in Poland.

43.1 Introduction

The present development of transport attempts to integrate all its modes in time and space, locally, regionally and internationally. The accessibility and hinterland of sea and inland ports determine the level of intra- and intermodal integration in

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logistics chains. Ports, located at the land–water interface, become basic links of container logistics chains. Their seamless operation is essential for the minimization of transport time and costs.

Disproportions exist in the modal split, particularly large differences in many countries concerning the engagement of specific transport units in cargo carriage processes. Therefore, the key objective is to change existing trends in the market and more fully use now underestimated modes, mainly inland waterway transport. However, successful operation of inland waterway transport depends on geographical location and natural conditions; hence, its potential is not always fully exploited. In some countries, it is only marginal in the overall transport system.

The article presents the concept of transport organization model in container-based logistics chains, based on inland waterway transport, with frequent references to the river-seaport of Szczecin. Sample heading (third level)—only two levels of headings should be numbered. Lower-level headings remain unnumbered; they are formatted as run-in headings.

43.2 The Structure of Container Logistics Chains

A well-functioning logistics chain is necessary to efficiently handle containerized cargo. Keeping the container flow smooth between the chain links requires effective planning, management and control of logistics processes. The effectiveness of these processes depends largely on the efficiency of the specific transport mode.

Container logistics chains are a technological combination of the container handling and storage points with transport routes, where financial, documentation, organizational and other actions and operations are coordinated. They are intended to combine port operators with other participants (entities) operating in, inter alia, supply and distribution zones (Fig. 43.1) [1].

The effectiveness of container logistics chains is based on:

– Fast and efficient flow of containerized cargo to provide high-level services in the specific place and time;
– Flexibility to changing market conditions;
– High technological level of implemented processes of container transport, handling and storage in all links of the logistics chain;
– Use of modern technologies and methods to ensure smooth flow of cargo and information.

With high-tech port shoreside facilities, the container handling operations are carried out very quickly at low expenditures, which generates low charges. It is also important to efficiently do customs clearance of containers in transit.

In international trade, the key link of logistics chains is sea and inland ports, which play a role of generally accessible centre of information on cargo-handling potential, cargo flow and the feeder service capabilities of each transport mode.

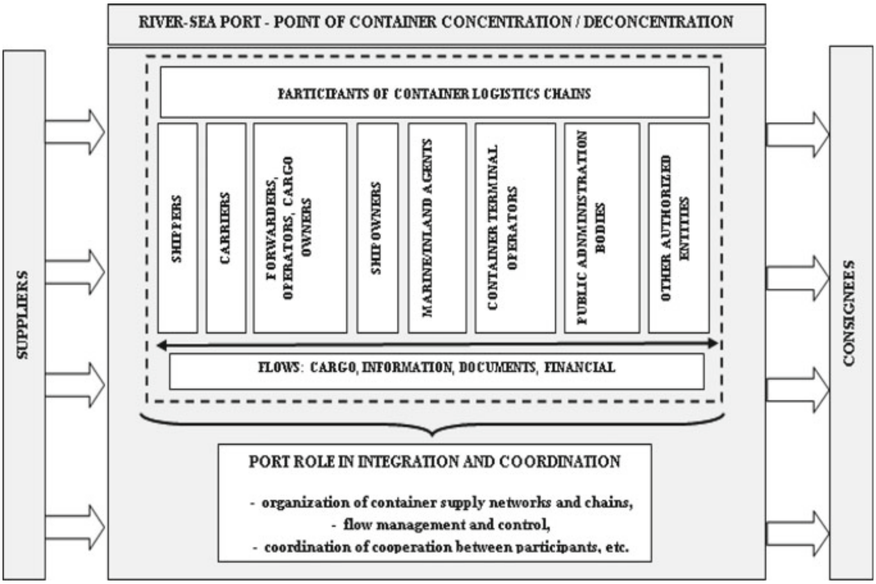

Fig. 43.1 River-seaport as a point of integration and coordination in container logistics chains [own elaboration]

The operating international container supply chains, owing to large-scale logistics operators, are becoming increasingly more complex. This is closely related to the preferences and requirements of customers, who expect the ports to provide integrated services in container supply chains. This can be achieved by the implementation of in-port information systems that integrate all of the participants in the chain, providing them with continuous and reliable flow of information on the state and location of containerized cargo. The ongoing technological progress in ports changes their role and strategic position in container logistics chains. The existing potential of the river-seaport of Szczecin creates all the opportunities to create a logistics hub, where inland navigation could play a significant role [1].

43.3 The Factors of Inland Transport Inclusion in Container Logistics Chains

Inland waterway transport contributes to the sustainability of the transport system and the change to the mode of transport that is more energy efficient, safer, more reliable and, above all, environment-friendly. It is a basic element of the European transport system. However, its importance and position compared to other modes differ from country to country. In one case, despite good geographic and natural conditions, it will have a minor role in the overall national transport system. In another case, it will be considered as equal to other modes of transport, and its potential and resources are fully used, due to its strengths: inland waterway transport is the most economical and most environment-friendly way of carrying goods, an effect of low energy use per one ton of cargo and low external costs, low emissions of pollutants and noise, and few collisions and other accidents that have costly consequences. Besides, the means of transport and infrastructure are highly durable, vessels have ample cargo space and relatively small areas of land are needed for the operations.

The range of cargoes carried through inland waterways is wide, from dry and liquid bulk to containerized goods and oversized pieces adds to the list of advantages, as it allows the shipowner to cooperate with a number of contractors. Besides, inland waterway ships emit less harmful substances per one ton of cargo because their corresponding power demand of 0.2–0.4 kW is much lower than that of trucks (8–10 kW) and lower than power demand in rail transport (0.8–1 kW) [2–4].

Due to the increasing share of containers in overall movement of goods, inland waterway transport also witnesses a growth (over 10%). The largest quantities of goods are carried by inland waterway vessels in Holland, Belgium and Germany, mainly to/from the ports in Antwerp and Rotterdam, as well as Hamburg or along the Rhine corridor [3.5].

The transport of containerized cargo via inland waterways depends on appropriate waterway parameters, which according to European requirements adopted by AGN agreement should meet the standards of classes IV–VII (COM 2013). The document "The guidelines for inland waterways in Poland for the years 2016–2020 with the 2030 perspective" adopted by the government on 14 June 2016 prioritizes the achievement of international class of navigation on Polish waterways (E30, E40 and E70) and their inclusion in the European network of waterways [5]. This is necessary for the completion of container transport over long distances and for relatively large barge trains.

In order to meet market requirements, investments are needed to improve cargo-handling infrastructure and ensure the appropriate storage areas in ports. The development of inland waterway shipping will fill in a niche in Poland's transport system, especially in efficient links between Polish seaports and other links of container logistics chains.

In conjunction with the policy of sustainable transport development, which involves transferring freight from roads to railways and inland waterways (COM 2011), it seems that Odra as a transport route would be—after making it navigable along the entire course—one of the key inland waterways in this part of Europe.

Odra Waterway (OW) is an important segment of the historical Odra Transport Corridor. It is functionally related to cargo trade services and connects the city of Szczecin and sea-river ports of the Odra estuary with Berlin and Western Europe through Odra(Oder)-Havel and Oder-Spree canals. Sixteen infrastructure investment projects are underway, expected to be completed by 2022.

Given that Szczecin is located along the international E30 route linking the Baltic Sea with the River Danube in Bratislava, which coincides with the corridor of the TEN-T base network running to Ostrava, the restoration of inland waterway transport may have a very positive impact for the development of the port of Szczecin. Together

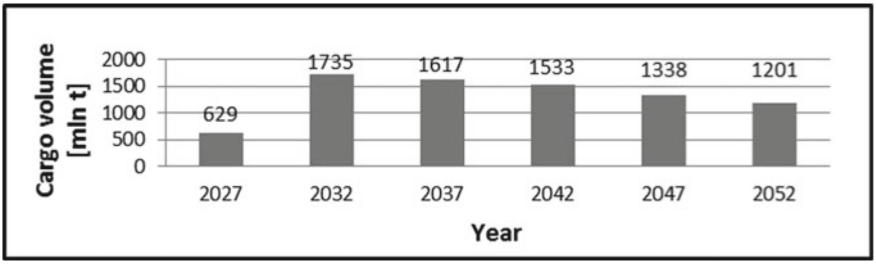

Fig. 43.2 Forecast increase of container throughput in the port of Szczecin, after the fairway is dredged to 12.5 m (own elaboration based on [8])

with the port of Świnoujście, it is one of the closest points of access to the Baltic for many industrial centres in the south (e.g. Czech Republic). The restoration of navigation on the Odra would be important in the context of the planned connection of three rivers: Odra–Danube–Elbe. The port of Szczecin is directly connected to the national road No 10, linked with the express road S3, motorway A6 and the main railway E59/CE59. The Odra Waterway provides a transport route to the south of the country and countries of Western Europe.

The perfect location of the port in Szczecin and inland connection with the southern part of Poland and the cross-border nature of the Odra is the largest asset for the creation of intermodal hub of container logistics chains.

The fairway linking Świnoujście and Szczecin through a channel 10.5 m deep and 90 m wide allows for entry of ships with a maximum draft of 9.15 and 215 m length. With its inland location, Szczecin is in the worst situation among competing ports due to limited technical parameters of the fairway. A recently signed contract for deepening the Świnoujście–Szczecin fairway to 12.5 m along a 62-km section and widening to 100 m will definitely improve the conditions of navigation and operational parameters of the port. Once the project is completed, the maximum draft of ships heading to Szczecin will rise from 9 to 11 m [6, 7].

Figure 43.2 shows a projected throughput of containerized cargo for the fairway 12.5 m deep. The drop of container volume forecast for 10 years after the completion of investment is due to limited container capacity of the port. Further development of container services will depend on the expansion of Ostrów Grabowski.

When implemented, the concept of building an inland CCIC terminal in Dunikowo, which will be located 15 km away from the port of Szczecin by a railway line, 1 km from A6 motorway, only 160 km from Berlin, will create opportunities and facilitate transport of freight to and from Germany and Scandinavia. Containers delivered by land will be handled in the terminal, which will relieve the river-seaport of Szczecin and will allow for increasing the container handling capacity in this part of Poland. Part of the containers will be stored in storage areas located in an economic zone.

43.4 A Simplified Model of Transport Organization in a Container Logistics Chain: The Case of the River-Seaport of Szczecin

The extent and role of transport function are dependent on how many transport routes reach a port, technological standards and efficiency of transport means use. Transport availability for containerized cargo is an essential factor of well-functioning container logistics chains. Containers are delivered to ports of regional importance by feeder ships that take over containers from large fully cellular container ships or other in hubs adapted to handle containers.

The strategy for the management of container logistics chain should address the configuration, i.e. the choice of location for the transshipment of containers and all associated container-specific operations. The aim of functional integration is to connect in the most efficient manner all links in the container logistics chain.

In the port of Szczecin, cargo transshipment is generally barge–ship and ship–barge operation. Cargo may also be moved from barge to a storage area and the other way, so that the transshipment is indirect. As the port of Szczecin is primarily a seaport handling mainly seagoing vessels, an inland ship to be served on the ship/shore basis can be handled only when a berth is clear [9]. This situation is mainly due to insufficient number of berths adapted or built for handling the fleet of inland ships. Besides, the handling of barges in direct transshipment to/from ship is sometimes difficult, because the cargo-handling gear has limited reach. Therefore, indirect transshipment involving inland ships is considered to face insufficient cargo-handling capacity. Containers are delivered to the terminal in Szczecin by sea, while from the hinterland mainly by trucks, partly by rail, as shown in Fig. 43.3.

The existing situation offers opportunities for inland waterway transport to handle freight services related to the hinterland and to function as a vital link of container supply chains. In view of the planned investment in the waterway infrastructure (dredging of the Szczecin–Świnoujście fairway, the modernization of the OW) and cargo terminals (expansion of the terminal on Ostrów Grabowski, construction of inland CCIC terminal in Dunikowo), the process is indeed desirable. Figure 43.4 shows applica-

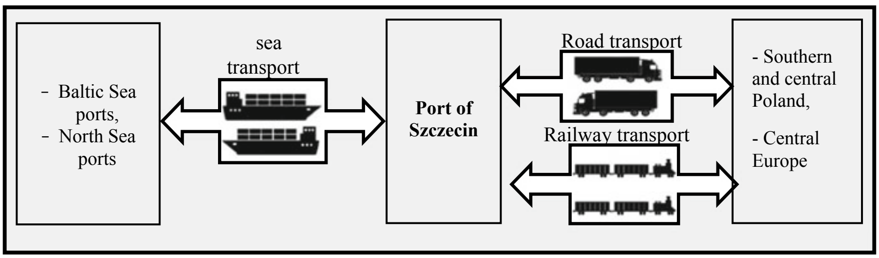

Fig. 43.3 Previous scheme of transport organization in the container supply chain in port of Szczecin [own elaboration]

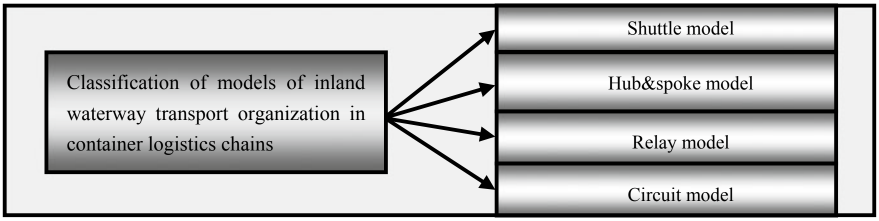

Fig. 43.4 Models of inland transport organization in container logistics chains [own elaboration]

Table 43.1 Characteristics of inland transport organization models in container logistics chains [own elaboration]

No.	Type of the model	Specification
1.	Shuttle model	It is the simplest of the models and consists in providing containers directly from the point of loading to the point of unloading. The empty vehicle returns to the initial point, where it is loaded again
2.	Hub and spoke model	In this model, containers are delivered from one point of loading to many points of discharge. The transport vehicle is sent with cargo to a destination, where it is discharged. Then, it goes back to the initial point to be loaded again and moves to another destination. The process ends when the cargo is delivered to all destinations
3.	Relay model	The relay model uses combined transport. The cargo from the loading point is carried to the transshipment point. The cargo is transshipped to another, smaller, transport vehicle, while the original larger transport vehicle returns empty to the point of loading. The goods are delivered to the destination. These actions may be repeated as many times as there are transshipment points between the loading point and the destination
4.	Circuit model	In this model, the whole route of container transport is planned to cover many destinations. The containers taken at the initial point are shipped to many consignees. From the initial point to the last consignee, the vehicle moves with cargo. The vehicle moves empty only in the final part of the route, from the final consignee to the initial point

ble models of inland transport organization in container logistics chains. There are shuttle, hub and spoke, relay and circuit models. Each of them is briefly described in Table 43.1.

The choice of inland transport organization model in container logistics chains is determined by many factors. The most important are: transport demand (determined by the quantities and type of containers), the parameters of transport units, the cost and time length of transport. The model of transport organization is also affected by factors such as the availability and capacity of waterways and roads and cargo-

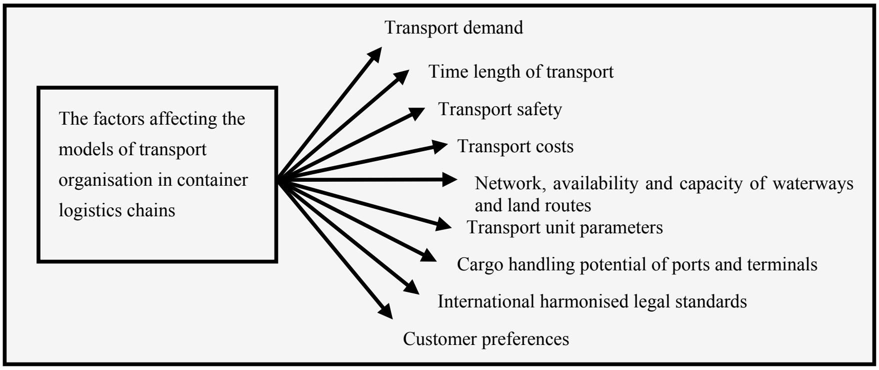

Fig. 43.5 Factors affecting the models of container logistics chain organization [own elaboration]

handling potential in ports and terminals. Figure 43.5 shows the factors affecting the organization models of container logistics chains.

Before we consider the spatial configurations of container logistics chains, we should first indicate the interdependence with the system of functional relationships. The creation of specific spatial structures makes sense only if they properly perform specific functions [10].

The presented algorithm (Fig. 43.6) for choosing a variant of transport organization models in container logistics chains, apart from the above-mentioned factors affecting these models, takes into account an analysis and assessment of solution options. The final choice of the transport organization model in container logistics chains depends on the criteria adopted in an analysis and assessment and the methods and mathematical tools used.

Figure 43.7 shows an example scheme of transport organization in the container supply chain in port of Szczecin, including inland waterway transport which is used in this case for taking over containerized cargo delivered to the port by sea as well as those from the hinterland.

In the first variant (cargo delivered by sea), after transshipment to inland vessels, containers are transported to the port hinterland, e.g. logistics centres located nearby or directly by the waterway, which would relieve storage yards and cargo terminals in the port. Intermodal units would be taken away from logistic centres by road or rail.

In the second variant (taking containers delivered to port from its hinterland), containers would be delivered to logistics centres by road or rail. Then, the cargo would be carried by inland waterway vessels and transported directly to the river-seaport, where they could be stored for a short time or transshipped directly onto a seagoing ship. This option would allow for minimizing the storage time of transport-ready containers and thus optimizing the use of storage area.

The transfer of containerized cargo from roads onto rivers and canals and interception of new flows of containers should create a positive impact on the functioning

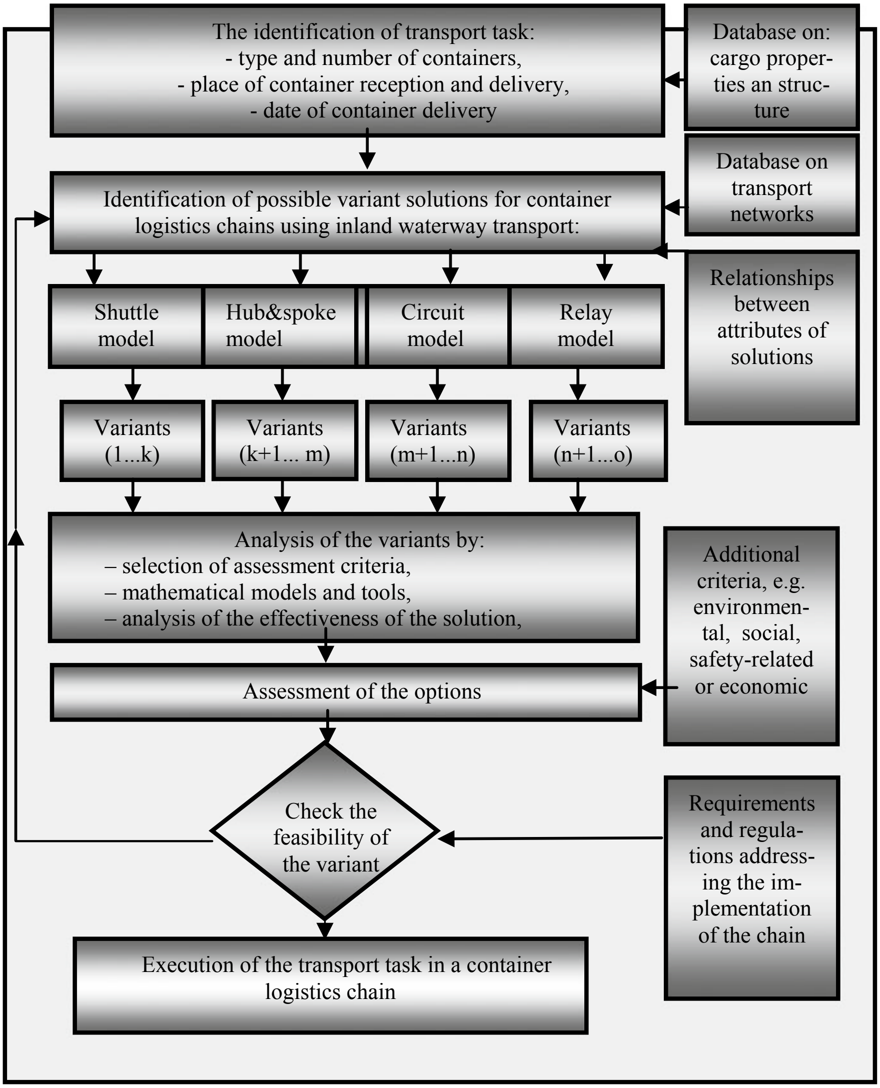

Fig. 43.6 Simplified algorithm for choosing the transport organization model in container logistics chains [own elaboration]

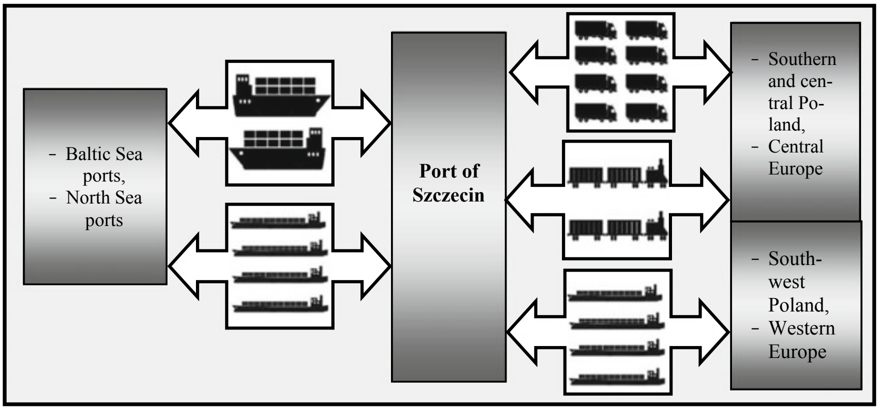

Fig. 43.7 Diagram of the transport organization in the container supply chain in the port of Szczecin, including inland waterway transport [own elaboration]

of the port and the whole region. The generation of container transport demand using inland waterway transport should increase the level of road safety and reduce congestion as a result of the lower level of road transport deliveries. Besides, one could expect reduced external transport costs, e.g. due to a drop in the number of road accidents and their consequences, and lower emissions of exhaust gases. The latter would go in line with the pro-ecological strategy of transport development as set forth in the present EU transport policy.

43.5 Conclusions

The functional integration of container logistics chains necessitates spatial integration, which in turn entails the use of available modes of transport at the specific place and time. The location of container terminals in river ports is an important factor that boosts the development of container logistics chains based on inland waterway transport. It is imperative that in future they should be an integral link to European logistics chains. The location of the port of Szczecin on the River Odra naturally facilitates its role as a logistics centre handling containers on east–west and north—south routes, and fully integrates all modes of transport. Taking into account the planned strategic infrastructure investments (deepening of the Szczecin-Świnoujście fairway and the modernization of the Odra Waterway) and improvement of cargo terminals, one can expect that this direction of the port development is desirable.

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Chapter 44
Management of Ship-Generated Waste Reception at the Port of Szczecin as a Key Component in the Reverse Logistics Chain

Agnieszka Deja, Roma Strulak-Wójcikiewicz and Magdalena Kaup

Abstract Waste reception management processes and downstream waste management are a key component of reverse logistics in waste management. The paper discusses the problems of management in the reception of waste and cargo residues from ships at ports as a place where all kinds of pollution are generated, received and disposed of in parallel. The paper presents the role of reverse logistics in waste management and provides a description of selected legislation governing the reception of ship-generated waste and cargo residues from seagoing vessels. Furthermore, we have analysed the system for the reception of ship-generated waste and cargo residues at the sea-river port of Szczecin covering all ships using quays on its premises. Additionally, we discuss the importance of efficient management of the reception and downstream management operations for financial reasons, to minimise the cost to the logistics system and the environment with a view to protecting the environment.

44.1 Introduction

The growing significance of sustainability considerations and the increasing public awareness in this respect cause countries to place an increasing emphasis on measures mitigating the adverse impact of maritime transport on the ecosystem. A broad range of international legal regulations have been adopted to protect the marine environment, with the objective to ensure that future generations will be able to take

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advantage of whatever the environment has to offer while keeping it protected and remaining accountable for any environmental damage [1]. Due to the key role played by seaports in the transport network and the growing number of ships calls at ports, new requirements relating to the protection of the marine environment have been imposed on both ships and seaports.

In order to reduce the adverse impacts of ship-generated pollution on the marine environment, EU seaports have been obligated to implement EU and national ship-generated waste management regulations. For instance, the legislation in force requires seaports to provide adequate facilities on their premises for the reception of waste and cargo residues from ships and to apply appropriate waste management procedures. The effective management of waste and cargo residues from ships at seaports allows to minimise dumping of wastes at sea by ship users, contributing to the improvement of the marine environment [2].

The goal of the paper is to analyse the management process for the reception of ship-generated waste and cargo residues at the sea-river port in Szczecin as well as downstream waste management practices. Proper waste reception management and waste disposal are a key component of reverse logistics in waste management. This is particularly important in the case of reception of waste and cargo residues from ships at ports, where all kinds of pollution are generated, received and disposed of in parallel.

44.2 Reverse Logistics in Waste Management

The growing interest in pro-environmental actions and sustainable development feed into the concept of ‘reverse logistics’, which is treated as an instrument addressing environmental challenges [3]. Polish and international scientific literature offers a wide selection of different terms, synonyms and definitions for ‘reverse logistics’. In Polish sources, reverse logistics is also termed as ‘logistyka odwrotna’ (opposite logistics), ‘ekologistyka’ (ecologistics), ‘logistyka utylizacji’ (disposal logistics), ‘logistyka odpadów’ (waste logistics), ‘logistyka odwrócona’ (reserved logistics) and ‘logistyka powtórnego zagospodarowania’ (reuse logistics) [4], while foreign references mention ‘aftermarket logistics’, ‘retrogistics’, or ‘aftermarket supply chain’.

Reverse logistics is a field of logistics examining the flow patterns of end-of-life products. Those products are waste and in this context, reverse logistics is perceived as a new waste disposal approach based on two complementary categories of purposes: environmental and economic purposes [5]. Reverse logistics is a relatively new term. It first appeared in scientific literature in the 1980s. Lambert and Stock [6] defined reverse logistics as a reverse material flow opposite to supply chain. In the 1980s, Murphy and Poist [7], inspired by reverse product flow, defined reverse logistics as a material flow of products from consumers to producers in the supply chain. This definition was accepted by Pohlen and Farris [8], who named the final consumer and emphasised that the product flow was reverse in the supply chain, however, without identifying the main activities within reverse logistics. In the 1990s, the concept

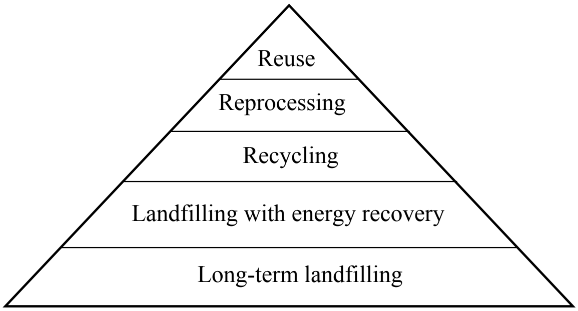

Fig. 44.1 Hierarchy of recovery of value from waste. Adapted from: [12]

of reverse logistics was still evolving. Stock [9] devised a definition which stressed the role of recycling in the logistics of waste disposal and reuse. This approach was summarised by Kopicky [10], who built on the reverse logistics chain, adding information flow supporting the functioning of the chain. In the late 1990s, Rogers and Tibben-Lembke [11] defined reverse logistics as the process of planning, implementing and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal.

Based on the above definitions, it is appropriate to recognise recycling as the main point of reverse logistics. Recycling is understood as a recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes; it includes the reprocessing of organic material (organic recycling) but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. Figure 44.1 shows the hierarchy of recovery of value from waste.

The most desirable level in the hierarchy of recovery of value from waste is reuse. It means that a product is reused without any further treatments. The next hierarchy level is reprocessing, understood as reuse in whole or in part following regeneration or repair processes. Reuse reduces the quantity of waste by the portion that will be reused. The next stage is the recycling process. This process mainly involves the recovery of secondary raw materials from waste or end-of-life goods [13]. Some materials can be reused time and time again, provided that appropriate technologies are employed. According to J. Szołtysek, the function of reverse logistics at this stage is to create an efficient system for the segregation, collection and receipt of end-of-life goods and their components in the recycling system. Landfilling is classified into landfilling with energy recovery and long-term landfilling, which constitutes the lowest grade in the hierarchy. Practices enabling the recovery of useful energy from waste are given priority.

The processes of waste collection, handling, transport and disposal can be organised using a variety of technologies and solutions, and the effectiveness of every single element determines the performance of the waste management system as a whole.

Waste is subject to a wide range of legal regulations which set out measures geared towards protecting the environment and human health and lives. They are aimed at preventing and mitigating adverse impacts of waste generation and management on the environment and human health. It is, therefore, particularly important to minimise the negative effects of use and to improve waste management performance. Both Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and the Act on waste of 14 December 2012 offer very broad definitions of waste. Waste means any substance or object which the holder discards or intends or is required to discard. The term ‘recovery’ has an equally broad definition of a process the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function.

44.3 Legislation Governing the Reception of Ship-Generated Waste and Cargo Residues from Seagoing Vessels

The most important international laws governing the protection of marine waters and waste management in the marine environment include:

- The International Convention for the Prevention of Pollution from Ships [14]—MARPOL 73/78 (MARPOL Convention 73/78—Rules of the International Convention for the Prevention of Pollution from ships 1973, done in London on 2 November 1973, as modified by the Protocol done in London on 17 February 1978 (OJ 1987 No. 17, item 101) and the Protocol [15] done in London on 26 September 1997 (OJ 2005, No. 202, item 1679);
- The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 [16]—called the London convention (LC 1972), done in Moscow, Washington D.C., London and Mexico on 29 December 1972, in effect from 30 August 1975;
- The Convention on the Protection of the Marine Environment of the Baltic Sea Area [17]—called the Helsinki Convention, dated 9 April 1992.

Waste management considerations pose a considerable challenge to European Union member states. The main objective of Community law in the area of organisation of ship-generated waste and cargo residues is to ensure a high level of protection of the marine environment. In 2000, with a view to reducing illegal dumping at sea and some other considerations, the Council of the European Union adopted Directive 2000/59/EC of the European Parliament and of the Council on port reception facilities for ship-generated waste and cargo residues. The directive is a particularly important piece of legislation in the field of reception of ship-generated waste and cargo residues in the European Union. It lays down a certain framework under which the member states are obliged to follow environmental standards, while being free to choose the measures used to achieve them. This document sets forth the main principles for the management of ship-generated waste at EU ports. Detailed requirements for reception facilities are laid down in Article 4, which provides that member states must ensure the availability of port reception facilities without causing undue delay to ships. The Directive does not impose any specific requirements for port reception facilities, stating only that they must be capable of receiving the types and quantities of ship-generated waste, taking into account the operational needs of the users of the port. Particular emphasis is also placed on the development and approval of a waste reception and handling plan, which must be done by the member states every three years [1].

National laws incorporate the provisions of the above-discussed international agreements and European Union legislation relating to the application and use of port reception facilities (such as the MARPOL Convention 1973/78, the Helsinki Convention and Directive 2000/59/EC). The key piece of national legislation in this area is the Act of 12 September 2002 on port reception facilities for ship-generated waste and cargo residues. It lays down, inter alia, the principles of handling of ship-generated waste and cargo residues at ports, including without limitation the responsibilities of port authorities with regard to providing access to port facilities, the principles of developing and approving ship-generated waste and cargo residues management plans and the calculation of port facility maintenance and operation fees [18].

Another instrument of relevance to the issues of waste management is the Act on the prevention of pollution by ships. This act applies to ships in Polish sea areas and ships of Polish nationality outside those areas, with the exception of the floating craft of the Polish Navy, border Guard, police and special service ships [19]. The Act on the prevention of pollution by ships contains a provision prohibiting ships from doing anything at sea that would cause marine pollution. With regard to the protection of marine waters against pollution, the Act prohibits the dumping of waste and other substances by ships of Polish nationality travelling in the Baltic Sea. The prohibition extends to ships of foreign nationality within Polish sea areas. Further, waste or other substances intended for dumping in the Baltic Sea must not be loaded onto ships in the Polish territorial waters [19].

Waste delivered by ships at the port must be appropriately disposed of on the land side as well. In this respect, waste management is regulated by the Act on waste of 14 December 2012. This document includes waste management guidance aimed at minimising the adverse environmental impacts of waste. It focuses on the problems of waste management and means of mitigating the effects of consumption of waste-generating resources [20].

One of the most important regulations governing ship-generated waste management is the Regulation of the Minister of Transport, Construction and Maritime Economy of 17 January 2013 on the submission of notifications of waste on board ships. The document covers pivotal issues, such as procedures for notifying waste carried on board to ports and other entities, the scope of the required information or a template of the notification form [21]. The information referred to above is transmitted via PHICS, a control and information system for Polish ports [22]. All guidance relating to the manner in which information is to be communicated forms the basis for the port to prepare its information on the procedure and manner of receiving ship-generated waste.

44.4 System for the Reception of Ship-Generated Waste and Cargo Residues at the Port of Szczecin and Downstream Waste Management

From the perspective of the problems of management of ship-generated waste and cargo residues, it is particularly important to distinguish between the following types of ship-generated pollution [14]:

- Ship-generated waste, which is all waste, which are generated during the service of a ship and fall under the scope of Annexes I, IV, V and VI to the MARPOL Convention 73/78 and cargo-associated waste other than cargo residues as defined in the Guidelines for the implementation of Annex V to MARPOL 73/78—until the delivery to port reception facilities;
- Cargo residues, which are the remnants of any cargo material on board which could not be placed in cargo holds (loading excesses and spillage) or which remains in cargo holds and other places after unloading procedures are completed (unloading excesses and spillage).

The system for the reception of ship-generated waste at the port of Szczecin covers waste generated on board during normal service. It does not cover any waste generated as a result of ship repairs or waste generated by inland waterway vessels. The types and categories of ship-generated waste are defined in accordance with the provisions of the Act on waste (and in particular with the provisions of the Regulation of the Ministry of Environment of 9 December 2014 on the waste catalogue), the provisions of the Act on port reception facilities for ship-generated waste and cargo residues and the provisions of the International Convention for the Prevention of Pollution from Ships, known as the MARPOL Convention. In line with the above, the types (according to the waste catalogue) and categories (according to the Convention) of waste received by the port are: oily waste and mixtures thereof, ship-generated waste (including non-hazardous waste, hazardous waste, including oily solid waste and catering waste), sewage, exhaust gas cleaning residues and cargo residues from ships.

In line with the Act on port reception facilities for ship-generated waste and cargo residues, the ship-generated waste reception system covers all ships using quays located within the seaport in Szczecin, both those owned by ZMPSiŚ S.A. and third-party quays.

Since 2004, the port of Szczecin has had the system for the reception of ship-generated waste and cargo residues and a disposal system in place. In accordance with the ‘Ship-generated waste and cargo residues management plan of the seaport in Szczecin', waste collection is the responsibility of contractors operating on behalf of the Szczecin and Świnoujście Seaports Authority (ZMPSiŚ S.A.). The waste collection companies are responsible for the proper reception of ship-generated waste, recording of waste collected from ships and transferring the waste for downstream management (either recovery or disposal). ZMPSiŚ S.A. plays an oversight role with regard to the overall performance of the system for the reception of ship-generated waste at the port, in particular as regards the appropriateness of waste management and compliance with applicable laws, independently of the statutory responsibility of the waste collection company.

The most important precondition of waste delivery is that the ship's master or agent must notify the waste carried by ship (in terms of type, quantities and composition) via the control and information system for Polish ports (PHICS) before entering into the seaport. The ship crew is obliged to separate the waste on board. Irrespective of the type of craft, every vessel must be equipped with operational waste transfer pumps to enable the reception of liquid waste. When a ship's master or agent notifies the intention to deliver waste, the waste collection company consults them to arrange for the delivery. If the port is unable to perform the service, the Port Coordination Department at ZMPSiŚ S.A. issues a certificate indicating the nearest port capable of performing the waste reception operation and presents it to the representative of the ship.

When the work is completed, the collection company provides the ship's master/agent with a document stating the scope of services provided. The 'Acknowledgement of receipt of ship-generated waste at the seaport in Szczecin' is a document used for the purposes of ship-generated waste recording by the collection company. For the ship's master, it serves as proof that the waste has been delivered at port. The data from the 'Acknowledgement' are entered in an electronic database of the ship-delivered waste record maintained by ZMPSiŚ S.A. This is used as a basis for periodic reports on the performance and utilisation of port reception facilities, as well as a source of information on how the collection company handles the waste it receives. Figure 44.2 shows the algorithm of ship-generated waste reception and downstream management for the port of Szczecin.

On the port premises, there are two main groups of waste reception, storage, transport, recovery and disposal facilities: (I) port reception facilities which are a part of port infrastructure and (II) other port reception facilities.

The Ostrów Grabowski sewage treatment plant is a port reception facility within the port infrastructure (I). The treatment plant is composed of two separate wastewater collection and treatment systems: (1) a mechanical biological urban wastewater treatment plant and (2) an aqueous liquid waste treatment and recovery facility. The aqueous liquid waste treatment and recovery facility comprises two process lines: (a) a process line for the treatment and recovery of liquid oily waste and (b) a process line for the treatment and recovery of hold wash water (contaminated with bulk cargo residues).

Other port reception facilities (II) include facilities managed by the waste collection company and its subcontractors, used for the reception and transport of waste from temporary storage sites to downstream management locations.

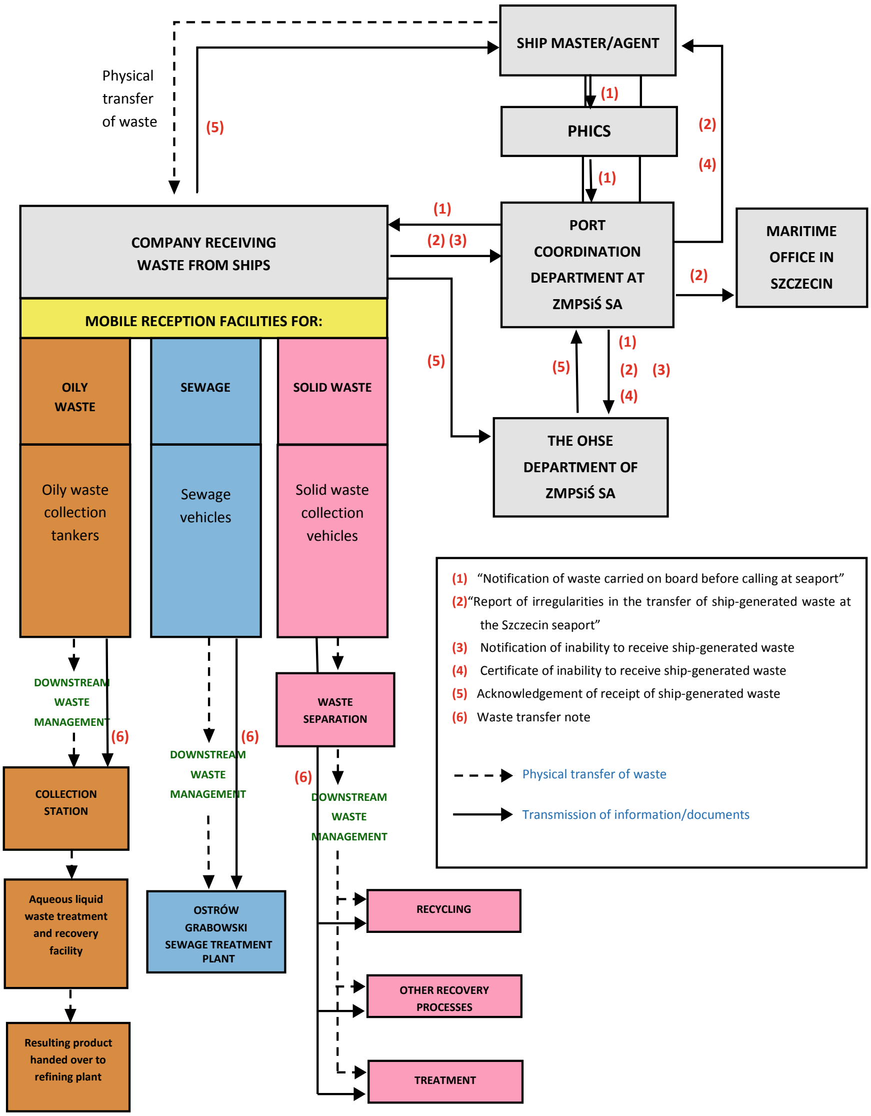

Fig. 44.2 Algorithm of ship-generated waste reception and downstream management (Own work based on: [23])

The facilities and plants used by specialist operators perform a number of functions, including waste reception, storage, transport and downstream management. Presented below is a classification of those facilities and plants by use. They are classified into four groups (catalogues):

- Catalogue 1—waste reception facilities;
- Catalogue 2—temporary storage facilities (e.g. depot of a waste collection company);
- Catalogue 3—facilities used for the transport of waste to storage sites or other downstream management facilities and plants;
- Catalogue 4—waste recovery and disposal facilities.

ZMPSiŚ S.A. keeps a record of the actual utilisation of port reception facilities using a software program called 'Odpady', which operates as a central record of quantities and types of waste received from ships as part of the ship-generated waste management system. It holds data on ships delivering waste at port on the usage of port reception, storage and transport facilities, as well as downstream waste management facilities and plants. The information collected in the database additionally includes ship name, waste delivery date, the point of origin of the ship, number of people on board, tonnage and manufacturing date of the ship and the quay where the craft was handled. The data entered in the program by waste management companies are monitored on an ongoing basis by the OHSE Department of ZMPSiŚ S.A.

44.5 Conclusions

Reverse logistics involves waste flows (which must be understood broadly) and related information. Therefore, one of its objectives is to integrate the flows in space and time and, by optimising the cost of flow, to safeguard the environment and to minimise the costs of the logistics system for waste.

Our analysis of the port's system for the reception of ship-generated waste and cargo residues and downstream waste management has shown that the management of ship-generated waste reception at the seaport in Szczecin by ZMPSiŚ S.A. is a key component of reverse logistics. A range of actors are involved in the entire process of reception of waste and cargo residues, on the ship's side, the port's side and beyond. In this process, parallel cash flows and material flows take place and information is exchanged between the entities involved in ship-generated waste management. To ensure the smoothness of the flows occurring in reverse logistics, aside from the efficient organisation and management of the process of collecting waste from their place of origin to the place of disposal, appropriate technical solutions have to be in place: reception facilities, means of transport and temporary waste storage sites, which make the whole process viable.

Therefore, a port is not only a place where waste is collected from ships, but most of all, it is a place where the efficient management of waste reception and downstream management operations become relevant in order to protect the environment and to minimise the cost to the logistics system for the waste.

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Chapter 45
Preliminary Balance of the Cold Accumulated in Polymetallic Nodules Stored on the Mining Ship

Tomasz Abramowski and Piotr Nikończuk

Abstract Continuous depletion of land resources of metals and other raw materials (e.g., energy) motivates humanity to seek new sources of obtaining raw materials. An alternative source of the metal ores is the seabed. During the industrial mining of polymetallic nodules from the ocean floor, the waste cold is accumulated in nodules and seawater transported vertically from a depth of 4000–6000 m, where there is a constant temperature of 1–2 °C. Part of cold returns back into the ocean with water and the sediment. The cold, which is accumulated in separated nodules, can be utilized in exploitation conditions of a mining or transport ship. The chapter presents a methodology for estimating the amount of cold extracted from the seabed and accumulated in nodules stored in mining vessel. The purpose of the calculations was to estimate the waste cold. Its amount clearly indicates the possibility of using it and reducing the energy consumption of some equipment and installations on mining and transport vessels, particularly in tropical environments where the deposits of polymetallic nodules are located. The cold accumulated in the nodules may be a cold source for a number of service processes of the mining and transport vessels.

45.1 Introduction

Continuous depletion of land resources of metals and other raw materials (e.g., energy) motivates humanity to seek new sources of obtaining raw materials. An alternative source of metal mining is the seabed. On the ocean floor, polymetallic

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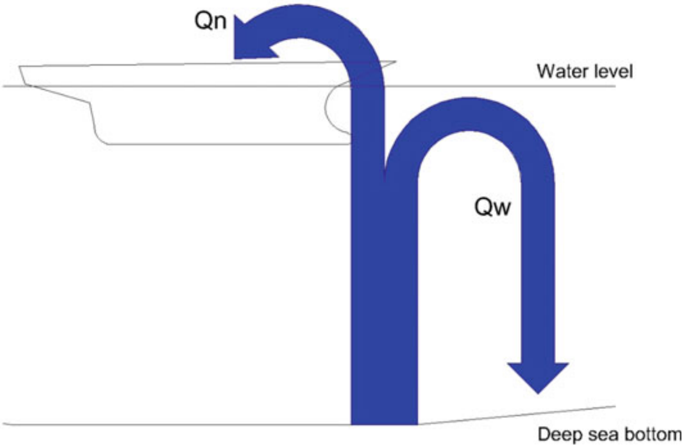

Fig. 45.1 Cold waste accumulated in nodules (Q_n) and in a mix of seawater with sediment (Q_w)

nodules containing many metals are formed with varying densities. The depth where the nodules are located is 4000–6000 meters below the water surface [1, 2]. The mining technologies and concepts are based on slurry extraction from the seabed bottom [3–7]. During the industrial extraction of nodules from the ocean floor, waste cold is also obtained. The temperature of the mined slurry is +2 °C. Part of the cold is returned back into the ocean with water and the sediment. The cold, which is accumulated in separated nodules, can be used in exploitation conditions of a mining or transport ship. The next part of this chapter presents a methodology for estimating the amount of cold extracted from the seabed and accumulated in nodules stored in the hold of extraction unit or transportation vessel (Fig. 45.1).

45.2 Methodology of the Balance of Cold Extracted from the Bottom of the Ocean

Studies on the vertical transport of nodules in raiser indicate different stream velocity of the water mixture with bottom sediment and elevated nodules [8–15]. At the presented model, a simplification was adopted based on the uniformity of the speed of the slurry. It means that slurry is mined out from the bottom of the ocean with the average volume flow dV/dt. The average volume fraction of polymetallic nodules in extracted slurry was marked as k_n, and the volume fraction of seawater with bottom sediment was assigned as k_w. The volumetric flow for the nodules is described by the equation

$$\frac{dV_n}{dt} = k_n \frac{dV}{dt} \tag{45.1}$$

Fig. 45.2 Nodules deposited in oceanic sediment, extracted on a board of research vessel using a box corer

and for a mixture of seawater with bottom sediment

$$\frac{\mathrm{d}V_\mathrm{w}}{\mathrm{d}t} = k_\mathrm{w}\frac{\mathrm{d}V}{\mathrm{d}t} \tag{45.2}$$

In Fig. 45.2 are shown nodules deposited in ocean sediment, extracted on a board of research vessel using a boxcorer. Figure 45.3 shows the process of extraction a larger amount of nodules using dredge.

The amount of collected waste cold accumulated in the nodules is equal to

$$Q_\mathrm{c} = \int_0^{t_m} \frac{\mathrm{d}V_\mathrm{c}}{\mathrm{d}t}\rho_\mathrm{c} c_\mathrm{c} \Delta T_\mathrm{c} \tag{45.3}$$

where

ρ_c Nodules density (kg/m^3),
c_c Specific heat of nodules (J/kgK),
ΔT_c Temperature difference (K).

The temperature difference ΔT_c is determined by the temperature of nodules T_c and the ambient temperature T_a:

$$\Delta T_\mathrm{c} = T_\mathrm{a} - T_\mathrm{a} \tag{45.4}$$

Fig. 45.3 Extracting larger amounts of nodules using a dredge

The extracted waste cold accumulated in water and sediment is determined in an analogous method

$$Q_c = \int_0^{t_m} \frac{dV_w}{dt} \rho_w c_w \Delta T_w \quad (45.5)$$

where

ρ_w Density of mixture of seawater and sediment [kg/m^3],
c_w Specific heat of the mixture of seawater and sediment [J/kgK],
ΔT_w Temperature difference [K].

The temperature difference ΔT_w is determined by mixture temperature T_w and the ambient temperature T_a:

$$\Delta T_w = T_a - T_w \quad (45.6)$$

In the above model of waste cold estimation for simplification, the same velocities of the seawater mix and slurry volume as well as the concurrences raised with it were assumed. In real conditions, the velocity of the water flow with the sludge is much higher, but the authors focused on the stream of extracted nodules. Studies on the density of nodules are presented in paper [16].

Table 45.1 Mean grades of Mn, Ni, Cu, and Co within the IOM exploration area. *Source* IOM materials

Exploration area	Mn mean [%]	Ni mean [%]	Cu mean [%]	Co mean [%]
B1	27.64	1.22	0.93	0.20
B2	31.05	1.29	1.26	0.18
H11	31.55	1.30	1.30	0.16
H22	30.93	1.28	1.27	0.17

In the case of nodules, it is also difficult to determine their physical properties, such as specific heat c_c and density ρ_c. These parameters depend on the chemical composition: The number of chemical elements and the chemical compounds created by them. In various regions of the ocean floor, the chemical composition of nodules is varied; therefore, variable values of density and specific heat of them are expected. The density of nodules has different values depending on the state of saturation with seawater.

As far as mineral composition of PN is concerned, it consists of crystalline (mainly manganese oxides) and amorphous (mainly hydrated iron oxides) mineral phases in different proportions, depending on processes responsible for nodule formation (hydrogenetic or diagenetic).

Concentration of relevant elements in nodules depends on the proportion of the main mineral phases the elements are associated with. Nodules are usually rich in Mn, Ni, Cu, and Co and Pb. For the B1 and B2 IOM exploration area, the mean grades of base metals are shown in Table 45.1.

45.3 Preliminary Case Study

A preliminary analysis of the amount of waste cold accumulated in metallic nodules was carried out. It applies to nodules mined out from B2 area. The study focused on the amount of waste cold extracted from the accumulated in wet nodules.

Due to the lack of conducted tests of the specific heat of nodules, the specific heat model was adopted. It takes into account the percentage of minerals presented in Table 45.1. It was assumed that the remaining volume of nodules is filled with sediment from the bottom of the ocean.

$$c_n = \sum \frac{f_i c_i}{100\%} \tag{45.7}$$

where i is the individual mineral nodules.

Table 45.2 shows the percentage fractions and specific heat of the individual components of nodules. Due to the lack of knowledge of the specific heat of sediment

Table 45.2 Percent fraction and specific heat of chemical elements [18] contained in nodules located in B2 area

Chemical element	Fraction value f_i [%]	Specific heat C_i [J/kgK]
Mn	0.315	486
Ni	0.0129	452
Cu	0.0126	386
Co	0.0018	427
Sediment[a]	0.6577	2400

[a]Value for sediment in the area of the eastern coast of Japan [17]

deposited in the area of nodules extraction, the specific heat of sediment on the seabed on the east coast of Japan was assumed [17].

On the basis of Eq. (45.7), the thermal capacity of c_n expressed in w [J/kgK] was calculated:

$$c_\mathrm{n} = 1743\left(\frac{\mathrm{J}}{\mathrm{kgK}}\right) \tag{45.8}$$

Nodules mining technology is still at the stage of research and development. At present, the mass rate of extraction of nodules is determined as

$$\frac{\mathrm{d}m}{\mathrm{d}t} = 75\left(\frac{\mathrm{kg}}{\mathrm{s}}\right) \tag{45.9}$$

According to the Eq. (45.3), the power flow of waste cold accumulated in nodules is equal

$$\frac{\mathrm{d}Q_\mathrm{n}}{\mathrm{d}t} = \frac{\mathrm{d}m}{\mathrm{d}t}c_\mathrm{n}\,\Delta T \tag{45.10}$$

On the basis of the above data, the cold flow was determined depending on the temperature difference

$$\frac{\mathrm{d}Q_\mathrm{n}}{\mathrm{d}t} = 130{,}725\,\Delta T\left(\frac{\mathrm{W}}{\mathrm{K}}\right) \tag{45.11}$$

The temperature of nodules extracted from the bottom of ocean is equal to 2 °C. Assuming the ambient temperature of 20 °C, the temperature difference is equal $\Delta T = 18$ K. For such values, the waste cold stream is equal to:

$$\frac{\mathrm{d}Q_\mathrm{n}}{\mathrm{d}t} = 2.353 \times 10^6\ (\mathrm{W}) \tag{45.12}$$

According to the above considerations, the cold accumulated in a mixture of water and sediment is estimated based on the assumption that the blend stream is the same as the stream of nodules. Also, the fraction coefficient of nodules is equal to $k_c = 0.2$ and fraction of water with sediment is $k_w = 0.8$.

45.4 Conclusions

The purpose of the considerations was to estimate the waste cold accumulated in the extracted nodules. Its amount clearly indicates the possibility of using it and reducing the energy consumption of some equipment and installations on mining and transport vessels. The waste cold accumulated in nodules may constitute the low heat source for many processes of handling the transport unit.

Presented calculations are a preliminary estimation of waste cold accumulated in nodules. Correct determination of waste cold requires additional investigation of the properties of nodules. Due to their diverse composition in various areas of the ocean floor, the place of their extraction should be taken into account.

The authors also work on the development of low-energy technologies of waste cold management.

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Chapter 46
Design and Development of a Portable Wireless Axle Load Measuring System for Preventing Road Damages

Buddhi Herath, B. A. D. J. C. K. Basnayake, Dimuthu Wijethunge, Y. W. R. Amarasinghe and W. K. Mampearachchi

Abstract The longevity of road infrastructure is a crucial element of sustainable transportation. Although laws are present to prevent overweight vehicles damaging roads and highways which are not designed to withstand excessive loads, the authorities face practical difficulties in their enforcement given the lack of convenient vehicle weight measuring methods. A portable wireless axle load measuring system (PWALMS) is designed through structural analysis and is developed by employing strain gauges, which is capable of measuring 1 ton with a safety factor of 3.4. Four individual portable pads are kept on to which the vehicle is driven and each will measure the axle loads. A control unit then acquires the data which is wirelessly transmitted to a computer and is displayed through a GUI. An improved model is finally proposed to mitigate the transverse strain felt by strain gauges.

46.1 Introduction

Transportation is one of the key aspects of modern human life. Recently, many investments are made to improve the quality and speed of the transportation systems. As a result, highways, metro systems and bullet trains become increasingly popular even in developing countries. However, it is mandatory to carefully maintain that infrastructure due to their high investment. In many countries, overloaded vehicles on roads are usually not monitored or regulated. But it can cause severe damage

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to the transportation system by causing road accidents and excessive wearing or damaging the road infrastructure itself. In this work, we have introduced a portable axle load weighing system to detect axle loads of the vehicles. Using the device, proper regulations can be made and suitable tariffs can be introduced based on the damage that vehicle causes to the road.

Technology-wise axle load measuring system is well matured, and many research works related can be found. However, in most of those, the major focus is to improve device performance through electronic components or improving sensor performance. Oubich et al. have developed an algorithm to reconstruct the axle load signal on a limited bandwidth to measure dynamic loads with accuracy when vehicles are subjected to normal speeds [1]. Faruolo et al. analysed the dynamic measurement of the axle forces in vehicles carrying liquid at around $6\,\mathrm{km\,h^{-1}}$ [2]. Bajwa et al. developed cost-effective wireless weighing device with new modelling procedure to estimate gross vehicle weights [3].They have used vibration sensors in the pavement with temperature and acceleration compensation to detect axle loads. In many research works, piezoelectric sensors are used to measure axle loads [4–7]. However piezoelectric sensors are only suitable for dynamic measurements. When the vehicle is at rest on the platform, constant force will act on the piezoelectric elements which will produce no observable signal. On the other hand, strain gauge or load cell-based devices are suitable for both static and dynamic measurements [8]. In such devices, axle loads are calculated by measuring the deflection of a beam or plate. Structure and geometry of the plate are very critical, but such optimization is often overlooked.

In this work, we have used strain gauges to detect axle loads. Furthermore, plate geometry and structure were optimized to get the desired results from the device. By optimizing the plate geometry and structure, maximum bearable load on the plate was improved and transverse strain acting on the strain gauges was minimized. Signal processing unit, control system and user interface were developed to deliver the results to the user in a convenient manner. Device was powered by an installed rechargeable battery, and data from the device was wirelessly transmitted to the main control station.

46.2 Proposed System for the PWALMS

The working principle of the proposed design is shown in Fig. 46.1. Four axle pads are kept next to the four wheels, and the vehicle is driven onto them. Once the tire comes on top of the pad, the plate of the axle pad bends exerting a strain underneath the bending plate which will be sensed by the strain gauge. A strain gauge is a sensor which varies its resistance based on its strain. The resistance change will invoke a voltage in the Wheatstone bridge. The voltage will be picked up by the data acquisition (DAQ) device after which the data will be wirelessly transmitted to a portable computer to be indicated through a suitable GUI.

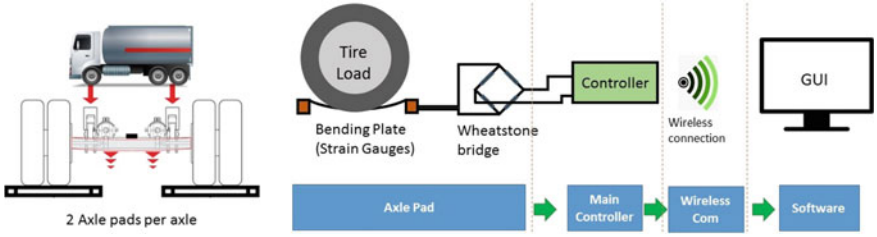

Fig. 46.1 Working principle of the proposed system

46.3 Design and Development of the Weighing Pad

The prototyped axle pad designed and developed which is shown in Fig. 46.2 was designed to measure a weight of 1 ton. The contact area of the tire footprint was set at 9 cm × 12 cm based on the study by Xiong et al. [9]. The plate dimensions were chosen after a few numerical studies which came to be 30 cm × 30 cm excluding the two legs. The aluminium alloy 6061 was chosen for the prototype given its properties such as less corrosion, low cost and high strength.

46.3.1 *Structural Analysis*

In order to find the placement of the strain gauges and to design the plate thickness, structural simulations were carried out in COMSOL Multiphysics (COMSOL, Inc. USA). To simplify the simulation, the legs were disregarded and the boundary conditions were imposed on the plate alone. The plate thickness was selected as 1 cm as the failure load was simulated. Figure 46.3a depicts the graph which includes the von Mises stress in MPa felt in the centre of the plate which portrayed a maximum stress for a given load. The yield stress of the aluminium alloy 6061 is 240 MPa. If the yield point is crossed, the material would deform plastically, which should

Fig. 46.2 Prototype design

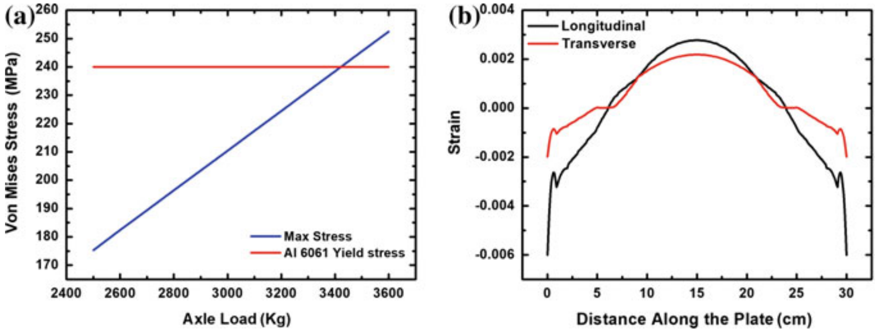

Fig. 46.3 **a** Failure load for the given plate thickness. **b** Longitudinal and transverse strains along the centreline underneath the plate

be avoided. The failure load given by the numerical analysis was 3421.6 kg. Thus, the unit has a safety factor of 3.4 which is required in instances where there will be impacts from the tire on the plate following braking.

46.3.2 Sensing Principle

To find the optimum placement for the strain gauges, the longitudinal and transverse strains along the centreline underside of the plate were evaluated for a load of 2500 kg, which is depicted in Fig. 46.3b. The mid-point (15 cm) of the plate showed the maximum strain for both directions longitudinal and transverse, which shows that the highest sensitivity is achieved in this location. It was decided to incorporate the strain gauges here. The two strain gauges were attached to the centre of the plate and were connected in a half-bridge arrangement. The Wheatstone bridge has two excitation voltage outputs to bias the bridge and two voltage inputs to read the differential voltage output of the bridge. Typically, the differential voltage output of the bridge is in the millivolts range. Initially, these signals are amplified by voltage amplifiers and are fed to an analog-to-digital converter (ADC) to obtain corresponding digital numeric values representing the bridge output.

According to Fig. 46.4, the equation of the Wheatstone half-bridge is

$$\frac{V_O}{V_{EX}} = \frac{Sg_2}{R + Sg_2} - \frac{R}{R + Sg_1} \tag{46.1}$$

where V_O is the output voltage and V_{EX} is the excitation voltage. However,

$$Sg_n = R(1 + G\epsilon_n) \tag{46.2}$$

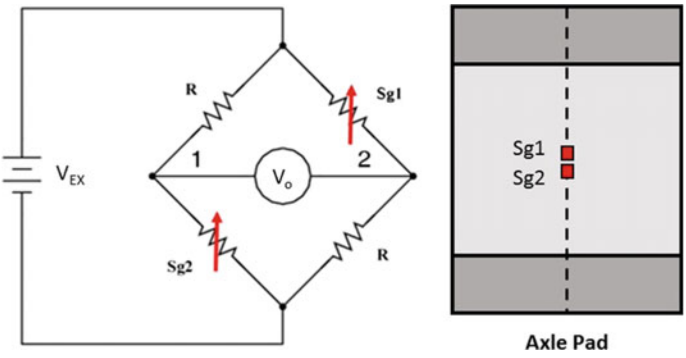

Fig. 46.4 Strain gauge locations

where G is the gauge factor ($G = 2$ for most metal foil strain gauges) and ϵ_n is the strain felt by each strain gauge. Given the symmetry of the strain gauges along the strain profiles, both gauges produce the same strain ($\epsilon_1 = \epsilon_2$). Then,

$$\frac{V_O}{V_{EX}} = \frac{G\epsilon}{2 + G\epsilon} \tag{46.3}$$

It is evident from Eq. (46.3) that for small strains ($G\epsilon <<< 2$), the V_o is almost linear.

46.4 Main Controller and Software Application

HX711 is a 24-bit ADC IC (integrated circuit) developed by Avia semiconductors. HX711 has software-selectable two channels for differential voltage inputs with inbuilt programmable gain amplifiers (PGAs). The chip can be connected with an external microcontroller via a digital serial interface, and it is capable of taking measurements up to 80 samples per second [10].

In this scenario, three ADC modules were used to develop three bridge interfaces to read three multiple bridge signals simultaneously, although only a single interface was used for the prototype. These modules were connected to the 8-bit microcontroller through the digital GPIOs, and the acquired ADC results were sent through the Bluetooth link to any connected devices as seen in Fig. 46.5. The connection of the bridge interfaces of ADCs was connected to the DB9 male connectors which were mounted on the front panel as shown in Fig. 46.6a. A Ni-MH rechargeable battery pack which is having sufficient energy to power up the circuitry for 5–6 h was used as the power source for the system.

Finally, a computer-based graphical user interface (GUI) was developed using Microsoft Visual Basic to operate the system, which is shown in Fig. 46.6b [11]. The

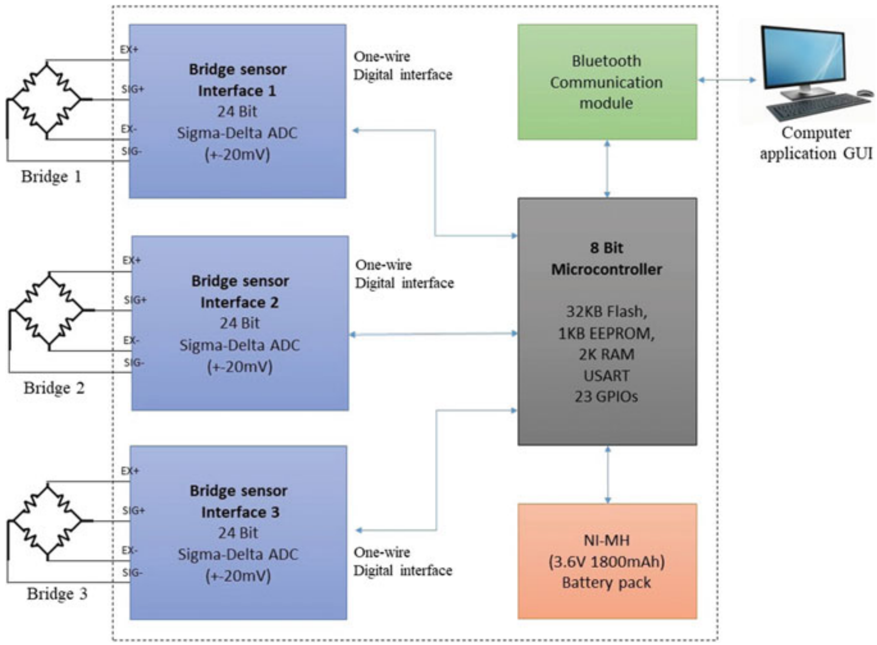

Fig. 46.5 Block diagram of wireless bridge sensor interface system

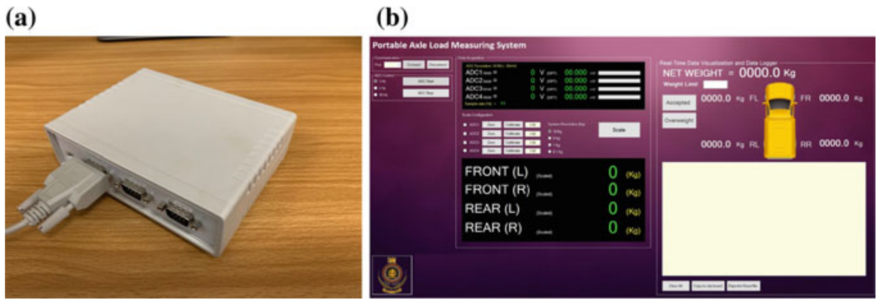

Fig. 46.6 **a** Developed three-channel wireless bridge sensor interface. **b** Developed three-channel wireless bridge sensor interface

developed GUI has capabilities to monitor four ADCs simultaneously. It further has four-scale displays including calibration and tare functions. Additionally, the GUI application is capable of data logging and report-generating (.CSV or MS Excel) features which can be useful in testing and validation purposes.

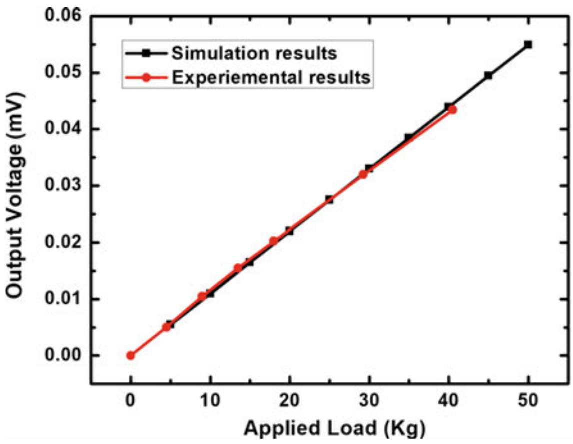

Fig. 46.7 Simulation results versus experimental results

46.5 Testing and Validation

For testing purposes, the strains were obtained in the COMSOL simulation by exerting weights of 5–50 kg with steps of 5 kg. Then, the output voltages corresponding to the strains were derived in millivolts through the equation. To compare the actual results against the simulation results, a known weight was used to calibrate the plate, several known weights were kept and the ADC values were noted. Given that 24 bits represented 20 mV in the ADC, the output voltages corresponding to the ADC values were found. These voltages were compared and are depicted in Fig. 46.7

The results show that the output voltages from both the simulation and the actual prototype coincide and hence the model is validated. Furthermore, the results indicate sufficient linearity between the applied loads and the output voltage.

46.6 Proposed Beam Model

A major drawback of the prototype is attaching of the strain gauges to the mid-point of the plate as the transverse strain is 78% of the longitudinal strain, thus affecting the strain gauge values [12]. To correct this, a new model was proposed which included a beam running underneath the plate as shown in Fig. 46.8a. The total thickness of the beam and the plate was fixed at 2.5 cm (thickness of the plate would then be 2.5 cm less than the thickness of the beam), and a parametric sweep function of COMSOL was employed to evaluate the thickness of the beam and the width of the beam. These dimensions were found for the model to withstand a failure load of 3421 kg (where the maximum stress is lesser than the yield stress of aluminium alloy 6061 which is 240 MPa as seen in Fig. 46.9b), which was the failure load of the plate model. Furthermore, the dimensions were selected which gives the least transverse strain

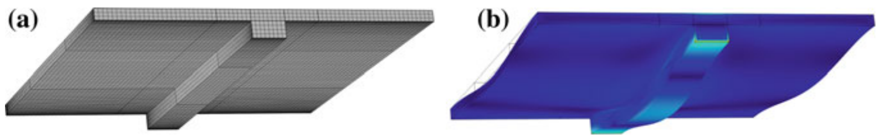

Fig. 46.8 **a** Mesh of the beam running underneath the plate. The elements of the mesh towards the two fixed ends were made progressively smaller for higher accuracy. **b** von Mises stress distribution of the beam model

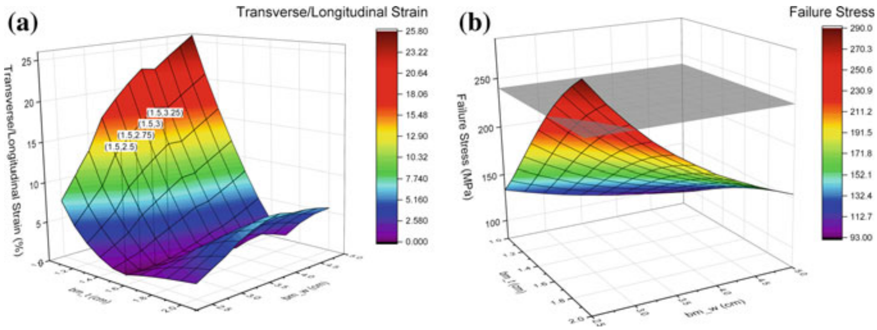

Fig. 46.9 **a** Ratio of transverse strain to longitudinal strain for varying beam thickness (bm_t) and width (bm_w). **b** Failure stress for varying beam thickness (bm_t) and width (bm_w). The plane of failure yield stress of 240 MPa is marked

compared to its longitudinal strain, as seen in Fig. 46.9a. Hence, the longitudinal and transverse strains underneath the beam were evaluated for 2500 kg as shown in Fig. 46.10. Finally, a set of dimensions were selected for beam thickness and beam width which were 1.5 and 3.0 cm, respectively. This selected model dropped the transverse strain to 0.12% of the longitudinal strain which is a significant drop which will reduce the transverse strain effect on the strain gauge significantly, thereby reducing the drawback of the initial plate model. Although the longitudinal strain of the beam model is only 61.3%, for the purpose of using strain gauges, it is an insignificant drop of sensitivity.

46.7 Conclusion

Numerical simulations supported the structural analysis in identifying the dimensions for the plate, and through the same, its failure loads were found and the strain gauge locations were identified. Two strain gauges were employed in a half-bridge arrangement whose analytical equation proved that it is linear for smaller strains. To acquire the signals, HX711 ADCs were used and the data wirelessly transmitted to be visualized in a computer-based GUI built using Visual Basic. Through the testing of the prototype, the experimental results closely matched the simulation results, thus

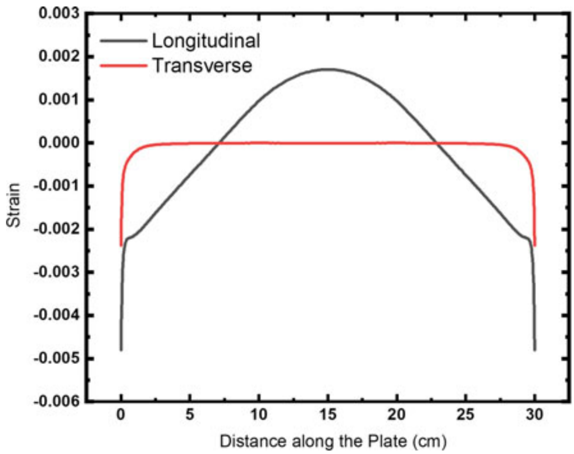

Fig. 46.10 Longitudinal and transverse strains of the beam model

validating the design. The proposed beam model proved superior to the prototyped plate model in reducing the transverse strains felt by the strain gauges at a negligible loss of sensitivity.

It would be interesting if future research could be conducted on structures with different geometries and various strain gauge locations for an analysis of sensitivity. Furthermore, it would be worth exploring the dynamic measuring of vehicles where the weight is measured while the vehicle is in motion, which could be performed with an altered algorithm using the same prototyped setup.

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Chapter 47
Selection of Sorbents for Removing Operating Fluids at the Vehicle Dismantling Station

Agnieszka Ubowska and Monika Olawa

Abstract Disassembly of any end-of-life vehicle must be carried out in an appropriate manner while maintaining the safety of the environment. At each dismantling station, funds must be deposited that prevent, stop, or assist in the elimination of possible leaks of operating fluids. Due to the variety of vehicles removed from vehicles in order to improve the process of removing emergency leaks, universal means should be selected. The paper presents the results of the sorbent absorption capacity test for various operating liquids removed at the vehicle dismantling station. The results of the research have identified a sorbent that wants the highest efficiency in relation to the operational fluids present at the vehicle dismantling station. The reduction in the number and amount of sorbents used may reduce the impact of their emergency outflows on the environment.

47.1 Introduction

For years, Poland has been struggling with the problem of cars imported to the country from the secondary market. These vehicles are heavily exploited, and their average age is about 11 years. In 2017, the average age of the vehicle in Poland stood at 13.8 years (up by 0.2 years vs. 2016) [1, 2]. Over half of the cars registered in Poland in 2017 were 16 and more years old (see Fig. 47.1). Older vehicles moving on Polish roads after a few years cease to be in working order, they are withdrawn from service, and then they are handed over to the dismantling station, where the management of automotive waste is carried out. In Poland, it is still a branch of the developing economy, as evidenced by the dynamic increase in the number of dismantling stations in the last decade [3].

The decommissioning car is a multi-material waste (Fig. 47.2). By achieving the best possible level of recovery of individual materials, it is possible to reduce the consumption of natural resources. The automotive industry excels in the recovery of

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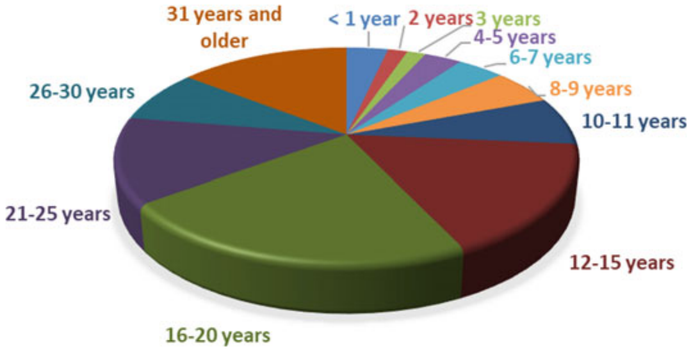


Fig. 47.1 Age of cars registered in Poland in 2017 [6]

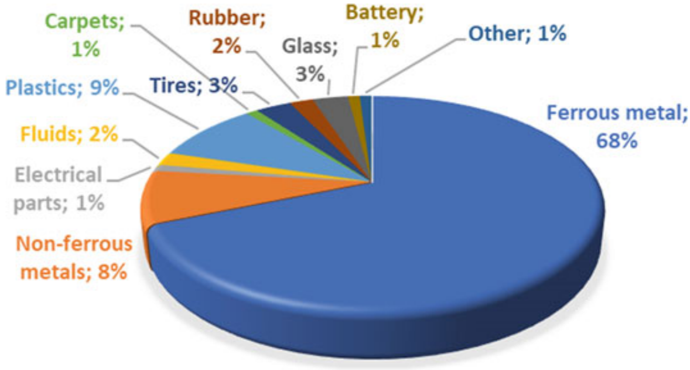


Fig. 47.2 Breakdown of car materials (by weight) [7]

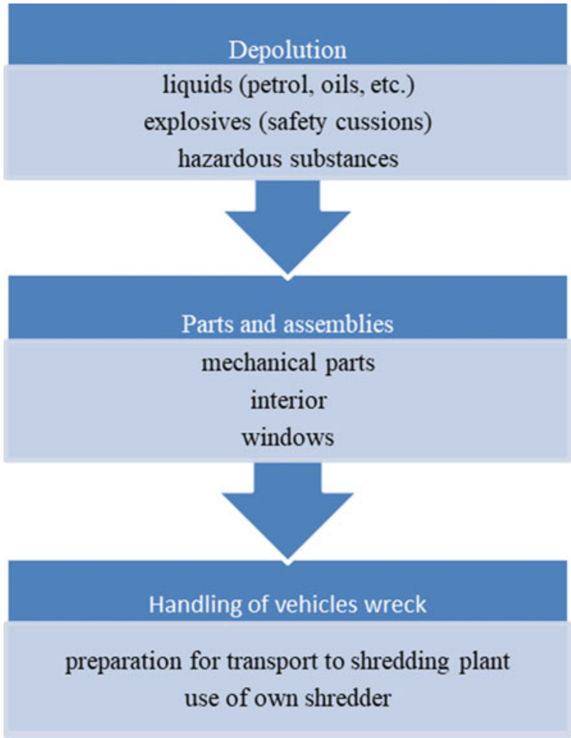
materials from scrapped vehicles. Recovered materials, components, or parts from end-of-life vehicles can be further recycled. Recycling is the basic way to reduce the negative impact of the automotive industry on the environment. This process reduces the mass of waste generated, and consequently the surface of their storage, minimizes the degradation of the natural environment as well as is a source of financial benefits (e.g., from the sale of spare parts) [4, 5].

The fundamental operation enabling recovery of factions that can be recyclable material is the process of dismantling end-of-life vehicles. The first process at the dismantling station is the removal of dangerous substances from vehicles (Fig. 47.3).

The problem of waste utilization does not only concern the withdrawal of cars from service. It also appears in the repair industry, where it is necessary to remove overspray sediments [9].

The removal of all fluids and operating gases, called the drying process, is the most important step in the dismantling process in ecological and safety terms. The following operating fluids are removed:

Fig. 47.3 General scheme of vehicle dismantling [8]



a. engine, transmission, and hydraulic oils;
b. other operating fluids (liquid fuel, coolants, as well as washer fluids and brake fluids) [10].

They may cause contamination of the land of dismantling stations and adjacent areas as well as waters due to undesirable spills in the event of improper securing of the vehicle receiving sector, storage or drying, or damage to tanks or unsealing of the installation. Oil vapors may also cause air contamination at the disassembly stations.

The dismantling of each vehicle must be carried out in an appropriate manner while maintaining the safety of the environment. In connection with the above, at each dismantling station, its individual sectors must be properly located on the site and equipped with such installations, devices, or materials that prevent, stop, or help in the elimination of possible leaks of operating fluids [10]. The average share of liquids for mid-sized vehicle is more than 20 kg [8].

The removal of fuel, overworked engine, transmission and hydraulic oils, cooling and braking fluids as well as from the sprinkler from the car is carried out using all kinds of specialist equipment. Depending on the degree of mechanization of the disassembly station, these can be vacuum devices that suck up fluids from vehicle components using suction probes for special sealed containers (separate for different types of liquids). In addition, such devices are equipped with protection against possible leakage, protecting inter alia against soiling the ground, overflowing tanks, or escaping vapors of these substances. The second type of devices, commonly used at dismantling stations, is those operating by gravity. This is due to the fact that after piercing the bottom of the fuel tank, the conduit is discharged into a hermetically sealed container. In larger dismantling stations, these devices can create a permanent installation with tanks that are built into the room wall to remove elements and hazardous substances from vehicles. In addition, in the stage of drying the vehicle, devices such as pneumatic screwdrivers (for making holes in tanks), collecting tubs mobile and fixed and supports lifted manually or pneumatically. When the recovery of liquids, which then constitute hazardous waste, takes place, mechanical pumps or pneumatic pumps are used to pump the drying devices from the drums into larger tanks. Before they are transferred to specialist recycling plants, they are stored outside the disassembly hall in the storage of operating fluids obtained from vehicles withdrawn from exploitation.

Sector removing fluids must be located on the cured, sealed, and covered space (not necessarily in the building). In addition, convenient access to storage containers for cars that collect them or pump their contents into their own tanks and transport them to these plants should be provided. As for the tanks themselves, they are single or double walled and equipped, among others, with in liquid level indicators, leakage indicators, connections (facilitating filling and emptying) and additionally in interceptor tubs or external metal coats, to improve safety against potential damage as well as leakage of hazardous substances into the environment.

Pursuant to the regulations, the stand for removing exploitation liquids from end-of-life vehicles must be equipped with an appropriate amount of sorption materials. Sorbents are all materials that are characterized by the ability to attract ions or molecules and retain them on their surface (adsorption process), either in their entire volume (absorption process) or simultaneous overlap of both phenomena (sorption process). These materials are porous solids with a large specific surface area and sorption capacity allowing the use of a small amount of them to collect and retain a large amount of liquids such as operating fluids. Proper selection of the type and amount of sorbents enables rapid neutralization of possible leakage of hazardous substances and thus provides protection of soil and groundwater [10].

47.2 Methodology of Research

The Westinghouse method has been used for studying the absorption capacity of sorbents [11]. Method involves:

– immersing 10 g of the sorbent contained in a cone of stainless steel mesh (Fig. 47.4) in the fluid for 10 min;
– standing cone with sorbent into the beaker to drain the excess substance for 5 min;
– weighting the sample and calculated the sorption capacity, from Eq. (47.1).

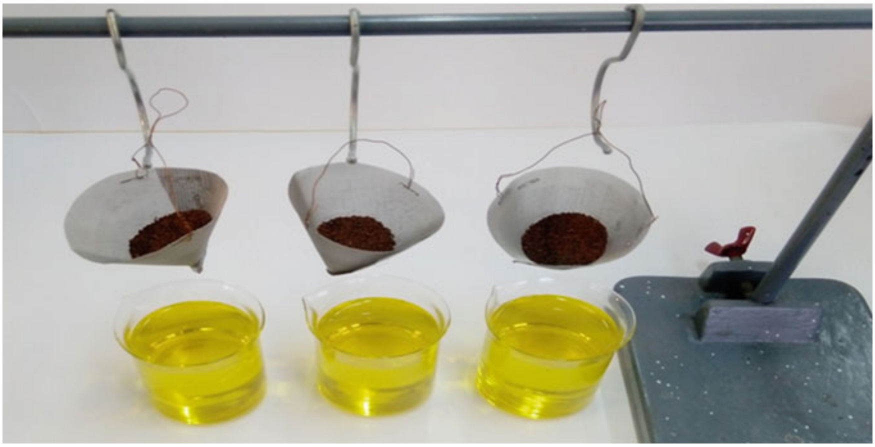


Fig. 47.4 Stand for determination of sorption capacity of sorbents

$$C = \frac{m_2 - m_1}{m_1} \quad (47.1)$$

where: C—sorption capacity, grams oil/grams sorbents; m_1—the mass of dry sorbent before oil sorption test, g; m_2—the mass of wet sorbent after sorption for 10 min, g.

Five DENSORB absorbent granules (DENIOS, Poland) were selected for the study (Fig. 47.5). All can be used on paved surfaces. Table 47.1 gives a characteristic of all tested sorbents.

Characteristics of operating fluids are shown in Table 47.2. These are liquids that are removed at the disassembly station in the process of drying out of end-of-life vehicles.

47.3 Results and Discussion

The choice of sorbent for use to remove spills based on comparing the sorption capacity. The tested sorbents differed in particle size, physical and chemical properties, so the absorbency of the tested sorbents was varied (Table 47.3). Most of the tested sorbents are universally applicable. In most cases, these sorbents were characterized by similar or lower absorption of oil substances than the oil sorbent all-weather oil binder. It showed the lowest absorbency with respect to summer washer fluid and antifreeze, while in the case of the last fluid it was practically useless (sorption capacity was 0.18 g antifreeze/g sorbent).

Determining the average value of sorbent's sorption capacity of all tested fluids allows to indicate one, the most effective (Table 47.4). Universal fine grain is very

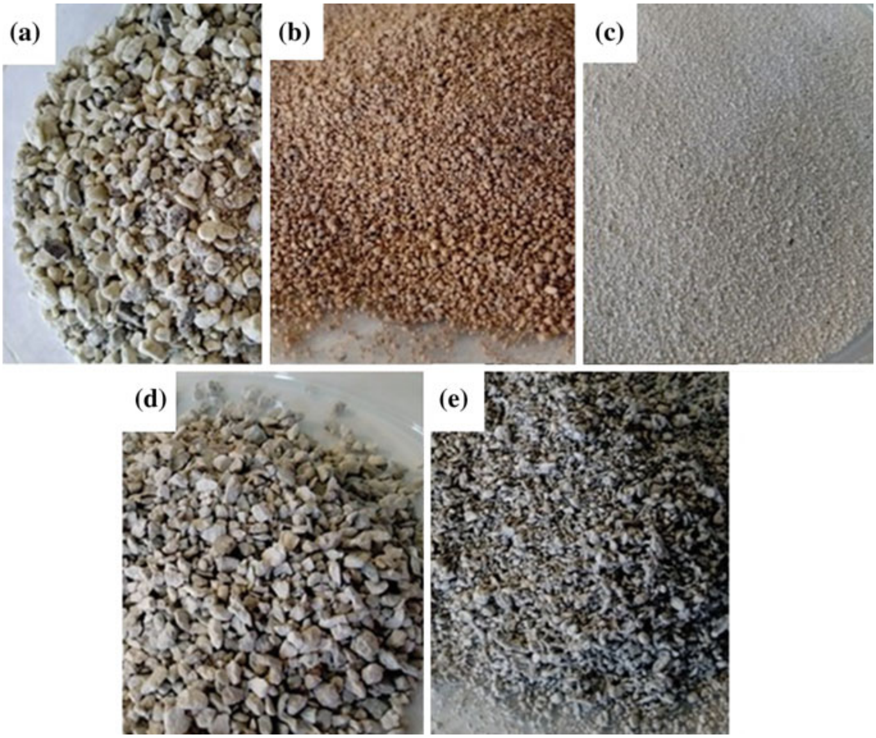


Fig. 47.5 Tested sorbents materials: DENSORB absorbent granules: **a** All-weather Oil Binder, **b** Absodan Plus, **c** Universal Fine Grain, **d** Universal Extra Coarse Granules, **e** Universal GranSorb

fine grain mineral sorbent; therefore, its contact surface with fluids is the largest. It is non-flammable in an unused state. Because of the light color (Fig. 47.5c), the identification of saturation level is ease.

The process of dismantling each vehicle must be carried out in an appropriate manner while maintaining the safety of the environment. In connection with the above, at each dismantling station, its individual sectors must be properly located on the site and equipped with such installations, devices, or materials that prevent, stop, or help in the elimination of possible leaks of operating fluids. Such materials include sorbents, whose usefulness is primarily determined on the basis of sorption capacity. Due to the variety of operating fluids removed from vehicles, it is worth looking for a universal sorbent. Limiting to one, absorbent material will shorten the employee's response time during emergency leakage, which will reduce the environmental impact of operating fluids.

Table 47.1 Characteristics of tested sorbents [12]

Sorbent	Type of material	Application	Granule size max., mm	Grain size min., mm	Bulk density, g/cm^3
All-weather Oil Binder	Polyurethane foam-based granulate	Oil	4.0	0.13	0.405
Absodan Plus	Moler-based mineral granules (calcinated)	Universal	1.0	0.50	0.533
Universal Fine Grain	Mineral granules based on calcium silicate hydrate	Universal	1.0	0.13	0.595
Universal Extra Coarse Granules	Sepiolite-based mineral granules	Universal	6.0	0.50	0.720
Universal GranSorb	Granules based on recycled cellulose	Universal	3.4	0.40	0.512

47.4 Conclusion

In order to limit the negative impact of a disassembly station on the environment, the hazardous substance removal sector should be properly protected. In the case of drying cars from operating fluids, sorbents are one of the most important materials that are to protect the area of the dismantling station against contamination. The effective protection of soil and groundwater depends on their absorbency and universality. The absorption of selected sorbents was determined by the experimental Westinghouse method. The sorption capacity of sorbents was determined using eight different types of operating fluids: summer and winter washer fluids, antifreeze, brake fluid, transmission fluid, engine fluid, diesel, and gasoline. The most universal sorbent, characterized by high absorption of operating fluids, was mineral sorbent Universal Fine Grain.

Table 47.2 Characteristics of operating fuels

Operating fluid	Composition of mixture	CAS number	Producer
Summer windshield washer fluid	Water Methanol Benzisothiazolinone Methylisothiazolinone	7732-18-5 67-56-1 2634-33-5 268-2-20-4	Norauto
Winter windshield washer fluid	Ethanol (<30%) Non-ionic surfactants (<5%) Silica nanoparticles Glycerin Colorant	64-17-5 N/A 7440-21-3 56-81-5 N/A	Norauto
Antifreeze	Ethylene glycol Sodium 2-ethylhexanoate	107-21-1 19766-89-3	Platinum oil
Brake fluid	Triethylene glycol monobutyl ether (20–45%) Diethylene glycol (10–25%) 2-(2-Butoxyethoxy)-ethanol (1–3%) 2-(2-Methoxyethoxy)ethanol (<3%)	143-22-6 111-46-6 112-34-5 111-77-3	Frodo
Transmission fluid	Distillates (petroleum)	64742-65-0	Norauto
Engine fluid	Zinc dialkyl dithiophosphate (0.52–1.029 wt%) Calcium long chain alkylphenol sulfide (0.1 < c < 0.50 wt%) Organomolybdenum amide (0.1 < c < 0.50 wt%)	68649-42-3 90480-91-4 445409-27-8	Orlen oil
Diesel	Diesel oil No. 2—engine fuels diesel	68476-34-6	Circle K
Gasoline	Gasoline (<100% v/v) ETBE (≤15% v/v) MTBE (≤15% v/v) Ethanol (≤15% v/v)	86290-81-5 637-92-3 1634-04-4 64-17-5	Circle K

Table 47.3 Operating fluids sorption capacity (grams fluid/grams sorbent)

Operating fluid	Sorption capacity				
	All-weather Oil Binder	Absodan Plus	Universal Fine Grain	Universal Extra Coarse Granules	Universal GranSorb
Summer washer fluid	0.63	1.02	1.12	0.75	1.03
Winter washer fluid	1.67	0.98	1.07	0.64	1.04
Antifreeze	0.18	1.24	1.44	0.79	1.33
Brake fluid	1.55	1.22	1.49	0.52	0.91
Transmission fluid	1.48	1.12	1.20	0.42	1.06
Engine fluid	1.58	1.12	1.15	0.43	1.00
Diesel	1.02	0.95	1.09	0.36	0.64
Gasoline	0.88	0.67	0.86	0.26	0.41

Table 47.4 Average value of sorption capacity (grams fluid/grams sorbent)

Sorbent	Average value of sorption capacity
All-weather Oil Binder	1.12 ± 0.54
Absodan Plus	1.04 ± 0.18
Universal Fine Grain	1.18 ± 0.20
Universal Extra Coarse Granules	0.52 ± 0.19
Universal GranSorb	0.93 ± 0.28

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Chapter 48
Road Transport of High Consequence Dangerous Goods—Assessment of Terrorist Threat (Case Study)

Agnieszka Ubowska and Renata Dobrzyńska

Abstract The actions of terrorists, which are intensifying in recent years, result in strengthening the law, so that terrorist attacks can be better prevented and threats counteracted. These changes also included provisions on the transport of dangerous goods, among which a group of materials was selected that could become a tool in the hands of terrorists. These are high consequence dangerous goods. Consequences of an incident with the use of acetone tanker for terrorist purpose were presented. In order to analyze the impact of the threat, the ALOHA program was used. The conditions of the incident that took place in Berlin in December 2016 were adopted. The most likely result of the attack was burning acetone which formed a pool fire after unsealing the tank. The resulting thermal radiation would kill numerous people. The results of the simulation confirm the importance of the development of transportation and its security.

48.1 Introduction

In recent years, terrorism involving the use of trucks has occurred in Europe. The assassins drove speeding vehicles into crowds of people, choosing metropolises and their main arteries. An example is the attack in Germany, which took place in December 2016, where a man plowed a lorry into a Christmas market in the heart of Berlin killing 12 people and leaving 50 injured [1]. The stolen truck was carrying steel. What would happen if a vehicle carrying dangerous goods was abducted instead?

Vehicles transporting hazardous materials like flammable or toxic substances can be potentially hijacked and blown up. The share of dangerous goods transport in the total transport of each European country in 2017 was around 4%. Poland had a lower share (2.6%) [2]. Over half of the transported materials are flammable liquids (Fig. 48.1). High-risk goods are among the transported goods. This group was

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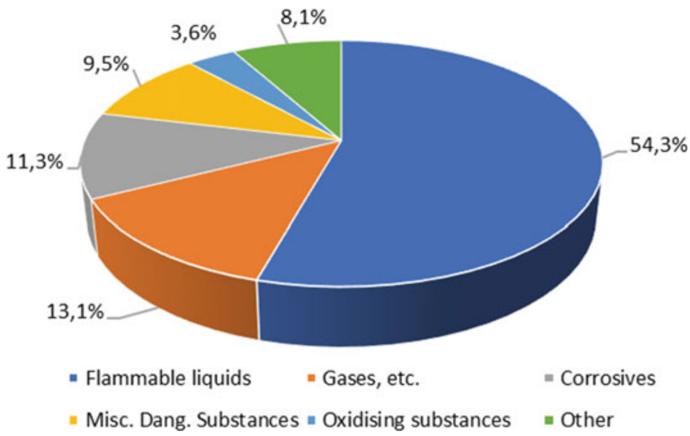

Fig. 48.1 Road freight transport of dangerous goods by type of goods [2]

separated in 2005. These are materials *(…) which have the potential for misuse in a terrorist event and which may, as a result, produce serious consequences such as mass casualties, mass destruction or, particularly for Class 7, mass socio-economic disruption* [3]. The classification of dangerous goods in this group is based on the amount of transported goods in accordance with Table 48.1.

In order to reduce the risk that may arise from the use of dangerous goods for deliberate acts of a criminal nature (theft of means of transport used to move these goods, theft of dangerous goods being transported, their improper use), ADR provisions put in place additional security measures related to their transport. During their transport, special procedures should be applied, and the carrier is obliged to create and implement a security plan [4–6].

In order to minimize security risks carriers, consignors and other participants engaged in the transport of high consequence dangerous goods must adopt, implement and comply with a security plan. High consequence dangerous goods security plans should refer to the ADR guidelines and include the following elements:

– specific allocation of responsibilities to competent and qualified persons,
– list of dangerous goods or types of dangerous goods concerned,
– review of current operations and assessment of security risk,
– list of measures to reduce the risk of exposure in accordance with the roles and responsibilities of the participants' inclusive training methods, security policies, operating practices and necessary equipment and tools for hazard reduction,
– effective and up-to-date procedures for reporting and dealing with security threats, breaches of security and security-related incidents,
– procedures or the evaluation, testing, periodic review and update of security plans,
– measures to ensure the physical security of the transport information contained in the plan,

Table 48.1 High consequence dangerous goods [3]

Class	Division	Substance or article	Quantity		
			Tank, l	Bulk, kg	Packages, kg
1	1.1	Explosives	[a]	[a]	0
	1.2	Explosives	[a]	[a]	0
	1.3	Compatibility Group C Explosives	[a]	[a]	0
	1.5	Explosives	0	[a]	0
2		Flammable gases (classification codes including only the letter F)	3000	[a]	[b]
		Toxic gases (classification codes including letters T, TF, TC, TO, TFC or TOC) excluding aerosols	0	[a]	0
3		Flammable liquids of packing Groups I and II	3000	[a]	[b]
		Desensitized explosives	[a]	[a]	0
4.1		Desensitized explosives	[a]	[a]	0
4.2		Packing Group I substances	3000	[a]	[b]
4.3		Packing Group I substances	3000	[a]	[b]
5.1		Oxidizing liquids of packing Group I	3000	[a]	[b]
		Perchlorates, ammonium nitrate and ammonium nitrate fertilizers	3000	3000	[b]
6.1		Toxic substances of packing Group I	0	[a]	0
6.2		Infectious substances of Category A	[a]	[a]	0
7		Radioactive material	3000 A_1 (special form) or 3000 A_2, as applicable, in Type B or Type C packages		
8		Corrosive substances of packing Group I	3000	[a]	[b]

[a]Not relevant
[b]The provisions of 1.10.3 do not apply, whatever the quantity is
[c]A value indicated in this column is applicable only if carriage in tanks is authorized, in accordance with Chapter 3.2, Table A, column (10) or (12). For substances that are not authorized for carriage in tanks, the instruction in this column is not relevant
[d]A value indicated in this column is applicable only if carriage in bulk is authorized, in accordance with Chapter 3.2, Table A, column (10) or (17). For substances that are not authorized for carriage in bulk, the instruction in this column is not relevant

– measures to ensure that the distribution of information relating to the transport operation contained in the security plan is limited, as far as possible, to only those who need to have it [2].

Participants in the transport process should cooperate with each other and with the competent authorities in the exchange of information on threats, the use of appropriate security measures and proceedings in case of security incidents.

Vehicles carrying high consequence dangerous goods should have appropriate systems and devices to protect the vehicle and cargo from theft. The use of these measures must not lead to difficulties in the case of rescue and fire-fighting operations [2, 7, 8].

48.2 Methodology of Research

The ALOHA program (Areal Locations of Hazardous Atmospheres, Version 5.4.7) together with the cooperating MARPLOT program (Mapping Applications for Response, Planning, and Local Operational Tasks), which is part of the package CAMEO software, were used to assess the impact on various potential event scenarios during the collision of a tanker transporting high consequence dangerous goods. ALOHA is a program used to assess the release of dangerous chemical substances in the form of vapor/gas into the atmosphere, which allows to estimate the chemical cloud diffusion based on the toxicological and physicochemical properties of the released substance. It can model flammable gas clouds, Boiling Liquid Expanding Vapor Explosions (BLEVEs), jet fires, pool fires, and vapor cloud explosions. The heavy gas model was adopted for the calculations. ALOHA finds the flammable area by using 60% of the lower explosive limit value (LEL). The LEL value for acetone is 26,000 ppm [9].

The subject of the analysis was the scenario of a potential collision of a tanker transporting acetone (Class 3 Flammable liquids) assuming unsealing of 33×8 cm, resulting from mechanical damage. Damage occurs at half the height of the tank. In this scenario, it was assumed that the incident occurred on December 19, 2016, at the Breitscheidplatz in Berlin, i.e., in the place and time when the actual truck attack occurred. The following weather conditions were adopted:

– temperature: 3 °C,
– humidity 81%,
– atmospheric pressure: 1031 hPa,
– wind blowing from 170° South to North, 3 m/s,
– passing clouds [10].

Acetone is the most popular solvent used industrially. It is a colorless liquid which dissolves in water. Acetone evaporates easily. Its presence can be simply identified due to its distinctive characteristic smell. The most important information about acetone from the point of view of the road accident is presented below:

Table 48.2 Technical specification of jumbo tanker [13]

Parameter	Value
Tanker code according to ADR	L4BH
Classes of goods admitted for transport according to ADR	3, 4.1, 5.1, 6.1, 8, 9
Width	2550 mm
Length	13,400 mm
Diameter	2150/2300 mm
Height	3780 mm
Tank capacity	51,000–53,000 dm^3

a. fire hazard:

- highly flammable—easily ignited by heat, sparks or flames,
- vapors may form explosive mixtures with air,
- vapors may travel to source of ignition and flashback, most are heavier than air,
- runoff to sewer may create fire or explosion hazard,
- containers may explode when heated,

b. health hazard:

- inhalation: vapor irritating to eyes and mucous membranes,
- ingestion: low order of toxicity but very irritating to mucous membranes,
- skin: prolonged excessive contact causes defatting of the skin, possibly leading to dermatitis,

c. isolation and evacuation:

- as an immediate precautionary measure, isolate spill or leak area for at least 50 m in all directions,
- for large spills, consider initial downwind evacuation for at least 300 m,
- in case of tank truck fire isolate for 800 m in all directions; also, consider initial evacuation for 800 m in all directions [11, 12].

It was assumed that the jumbo tanker was damaged halfway up the tank. Its technical parameters are listed in Table 48.2. The tanker was filled in 79%.

48.3 Results and Discussion

Three types of tank failure were considered:

(a) leaking tank—acetone is not burning and forms an evaporating puddle,
(b) leaking tank—acetone is burning and forms a pool fire,
(c) BLEVE—tank explodes and acetone burns in a fireball.

Table 48.3 Toxic area of vapor cloud

Threat zone	Range, m
AEGL-3 (60 min) = 5700 ppm	96
AEGL-2 (60 min) = 3200 ppm	147
AEGL-1 (60 min) = 200 ppm	850

Table 48.4 Flammable area of vapor cloud

Threat zone	Range, m
60% LEL = 15,600 ppm (flame pockets)	38
10% LEL = 2600 ppm	169

48.3.1 Leaking Tank—Acetone Is Not Burning

Total amount released during the event was 16,970 kg. Maximum average sustained release rate was 352 kg/min. If the acetone escaped as a liquid and formed an evaporating puddle, the puddle would have spread to a diameter of 88 m. In the case of evaporating puddle, there were toxic and flammable areas of vapor cloud. Tables 48.3 and 48.4, respectively, present the analysis results of the toxic and flammable areas of vapor cloud. Threat zones were marked on the map of Berlin (Figs. 48.2 and 48.3).

Acetone is relatively less toxic than many other industrial solvents. However, at high concentrations, acetone vapor can cause central nervous system depression, cardiorespiratory failure and death. As previously mentioned, acetone acts to irritate mucous membranes. At a distance of 96 m from the tank (according to the wind direction), there is the airborne concentration of acetone above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death (for a 60 min exposure duration). AEGL-2 (the airborne concentration of acetone above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape) reaches 147 m. The recommended insulation distance (at least 300 m downwind) is therefore sufficient. Immediate evacuation of people from this area would exclude toxic effects.

The more dangerous area, where flame pockets could occur, reached 38 m (Table 48.4). Threat zone greater than 15,600 ppm was not drawn (Fig. 48.3) because effects of near-field patchiness made dispersion predictions less reliable for short distances. The acetone-air concentration is below the lower explosive limit. The risk that the cloud could inflame is negligible.

48.3.2 Leaking Tank—Acetone Is Burning

As a result of damage to the tanker, a puddle of 24 m in diameter would spread. If the puddle was ignited by a spark or a flame, acetone would burn. The maximum flame

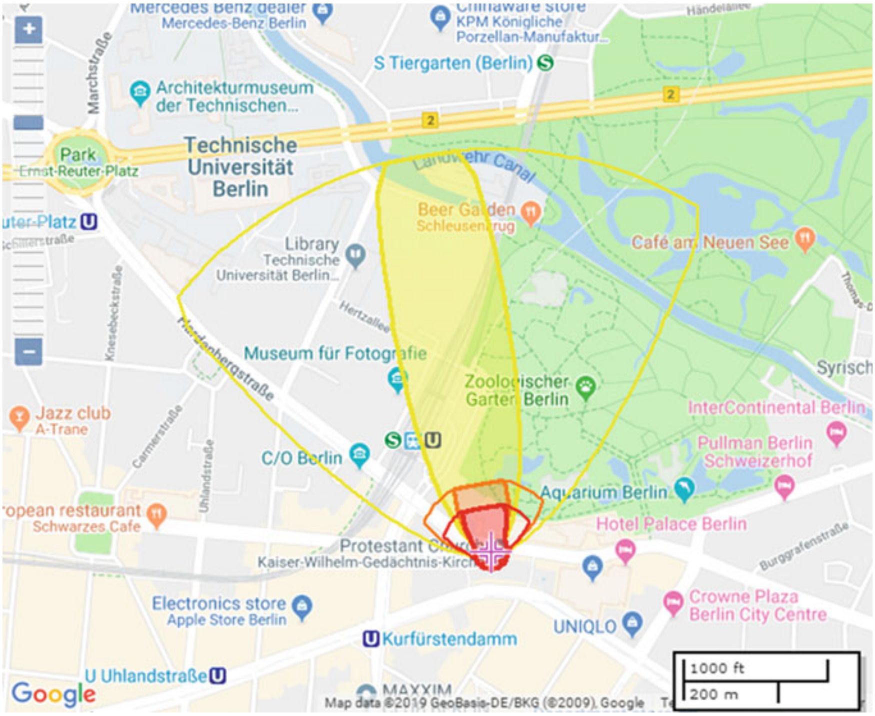

Fig. 48.2 Toxic area of vapor cloud (– AEGL-3, – AEGL-2, – AEGL -1)

length for the adopted scenario was 23 m. 11,432 kg of acetone burned in 23 min The maximum burn rate was 1220 kg/min. The thermal radiation from pool fire is presented in Table 48.5. Figure 48.4 shows the thermal radiation from pool fire on the map of Berlin.

Due to the analyzed nature of the event (Christmas market), there was a high probability of ignition sources. In the event of acetone ignition, people who were within 60 s at a distance of 34 m could die. Over the area of over 3600 m^2, there could be up to several hundred people. Panic, which accompanies such situations, may prevent escape from that area. People within 49 m of the tanker would experience second-degree burns.

48.3.3 Tank Explodes—Acetone Burns in a Fireball

The effects of BLEVE depend, among other things, on the mass of the substance in the tank. In the event of an explosion of the acetone tank and the entire contents of the tank would ignite, a fireball with a diameter of 183 m would be created. The burn duration would be 12 s. BLEVE hazards include thermal radiation (Table 48.6).

Fig. 48.3 Flammable area of vapor cloud greater than 2600 ppm

Table 48.5 Thermal radiation from pool fire

Threat zone	Range, m
10.0 kW/m^2 = potentially lethal within 60 s	34
5.0 kW/m^2 = second-degree burns within 60 s	49
2.0 kW/m^2 = pain within 60 s	76

A common BLEVE scenario happens when a container of liquefied gas is heated by fire, increasing the pressure within the container until the tank ruptures and fails. This scenario is therefore the least likely.

48.4 Conclusion

The results of the analysis, using the ALOHA program, showed that in the event of unsealing the acetone tank the serious consequences of the accident could have a much greater impact than in the case of a terrorist attack using a truck. In the adopted scenario, the most likely threat is the burning of acetone and it is forming a pool fire. The intensity of thermal radiation that could cause death within a minute would

Fig. 48.4 Thermal radiation from pool fire (– 10.0 kW/m^2, – 5.0 kW/m^2, – 2.0 kW/m^2)

Table 48.6 Thermal radiation from fireball

Threat zone	Range, m
10.0 kW/m^2 = potentially lethal within 60 s	334
5.0 kW/m^2 = second-degree burns within 60 s	476
2.0 kW/m^2 = pain within 60 s	746

cover the area within a radius of 34 m. This is a large range considering the time and place of the incident. That is why it is so important to monitor and properly supervise the transport of high consequence dangerous goods.

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Chapter 49
The Impact of Equipment Materials on the Fire Safety of Coaches

Renata Dobrzyńska

Abstract Fires of means of public transport may pose a serious threat to human health and life and cause damage to the environment and economic losses. The majority of them are fires of coaches. They represent approximately 80% of fires all means of public transport. Equipment materials may have an impact on the development of the coach fire. The greatest fire hazard can be caused by materials of coach seats: polyurethane foams and back cover materials. Flammability tests of such materials required by Regulation No 118 were carried out: vertical burning rates and melting behaviour of materials. The assessment of the fire hazard of coaches was made on the basis of the obtained results. The minimum requirements set out in Regulation No 118 of the Economic Commission for Europe of the United Nations (UNECE) [1] may not be sufficient to ensure the coaches fire safety.

49.1 Introduction

Statistical data on public transport fires in Poland in 2010–2018 indicate a high share of coach fires [2]. Table 49.1 shows the number of fires in Poland of all means of public transport and coaches in 2010–2018. Coach fires represent approximately 80% of fires all means of public transport (Fig. 49.1).

Fire safety of means of transport depends largely on the combustion properties of materials constituting structural elements and furnishing. These properties include inter alia: ignitability, smoke formation, toxicity of thermal decomposition products and combustion of these materials, intensity of heat release and rate of flame spread on the material surface. Both the course of the fire and the safety of people in the burning vehicle depend on these properties of materials [3–5]. There are materials available in the market that can slow down the course of fire or can cause its growth, posing a direct threat to people's health and life.

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Table 49.1 Number of fires of all means of public transport in Poland [2]

	Year								
	2010	2011	2012	2013	2014	2015	2016	2017	2018
Number of fires of means of public transport TOTAL	339	286	284	233	228	224	204	216	223
Number of coach fires	240	207	219	191	182	178	165	177	181
Number of passenger railway fires	66	55	41	26	31	26	28	24	27
Number of passenger aircraft fires	0	0	0	0	2	0	0	0	1
Number of passenger ships and ferries fires	3	0	0	1	0	1	2	0	0

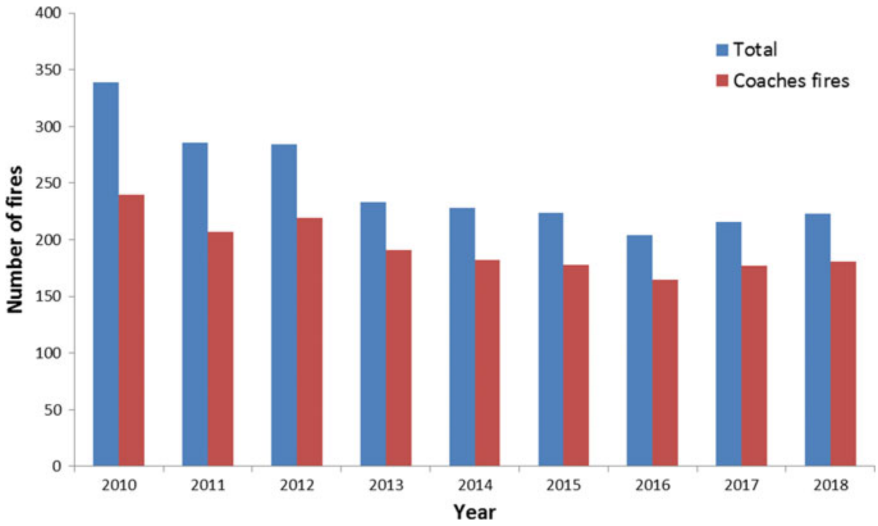

Fig. 49.1 Number of fires of all means of public transport and coaches in Poland in 2010–2018

The coach fire is very dynamic. Most often, it ends with a complete burning down of the vehicle. The requirements for materials constituting the furnishing for coaches are specified in Regulation No 118 of the Economic Commission for Europe of the United Nations (UNECE). This Regulation applies to the burning behaviour (ignitability, burning rate and melting behaviour) of materials used in vehicles of categories M_3, Classes II and III.

M_3 category vehicles are used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes. "Class II" means vehicles constructed principally for the carriage of seated passengers, and designed to allow the carriage of standing passengers in the gangway and/or in an area which does not exceed the space provided for two double seats. "Class III" means vehicles constructed exclusively for the carriage of seated passengers [6].

The requirements are presented in Table 49.2.

If materials meet the requirements of vertical burning rate, then they are considered to fulfil the requirements of horizontal burning rate too.

49.2 Burning Behaviour Tests of Furnishing Materials Used in Coaches

Materials available in the Polish market, which due to their properties could be useful for the production of coach seats, were selected for flammable properties' tests.

Table 49.2 Requirements for materials acc. Regulation No 118 [1]

Material	Test Method	Measured parameter	Evaluation criteria
(a) Material(s) and composite material(s) installed in a horizontal position in the interior compartment; and (b) Insulation material(s) installed in a horizontal position in the engine compartment and any separate heating compartment	Regulation No 118 Annex 6	Horizontal burning rate *B*	Taking the worst test results into account, *B* < 100 mm/min or if the flame extinguishes before reaching the last measuring point
(a) Material(s) and composite material(s) installed more than 500 mm above the seat cushion and in the roof of the vehicle, (b) Insulation material(s) installed in the engine compartment and any separate heating compartment	Regulation No 118 Annex 7	Melting behaviour	Taking the worst test results into account, no drop is formed which ignites the cotton wool
(a) Material(s) and composite material(s) installed in a vertical position in the interior compartment, (b) Insulation material(s) installed in a vertical position in the engine compartment and any separate heating compartment	Regulation No 118 Annex 8	Vertical burning rate V_i	Taking the worst test results into account V_i < 100 mm/min or if the flame extinguishes before the destruction of one of the first marker threads occurred

The tested materials were: polyurethane foams with different densities and compositions (PU1, PU2), polycarbonate/acrylonitrile-butadiene-styrene composite (PC/ABS), polypropylene (PP) and Polyamide 6.6 (PA 6.6). Due to trade secrets, the names of products and their exact composition were not given.

49.2.1 Test to Determine the Melting Behaviour of Materials

Method. A sample is placed in a horizontal position and is exposed to an electric radiator. A receptacle is positioned under the specimen to collect the resultant drops.

Some cotton wool is put in this receptacle in order to verify if any drop is flaming. The radiated heat from the apparatus, measured on a surface which is situated parallel to the surface of the radiator at a distance of 30 mm, shall be 3 W/cm^2.

The test samples shall measure: 70 mm × 70 mm. Samples shall be taken in the same way from finished products, when the shape of the product permits. When the thickness of the product is more than 13 mm, it shall be reduced to 13 mm. The total mass of the sample to be tested shall be at least 2 g. If the mass of one sample is less, a sufficient number of samples shall be added.

When the radiator is positioned above the sample, timing is started. If the material melts or deforms, the height of the radiator is modified to maintain the distance of 30 mm. If the material ignites, the radiator is put aside three seconds afterwards. It is brought back in position when the flame has extinguished, and the same procedure is repeated as frequently as necessary during the first five minutes of the test. After the fifth minute of the test:

– if the sample has extinguished (whether or not it has ignited during the first five minutes of the test), leave the radiator in position even if the sample reignites;
– if the material is flaming, await extinction before bringing the radiator into position again.

In either case, the test shall be continued for an additional five minutes.

Observed phenomena shall be noted in the test report, such as:

– the fall of drops, if any, whether flaming or not;
– if ignition of the cotton wool has taken place [1].

49.2.2 Test to Determine the Vertical Burning Rate of Materials

Method. Test consists of exposing samples, held in a vertical position, to a flame and determining the speed of propagation of the flame over the material to be tested.

The specimen holder shall consist of a rectangular frame of 560 mm high and shall have two rigidly connected parallel rods spaced 150 mm apart on which pins shall be fitted for mounting the test specimen which is located in a plane at least 20 mm from the frame. The mounting pins shall be not greater than 2 mm in diameter and at least 27 mm long. The pins shall be located on the parallel rods. The frame shall be fitted onto suitable support to maintain the rods in a vertical orientation during testing.

The gas supplied to the burner can be either commercial propane gas or commercial butane gas. The burner shall be positioned in front of, but below, the specimen such that it lies in a plane passing through the vertical centreline of the specimen and perpendicular to its face, such that the longitudinal axis is inclined upwards at 30° to the vertical towards the lower edge of the specimen. The distance between the tip of the burner and the lower edge of the specimen shall be 20 mm.

The samples dimensions are 560 × 170 mm. When the thickness of the sample is more than 13 mm, it shall be reduced to 13 mm.

The specimen shall be placed after the marker threads have been located on the pins of the test frame. The frame shall be fitted on the support so that the specimen is vertical. The marker threads shall be attached horizontally in front of and behind the specimen. The flame shall be applied to the specimen for 5 s. Ignition shall be deemed to have occurred if flaming of the specimen continues for 5 s after removal of the igniting flame. If ignition does not occur, the flame shall be applied for 15 s to another conditioned specimen.

The following times, in seconds, shall be measured:

(a) from the start of the application of the igniting flame to the severance of one of the first marker threads (t_1);
(b) from the start of the application of the igniting flame to the severance of one the second marker threads (t_2);
(c) from the start of the application of the igniting flame to the severance of one the third marker threads (t_3) and the corresponding burnt distances: d_1, d_2 and d_3 in mm.

The burning rate V_1 and the rates V_2 and V_3 shall be calculated (for each sample if the flame reaches at least one of the first marker threads) as follows:

$$V_i = 60 d_i / t_i \tag{49.1}$$

If the sample does not ignite or does not continue burning after the burner has been extinguished or if the flame extinguishes before the destruction of one of the first marker threads occurred, so that no burning time is measured, the burning rate is considered to be 0 mm/min [1].

49.2.3 Result and Discussion

Test results to determine the melting behaviour of selected materials. As a result of the test, the worst result of the three samples is taking into account. The results to determine the melting behaviour test of materials are shown in Table 49.3.

Table 49.3 Test results to determine the melting behaviour of materials

Tested material	PU1	PU1	PC/ABS	PP	PA 6.6
Drop is formed which ignites the cotton wool	No	No	No	Yes	No
Meeting the requirements of Annex 7 Regulation No 118	Yes	Yes	Yes	No	Yes

Fig. 49.2 PU1 sample before the test

Fig. 49.3 PU1 sample after the test

During the tests, it was observed that the PP samples burned completely after 370 s and drops were formed which ignited the cotton wool, while tested polyurethane foams did not burn with flame, only their flameless thermal decomposition occurred.

Figures 49.2 and 49.3 present a view of polyurethane foam samples before and after the test.

Test results to determine the vertical burning rate of materials. As a result of the test, the worst result of the three samples is taking into account. Test results to determine the vertical burning rate of selected materials are shown in Table 49.4, taking the worst test result into account.

Table 49.4 Test results to determine the vertical burning rate of materials

Tested material	PU1	PU2	PC/ABS	PP	PA 6.6
The flame time used, s	15	15	15	15	15
Time from the start of the application of the igniting flame to the severance of one of the first marker threads t_1, s	16	–	–	351	848
Time from the start of the application of the igniting flame to the severance of one the second marker threads t_2, s	23	–	–	408	–
Time from the start of the application of the igniting flame to the severance of one the third marker threads t_3, s	30	–	–	646	–
Burning time of the sample, s	45	20	15	744	963
Length of sample burn, mm	560	120	15	560	240
Burning drops	Yes	No	Yes	Yes	Yes
The burning rate V_1, mm/min	900	0	0	41	17
The burning rate V_2, mm/min	1017	0	0	57	0
The burning rate V_3, mm/min	1080	0	0	50	0
Meeting the requirements of Annex 8 Regulation No 118	No	Yes	Yes	Yes	Yes

The PU1 samples burned completely (Fig. 49.4a). The polypropylene samples also burned completely, but the burning rates were less than 100 mm/min. Polyurethane foam samples (PU2) and ABS PC samples did not ignite after the burner removing, so the burning rate is considered to be 0 mm/min. The tested PA 6.6 samples ignited, the igniting flames the severance of one of the first marker threads, but the flame extinguishes before the destruction of one the second marker threads. In this case, taking the worst test result into account, the burning rate was 17 mm/min (Fig. 49.4b).

Fulfilling the requirements of Regulation No 118 by the materials tested is shown in Table 49.5.

49.3 Conclusions

The materials used in coaches can cause fire hazard and affect the course of a coach fire. Not all materials tested do meet the requirements of Regulation No 118 (Table 49.5). Polyurethane foam PU1 and polypropylene tested cannot be used on coaches. The remaining materials tested (PU2, PC/ABS, PA 6.6) meet the evaluation criteria of both Annexes 7 and 8. However, it should be remembered that the rate

Fig. 49.4 Samples during the test: **a** PU1, **b** PC/ABS

Table 49.5 Fulfilling the requirements of Regulation No 118 by the materials tested

Tested material	PU1	PU2	PC/ABS	PP	PA 6.6
Meeting the requirements of Annex 7 Regulation No 118	Yes	Yes	Yes	No	Yes
Meeting the requirements of Annex 8 Regulation No 118	No	Yes	Yes	Yes	Yes
Meeting the requirements of Regulation No 118	**No**	**Yes**	**Yes**	**No**	**Yes**

of vertical combustion of materials and melting are not sufficient to assess the fire hazard of coaches. These are the minimum criteria. The development of fire and people's life will also depend on other fire hazard factors such as smoke, toxicity products of thermal decomposition and combustion of materials.

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Chapter 50
Energy Efficiency of Renewables to Cover Energy Demands of Petrol Station Buildings

Karolina Kurtz-Orecka and Wojciech Tuchowski

Abstract Petrol stations are an important infrastructure that support the development of the transportation industry. This paper focuses on the analysis of the energy efficiency of renewables to cover energy demands for space heating and cooling of petrol station buildings, in Central Europe climate. The analysis was performed as a case study on a typical petrol station building located in urban area. Due to cold climate conditions and quite high surface area-to-volume ratio, the passive building standard of the building envelope was introduced. The study has been focused on the comparison of energy efficiency of the typical gas station building with two different variants of energy source for heating, cooling, and water heating—typical one and sustainable one. The typical solution includes the condenser gas boiler for heating and water heating modes, and the air-source heat pump for cooling mode. In the sustainable variant, a reversible air-source heat pump solution has been proposed that allows for space heating and cooling as well as for the preparation of hot water all year round. In this variant, four refrigerants (R600a, R290, R1234ze, and R134a) were taken into consideration. As a result of the conducted analyzes, a high efficiency of the energy source in the form of the reversible air-source heat pump was found. The use of the air-source heat pump allows for a significant reduction of the annual final energy demands in the analyzed petrol station building compared to the use of a traditional gas heat source.

50.1 Introduction

Petrol stations (also known as service stations, filling stations, fuel stations, gas stations, gasoline stations or traffic stations [1]) are an important infrastructure that support the development of the transportation industry that significantly contributes to the European economy and industrial development. Filling stations buildings, like other building stock, are responsible for approximately 36% of all carbon emissions

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in the Union [2, 3]. Taking into account that almost 50% Union's final energy consumption is used for space heating and cooling, of which 80% is used in different types of buildings [2]. Energy used for space heating, ventilation, and space cooling systems represents over 50% of building energy demands in cold climates [4, 5], such as the climate of Central Europe. HVAC systems are by far the largest users of energy in commercial buildings, as such petrol–gas stations; therefore in order to optimize energy use, their energy efficiency is sought. And in this case, according to the recast of the directive on energy performance of buildings [2] the Union's energy efficiency ambitions are straight linked to considering deployment of renewables [2].

Petrol stations are an essential part of the modern world and they have numerous negative effects on the environment. Environmental concerns in petrol stations include: diesel and petrol spills, storm water pollution, soil and groundwater contamination, vapor recovery, and carbon emission from energy use [6–8].

Deep research in the field of sustainable design of petrol stations in Nigeria was carried out by Abdullahi and Adedayo [6]. Although authors took up their issues of necessary of reducing the resources' use (raw materials, water, and energy), their research is inconsistent with the Central Europe climate. The works of European researchers, such as [8, 9 or 10], are focused on the assessment of filling stations environmental impact than issues of their facilities energy use. The work of Jovanović and co-workers [11] sheds some light on the subject of the energy efficiency of petrol stations and the use of renewables for covering energy demands of their facilities, such as BAT with any particular examples.

This paper focuses on the analysis of the energy efficiency of renewables to cover energy demands for space heating and cooling of petrol station buildings, in Central Europe climate. The comparison of energy efficiency effect of applying air heat pump instead of a traditional solution using a natural gas as a fuel. Additional photovoltaic system was taken under consideration.

50.2 Analysis of Factors Affecting Energy Consumption of Petrol Stations

Most of the petrol stations located in urban areas and next to the highways operate retail outlets such as shops, catering point, car wash, and other service areas. Both general layout and site facilities and building room layout can influence the energy consumption of petrol station in operation. Electric energy, natural gas, and heating power are the main forms of energy consumed in operation steps. In relation to the petrol station buildings themselves, electric energy is mainly used for lightning, ventilation, and other facilities, and natural gas and heating power is mainly used for covering heating demands. There are several other factors that affect petrol station operation steps. These mainly include, among others selection of filling station site and design functional area, utilization of energy-saving materials, design during station construction, and use of energy-saving facilities [6].

50.2.1 Petrol Station Buildings

A petrol station building with full service should include service occupancy, office occupancy, production auxiliary rooms, life auxiliary rooms, and other facilities. The layout of both service occupancy and office occupancy is related to energy consumption. The petrol station building should keep energy conservation and emission reduction and ensure green and low-carbon environment. In the design of filling station buildings, energy conservation design methods, application of energy-saving materials, and measurements can influence the energy consumption. Reasonable shape coefficient (surface area-to-volume ratio, SA:V), window-to-wall ratio (GR), external sunshade, window opening area, natural lightning in design, energy-saving and thermal insulation material in construction can also efficiently decrease the energy consumption of petrol station building operation.

50.2.2 Supporting Facilities and Equipment of Filling Stations

Green and low-carbon petrol station cannot be realized without energy conservation and emission reduction of supporting equipment and facilities. These include heating or refrigeration equipment, water supply and derange equipment, and energy measuring equipment.

Petrol station energy consumption is mainly composed of air-conditioning, refrigeration, and heating systems. There are three aspects of energy consumption: choosing heating and cooling equipment, the energy source of heating and cooling load. Well-chosen heating or cooling equipment should have significant energy-saving potential.

The building sector consumes a significant share of electricity [12]. Energy saving in lighting and electrical equipment is of paramount importance. The energy consumption of electrical equipment in filling stations is due to lighting in the building and site of the station, security detection, and auxiliary equipment. To reduce energy consumption, energy-efficient lighting facilities and electrical equipment should be chosen, as well as solar energy for lighting, heating, and auxiliary equipment should be used.

50.3 Research Method

The analysis was performed as a case study on a typical petrol station building located in urban area and climate conditions typical for Central Europe, as a calculation model. General description of the building is presented in Table 50.1. Due to cold

Table 50.1 Description of the model of petrol station building

Description		Value
Building shape	Number of floors	1
	SA:V ratio	0.77 m^2/m^3
	GR ratio	16.5%
Orientation of the main façade		South
Building area		147.5 m^2
Heated space		147.5 m^2
Cooled space		95.6 m^2
Heat transfer coefficient	Opaque barrier construction	0.15 $W/m^2/K$
	Windows and façade	0.80 $W/m^2/K$
Air tightness		0.6 h^{-1}
The power demand for space heating		4.91 kW
Heat load for heating mode		33.3 W/m^2
The power demand for space cooling		0.7 kW
Heat load for cooling mode		7.0 W/m^2

Table 50.2 Climate data—external temperature, given in °C

Month	1	2	3	4	5	6	7	8	9	10	11	12
Arithmetic average	0.2	1.0	4.3	9.6	14.2	17.3	19.5	18.6	14.4	9.1	5.0	1.6
Standard deviation	3.0	2.2	2.5	1.5	1.4	1.0	1.5	1.4	1.3	1.4	1.3	3.2

climate conditions and quite high surface area-to-volume ratio (SA:V), the passive building standard of the building envelope was introduced.

Energy efficiency of traditional solution of technical system equipment and sustainable one was considered. The energy and power demands for space heating and space cooling, ventilation, and hot water, calculated according to the EN ISO 13790 and EN 12831 standards [13, 14] were taken into consideration. Used climate data include: design external air temperature for winter season −16 °C, design external temperature for cooling season +30 °C, average monthly temperature of external air (Table 50.2), average monthly value of the ratio of the diffuse to global horizon irradiation (Table 50.3), and the monthly sum of solar radiation energy faced in the direction of the equator (Table 50.4). Solar radiation data have been derived from satellite data with hourly resolution. The MAGIC algorithm has been used, and the data cover the period 2007–2016 [15, 16].

Table 50.3 Climate data—ratio of diffused to global irradiation

Month	1	2	3	4	5	6	7	8	9	10	11	12
Arithmetic average	0.8	0.7	0.5	0.4	0.5	0.5	0.4	0.5	0.5	0.6	0.8	0.8
Standard deviation	0.03	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.04

Table 50.4 Climate data—global irradiation at angle 90° facing in the direction of the equator, given in kWh/m^2/month

Month	1	2	3	4	5	6	7	8	9	10	11	12
Arithmetic average	30.2	54.4	96.5	117.7	105.6	96.4	100.8	106.2	107.7	75.8	37.2	25.8
Standard deviation	5.1	18.2	17.3	20.2	13.4	7	8.9	14.3	15.1	16	14	5.1

50.4 Heating/Cooling and Hot Water Preparation Systems' Solutions

50.4.1 The Traditional Variant with the Use of Natural Gas

In the solution of building technical systems adopted as traditional, it was assumed that the energy demands for space heating and hot water heating were covered from heat source in the form of a condensing gas boiler. The cooling system was based on an air-source heat pump with commonly used refrigerant 134a. Such solutions are well known and commonly described.

50.4.2 The Air-Source Heat Pump as the Main Energy Source for Space Heating and Cooling and Hot Water Preparation

In the sustainable solution of building technical systems, an air-source reverse heat pump was assumed. It allows for space cooling in the summer and space heating in the winter season. Additionally, this solution allows you to prepare hot water all year round. The energy efficiency in a such solution depends mainly on the temperature difference between heat exchangers (the evaporator and the condenser). The higher the temperature difference, the coefficient of performance (COP) is lower. By analyzing the COP value, one can estimate the costs of heat or cool production by the device. The evaporating temperature of the refrigerant (in the heating mode) depends on the ambient temperature—in this case the outside air temperature.

Variant 1—heating mode and hot water preparation. The installation of air-source heat pump include: a compressor, hot water buffer tank (condenser), a driver,

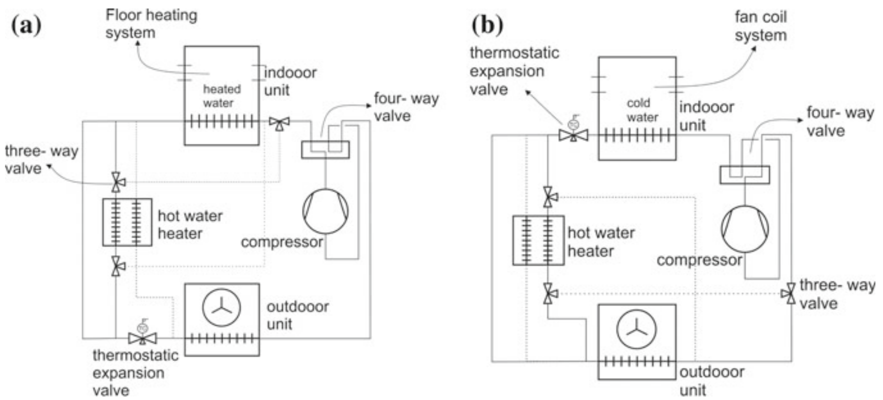

Fig. 50.1 Diagram of the installation of a reversible air heat pump with the possibility of preparing hot water all year round—**a** heating mode, **b** cooling mode

floor heating installation, domestic hot water buffer tank, thermostatic or electronic expansion valve, an evaporator (outdoor unit) (see Fig. 50.1a). In the solution, the heat pump transports the refrigerant to the condenser which is also a buffer tank based on multi-stratification system. In the buffer tank, hot water is drawn through the floor heating installation. Hot water is directed to the manifold and then to the loops located in the floor. After returning the heat, the water returns to the buffer for warming up. The refrigerant after putting the heat of superheat in the buffer tank for heating mode it is directed to the second one—buffer tank of domestic hot water. The condensed refrigerant is then expanded to evaporating temperature and pressure and directed to the evaporator. In the evaporator (outdoor unit), the refrigerant evaporates by taking heat from the air.

Variant 2—heating mode and hot water preparation. The installation of air-source heat pump include: a compressor, an ice water buffer (the same as winter buffer tank for heating mode), a fan coil unit (air coolers), hot utility water buffer tank, a condenser (outdoor unit), thermostatic or electronic expansion valve. In summer, the heat pump cools the water in a buffer tank that was used for heating in winter. The four-way valve is switched over, and the role of the heat exchangers changes. The heat is taken from the chilled water and transported to the outdoor unit (condenser). The chilled water from the tank is directed to the cooling system in which the internal air is cooled. Part of the heat from the space cooling is used to heat domestic hot water. If the assumed water temperature is reached, excess heat is directed by a bypass to the condenser (outdoor unit) where heat is dumped into the outside air. Hot water is heated all year round in a buffer tank based on multi-stratification system. A pipeline from the condenser and the evaporator passes through the tank. Both have a bypass (they work according to the heat pump's operating mode).

In a reversible air heat pump installation, each heat exchanger has a separate expansion valve. This allows to use of thermostatic expansion valves to power streams. It

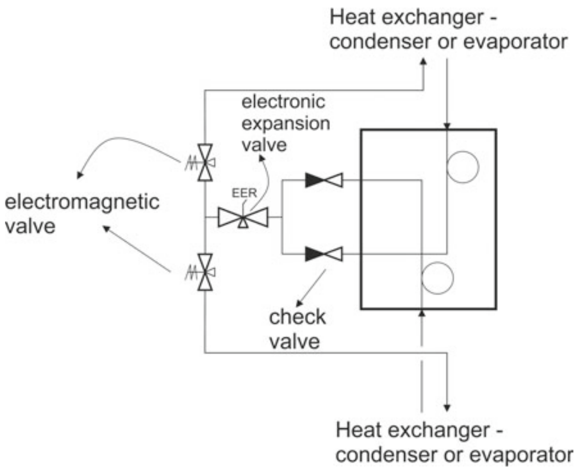

Fig. 50.2 Solution of the hot water buffer tank with one expansion valve

Table 50.5 Assumptions for thermodynamic calculations of heating and cooling circuits

Data description	Heating mode	Cooling mode
Required capacity (kW)	5	1
Temperature of the water feeding the installation, t_w (°C)	30	7
Refrigerant condensing temperature, t_k (°C)	40	40
Subcooling temperature, t_d (°C)	35	35
Design temperature of outside air, t_p (°C)	−16	30
Boiling point of the refrigerant, t_o (°C)	−20	0
Overheating on a thermostatic expansion valve, ΔTzr (K)	5	5
Suction temperature of the compressor, t_{ss} (°C)	10	10
Isentropic efficiency of the compressor, η_{is}	0.6	0.7

is also possible to use one expansion valve that will supply both heat exchangers. A complicated control system would require an electronic expansion valve in this case. Figure 50.2 shows the connection diagram for a hot water buffer tank with one electronic expansion valve. The control algorithm for such a solution should take into account the order in which the electromagnetic isolation valves are opened. In order to protect the system against overflow of refrigerant, check valves are provided in the concept.

Four different refrigerants were taken into consideration: R600a, R290, R1234ze, and R134a. The assumptions taken for the calculation of system efficiency in heating and cooling mode are summarized in Table 50.5.

50.5 Results and Discussion

50.5.1 Energy Efficiency of Energy Source in Operating Modes

Results of calculations of energy efficiency of the reversible air-source heat pump depending on used refrigerant and operating mode are summarized in Table 50.6. Calculated energy efficiency of the reversible air-source heat pump for all refrigerants in heating mode is similar and for the assumed calculation conditions (Table 50.5) is higher than 3. Compared to the efficiency of a gas condensing boiler, this efficiency is 178% higher for refrigerant R290 and 186% for refrigerant R1234ze. In cooling mode, the results of energy efficiency of the reversible air-source heat pump are much more varied, i.e., from 3.83 for the refrigerant R290 to 5.13 for the refrigerant R1234ze. For the traditional system, it was assumed that the commonly used refrigerant R134a was used, so the energy efficiency of this system in cooling mode is the same in both cases.

Analyzing the energy efficiency of heating and cooling systems based on the reversible air-source heat pump, the refrigerant R1234ze seems to be the most promising of the analyzed refrigerants, due to its highest efficiency in both heating and cooling mode.

50.5.2 Energy Demands for Space Heating and Cooling

Useful energy demands for space heating and cooling, calculated on the basis of data from Tables 50.1, 50.2, 50.3, and 50.4, are given in Table 50.7. Results of calculations of final energy demands for space heating and cooling, and water heating depending on the characteristics of technical systems are summarized in Table 50.8.

The share of total auxiliary energy in the annual final energy demand for space heating and cooling, and water heating ranges from 23.1 to 24.1% for the heat and chill source in the form of the air-source heat pump, and ranges 11.6% for a traditional source of heat and chill.

Table 50.6 Energy efficiency of heating/cooling sources for different operation modes

Heating/cooling source		Heating mode	Cooling mode
Air-source heat pump—refrigerants	R600a	3.05	3.92
	R290	3.03	3.83
	R1234ze	3.16	5.13
	R134a	3.01	4.25
Condenser gas boiler/air-source heat pump (R134A)		1.07	4.52

Table 50.7 Useful energy demands for space heating and cooling, $kWh/m^2/a$

Operation mode	Heating	Cooling	Water heating
Arithmetic average	47.92	0.19	8.95
Standard deviation	6.19	0.15	–

Table 50.8 Annual energy demands for space heating and cooling, including annual auxiliary energy demands in technical systems, and total annual final energy demands for heating, cooling, and water heating, given in $kWh/m^2/a$

Operating mode		R600a	R290	R1234ze	R134a	Gas/R134a
Heating	Average final demand	19.36	19.48	18.68	19.61	55.18
	Standard deviation	2.50	2.52	2.41	2.53	7.13
	Auxiliary energy	5.0	5.0	5.0	5.0	6.26
	Average final energy	24.35	24.48	23.68	24.61	61.43
Cooling	Average final demand	0.06	0.06	0.04	0.05	0.05
	Standard deviation	0.04	0.04	0.03	0.04	0.04
	Auxiliary energy	1.62	1.62	1.62	1.62	1.62
	Average final energy	1.67	1.68	1.66	1.67	1.67
Hot water	Average final demand	3.33	3.36	3.06	3.30	10.30
	Auxiliary energy	0.30	0.30	0.30	0.30	0.74
	Average final energy	3.63	3.66	3.36	3.60	10.60
Total annual final energy demands		29.66	29.82	28.70	29.89	74.14

The high efficiency of the air-source heat pump allows for a significant reduction in the annual final energy demands for space heating and cooling, and water heating in relation to the annual final energy demands covered from the traditional source of heating and cooling. The average difference of total annual final energy demands is equal to 60.2%. The biggest difference was obtained for the refrigerant R1234ze. It amounted 61.3%. For the other refrigerants, the difference was on the level from 59.7 to 60.0%.

The efficiency of using the refrigerant that allows for high energy efficiency of the energy system in cooling mode depends on the energy demands for space cooling and the duration of the cooling seasons. And in the case of the refrigerants analyzed, the R1234ze refrigerant allowed for the highest system efficiency in cooling mode (5.13, see Table 50.6); however, the obtained high efficiency of the R1234ze refrigerant system did not translate into a significant reduction in cooling energy demand in relation to systems with other refrigerants (R600a, R290, and R134a) due to the short cooling season in the analyzed gas station building.

50.6 Conclusions

Petrol stations are important infrastructure that support the development of the transportation industry. In order to realize green, low-carbon transportation system, it is important to reduce the energy consumption of filling stations. There are many factors affecting energy consumption of petrol stations. One of them is efficiency of energy source.

The study was focused on the comparison of energy efficiency of the typical gas station building with two different variants of energy source for heating, cooling, and water heating. As a result of the conducted analyses, a high efficiency of the energy source in the form of the reversible air-source heat pump was found. Its energy efficiency depending on the refrigerant fluctuated in heat mode from 3.01 to 3.16, while in cooling mode from 3.83 to 5.13. The use of the air-source heat pump allows for a significant reduction of the annual final energy demands in the analyzed petrol station building compared to the use of a traditional gas heat source.

The efficiency of using the refrigerant that allows for high energy efficiency of the energy system in cooling mode depends on the energy demands for space cooling, and the duration of the cooling seasons.

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Chapter 51
The Influence of Refrigerants Used in Air-Conditioning Systems in Motor Vehicles on the Environment

Wojciech Tuchowski and Karolina Kurtz-Orecka

Abstract Over 95% of new cars in the EU have air conditioning which significantly contributes the global warming by emitted flue gases, and of refrigerants with a high global warming potential. Evaluation of the environmental performance of refrigerants commonly used in mobile air-conditioning systems requires a lifecycle approach. With regard to global climate change, the total equivalent warming impact (TEWI) approach is generally used. The paper presents analyses of the TEWI indicator for automotive air-conditioning systems operating with selected refrigerants. The analysis of the total CO_2 emission to the atmosphere which accompanies the work of mobile air-conditioning installations has been made. Leaks from the installation and the type of burned fuel have been taken into account. As indicated, they have a significant impact on the final value of the amount of carbon emission to the atmosphere. The division of the TEWI index into three basic components has been presented, and an analysis of their impact on the final CO_2 emission has been carried out. Based on the carbon emission rates from the fuel combustion and the GWP refrigerant, the ecologically equivalent number of kilometers required to pass the vehicle corresponding to the emission of 1 kg of refrigerant to the atmosphere was calculated.

51.1 Introduction

Global environmental impacts due to greenhouse gas emission to the atmosphere have been associated with refrigeration systems during recent years. Refrigerants and their combinations with water, oil, and other substances can affect vehicle systems physically and chemically. If they have detrimental properties, they can endanger property, persons, and the environment when escaping from the mobile air-conditioning system (MACs) [1]. Different environmental metrics are used to facilitate decision-making process of selection of refrigerant with low global warming potential. The concept of

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total equivalent warming impact (TEWI) is a useful tool when studding the influence of a refrigeration system on global warming. The TEWI combines the direct emission of CO_2 due to refrigerant leakage and refrigerant losses at the end of the system's life [1–5]. The TEWI index consists of three components. Its first component, the TEWI I, is associated with refrigerant losses through leaks in the system. They arise quite often in car installations due to vibrations coming from engine operation and driving. The level of refrigerant leakage is estimated annually at about 50% of its filling [6]. The TEWI I takes into account accidents and service losses and is linked to the other environmental metric—global warming potential (GWP) [1, 3–5], which defines the emission of a given refrigerant as equivalent to carbon emission. For example, if the global warming impact of the refrigerant R134a is equal 1430, it means that the emission of 1 kg of this refrigerant is ecologically equivalent to the emission of over 1.4 tons of CO_2.

In addition, each car emits fuel combustion products to the atmosphere. Passenger cars and vans according to the European Automobile Manufacturers Association are responsible for the emission of 13% of greenhouse gases into the atmosphere [7]. For this reason, according to the European regulation on carbon emission [8] for 2021, passenger cars will not be allowed to emit more than 95 g of CO_2 per 1 km. From 2019, every gram of carbon emission above the set norm will cost the producer 95 Euro. What's more, the penalty will be imposed on each sold vehicle. On the other hand, a bonus system for models that will emit less than 50 g of CO_2 per 1 km is a bonus—in 2020, when calculating the average car emissions sold by a given manufacturer, such a car will be counted as two, a year later as 1.67 and then as 1.33 in 2021. In 2022, the bonus program will be terminated.

The average carbon emissions of cars sold in 2017 in the European Union were set at 118.1 g per 1 km [9], which means that it increased by 0.3 g per 1 km. It is true that this is not much, but in previous years there were declines every year (see Table 51.1). Meanwhile, the average SUV car sold in Europe in 2017 emitted 133 g CO_2 for each traveled kilometer [10].

Table 51.1 Average carbon emission of cars sold in the EU in period 2010–2017 [9, 10]

Year	CO_2 emission, g/km
2010	140.8
2011	136.2
2012	132.5
2013	136.6
2014	123.3
2015	119.2
2016	117.8
2017	118.1

51.2 Comparison of Refrigerants R1234yf and R744 (CO_2) in Terms of Their Environmental Impact and System Operation

During the operation of mobile air-conditioning system, the refrigerant R1234yf behaves similar to the refrigerant R134a. The only modification necessary to use the refrigerant R1234yf is a new expansion valve that increases the mass flow of the medium to compensate for the lower heat of evaporation. However, the global warming potential (GWP) of the refrigerant R1234yf is 4 and is significantly lower than in the refrigerant R134a, which value is 1430. The increasingly popular substance used in refrigeration is carbon dioxide, a refrigerant with R744 symbol. Its GWP index is equal to 1 and is the base value for calculating the global warming potential for other refrigerants. Due to the increasingly important impact of automotive air-conditioning systems on the creation of the greenhouse effect, in accordance with the European legislation [11] from January 1, 2017, only refrigerants with GWP index lower than 150 can be used in mobile air-conditioning systems of new vehicles. Refrigerants R1234yf and R744 meet the requirement, but the refrigerant R1234yf contains in its structure a fluorine that in combination with water can form hydrofluoric acid. Such a situation can arise, for example, when extinguishing a burning vehicle.

Air-conditioning systems designed to work with the refrigerant R744 work under pressure up to ten times higher than those designed to work with the refrigerant R1234yf. In the summer, the peak pressure is about 100 bar and is above the critical pressure level (supercritical circulation). It makes the control system more complicated, but it is not a technical problem. The COP energy efficiency ratio is comparable under moderate climate conditions, but slightly lower in hot and humid climatic zones. However, the mobile air-conditioning system with the refrigerant R744 can be designed to compensate for lower COP values. Such installations are smaller due to the higher cooling capacity of the refrigerant R744 volume [12]. Due to higher operating pressures, the R744 system requires the use of special construction materials with increased strength. It contributes to a greater weight of the mobile air-conditioning system and thus to a greater weight of the entire vehicle and higher fuel consumption and thus more exhaust gases (including CO_2).

51.3 Environmental Metric TEWI and Its Interpretation

The total equivalent warming impact (TEWI) index indicates three areas of human activity related to the operation of refrigeration equipment and heat pumps. It is used to assess the impact of the operation of these devices on the global warming process, including the direct emission of refrigerant to the atmosphere and the indirect impact of carbon emissions during the production of energy necessary for the operation of refrigeration equipment and heat pumps in the period corresponding to

Table 51.2 Environmental metrics of selected refrigerants [7]

Refrigerant	Global warming potential (GWP)	Ozone depletion potential (ODP)
R12	10,200	1
R134a	1420	0
R1234yf	4	0
R744 (CO_2)	1	0
R152a	138	0
R290 (propane)	3	0

their operational durability [1]. A comprehensive TEWI representation is given by [1, 4, 13]:

$$\text{TEWI} = (\text{GWP} \times L \times n) + (\text{GWP} \times m[1 - \alpha_{\text{rec}}]) + (n \times E_{\text{an}} \times \beta) \quad (1)$$

where

GWP global warming potential, related to carbon emission;
L annual losses of the refrigerant through leaks [kg, %];
n the life period of the device, [years];
m filling with a refrigerant, [kg];
α_{rec} degree of recovery (0–1);
β carbon emission factor of the energy production, [kg/kWh];
E_{an} annual energy consumption, [kWh].

The TEWI index captures both relatively easy to determine component values related to energy consumption or the impact of recovery losses, as well as a much more difficult to estimate component value taking into account the impact of losses arising as a result of leaks. It should be noted that determining the value of the TEWI index also gives an interesting opportunity to compare the same applications not only to the global warming impact of alternative refrigerants, but also the impact of design changes leading to reduce the energy consumption (see Table 51.2).

When referring to mobile air-conditioning devices in vehicles, additional fuel consumption for the operation of the system should be taken into account; hence, the TEWI index representation is given by:

$$\text{TEWI} = (\text{GWP} \times L \times n) + (\text{GWP} \times m[1 - \alpha_{\text{rec}}]) + (a \times S \times \beta_1) \quad (2)$$

where

a average fuel consumption per 100 km, [l/100 km] (see Table 51.3);
m average annual mileage of the vehicle, [km/a];
α_{rec} degree of recovery (0–1);
β_1 carbon emission from the fuel consumption, [kg CO_2/l] (see Table 51.3).

Table 51.3 Fuel consumption and carbon emission indicators of fuels [6, 14, 15]

Fuel	Carbon emission from the fuel consumption, β_1, kg/l	Fuel consumption indicator, a, l/100 km
Gasoline	2.32	8.0
Diesel	2.67	6.9
Liquefied petroleum gas	1.48	10.2

In order to facilitate the analysis of the impact of individual components of the TEWI index on the final result of the amount of carbon emitted to the atmosphere, the TEWI index was divided into three groups given by:

$$\text{TEWI I} = (\text{GWP} \times L \times n) \tag{3}$$

$$\text{TEWI II} = (\text{GWP} \times m[1 - \alpha_{\text{rec}}]) \tag{4}$$

$$\text{TEWI III} = (\alpha \times S \times \beta_1) \tag{5}$$

The value of the TEWI I component depends on the leakage of refrigerant during the operation of the installation. The value of the TEWI II component depends on filling the system with the refrigerant and on the amount of refrigerant recovered during the service. The value of the TEWI III component depends on the energy production used to drive the installation (in the case of automotive air-conditioning installations, it is the amount of fuel burned per unit of the distance traveled by the vehicle).

51.4 Computational Analysis of the TEWI Index

The TEWI index analysis was carried out for a passenger car and various fuels and the following assumptions:

- annual car mileage—12,000 km;
- average fuel consumption in accordance with Table 51.3;
- refrigerants: R12, R134a, R1234yf, R744, R152a, R290;
- GWP index in accordance with Table 51.2;
- annual losses of the refrigerant through leaks taking into account accidents and service losses—50%;
- average refrigerant charge value—1 kg [6];
- the life period of the device—1 year;
- degree of recovery—0.5 [6];
- carbon emission from the fuel consumption in accordance with Table 51.3;
- fuels—petrol, diesel, liquefied petroleum gas (LPG).

Figures 51.1, 51.2, 51.3, 51.4, 51.5, and 51.6 show the TEWI index values of automotive air-conditioning systems cooperating with selected refrigerants. The calculations used a number of assumptions which define, among others time frame for the operation of the installation, the level of filling the system with refrigerant, and the carbon dioxide emission indicator from fuel combustion. It should be noted that the emissivity index is the average value for vehicles operated in Central Europe. The emissivity index depends on the efficiency of fuel combustion and the condition of the engine. In new vehicles, it is relatively higher and deteriorates with the operational period. Current averaged values of this indicator are reported, among others by KOBiZE [14].

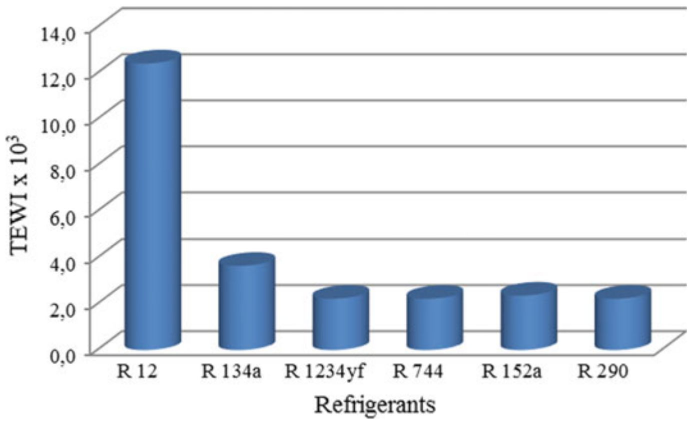

Fig. 51.1 TEWI index value for selected refrigerants calculated when burning gasoline fuel

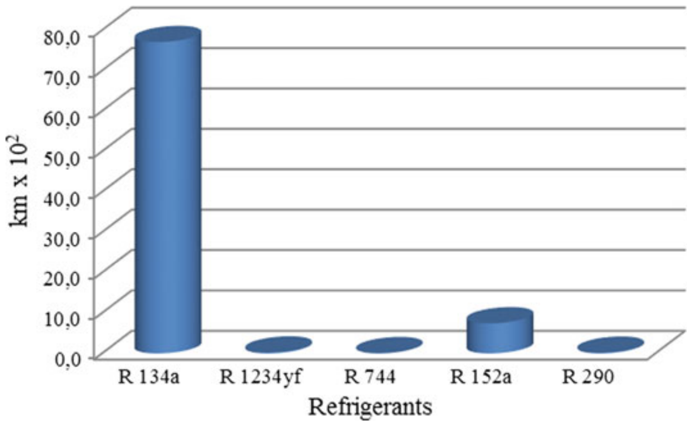

Fig. 51.2 Number of kilometers driven by a vehicle burning gasoline fuel that is ecologically equivalent to the emission of 1 kg of the selected refrigerants

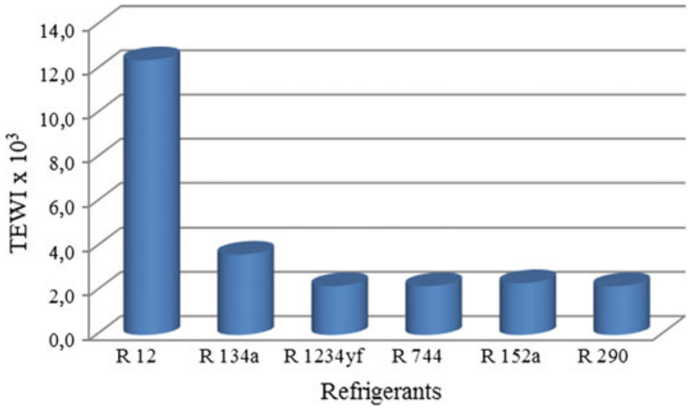

Fig. 51.3 TEWI index value for selected refrigerants calculated when burning diesel fuel

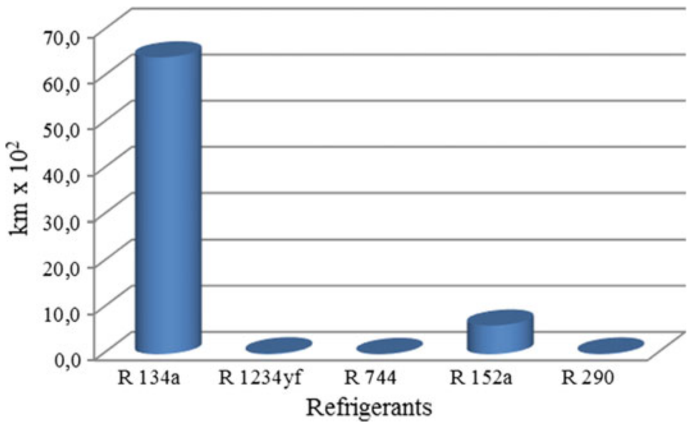

Fig. 51.4 Number of kilometers driven by a vehicle burning diesel fuel that is ecologically equivalent to the emission of 1 kg of the selected refrigerants

As it results from the calculations made on the basis of the assumptions, the biggest carbon emission into the atmosphere by mobile air-conditioning systems is in the case of refrigerant R12. This substance is currently not used in vehicle installations due to the environmental metrics ODP and GWP (see Table 51.2).

Currently, the most commonly used refrigerant in automotive refrigeration systems is the refrigerant R134a. Its replacement according to the EU decision [11] is the refrigerant R1234yf. According to calculations of the TEWI index, the difference in the total carbon emission to the atmosphere by the mobile air-conditioning system for these two refrigerants is equal to approximately 1400 kg of CO_2 per year. It should be noted that the analysis adopted the same COP energy efficiency coefficients for each car air-conditioning system. The total annual carbon emission from the vehicle

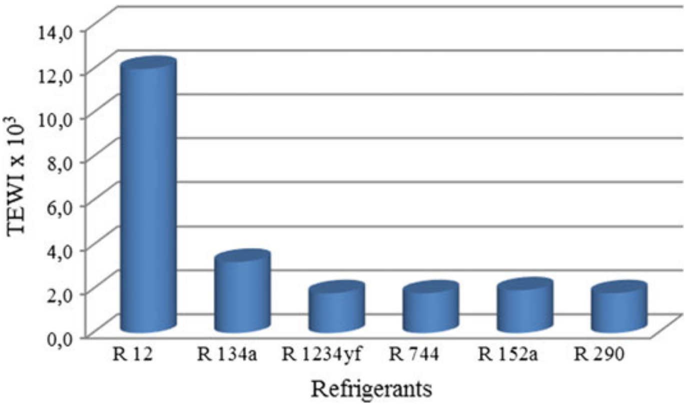

Fig. 51.5 TEWI index value for selected refrigerants calculated when burning liquefied petroleum gas fuel (LPG)

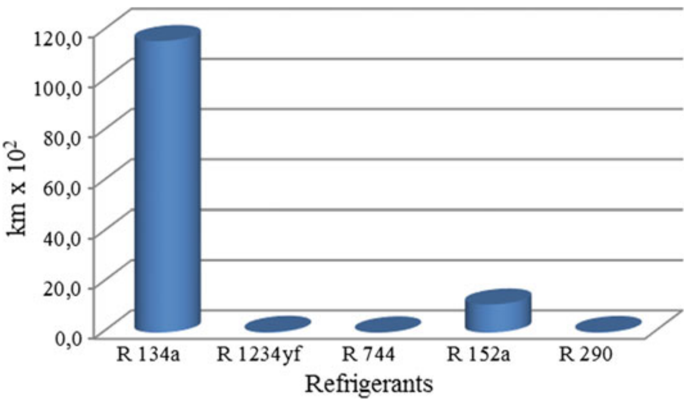

Fig. 51.6 Number of kilometers driven by a vehicle burning liquefied petroleum gas fuel (LPG) that is ecologically equivalent to the emission of 1 kg of the selected refrigerants

results from the TEWI I index and the TEWI II index as well as emission from the fuel contribution.

As it results from the analysis, the emission of 1 kg of refrigerant is in ecological terms equivalent to covering about 7700 km with a typical modern car that burns gasoline, which the mobile air-conditioning installation works on the basis of the refrigerant R134a. In the case of diesel fuel contribution, the equivalent number of kilometers of travel is around 6400, while in the case of liquid petroleum gas fuel (LPG) it is about 11,600 km. These values are strongly correlated with the relatively high GWP environmental index, which for the refrigerant R134a is equal 1430. For the refrigerant R1234yf, the equivalent number of driven kilometers in terms of ecology is equal to approximately 22 km in the case of gasoline fuel contribution, about 18 km in the case of diesel fuel contribution, and about 32 km in case of liquid

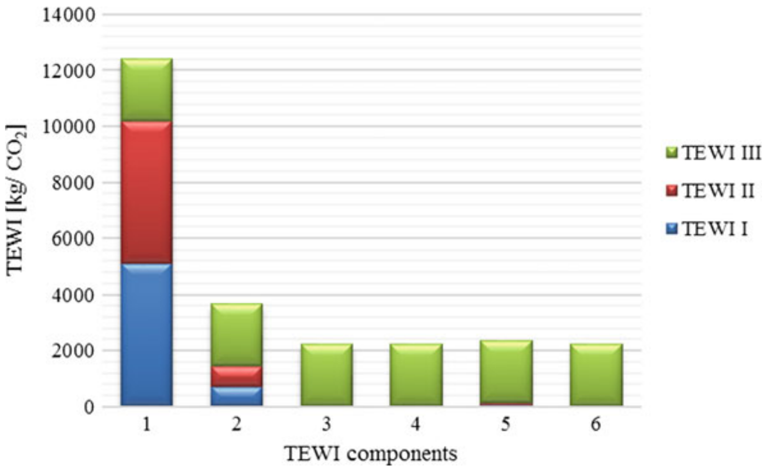

Fig. 51.7 Influence of TEWI index components on the final value of the amount of carbon emission to the atmosphere by a mobile air-conditioning system

petroleum gas fuel (LPG). Figure 51.7 shows the impact of individual components of the TEWI index (TEWI I, TEWI II, and TEWI III) on the final value of carbon dioxide emissions to the atmosphere. It can be seen that the components TEWI I and TEWI II play a key role for refrigerants with a high GWP index, while for refrigerants with a relatively low GWP, the value of these components is negligible. The TEWI III component has a decisive influence on the value of the global value of the TEWI index in this case.

51.5 Conclusions

As it results from the analysis, vehicles powered by liquid petroleum gas fuel (LPG) have about 10% lower the TEWI index compared to gasoline and diesel-fueled vehicles. For the refrigerant R134a, the TEWI index for gasoline vehicles has been estimated as equal to 3657.2 kg of CO_2, for diesel fuel vehicles as equal to 3640.76 kg of CO_2, and for liquid petroleum gas fuel as equal to 3241.52 kg of CO_2. It can also be stated that vehicles fueled with gasoline and diesel oil, in the analyzed scope of work of the mobile air-conditioning system, have a very similar value of the TEWI index.

Currently, according to the European Commission Directive 2006/40/EC, from January 1, 2017, only refrigerants with the GWP index lower than 150 may be used in air-conditioning systems of new vehicles. Such requirement means that when analyzing the TEWI index, the components of the TEWI I and the TEWI II can be omitted in the assessment of the environmental impact of automotive air-conditioning systems.

In the course of work related to the minimization of carbon dioxide emissions, the focus should be primarily on improving fuel combustion efficiency.

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Chapter 52
The Impact of Refrigerants on the Efficiency of Automotive Air-Conditioning System

Wojciech Tuchowski and Karolina Kurtz-Orecka

Abstract Over 95% of new cars in the EU have air conditioning which significantly contributes the global warming by emitted flue gases, and of refrigerants with a high global warming potential (GWP). The paper analyzes automotive conditioning systems in terms of energy efficiency. Currently, in these systems the most popular refrigerants are R134a (GWP = 1430) and R1234yf (GWP = 4). There are some controversies related to the impact of R1234yf on human health, especially during road collision and depletion of the system. The tendency in automotive air-conditioning systems is to shift from refrigerants that were safe for man but not to the environment, on ones that are pro-ecological but can be dangerous to human health and life. The article also presents an overview of the most popular synthetic refrigerants used in automotive air conditioning over several decades in Europa, like R12, R134a, and currently used in the new systems—R1234yf. Due to the environmental impact of refrigerants, the EU imposes tougher requirements for these substances. European Commission Directive 2006/40/EC provides that from January 1, 2017, only refrigerants with GWP lower than 150 may be used in air-conditioning system of new cars. This requirement is now met by synthetic refrigerant R1234yf and natural one R744 (carbon dioxide). The environmentally friendly (GWP = 1) and not posing a threat to humans, R744 seems to be a future-proof alternative to refrigerant R134a.

52.1 Introduction

Substantial automotive air conditioning can be already seen in the solutions from 1930, when first special water coolers were installed in vehicles. They allowed the water to evaporate, which in turns allowed to lower the air temperature in passenger compartments. These devices were mounted outside the vehicle and cold air was forced inside through the open window [1]. Currently, over 95% of new cars in the EU have air conditioning which significantly contributes the global warming by

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emitted flue gases, and of refrigerants with a high global warming potential (GWP). Mobile air conditioning (MACs) has three separate impacts on global warming: (1) the effects of refrigerant inadvertently released to the atmosphere from collisions; (2) the efficiency of the cooling equipment due to the carbon emission from burning fuel to power the system; (3) the carbon emission from burning the fuel to transport the system [10]. The environmental warming impact of refrigerants is being studied by many scientists, including [4, 5, 10] and others. To reduce emission of fluorinated greenhouse gases from mobile air-conditioning systems, the European Directive on MACs introduces a gradual ban on these gases in passenger cars [7].

Some of the used refrigerants may have bad influence on human health. Exposure of vehicle occupants can occur when refrigerant enters passenger compartments due to sudden leaks in air-conditioning systems, leaks caused by collisions, or leaks following services [12]. The largest number of exposures of vehicle occupants is reported for leaks caused by accidents, and the second one for leaks following services [12].

A MACs in its construction is not so different from usual refrigeration system, which can be found even in domestic refrigerators or heat pumps. The only differences between them are in the way the compressor is driven, and most importantly, flexible rubber connections instead of fixed ones, which results from changing operating conditions. A mobile air-conditioning system is exposed to large vibrations which result from engine operation and vehicle movement. In both cases, the compressor in a closed compressor circuit compresses the refrigerant, which gives heat to the environment and takes it from the car cabin or, in the case of a refrigerator, from its interior. The thermodynamic transformations of the refrigerant are exactly the same. They are designed to take away or deliver heat to passenger compartments. The refrigerant itself is a low-boiling substance, which means its boils at a temperature much lower than 0 °C.

52.2 Refrigerants Used in MACs

Refrigerants are evaluated in many aspects. Among others, they are classified because of: (1) origin (natural/synthetic refrigerants); (2) composition (homogeneous/multi-component refrigerants). There is also introduced systematics of these substances in terms of their chemical composition includes: CFC—chlorofluorocarbon; HCFC—hydrochlorofluorocarbon; HFC—hydrofluorocarbon; HFO—hydrofluoroolefin; HFE—hydrofluoroether; FC—fluorocarbon; HC—hydrocarbon. One of the most important divisions of refrigerants is the division due to their flammability and toxicity [9]. These substances are called controlled ones due to that their emission causes the breakdown of ozone in the stratosphere and contribute to the greenhouse effect incensement. In order to assess refrigerants in this respect, environmental indicators were introduced [6, 9]: ODP—ozone depletion potential, GWP—global warming potential, and TEWI—total equivalent warming impact. The impact of the operation of automotive air-conditioning systems on global warming, based on the analysis of the TEWI index can be found, among others, in [14]. The TEWI index determining the relative importance of the direct and indirect effects is used to assess the effect of air-conditioning system on global warming throughout its operation as the GWP function [9].

The first synthetic refrigerant used in automotive air conditioning was refrigerant R12 [6]. In late 1973, Rowland and Molina put forward a thesis on the effect of CFC compounds emission on the ozone depletion [2]. Subsequently, pursuant to the Montreal Protocol (1987) concerning, inter alia, actions to protect the ozone layer, it was decided to remove refrigerant R12 from automotive refrigeration systems. For this reason, since 1994, refrigerant R134a has been used as R12 alternative. Nowadays, refrigerants used in MACs must strictly have ODP index equal 0. Additionally from the beginning of 2017 only refrigerants with GWP lower than 150 may be used in air-conditioning system of new cars [7]. For this reason, the refrigerant R134a due to its very high GWP equal 1430 has to be replaced. One of the alternative refrigerants is R1234yf. It belongs to HFO group, has no impact on the ozone layer, and is characterized by a low GWP index. Table 52.1 compares the refrigerants most commonly used in MACs over the last several decades.

As is clear from the research works [13, 15, 19] on the refrigerant R1234yf, it is environmentally friendly but can be dangerous for people's health and life. Such a situation may occur especially during leakage of this substance due to unsealing of the air-conditioning system [12]. During the frontal collision of the car, the heat exchanger (condenser/evaporator) located in the front of the car is most exposed to damage. The R1234yf gas vapors may be exposed to hot surfaces or an open flame. The side-effect of the decomposition of R1234yf under the influence of heat is the release of hydrogen fluoride, which in combination with water, e.g., fire extinguishing water, forms hydrofluoric acid. Hydrogen fluoride irritates the respiratory system, has a sharp smell, easily penetrates into the body without feeling pain, also through the skin, leading to the death of a human, unless it is subjected to immediate rescue. Penetrating from the engine compartment through the ventilation system into the interior of the car, it easily digests elements made of plastic and even glass [11].

52.3 Research Method—Thermodynamic Calculations of Cooling Circuits for Synthetic and Natural Refrigerants

The most popular refrigerant used in mobile air-conditioning systems is still R134a. It has been replaced the withdrawn from use and production of R12 refrigerant due to R12 significant impact on the ozone layer and contributing to the greenhouse effect. Currently, refrigerant R134a is withdrawn from car air conditioning. Alternative refrigerants that meet the index GWP index <150 [7] and there are technical reasons to use them in a car air-conditioning system include:

Table 52.1 Selected properties of refrigerants used in MACs [3, 8]

Properties	R12 (ISCEON 12)	R123a (Suva 134a)	R1234yf (Opteon yf)
Chemical formula	CCl_2F_2	$C_2H_2F_4$	$C_3H_2F_4$
Molar mass, g/mol	120.91	102.03	114
Boiling point (1.013 bar), °C	−29.75	−26.10	−29.4
Critical temperature, °C	111.97	101.1	95
Critical pressure, bar	41.4	40.6	34
Stream pressure (25 °C), bar	6.5	6.6	6.7
Critical density, kg/m^3	565	511.9	478.01
Specific heat of liquid (25 °C), kJ/kg/K	1.00	1.44	1.39
Specific heat of stream (25 °C), kJ/kg/K	0.606	0.85	0.91
ODP index, –	1	0	0
GWP index, –	10,200	1430	4
Temperature of self-ignition, °C	–	>750	405
ATL index (atmospheric life time), years	130	16	0.03
Concentration of explosion limit in the air, %	–	–	6.2–12.3
Preferred oil	PAG[a]	PAG[a], POE[b]	PAG[a], POE[b]
Security group	A1	A1	A2L

[a]Poly alkaline glycol
[b]Polyolester

– R1234yf with GWP index equal 4;
– R744 (CO_2) with GWP index equal 1;
– R152a with GWP index equal 142;
– R290 (propane) with GWP index equal 3;
– R600a (isobutene) with GWP index equal 3.

The value of GWP index for the refrigerant R12, according to various estimates, is higher than 10,000, whereas for the refrigerant R123a is equal 1430.

For the thermodynamic analysis of cooling circuits, synthetic refrigerants R12, R134a, R152, and R1234yf were selected. Energy software [16, 18] were used to calculate the energy efficiency of refrigeration systems (MACs). Thermodynamic calculations were carried out for the same operating conditions of the device, assuming the following assumptions:

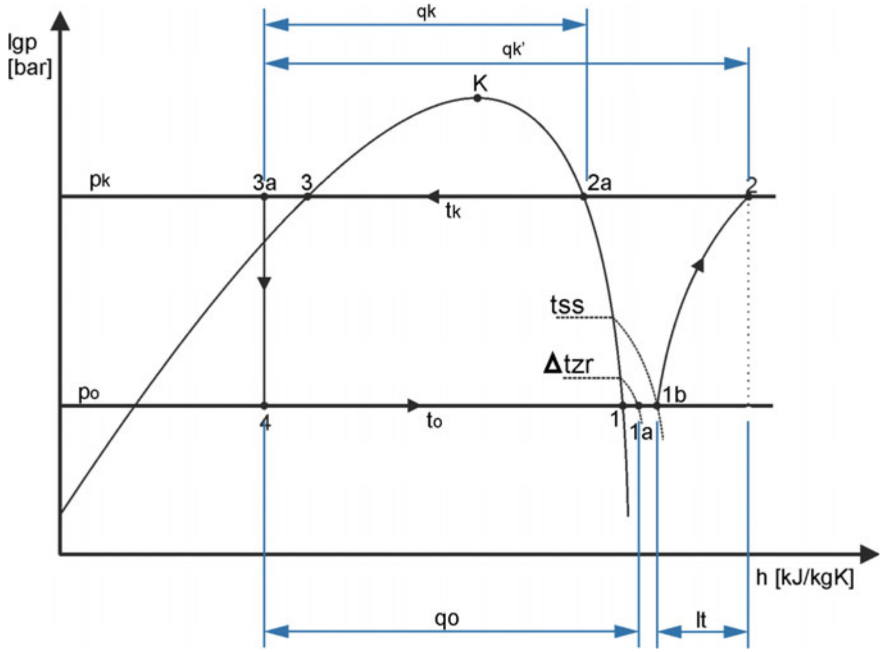

Fig. 52.1 Superheated circulation with sub-cooling in the lgp–h system

- external air temperature, $t_p = 30$ °C;
- air temperature in the vehicle cabin, $t_{\text{kab}} = 20$ °C;
- evaporation temperature of the refrigerant, $t_o = 10$ °C;
- condensing temperature of the refrigerant, $t_k = 40$ °C;
- overheating on the expansion vale, $\Delta\text{tzr} = 5$ K;
- isentropic efficiency of the compressor, $\eta_{\text{is}} = 0.7$;
- suction temperature of the compressor, $t_{\text{ss}} = 18$ °C;
- cooling capacity, $Q_o = 3$ kW;
- cooling of the liquid medium in the condenser, $t_d = 5$ K.

Figure 52.1 shows the most commonly used circuit in this type of systems, superheated with internal sub-cooling.

The unit cooling capacity determines the relationship:

$$q_o = h_{1a} - h_4 \tag{1}$$

The individual compression work is given as:

$$l_t = h_2 - h_{1b} \tag{2}$$

The unit efficiency of the condenser (the total heat given) describes the formula:

$$q_{\mathrm{kr}} = h_2 - h_{3a} \tag{3}$$

The theoretical refrigeration efficiency coefficient of the circulation is given as:

$$\mathrm{COP_{CH}} = q_o/l_t = Q_o/N_t \tag{4}$$

Theoretical power of the compressor motor determines the relationship:

$$N_t = \dot{m}\, l_t \tag{5}$$

Mass refrigerant stream describes the formula:

$$\dot{m} = Q_o/q_o \tag{6}$$

Proper heating capacity (condenser power)

$$Q_k = \dot{m}\, q_k \tag{7}$$

Natural refrigerants were also analyzed: R290 and R600a. The calculations were carried out using analogous methodology as in the case of synthetic refrigerants.

52.4 Results and Discussion

Results of calculations in the form of comparison of synthetic refrigerants R12, R134a, R152, and R1234yf in terms of system operation is presented in Table 52.2. As can be seen from the results, refrigerant R152a shows a similar level of energy efficiency and seems to be a good alternative to the withdrawn refrigerant R134a. Both refrigerants are characterized by high energy efficiency, the working pressures in the system are similar. From the point of view of mass flow rate, steam density and, what follows, pressure drops in the flow, it is more beneficial [17].

Results of calculations in the form of comparison of natural refrigerants R290 and R600a in terms of system operation are presented in Table 52.3. The refrigerant R744 (CO_2) works in supercritical circulation, which does not allow for exact comparison of system operation parameters with those working in the area of wet steam. It is worth noting, however, that some experimental works indicate that the installation with CO_2 is more effective than currently used installations with R134a, while these tests are not equivalent due to the different constructions of the analyzed solutions [14].

The obtained results confirm that natural refrigerants as R290 and R600a are an energetically justified alternative to the refrigerant R134a. Both propane and isobutene demonstrate high energy efficiency in the analyzed range of variability of the mobile air-conditioning system operation parameters.

Table 52.2 Comparison of synthetic refrigerants in terms of system operation

Properties	R12	R134a	R1234yf	R152a
q_o, kJ/kg/K	123.5	159.7	134.0	257.2
l_t, kJ/kg/K	21.8	27.8	25.7	43.9
q_{kr}, kJ/kg/K	134.5	170.3	142.1	269.0
$q_{kr'}$, kJ/kg/K	150.1	190.3	162.7	304.5
$\dot{m}$, kg/s	0.024	0.019	0.022	0.012
N_t, kW	0.53	0.52	0.57	0.52
Q_k, kW	3.27	3.20	3.13	3.23
COP_{CH}, –	5.66	5.77	5.26	5.77

Table 52.3 Comparison of natural refrigerants in terms of system operation

Properties	R290	R600a
q_o, kJ/kg/K	301.2	295.1
l_t, kJ/kg/K	51.3	55.1
q_{kr}, kJ/kg/K	320.4	330.6
$q_{kr'}$, kJ/kg/K	355.8	354.1
$\dot{m}$, kg/s	0.01	0.01
N_t, kW	0.51	0.55
Q_k, kW	3.19	3.31
COP_{CH}, –	5.88	5.45

The disadvantage of refrigerants from the group of hydrocarbons is their flammability. For this reason, they are classified in the A3 safety group. Refrigeration equipment filled with these substances is subject to explosion-proof regulations, and construction requirements are contained in relevant standards (EN 378, DIN 7003).

52.5 Conclusions

Refrigerants used in automotive air-conditioning systems are classified as controlled substances. This means that their production, distribution, and leakage to the atmosphere should be constantly monitored. As demonstrated by known theoretical analyses and experimental studies, new synthetic factors meet environmental requirements, but in some cases show low energy efficiency. In addition, their impact on human health and life is often neglected. Currently, the EU's tightening requirements force manufacturers to look for refrigerants that, in addition to neutral behavior in relation to the environment, will also be safe in operation.

The European Union aims to minimize the negative impact of cooling, heating, and air-conditioning installations on the natural environment. This is also evident in the case of automotive air-conditioning systems in which from January 2017 only refrigerants with GWP indicators not higher than 150 may be used [7].

The study was focused on properties evaluation of synthetic and natural refrigerants that could be used as alternative refrigerant for R134a one. There were taken under consideration refrigerants: from synthetic group R1234yf and R152a, and from natural group R290 and R600a. All refrigerants were compared to the base ones: R12 and R134a. As the analysis showed, the refrigerant R152a seems to be more favorable in terms of energy efficiency as the refrigerant R134a than R1234yf. Its energy efficiency with the assumption made is higher than R1234yf by about 9%. In relation to the refrigerant R134a, any change in efficiency is noticed, whereas the mass flow of refrigerant allows the selection of a smaller compressor. Unfortunately, the flammability of the refrigerant R152a at least for the moment eliminates it from general use.

Both isobutene (R600a) and propane (R290) show higher efficiency compared to the refrigerant R1234yf, by approx. 3% and by approx. 12%, respectively. Unfortunately, their flammability is also an obstacle here. Initially, it did not meet with the approval of representatives of motor vehicles companies, although it is strongly promoted by the European Union. In addition, many studies confirm its negative impact on human health and life. This objection resulted in a work on alternative refrigerants that meet the EU directives. Such alternative refrigerants include, for example, R744—carbon dioxide. Currently, in the European Union, but not only, cars containing this factor in the air-conditioning system are used. As research has shown, it is completely safe for people's health and life, even when it is leaking. Installations using CO_2 as a refrigerant show a similar COP value with installations using R1234yf, taking into account the same operating parameters. The advantage is that it is not necessary to dispose of the refrigerant R744 when scrapping the vehicle. The disadvantage is undoubtedly higher (about 10 times) system pressure (supercritical circulation). However, it does not cause problems related to process control.

In addition to CO_2, R600a (isobutene) and R290 (propane) are also interesting alternative refrigerants for mobile air-conditioning systems in terms of ecology and price. However, these are flammable substances (belonging to the A3 safety group) and therefore require different installation designs and additional safeguards.

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Author Index

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