Part III

Solutions for Sustainable Product Development

T. Buchert, Chair of Industrial Information Technology, Institute for Machine-tools and Factory Management, Technische Universität Berlin, Berlin, Germany

As shown in the previous book part, innovations in manufacturing tech-nologies have the potential for significant reduction of resource consumption as well as for decreasing health related workplace-risks at the same time. Nevertheless, once a product is manufactured its sustainability performance along the whole lifecycle is already determined to a large degree. In this context the product design stage can be seen as a major lever which defines for example necessary manufacturing steps, longetivity of product usage and potentials for material recovery once the product is disposed.

A sustainable design starts by limiting potential harmful effects of the product along its whole lifecycle for various stakeholders. Classical exam-ples in this context are gaseous emissions contributing to anthropogenic climate change, toxic liquid and solid waste or unnecessary cost for the company, customers or the society. Despite the prevention of negative effects sustainable products also provide opportunities to fulfil human needs and provide value in all areas of human living (in particular mobil-ity, production and energy). Solutions in this context comprise for exam-ple sophisticated highly quality products making everyday life easier, frugal innovations to address basic needs in developing countries or mechanisms for fostering societal cohesion by including people with disabilities or the elderly.

Sustainable Product Development characterizes the science and art of foreseeing the whole product lifecycle by handling multiple decision criteria at the same time to find a compromise between all involved stakeholders including the company, society, environment and future generations. Hence, research on sustainable product development focuses on a diverse set of research questions of which some are listed below in an exemplary manner:

I.What constitutes a sustainable product?

II.How can sustainability be integrated into the design/design management process?

III.Which forms of decision support are necessary to enable stake-holders for sustainable product development?

Research on these questions under the label of sustainability is conducted since approximately 10 years making it a relatively new area of research. However, since sustainable product development is grounded in the field of Ecodesign there are almost 30 years of experience comprising a massive amount of publications, industrial application cases and a large variety of tools and methods which have been developed in that context.

The first contribution to this book part will take a closer look at how the research field evolved with the years from pure Ecodesign to an inte-grated view of sustainable product and business model design enabling the transition to a circular economy. Furthermore, an outlook is given how the journey will continue in the future and what will be the main challenges to solve before sustainable value creation can be achieved from a product development perspective.

An example how the three above-mentioned questions can be addressed in a corporate context can be found in the second contribution of this book part. Here it is discussed how the rather fuzzy concept of sustainability can be integrated into conventional product development processes in producing companies. In this context the target-driven approach for Sustainable Product Development searches for ways to increase transparency of decision making. After naming the challenges for definition and validation of sustainability targets options for decision support are presented. The approach utilizes software support which is embedded into existing engineering IT tools.

The third contribution focuses on the end of life phase of the product lifecycle which recently gained increased attention through research on enabling a circular economy. The main challenge in this context is to guarantee that added-value, embedded in a manufactured product can be conserved after its first utilization period. Additional usage phases can be achieved through direct reuse, remanufacturing or repurposing. Since these end of life options need to be considered in product design already possible options for implementation are discussed and practical guidelines are presented.

From Ecodesign to Sustainable Product/Service-Systems: A Journey Through Research Contributions over Recent Decades

Tim C. McAloone and Daniela C.A. Pigosso

Abstract Corporate approaches towards sustainability integration into product development have significantly evolved since the early 1990s. Ecodesign, defined as the integration of environmental issues into product development, arose in the 1990s as a key concept for the enhancement of products' environmental performance. An intense development of ecodesign methods and tools could be observed in the 1990–2010 period, leading to successful pilot cases in industry, in which environmental gains were demonstrated. In the 2010s, the need for a systems perspective to solve the environmental crisis has been highlighted, and the concept of product/service-systems started to gain momentum due to the high potential for enhanced environmental performance and improved competitiveness, by means of new business models and dematerialization. Recently, a transition towards Circular Economy and the integration of social innovation into sustainability initiatives can be observed, which leads to strategic and holistic sustainability considerations in the design of complex systems. In this chapter, the evolution of sustainability concepts and their integration into product development is presented and exemplified in three periods: 1990–2010; 2010–2020 and 2020–2030. While the first two periods present the actual development of the field, the last period represents the evaluation and projection of the trends developed by the authors. By analysing the three periods, the authors aim to discuss the journey from ecodesign to sustainable product/service-systems over the last decades, experienced by academia and practitioners, and to highlight their views on how the field is going to develop over the next 10 years.

Keywords Ecodesign · Product/service-systems · Sustainable innovation · Circular Economy

---

T.C. McAloone (✉) · D.C.A. Pigosso
Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: tmca@dtu.dk

R. Stark et al. (eds.), *Sustainable Manufacturing*, Sustainable Production,
Life Cycle Engineering and Management, DOI 10.1007/978-3-319-48514-0_7

1 Introduction

Since the early 1990s academics and practitioners have been placing increasing focus on sustainability awareness in the product development process, by means of tools, methods and targeted projects towards sustainability enhancement. In the early years, the focus was on designing better for environmental concerns, from which period we see the beginnings of what today is a huge catalogue of approaches towards life cycle assessment and ecodesign, to name just two of the very popular environmental improvement approaches. The important questions are: how does it look today? In which dimensions have we developed our knowledge? How has the world changed since we began to work with ecodesign? And are we effectively developing our competencies, in order to be more effective in our approach to continued sustainability enhancement?

In an attempt to answer the above questions, the authors have carried out a review and reflection of the previous and current decades, before projecting our thoughts onto what we see may be the foreseeable future for sustainability enhancement through business- and product development. To help to make this reflection, three time periods and nine dimensions have been identified, so as to characterize the general sustainability focus, over time. The time periods in focus are 1990–2010 (characterised as the rise and establishment of ecodesign); 2010–2020 (a systems perspective on ecodesign); and 2020–2030 (perspectives for a sustainable and Circular Economy). The nine dimensions identified for the review and reflection exercise were the following:

- **Main goals/objectives:** This dimension was included to highlight what was the main sustainability design object of the company, in the given time period, ranging from very concrete artefact-focused objectives to more cognitive objectives seen in more recent times.
- **Expected results:** This denotes the main focus of industry/society in each given time period, also indicating the level of proactivity towards sustainability within the given period.
- **Main aim:** This dimension marks whether the main aim of the sustainability effort is towards building, implementing, or fully integrating tools into the organisation.
- **Basic approach:** This dimension helped the authors to differentiate, whether the general approach to sustainability improvement could be characterised as being singular problem-focused, system-oriented, or holistic.
- **Envisaged cost-benefit:** The general attitude of industry, towards sustainability's value contribution was charted in this dimension, to provide a candid image of the general level of expectation towards sustainability.
- **Sustainability ambition:** This dimension denotes which combination of the three so-called pillars of sustainability (environmental-social-business) were most in focus in the given time period.

- **Business mindset:** This dimension was included in order to differentiate between incumbent take-make-waste (or ‘linear’) business mindsets, or whether a more circular mindset was evident in a given time period.
- **What are we changing:** This dimension was added to place focus on what the main objective of sustainability efforts typically was in a given time period, whether it be to make direct product improvements, more systemic process improvements, or a generally holistic focus on the competencies of the professionals in the product development organisation.
- **Decision-making level:** This final dimension was used to mark which dominant part of the organisation was most instrumentally being engaged, in a given time period.

The following sections review and reflect on the activities, campaigns, research, industry examples, and key results gained from each of the three respective time periods. The above sustainability dimensions are used as way of structuring this reflection. A progression and a development can be observed, in the three time periods considered.

2 1990–2010: The Rise and Establishment of Ecodesign

Over the 1990–2010 period, companies have significantly evolved their approaches towards the integration of sustainability into their business activities, developing from a passive and reactive stance, towards the adoption of more preventive and proactive approaches.

The business concern related to sustainability issues in this period was directly related to the intensification of environmental awareness in the 1970s and 1980s. The increased awareness was a consequence of the pollution caused by a generally passive attitude until then adopted by industry, where almost no mechanisms for pollution control were in place.

Within the passive approach, industrial waste generated in the production processes by manufacturing companies was disposed directly in the environment without any kind of treatment, leading to a severe pollution of the environmental compartments (soil, air and water) and causing serious damage to both human health and quality of life.

In recognition of the pollution effects on human health and the environment, governments worldwide started to intensify their environmental legislation programmes in the 1980s, which aimed at regulating companies’ activities concerning pollution control. From this development and strengthening of environmental legislation, companies started to shift from a passive stance towards the adoption of what we today would call reactive approaches, which focused on the so-called ‘end-of-pipe’ solutions.

The ‘end-of-pipe’ solutions aimed at reducing the pollution potential of industrial waste, so as to comply with the enacted legislation, by investing in technologies, which were chiefly intended for the treatment of industrial wastewater, solid waste and gases generated in the production processes. Due to the relatively high investments for the implementation of ‘end-of-pipe’ solutions, there was a strong tendency to understand environmental and sustainability issues as a cost to the organization, rather than as an opportunity.

In the early 1990s, a preventive approach emerged in a context in which companies started to improve their manufacturing processes, in order to minimize the increasing costs related to ‘end-of-pipe’ solutions, to comply with the ever-constraining legislation and to increase resource efficiency. Concepts such as Pollution Prevention and Cleaner Production were key in the period, when the preventive approach was at its highest. The aim was to reduce the waste generation directly at its source, i.e. in the production processes, thereby reducing treatment and final disposal costs (UNEP 2004; Ahmed 2012).

Besides being driven by legal aspects, this change in attitude was also due to the recognition of the real costs associated to the traditional ‘end-of-pipe’ approaches. In addition to the costs usually attributed to treatment and disposal, there are other costs that are usually not taken into account, such as, for example, costs related to the loss of resources (raw materials, water, energy, etc.), legal and regulatory non-compliance, corporate image, to name a few. Typically, for every dollar accounted for waste treatment or disposal, a further two to three dollars are ‘hidden’ or simply ignored, even in well managed and large companies (UNEP 2004).

Despite the innumerous benefits of reactive and preventive approaches to sustainability enhancement, they alone are not enough to deal with the sustainability challenges that our society was—and still is—facing, due to the ever-increasing production and consumption of products.

In the late 1990s, the recognition that products were at the origin of most of the pollution and resource depletion caused by our society became evident and a transition to a more proactive approach could be observed. At that time, companies started to realize that all products caused some sort of impact, not only during the manufacturing processes, but also throughout their entire life cycles, from raw material extraction through manufacturing, use and final disposal (Fava 1998).

In this context, ecodesign emerged as a promising approach for the integration of environmental considerations in product development processes, where the opportunities for enhancement of the environmental performance across the product life cycle was estimated to be around 80 % (through the definition of materials, suppliers, product performance, etc.) (Mcaloone and Bey 2009). The introduction of the life cycle thinking was associated with efforts to increase efficiency throughout the product life cycle (Brezet et al. 1999; Sherwin and Bhamra 1999; Stevels et al. 1999).

To enable ecodesign implementation in companies, several methods and tools were developed by industry and academia in this period. Several approaches for the

	-20 YEARS
Main goal/objects	Product
Expected results	End-of-pipe → proactive
Main aim	Tool building
Basic Approach	Singular problem approach
Envisaged cost-benefit	Sustainability = cost
Sustainability ambition	Environment
Business mindset	Linear economy
What are we changing	Improve the product
Decision-making level	Operational

Fig. 1 The rise and establishment of ecodesign (1990–2010)

evaluation of the environmental performance of products (e.g. through Life Cycle Assessment (LCA) and similar approaches) were developed and ecodesign guidelines for enhanced environmental performance of products were consolidated for different product types and industrial sectors (Caspersen and Sørensen 1998; Brezet et al. 1999).

The basic approach at this moment was focused on specific product issues (e.g. minimization of weight, elimination of hazardous substances, enhancement of energy efficiency, etc.). At this time, and due to the previous experience with end-of-pipe approaches, which were costly and mainly there for legislative compliance, sustainability was chiefly viewed as a necessary cost, with only very few companies being able to demonstrate the business benefits linked with ecodesign implementation.

The take-make-waste paradigm of the linear economy was the main paradigm in most of the companies at this time, although initial discussions regarding the impacts and importance of the end-of-life of products started to enhance towards the end of the 2010s (Rose et al. 2002). Most of the actions taken for ecodesign implementation were at an operational level, looking mainly at the product level and from a strict design perspective, linked to material and energy efficiency.

By the end of the 2010s, more than 100 different methods and tools were developed, but the broad uptake by industry was not as expected (Baumann et al. 2002) and new challenges started to be observed by society (Pigosso et al. 2015). At that time, there was a need to evolve the ecodesign concepts and allow for a broader implementation and uptake by industry. Figure 1 provides a summary of the main characteristics of corporate sustainability in the 1990–2010 period.

3 2010–2020: A Systems Perspective on Ecodesign

In the period 2010–2020 (which encapsulates the current time of writing), a shift can be observed in society, away from the more reactive, tool-building and singular problem-focus of the first era. In this period, a new wave of globalization is in full flow, enabled by technology and near-instant availability of products and services, all around the world. As the world gets smaller, so to speak, singular products often become commoditized, with their perceived value reducing to a minimum. For instance, the increased rate of commoditization can seem like a vastly negative trend, environmentally, due to ever-shortening product lifetimes and large bouts of waste, within a linear economy. However, two counter-developments have emerged, namely the embedding of high value in high quality products; and the emergence of product/service-systems onto the market. High-value, high-quality products (e.g. premium-priced smartphones and high-end portable computers) indeed provide some of the answer to the previous era's problem with commoditization and product waste. Product/service-systems, PSS (which effectively are purposely co-developed product and service bundles) are also increasingly normal in both B2B and B2C markets. PSS come with new business models, which often focus on providing more value-add from one installed base of a product, by means of some form of product life extension (often through sharing), and therefore dematerialization of the physical artefacts, which are component parts of the PSS under offer (Bey and Mcaloone 2006).

It is in this time period that many companies are starting to formulate sustainability goals, together with ways in which these will be measured, be they environmental, social and/or business-oriented. The very intensive period of tool building has slowed in this decade, with more emphasis being placed on how to actually successfully select from the large lists of tools and methods and implement the most suitable tools within the company (Pigosso et al. 2011; Bovea and Perez-Belis 2012). This is a positive development, as we can identify over 800 ecodesign best practices already (Pigosso et al. 2014)—the focus must now be on how to ensure successful implementation of these tools and methods into the business- and product development processes of the enterprise.

Together with the shift from products to PSS as a standard sustainability design object, the basic approach has shifted, so as to incorporate more sustainable decision points at a given time, thereby encompassing a systems approach towards sustainability enhancement. Nevertheless, many companies are not yet realizing the full benefit of their efforts towards sustainability improvement, often rendering sustainability as an activity that may not any longer be seen as a net cost to the company, but is still not a sufficient value-creator in itself.

In this decade, social sustainability is a clear focus point for the organization and a number of projects (often in collaborations between academia and enterprises) have been completed, where social sustainability methods and metrics have been developed, tried and tested (Ny et al. 2006; Boström 2012).

	-20 YEARS	- 0 - TODAY	10+ YEARS	Examples
Main goal/objects		PSS		
Expected results		Proactive → Sustainable		
Main aim		Tool implementation		
Basic Approach		System approach		
Envisaged cost-benefit		Sustainability = no extra value		
Sustainability ambition		Environment + (social)		
Business mindset		Close the loops		
What are we changing		Improve the process		
Decision-making level		Tactical		

Fig. 2 A systems perspective on ecodesign (2010–2020)

Western society is beginning to pay increasing attention in this decade to closing loops, rather than operating in a linear economy. Focus is increasingly being placed on takeback schemes, Design for Recycling activities, new business models to revalorize waste, and new forms of artefact sharing systems (e.g. bike-sharing, car-sharing, tool-sharing, to name but a few) (McDonough and Braungart 2010). We are by no means circular in our approach, but closed loop activities are beginning to be favoured over linear economy activities.

Looking inside companies and universities, we can see increasing focus being placed on how to create better processes towards sustainable product development, rather than simply creating yet another tool or a method. With this elevation of activities to the level of PSS, systems thinking and closed loop operations, companies are increasingly engaging the middle-management (tactical) levels of their business- and product development activities, in order to understand how to leverage greater parts of the companies' value-adding activities, through more tactical deployment of sustainability thinking (Tukker 2004). Figure 2 shows a summary of the main characteristics of corporate sustainability in the 2010–2020 period.

4 2020–2030: Perspectives for a Sustainable and Circular Economy

An even more significant transition to corporate sustainability is expected in the upcoming decade. Although predicting the future is impossible, we have attempted to develop a scenario of how current initiatives might possibly deploy over the next decade, based on an analysis of current trends and past developments.

Increasing recognition of the need to mitigate the effects of population growth, wealth increase and human consumption is currently leading several international organizations to consensually highlight the need for a significant change in our economic system, in order to respect planetary boundaries (Steffen and Stafford Smith 2013; Häyhä et al. 2016). Some examples of sustainability-related initiatives include: the roadmap for developing energy efficient and low-carbon societies by 2050, developed by the European Union; the 'green growth' framework to foster economic growth while ensuring the availability of natural resources, by the Organisation for Economic Co-operation and Development (OECD); and the Sustainable Development Goals (SDGs), launched by the United Nations in 2016. In order to reach global and European development goals, the private and governmental sectors in Europe need to undergo a large and systemic transition.

Due to the recognition of the systemic sustainability challenge faced by our society, a change towards extended collaboration within and across value chains is expected. Collaboration must be focused on developing new solutions and economic systems, bringing together different stakeholders in society, that help addressing the planetary boundaries (Steffen and Stafford Smith 2013).

An increasing amount of businesses will be maturing their approaches towards sustainability and increasingly integrating sustainability into not just the high-level strategic goals of the company, but also the everyday business and product development processes. This will allow each and every decision in the organization to be taken based on solid and conscious sustainability considerations. It will also give rise to a holistic approach, in which the connections and interfaces among complex systems are considered and their dynamic natures understood.

Competences will be significantly enhanced to be able to cope with the understanding of complex problems and the collaborative development of efficient solutions. Sustainability will be defined and committed at a strategic level in organizations and the deployment into the tactical and operational levels will be enabled by the enhanced maturity of companies on sustainability enhancement.

At this point, companies will have the contents and the context to be able to understand that sustainability equals business, and that there is no other alternative way of being successful in a business context. In fact, such signs are already evident in the very leading-edge corporations, which have put a direct relationship between sustainability and business-enhancing innovation (Ellen MacArthur Foundation 2015a). First on achieving a critical mass of this type of company, recognizing the opportunities of business-driven sustainability action, will we see that the sustainability concept defined as the balance between the environmental, social and economic dimensions will finally be fully met.

In the next decade, problems and risks related to resource scarcity and product disposal will be minimized by an enhanced uptake of the concept of Circular Economy (Ellen Macarthur Foundation et al. 2015), which is currently being boosted in many parts of the world.

Circular Economy is increasingly seen as a key approach to operationalizing goals and supporting the transition by enhancing competitiveness, economic growth and sustainability in many parts of modern society. Circular Economy is defined by the Ellen MacArthur Foundation as "*an economy that provides multiple value creation mechanisms, which are decoupled from the consumption of finite resources*" (Ellen MacArthur Foundation 2015a). Unlike the traditional linear 'take-make-waste' approach, the goal of Circular Economy is to seek to respect planetary boundaries through increasing the share of renewable or recyclable resources, whilst reducing the consumption of raw materials and energy and thus bringing down emissions and material losses (EEA 2016). Creating a Circular Economy requires fundamental changes throughout the value chain, from innovation, product design and production processes all the way to end of life, new business models and consumption patterns (EEA 2016).

Large and established, as well as small and start-up players in the industry are increasingly recognizing the need to commercialize secondary raw materials, to ensure spare-parts availability and to actively begin to devise alternative and innovative business models, disruptive to their current ways of working (2016). Among the strategies being addressed are: expansion of high value-added services; focus on Total Cost of Ownership (TCO) over the product lifetime; outsourcing agreements and rental offerings; technical leadership; and optimized product quality. Manufacturers are increasingly positioning their offerings, such as equipment financing; training for the best use of machines; fleet management; and equipment relocation services, as ways in which to enhance their value propositions to their customers. The positive news is that these new value propositions by the industry are potential components of a circular business model approach.

A successful transition to Circular Economy requires a systemic change in the way companies understand and do business, with sustainability as a strong foundation. Circular Economy will be enabled by the combined application of three component elements: (i) Business Model Innovation; (ii) Sustainable Design and Ecodesign; and (iii) Internet of Things coupled with Digital Transformation.

One of the most powerful enablers of a circular economy is sustainable business model innovation (Chun and Lee 2013; Pigosso and McAloone 2015; Reim et al. 2015). Business models that successfully incorporate Circular Economy principles have a direct and lasting effect on the social, economic and environmental systems (EEA 2016). Taking a sustainable business model view on Circular Economy promotes the integration of suitable approaches such as ecodesign, reuse, sharing, leasing, repair, refurbishment and recycling. By integrating the most suitable of these approaches to one's business- and product development will play a significant role in maintaining the utility of products, components and in realizing circular business models (EEA 2016).

Circular Economy business models can only be realized by the development of products, services and Product/Service-Systems that can be easily disassembled, remanufactured, recycled and reused (Bakker et al. 2014; Tukker 2015). Common approaches for the design of circular products includes the application of Design for Recycling, Design for Remanufacturing and Design for Disassembly methods, tools and guidelines (Sundin and Bras 2005; Pigosso et al. 2010; Achillas et al. 2013). Nevertheless, in order to ensure a superior sustainability performance of products, the entire life cycle of products need to be considered.

	-20 YEARS	- 0 - TODAY	10+ YEARS	Examples
Main goal/objects			Collaboration	
Expected results			Sustainable → Restoratory	
Main aim			Consolidated integration	
Basic Approach			Holistic approach	
Envisaged cost-benefit			Sustainability = business	
Sustainability ambition			Environment + social capital + economic	
Business mindset			Fully circular economy	
What are we changing			Improve our competencies	
Decision-making level			Strategic	

Fig. 3 Perspectives for a sustainable and circular economy (2020–2030)

Circular Economy can benefit greatly by equipping products with intelligence, so that they can adapt and respond to change and remain fit-for-purpose over longer time periods (Ellen MacArthur Foundation 2015b). A whole new range of virtual services and sharing economy platforms support the prolonged technical lifetime (and sometimes also up-cycling) of products by monitoring the condition of individual components or whole product systems.

In this context, Circular Economy will lead to the development of innovative business models, products, value chains, partnerships, and technologies that will enable a much more and efficient closed loop of materials and energy—and ultimately a more robust economy.

Due to the significant undermining of planetary boundaries caused through the industrial activities of the past century, it is increasingly recognized that the sustainability concept will need to embrace restoratory concepts, so as to reestablish the planetary boundaries at safe levels and not undermine life on Earth (Fig. 3).

5 Summary and Final Remarks

This chapter has provided our reflection of the development and evolution of sustainability initiatives and approaches observed since the 1970s in a corporate context. The reflection has structured in three distinct periods, which are characterized by their own specificities, challenges and focus areas (Fig. 4).

Despite the common perception that we are still struggling with the same issues since the early stages of corporate sustainability initiatives, a clear change in patterns and a significant evolution of the discussion is observed. Governmental bodies, universities, non-governmental organizations, companies and the civil society have significantly raised and enriched the debate around sustainability.

	-20 YEARS	- 0 - TODAY	10+ YEARS
Main goal/objects	Product	PSS	Collaboration
Expected results	End-of-pipe → proactive	Proactive → Sustainable	Sustainable → Restoratory
Main aim	Tool building	Tool implementation	Consolidated integration
Basic Approach	Singular problem approach	System approach	Holistic approach
Envisaged cost-benefit	Sustainability = cost	Sustainability = no extra value	Sustainability = business
Sustainability ambition	Environment	Environment + (social)	Environment + social capital + economic
Business mindset	Linear economy	Closing the loops	Fully circular economy
What are we changing	Improve the product	Improve the process	Improve our competencies
Decision-making level	Operational	Tactical	Strategic

Fig. 4 A journey through research contributions over the recent decades (1990–2030)

Furthermore, industry interest and uptake at the strategic, tactical and operational levels is following a steady increase—although many challenges are still faced for full sustainability integration.

In order to be able to cope with the sustainability challenges faced by our society and respecting the planetary boundaries, the speed of change and actual uptake by industry and a varied set of stakeholders must enhance significantly over the next decade. At the same time that ambitious targets must be set, it is important that industry companies take a systematic and step-by-step approach towards enhancing their organizational maturity to be able to develop and perpetuate successful and sustainable businesses.

References

Achillas, C., D. Aidonis, C. Vlachokostas, et al. 2013. Depth of manual dismantling analysis: A cost-benefit approach. *Waste Management* 33: 948–956. doi:10.1016/j.wasman.2012.12.024.

Ahmed, K. 2012. *Getting to green : A sourcebook of pollution management policy tools for growth and competitiveness*. Washington, DC.

Bakker, C., F. Wang, J. Huisman, and M. den Hollander. 2014. Products that go round: Exploring product life extension through design. *Journal of Cleaner Production* 69: 10–16. doi:10.1016/j.jclepro.2014.01.028.

Baumann, H., F. Boons, and A. Bragd. 2002. Mapping the green product development field: Engineering, policy and business perspectives. *Journal of Cleaner Production* 10: 409–425. doi:10.1016/S0959-6526(02)00015-X.

Bey, N., and T.C. Mcaloone. 2006. From LCA to PSS—making leaps towards sustainability by applying product/ service-system thinking in product development. In *13th CIRP International Conference on Life Cycle Engineering*, 571–576.

Boström, M. 2012. A missing pillar? Challenges in theorizing and practicing social sustainability: Introduction to the special issue. *Sustainability: Science, Practice, Policy* 8: 1–13.

Bovea, M.D., and V. Perez-Belis. 2012. A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. *Journal of Cleaner Production* 20: 61–71. doi:10.1016/j.jclepro.2011.07.012.

Brezet, H., A. Stevels, and J. Rombouts. 1999. LCA for EcoDesign : The Dutch Experience Ab Stevels design for sustainability program Delft University of Technology. In *First International Symposium On Environmentally Conscious Design and Inverse Manufacturing, 1999. Proceedings. EcoDesign'99,* 36–40.

Caspersen, N.I., and A. Sørensen. 1998. Improvements of products by means of lifecycle assessment: High pressure cleaners. *Journal of Cleaner Production* 6: 371–380.

Chun, Y.-Y., and K.-M. Lee. 2013. Life cycle-based generic business strategies for sustainable business models. *Journal of Sustainable Development* 6: 1–15. doi:10.5539/jsd.v6n8p1.

EEA. 2016. *Circular economy in Europe: Developing the knowledge base*. Luxembourg.

Ellen MacArthur Foundation. 2015a. *Growth within: A circular economy vision for a competitive Europe*, 100.

Ellen MacArthur Foundation. 2015b. *Intelligent assets: Unlocking the circular economy potential*.

Ellen Macarthur Foundation, SUN, Environment MC for B. 2015. *Growth within: A circular economy vision for competitive Europe.*

Fava, J.A. 1998. Life cycle perspectives to achieve business benefits: From concept to technique. *Human and Ecological Risk Assessment* 4: 1003–1017. doi:10.1080/10807039891284947.

Häyhä, T., P.L. Lucas, D.P. van Vuuren, et al. 2016. From Planetary Boundaries to national fair shares of the global safe operating space—How can the scales be bridged? *Global Environmental Change* 40: 60–72. doi:10.1016/j.gloenvcha.2016.06.008.

Mcaloone, T.C., and N. Bey. 2009. *Environmental improvement through product development—A guide*, 1st ed. Copenhagen: Denmark.

McDonough, W., and M. Braungart. 2010 *Cradle to cradle: Remaking the way we make things*. Macmillan.

Ny, H., J.P. MacDonald, G. Broman, et al. 2006. Sustainability constraints as system boundaries—An approach to making life-cycle management strategic. *Journal of Industrial Ecology* 10: 61–77. doi:10.1162/108819806775545349.

Pigosso, D.C., and T.C. McAloone. 2015. Supporting the development of environmentally sustainable PSS by means of the ecodesign maturity model. *Procedia CIRP* 30: 173–178. doi:10.1016/j.procir.2015.02.091.

Pigosso, D.C.A., T.C. McAloone, and H. Rozenfeld. 2014. Systematization of best practices for ecodesign implementation. In *International Design Conference—DESIGN 2014*, 1651–1662. Croatia: Dubrovnik.

Pigosso, D.C.A., T.C. McAloone, and H. Rozenfeld. 2015. Characterization of the state-of-the-art and identification of main trends for Ecodesign Tools and Methods: Classifying three decades of research and implementation. *Journal of the Indian Institute of Science* 95: 405–427.

Pigosso, D.C.A., H. Rozenfeld, and G. Seliger. 2011. Ecodesign Maturity Model : Criteria for methods and tools classification. *Advanced Sustainable Manufacturing* 241–245.

Pigosso, D.C.A., E.T. Zanette, A.G. Filho, et al. 2010. Ecodesign methods focused on remanufacturing. *Journal of Cleaner Production* 18: 21–31. doi:10.1016/j.jclepro.2009.09.005.

Reim, W., V. Parida, and D. Örtqvist. 2015. Product-service systems (PSS) business models and tactics—a systematic literature review. *Journal of Cleaner Production* 97: 61–75. doi:10.1016/j.jclepro.2014.07.003.

Rose, C.M., K. Ishii, and A. Stevels. 2002. Influencing design to improve product end-of-life stage. *Concurrent Engineering: Research and Applications* 13: 83–93. doi:10.1007/S001630100006.

Sherwin, C., and T. Bhamra. 1999. Beyond engineering: ecodesign as a proactive approach to product innovation. In *Proceedings of the First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 41–46. doi:10.1109/ECODIM.1999.747578.

Steffen, W., and M. Stafford Smith. 2013. Planetary boundaries, equity and global sustainability: Why wealthy countries could benefit from more equity. *Current Opinion in Environmental Sustainability* 5: 403–408. doi:10.1016/j.cosust.2013.04.007.

Stevels, P.A., B. Sk, P.O. Box, and N.-J.B. Eindhoven. 1999. *Integration of EcoDesign into business, a new challenge*, 27–32.

Sundin, E., and B. Bras. 2005. Making functional sales environmentally and economically beneficial through product remanufacturing. *Production* 13: 913–925. doi:10.1016/j.jclepro.2004.04.006.

Tukker, A. 2004. Eight types of product–service system: Eight ways to sustainability? Experiences from SusProNet. *Business Strategy and the Environment* 13: 246–260. doi:10.1002/bse.414.

Tukker, A. 2015. Product services for a resource-efficient and circular economy—A review. *Journal of Cleaner Production* 97: 76–91. doi:10.1016/j.jclepro.2013.11.049.

UNEP. 2004. Guidelines for the integration of cleaner production and energy efficiency.

(2016) European Forum for manufacturing debates circular economy. http://www.cece.eu/news-and-events/news-details/article/european-forum-for-manufacturing-debates-circular-economy/.

Design for High Added-Value End-of-Life Strategies

Tom Bauer, Daniel Brissaud and Peggy Zwolinski

Abstract Sustainable manufacturing is a rising issue. Ensuring both consumer satisfaction and minimal environmental impact is very challenging. In that whole process, it is customary to say that the design stage determines 80 % of the future environmental impact. One way to contain this impact at an acceptable level is to manage the products' end-of-life from the design activities. This chapter points out product reuse strategies—i.e. *direct reuse and remanufacturing*—aiming at conserving the added-value of used products as much as possible into new products. The first contribution attempts to provide a state-of-the-art of design for these high added-value end-of-life strategies. Direct reuse and remanufacturing are thus analysed and the principal design guidelines are furthermore given, classified according to three dimensions: product, process and business model. This chapter then contributes to enlarging the spectrum of reuse strategies, presenting an innovative end-of-life strategy: repurposing. It consists of reusing products in other applications after transformations. The main challenges of such a strategy will be discussed.

Keywords Design for X · End-of-life strategy

1 Introduction

There is a need to improve the environmental orientation of products and the management of their end-of-life (EoL) represents one way of achieving this. Many studies argue that it could be initiated from different actors: customers, pushing for greener products; companies, willing to reduce the environmental footprint of their products as much as increasing their revenues; or regulation, favouring

---

T. Bauer (✉) · D. Brissaud · P. Zwolinski
Univ. Grenoble Alpes, CNRS, G-SCOP, 38000 Grenoble, France
e-mail: tom.bauer@grenoble-inp.fr

R. Stark et al. (eds.), *Sustainable Manufacturing*, Sustainable Production,
Life Cycle Engineering and Management, DOI 10.1007/978-3-319-48514-0_8

low-impact-products and obligating producers to handle their end of life processes, beginning with the design phase (Global Reporting Initiative 2013; Goodall et al. 2014).

An end-of-life strategy refers to the manner in which one manages the product right after its user has discarded it. The focus today is on end-of-life strategies that maximise the value of the products, so-called reuse strategies. These strategies have key characteristics that must guide designers to facilitate their initial setup. This chapter tries first of all to make these strategies clear as well as outline what the drivers are for the most adapted designs. An exploration follows, of how the main end-of-life strategies maximise the value of products, along with how to support product designers in their willingness to pursue these maximizing-value strategies.

These end-of-life strategies and their consequences on the design of products are now well-known and shared among companies: the product characteristics, its performances and the recovering process are described in literature. Nevertheless, the discussion is open to proposing new strategies that retain more and more added value of used products for the purpose of ultimately manufacturing innovative products. Repurposing, meaning that end-of-life products can be revamped into different applications than the former ones to prolong their lifetime, needs now to be understood, modelled and analysed in pursuit of guaranteeing its implementation and its potential value.

Following this introduction, the chapter describes the product end-of-life strategies in Sect. 2, before focusing on high added-value strategies, and reuse strategies, in Sect. 3. They will be described in terms of product, process and business model characteristics and an overview of the main guidelines for assisting the product design work will be summarized. Section 4 paves the way for the repurposing strategy to be presented and discussed.

2 High Added-Value End-of-Life Strategies

The need to define a product end-of-life strategy takes place when the product is considered as a ‘waste’ (European Commission 2008). The European Commission (2008) defines *waste* as: “any substance or object which the holder discards or intends or is required to discard.” Depending on its type, characteristics and working conditions, the discarded product may follow one or another strategy. ISO proposes a classification of end-of-life strategies though the standard 14062 (ISO 2002), which has been ranked depending on potential environmental gains: (a) prevention, (b) reuse, (c) recycling, (d) energy recovery and (e) disposal; (European Commission 2008). In this chapter, the focus is set on strategies which aim at maintaining as much added-value in products as possible.

First of all, energy recovery and landfilling do not represent sustainable strategies since they do not recover any element of the products: both added value and material are destroyed. These strategies will be grouped under the “waste” label in the chapter (see 1 in Fig. 1). Recycling (see 2 on Fig. 1) consists of recovering

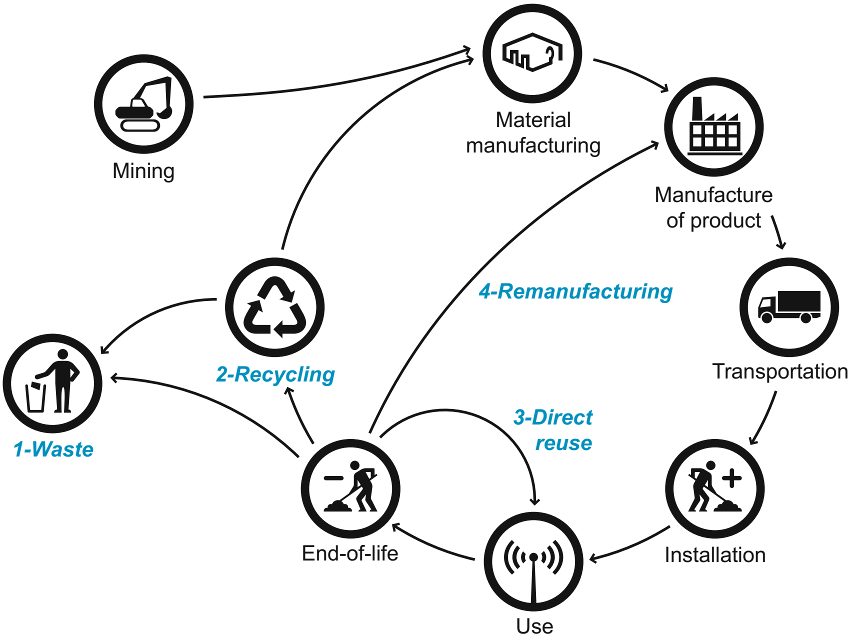


Fig. 1 Product lifecycle and the 4 main end-of-life strategies (adapted from Zhang 2014)

materials from the discarded products in order to avoid new raw material extraction and, in so doing, limit the environmental impact and supply issues. The recycling strategy destroys the added-value of the product and instead only recovers materials. The strategies that recover material and retain the product's added-value are called reuse strategies. It can be split in two distinct sub-strategies: direct reuse and remanufacturing. Direct reuse (see 3 on Fig. 1) is a process where the quality of the product and the market conditions allow for continued use of the same product by another customer. The remanufacturing strategy (see 4 on Fig. 1) concerns products that have to go through a new manufacturing process before being put back on the market. Indeed, direct reuse and remanufacturing both aimed at providing as-new products with at least the same guaranties and performances as a new product and for the same application. Finally, prevention mainly consists of avoiding the impact before the end of the product life, by minimizing wastes.

The paper focuses on end-of-life strategies that conserve added-value of products, meaning the materials after manufacturing transformation. These strategies are called "reuse strategies." The "quantity" of added-value retained, and the corollary "quantity" of transformation needed to recover the added-value missing, characterize the process of remanufacturing of the product from "high added-value retained—light remanufacturing process" (direct reuse strategy) to "less but real added-value kept—standard remanufacturing process" (remanufacturing strategy).

3 Design for Direct Reuse and Remanufacturing

The focus of this section is on reuse strategies happening right after the End-of-Use (EoU) of products. A distinction is made between Design for direct Reuse (DfdR) and Design for Remanufacturing (DfRem). Definitions, explanation and design guidelines are pointed out.

3.1 Definitions and Main Characteristics

The direct reuse strategy may be defined as: “any operation by which products or components that are not waste are used again for the same purpose for which they were conceived” (European Commission 2008). Gelbmann and Hammerl (2015) state that the performances of the directly reused product must be as good as a new one to achieve the same function while Arnette et al. (2014) assert that products have to be “good enough” to fulfil the following use. In any case, products need to be in sufficient working condition to be reused directly. Products which are reused directly are often however considered second-hand products and their components used to repair other products (Go et al. 2015) instead of becoming a product in and of themselves. This implies new products manufacturing instead of potential reuse of products. In terms of the manufacturing process, the direct reuse strategy involves already-used products’ collection from the waste stream, cleaning, sorting and testing of products (Gelbmann and Hammerl 2015; Go et al. 2015). These steps make it possible to solve potential problems and ensure their well-functionality so that they can be reused directly in similar applications (Pigosso et al. 2010; Arnette et al. 2014; Gelbmann and Hammerl 2015). The remaining unsettling factor about the definition of direct reused products concerns its legal status after the first use. Some authors (Gelbmann and Hammerl 2015) insist on considering them as wastes since the European Commission (2008) no longer does this. In the latter case, the product shall ceased to be defined as such upon following different steps to be reintroduced onto the market (European Commission 2008).

The remanufacturing strategy has largely been studied over the past decades. Lund (1984) gave the first definition of remanufacturing and stated it to be: “an industrial process in which worn-out products are restored to like-new condition.” This definition has been adapted by the European Commission (2015), which describes remanufacturing as “a series of manufacturing steps acting on an end-of-life part or product in order to return it to like-new or better performance, with corresponding warranty.” The most important matter to appreciate here is that manufacturing processes will be needed in order to bring products back to their original state or to a better state. In other words, the remanufacturing process attempts to recover as much added-value from the original manufacture as possible (Zwolinski et al. 2006; Gray and Charter 2008). The remanufacturing process may be slightly more complex than direct reuse. The starting point for remanufacturers is to obtain from the user, the collected-used products and return them to their factories. Sundin and Bras (2005) detail seven generic process steps for the remanufacturing business: inspection, storage, cleaning, disassembly, reassembly, repair and testing. These steps—in part or in full—are found in any remanufacturing activity whatever its sector of activity.

In both direct reuse and remanufacturing strategies, the objective is the same: deliver to the market a product that is similar to the initial one and built from the initial materials. They both ensure reuse objectives, while the main difference stems from the quantity of operations needed to make the product reusable again. If the process needed to rebuild the product is mainly a cleaning process, it is considered as direct reuse. Otherwise, if the process calls for machining and more complex operations, it constitutes a remanufacturing strategy. Both strategies aim at lowering our environmental pressure. Among the different end-of-life strategies, direct reuse is said to have the best environmental and economic advantages (European Commission 2008; Arnette et al. 2014; Go et al. 2015; Gelbmann and Hammerl 2015), while remanufacturing is second (Sundin and Bras 2005; Hatcher et al. 2011; Go et al. 2015). Gray and Charter (2008) quote that the remanufacturing strategy would require 85 % less energy than manufacturing. Direct reuse should not require new high energy consuming transformations. Furthermore, they would both preserve resources, as they could be seen as “a new product avoided.” Hatcher et al. (2011) furthermore add that it could be “a combination of new and reused parts.” The main drawback of both strategies lies in the efficiency-in-use of the product when reused. Indeed, direct reused and remanufactured products—even if they are as-good-as-new—may be less efficient than brand-new ones due to technological evolution.

3.2 Design for Reuse

In order to evaluate the different reuse strategies, i.e. direct reuse and remanufacturing—it is important to define a common framework of analysis in line with the customary design processes.

3.2.1 Different Reuse Strategies Under a Single Framework

When designing for sustainability purposes or for the environment, it is crucial to include all the different lifecycle steps, from cradle to grave—i.e. from raw material extraction to end-of-life stages, including manufacturing and use phases (Crul and Diehl 2009). From that point, a classic description of such strategies would distinguish products characteristics from manufacturing processes, or else design from production. This may come from bygone days when design office and production planning department were two separate entities. Nowadays, with integrated design, external parameters have to be considered all along the lifecycle of the product

(Brissaud and Tichkiewitch 2000). This leads to a better organisation of the overall offer, whether it be in terms of stakeholders' relationships, value creation, value chain of the offer, or any surrounding elements. All these elements are then gathered under the business model label. A parallel has already been made in the remanufacturing literature, where Gray and Charter (2008) pinpointed these three dimensions (called spheres) and distinguished Product characteristics from manufacturing Processes and Business Model features (P.P.BM. spheres). Indeed, Sundin and Bras (2005) and Zwolinski et al. (2006) detailed product characteristics and process activities considering external factors.

The P.P.BM. spheres are considered in this paper for the purpose of structuring the design guidelines. These guidelines help designers to define product and process parameters in line with the strategy of the company. The *product* area covers the product itself and its components. Their main characteristics are defined in order to distinguish products from different EoL strategies. The *process* concerns the different steps put in place in order to deliver the products and assign their respective characteristics. The Business Model defines the global strategy for delivering the product and its organisation. Each of these three spheres entails specific characteristics defined from literature in Bauer et al. (2016) and recalled in Tables 1, 2 and 3.

3.2.2 How to Design These Kinds of Products?

Design processes have largely been studied in the literature (Tomiyama et al. 2009). Design tools and methods have been well-known for years and many improvements have already been made, especially with integrated design (Brissaud and Tichkiewitch 2000). Indeed, designing a product implies the interaction from multiple areas of expertise in a single company. In that process, gathering the different actors from the early stages would facilitate the integration of the different constraints, whether they were linked to the product, the process, or the business model. From that point, the design process follows different steps to progress from the product idea to the product retirement (see Fig. 2).

Although they follow a reuse strategy at their end of use, to-be-reused products need to be considered like any other manufactured ones in the first place, so that the design phases between the two would not change much (Gray and Charter 2008). Despite that, the key issue for to-be-reused products lies in integrating the required parameters that are designed to ensure the end-of-life strategy. To be set up efficiently, they have to be integrated from the early design stages (Gray and Charter 2008). Hence, reuse can be seen as a classic integrated design, with specific attention to end-of-life parameters.

Table 1 Guidelines: process sphere (classified by characteristics)

Characteristics	Guidelines for reuse strategies	Guidelines for Remanufacturing strategy only
Stable process	Standardise and use common tools Reduce the diversity of components Reduce the variation in cores	
Inspection & Sorting	Minimise inspection time Mark inspection points clearly Minimise the number of different materials Use standard components	
Cleaning	Avoid components that can be damaged during cleaning process Minimise geometric features harming cleaning process Identify components requiring similar cleaning processes	Facilitate access to the cleaning process Ensure marking on product can survive cleaning process
Dis/Re-assembly	Avoid permanent fasteners that require destructive removal Increase corrosion resistance of fasteners Reduce the total number of fasteners Reduce the number of press-fits Standardise and use common fasteners (type and size)	Minimise disassembly and reassemblyt ime Arrange parts and components to facilitate assembly, especially the ones that are easily prone to damage Use assembly techniques that allow easy access to inspection points Use assembly techniques that allow upgrade Use assembly techniques that will withstand overall remanufacturing processes but that will not allow for damage to components that have the potential to be reused/remanufactured Use robust materials to ensure assembly operations
Storage	Ensure no damage during storage	
Remanufacturing		Standardise and use common processes
Testing	Minimise thenumber of tests Reduce test complexity Standardise tests Reduce the number of tests at the level required Facilitate tests of components Provide testing documentation	

3.3 Main Guidelines for Design for Direct Reuse and Remanufacturing

The reuse literature is already overflowing with design guidelines for facilitating the adoption of direct reuse and remanufacturing strategies (Ijomah 2009; Arnette et al. 2014; Go et al. 2015). In the same manner, three spheres have been proposed (Bauer et al. 2016) to characterise end-of-life strategies. The categorisation of

Table 2 Guidelines: product sphere (classified by characteristics)

Characteristics	Guidelines for reuse strategies	Guidelines for Remanufacturing strategy only
Reliable product	Select reliable materials Select reliable components	
Durable product	Select durable materials Select durable and robust components Prevent core damage Prevent part and surfaces against external environment Avoid components that can be damaged during cleaning process	Avoid components that can be damaged during inspection process Avoid components that can be damaged during disassembly process Avoid components that can be damaged during refurbishment process
Functional prob.		
High initial cost		
Efficient product		
Modularity / Upgradability		Standardise and use common materials, components and fasteners Use modular parts and components thus reducing complexity of disassembly because types of assembly techniques are reduced Structure the product and parts to facilitate ease of upgrade
Physical elements		Avoid permanent fasteners that require destructive removal Increase corrosion resistance of fasteners Standardise and use common fasteners (type and size) Reduce the total number of parts, components, fasteners, press-fits and joints Specify materials and forms appropriate for repetitive manufacturing
Stable technology	Standardise and use common materials, components and fasteners Standardise and use common interfaces Design reusable parts and components Facilitate access to components Facilitate switch of damaged components	
Documentation	Provide readable labels, text, and barcodes that do not wear off during the product's service life Provide good documentation of specifications, clear installation manuals and testing documentation Provide clear information about product, parts, components and materials Set up sacrificial parts to give an indication of the components' state of life	

Table 3 Guidelines: business model sphere (classified by characteristics)

Characteristics	Guidelines for reuse strategies	Guidelines for Remanufacturing strategy only
Ease of reuse	Verify the market acceptance of the offer Determine the internal skills needed	Reduce the rejection of remanufactured products
Ease of supply	Embed mechanisms into the product to ensure the return of cores Facilitate collection of core parts Facilitate Reverse logistics	
Economic motivation		
User profile		
Remanufacturing reason		
Partnership		
Legislation		
Environmental gains	Avoid toxic materials Determine the cleaner production anduse	

Fig. 2 Common design stages in product development

design guidelines according to one of the P.P.BM. sphere and then to the closest characteristic it would be linked to, is what is proposed here. Designers are therein provided with the guidance necessary for identifying which rule would lead to which characteristic. Some characteristics are created or renamed when the initial ones are not relevant enough for a design activity.

The two specific reuse strategies—direct reuse and remanufacturing, their characteristics and design guidelines are classified in Tables 1, 2 and 3. Guidelines dedicated to both direct reuse and remanufacturing were grouped together in one column labelled '*Guidelines for reuse strategies*', while the ones specific to remanufacturing were separated in the right-hand side column. Table 1 thus clusters characteristics and guidelines addressing the process Table 2 then gathers the different characteristics and guidelines connected to the product. The principal elements are related with direct product characteristics, such as durability and reliability, and physical elements facilitating the strategy—e.g. fasteners, parts…. The main process steps are recalled and specific guidance is provided. Finally, Table 3 covers the business model characteristics and guidelines. It is mainly a matter of organisation and reverse logistics.

Two points immediately stand out for careful discussion. First, it appears that some characteristics do not have any concomitant guideline. The reasons are that none of them has been identified in literature or due to the fact that the guideline was closer to another characteristic. The knowledge corpus will be increased with literature progress. The second point concerns the repartition of the guidelines. It appeared that all the guidelines related to direct reuse strategy were included in the remanufacturing strategy (grouped together in the column labelled '*Guidelines for reuse strategies*'). Nevertheless, some have only been identified in DfRem literature. This seems logical, however, as, the major difference between both is that remanufacturing implies more remanufacturing before the product could go back to the market. This is noticeable in the Tables 1, 2 and 3: all specific remanufacturing guidelines are directly or indirectly related to the remanufacturing process steps.

3.4 Discussion

The characteristics have been highlighted and organised according to the P.P.BM. spheres. Design guidelines from literature were then linked to the most relevant reuse characteristic. If everybody agrees on the end goal of maintaining a high level circular economy, the applications are not as numerous as expected (Gelbmann and Hammerl 2015). Reused products may not yet be well-accepted on the market (Arnette et al. 2014), nor are design guidelines practical enough for each particular product.

The primary difficulties in implementing the reuse strategies remain. One key parameter concerns the reverse logistic chain, hitherto not well addressed as it mainly depends on company decision-making (Hatcher et al. 2011; Go et al. 2015). Indeed, the crucial step is to retrieve already-used products in pursuit of ensuring direct reuse or remanufacturing. This issue has to be defined from the design stages (Go et al. 2015). That is, the company needs to know where the retired products will be, how to get them back, and how to set up the logistics for bringing them back to the company or to another defined point (Gelbmann and Hammerl 2015; Go et al. 2015). These steps may rely on partnerships (Gelbmann and Hammerl 2015). The second point is related to the difficulty in putting the strategies in place *a posteriori*, after the products have been designed and *lived* (Hatcher et al. 2011). The use of the precedent design guidelines may allow for partial avoidance of such problems, or at minimum, for identification of the weak points ahead.

The limits of the design guidelines for reuse strategies need also to be highlighted. First of all, characteristic to all guidelines is that they tend to be rather generic, which means they should be applicable to most of the products. Designers need to adapt them to the case at hand, yet the resulting specifications may conflict with the guidelines traditionally used in the domain. Secondly, some of the characteristics that have been highlighted in each sphere do not contain any guidelines either for direct reuse or remanufacturing. Two main reasons can be outlined here. Number 1: the characteristic is mainly related to the company strategy and its motivation for this kind of business—e.g. economic motivation, favouring legislation. All the same, no generic guideline is applicable as it is related to the company itself. Number 2: the characteristic is inherent to the product itself and is more related to product specifications than guidelines—e.g. high initial cost, efficient product. Guidelines, company specifications and product specifications are complementary and thus, it does not matter in what manner they find their way to the designer. In practice, when using DfdR and DfRem guidelines, a risk arises that designers follow the guidelines without integrating the initial product and process specifications and therein miss out on some crucial points. Guidelines are set up to facilitate the designer's job according to previous studies. Yet, every product is distinct from the others, so that requiring specific parameters may make one guideline irrelevant and may thus not apply.

4 The Repurposing Strategy

A rising EoL strategy in literature concerns "repurposing". Repurposing is a third reuse end-of-life strategy that complements the two previous ones. Much like other reuse strategies, repurposing allows for retention of added-value in used products.

4.1 Limits of Direct Reuse and Remanufacturing Strategies

Current reuse strategies—i.e. direct reuse and remanufacturing—aim at and succeed in preserving a part of the added-value of used products in the manufacturing of new products. The reuse process can be seen in three main issues (Fig. 3). The limits of each of them are analysed for the purpose of extracting the orientations for a complementary strategy that would increase the quantity of reused products.

The reuse strategy is a manufacturing strategy driven by market conditions. The assumption in direct reuse and remanufacturing is that the new product must at least offer the same levels of performances and of customers' satisfaction than the old product. The market can be limited by the number of like-new products that can be absorbed by the customers. The market must furthermore be open for new products. Opening the market involves upgrading or repurposing. Upgraded products are products of the initial family where performances and functions are different. Repurposed products are products that are sold for a different purpose and belong to a different product family. For example, electric vehicles' batteries can be recomposed to be reused in stationary applications.

The existence of the transformation process depends on the technical feasibility *(can the process push the product to the initial performance?),* the environmental performance *(is the reused process greener than the initial one?)* and the economic concern *(can the value chain be profitable?).* Because products are very often designed without any objective of reusing them, they cannot be disassembled

Fig. 3 The reuse end-of-life main process

without damage and, consequently, cannot be reused. It is thus clear that design is a very important phase to improve upon. Yet there are also remanufacturing processes that cannot give back the initial performances to the product. It is clearly the case today for batteries of electric vehicles that cannot be remanufactured for the simple reason that the technology is unable to recover the initial performance at a reasonable cost (Beverungen et al. 2016). The question of what to do with the stock of such batteries is an open issue.

The collection of already-used products depends on their quality *(does the core retain the quality for the expected performance?)* and quantity *(are there enough collected used products to make the business profitable?).* Quality issues could sometimes be overlooked if the question was raised of finding new applications where technical performances are not the key issue. Quantity depends on the efficiency of the collection process and the capacity of the market to absorb more products. Alongside the economic issue, the environmental issue of waste management can likewise figure in as a significant driver of the business.

Let us explain the concept with the example of electric vehicle batteries, currently under discussion in the literature. It starts with two claims: in a few years' time, the issue of waste management will be crucial because the performance of a battery cannot be recovered by technology, while the market of stationary applications calling for batteries is however exploding. The idea is to couple both claims and see whether electric vehicle batteries, no longer efficient enough for mobile applications, can be reused after transformation in stationary applications like lighting and housing. Idjis (2015) studied a recovery network for end-of-life electric vehicle batteries from "a technical-economic, organizational and prospective perspective." He identified the business model elements (the economic viability; legal requirements) that enable the repurposing of a company to manage reverse logistics for core supply, to rely on partnerships, and assessed the effective quantity of batteries for repurposing into stationary applications as well as the properties at the end-of-use. Beverungen et al. (2016) identified and validated with experts the functional and non-functional requirements for repurposed batteries from EV to stationary applications. Based on a battery expert interview and literature (Ahmadi et al. 2014; Bauer et al. 2016; Beverungen et al. 2016), the repurposing process seems to include the same steps as reuse strategies: inspection and sorting, cleaning, dis-/re-assembly, storage, repurposing operations and testing. The repurposing step would mainly rely on reconfiguring the different components and sub-assemblies of the products and include a few product developments in order to then fulfil new requirements or connect the components in the new fashion.

4.2 *Repurposing: Definition and Advantages*

Repurposing is a reuse end-of-life strategy that aims at preserving added-value of used products by reusing them in different applications and fields and in so doing, get around the remanufacturing and direct reuse strategies by targeting new markets.

Repurposing aims at maintaining high added-value products on the market as long as possible, to ultimately delay recycling or disposal. This strategy does not replace direct reuse or remanufacturing, but nevertheless fills a gap when these two last options are not applicable. No market cannibalisation may take place, as, the applications are distinct. This strategy should complete the list of reuse strategies and contributes to extended producer responsibility in the whole environmental consciousness equation (European Commission 2008). Company responsibility at the end of the first end-of-usage is transferred to the second life of the products. It could be done in as many cycles as possible until being transferred to the material recycling process. When the repurposing is properly implemented, the strategy is determined to be more environmentally friendly and less cost effective than manufacturing products from raw materials. The research only still has to prove in which conditions this performance may be present.

The repurposing process is close to a remanufacturing one (Fig. 4). The same types of operations are necessary, even when the combinations of parts are larger. The main difference is that the diagnostic phase on the quality of the used products collected (the product health) must be much more detailed and very intelligent in pursuit of orienting the core to the most adapted transformation process. Another difference of course lies in the technology for transforming the used product into a totally different product that must be developed, which then turns out to be easier in terms of repurposing. This strategy holds great potential for personalising new products. The principle that the performance criteria may evolve from one use to another points to real opportunity in that realm.

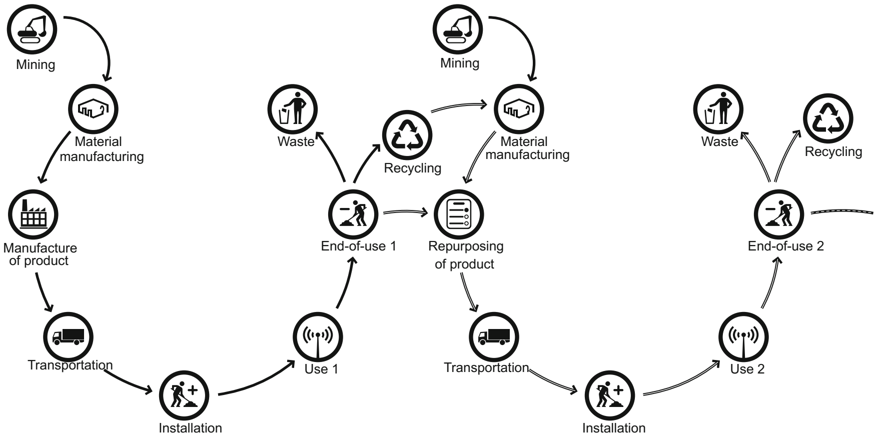


Fig. 4 Product lifecycle for repurposing, the end-of-life strategy

4.3 Short Discussion on Design for Repurposing

Design for repurposing represents a completely new issue. If it seems adapted to benefit from the guidelines for reuse strategies presented above, then the perspective of the design becomes totally different, meaning that the design drivers should be re-conceptualised.

The main discussion is on determining whether the best design strategy is to design the new products from a classical design process where the constraints of input elements are new (the collected parts and materials) but known, or to design products from scratch that would have several lives in different applications. The former calls for research in defining the specifications of a repurposed product along with the design rules for transforming a product with a repurposing approach. The latter seems to be much more optimal, but the uncertainty attached to the future of the product is so high that anticipating the actual usages and the time of the first use, yields only clues about short life products. Furthermore, additional difficulty stems from the number of different applications necessary for consideration before the original design phase. The new design approach, in the both cases, should include an objective of monitoring successive lives of the product in order to help decide on the parameters of the next life once the time comes.

The literature has commenced, with Beverungen et al. (2016) and Bauer et al. (2016) already proposing some characteristics of repurposed products and repurposing production systems. The repurposed system has to be durable and reliable, which means that few instances of breaking should happen during its lifetime, while its performance should be possible to predict. Safety issues must also be addressed differently, i.e. extra life products need to consider safety as a key element for the consumer. They highlight that modularity and standardization would help to that effect. In the end, however, the principles are the same: physical characteristics of products should facilitate the repurposing process. All these points have not yet been addressed in full in the design literature and further investigations are therefore needed.

5 Conclusion

Design for direct reuse and remanufacturing, the end of use strategies with the most added-value retained from used products, have already become a reality in companies and are in demand by society with sustainability ambitions. While direct reuse is mainly a logistics and control issue, remanufacturing aims at getting back to the initial performances of products. These two strategies have been fully examined in studies of the last years and their main characteristics were presented according to three spheres: product dimension, manufacturing processes and business model features (P.P.BM.). The design guidelines were collected and classified for an easy use by designers.

To open minds, a valuable strategy for reusing products in different applications than the initial ones were designed for is proposed: repurposing. The concept is clarified and the main issues for the design process have been highlighted. These pursuits are promising but need investigation to find the conditions for successful deployment.

References

Ahmadi, Leila, Michael Fowler, Steven B. Young, Roydon A. Fraser, Ben Gaffney, and Sean B. Walker. 2014. Energy efficiency of Li-Ion battery packs re-used in stationary power applications. *Sustainable Energy Technologies and Assessments* 8(December): 9–17. doi:10.1016/j.seta.2014.06.006.

Arnette, Andrew N., Barry L. Brewer, and Tyler Choal. 2014. Design for sustainability (DFS): The intersection of supply chain and environment. *Journal of Cleaner Production* 83(November): 374–390. doi:10.1016/j.jclepro.2014.07.021.

Bauer, Tom, Guillaume Mandil, Élise Naveaux, and Peggy Zwolinski. 2016. Lifespan extension for environmental benefits: A new concept of products with several distinct usage phases. In *Procedia CIRP*, 47:430–435. Product-Service Systems across Life Cycle. doi:10.1016/j.procir.2016.03.079.

Beverungen, Daniel, Sebastian Bräuer, Florian Plenter, Benjamin Klör, and Markus Monhof. 2016. Ensembles of context and form for repurposing electric vehicle batteries: An exploratory study. *Computer Science—Research and Development*, July, 1–15. doi:10.1007/s00450-016-0306-7.

Brissaud, Daniel, and Serge Tichkiewitch. 2000. Innovation and manufacturability analysis in an integrated design context. *Computers in Industry* 43(2): 111–121. doi:10.1016/S0166-3615(00)00061-0.

Crul, Marcel, and Jan Carel Diehl. 2009. *Design for sustainability: A step by step approach*. UNEP, United Nation Publications. http://www.d4s-sbs.org/.

European Commission. 2008. *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives*. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32008L0098.

European Commission. 2015. *Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the Loop—An EU Action Plan for the Circular Economy*. Bruxelles, Belgique. http://ec.europa.eu/environment/circular-economy/.

Gelbmann, Ulrike, and Barbara Hammerl. 2015. Integrative re-use systems as innovative business models for devising sustainable product–service-systems. *Journal of Cleaner Production* Special Volume: Why have 'Sustainable Product-Service Systems' not been widely implemented?, 97 (June): 50–60. doi:10.1016/j.jclepro.2014.01.104.

Global Reporting Initiative. 2013. G4 sustainability reporting guidelines—reporting principles and standard disclosures. Global Reporting Initiative. https://www.globalreporting.org/resourcelibrary/GRIG4-Part1-Reporting-Principles-and-Standard-Disclosures.pdf.

Go, T.F., D.A. Wahab, and H. Hishamuddin. 2015. Multiple generation life-cycles for product sustainability: The way forward. *Journal of Cleaner Production* 95(May): 16–29. doi:10.1016/j.jclepro.2015.02.065.

Goodall, Paul, Emma Rosamond, and Jenifer Harding. 2014. A review of the state of the art in tools and techniques used to evaluate remanufacturing feasibility. *Journal of Cleaner Production* 81(October): 1–15. doi:10.1016/j.jclepro.2014.06.014.

Gray, Casper, and Martin Charter. 2008. Remanufacturing and product design. *International Journal of Product Development* 6(3–4): 375–392.

Hatcher, G.D., W.L. Ijomah, and J.F.C. Windmill. 2011. Design for remanufacture: A literature review and future research needs. *Journal of Cleaner Production* 19(17–18): 2004–2014. doi:10.1016/j.jclepro.2011.06.019.

Idjis, Hakim. 2015. La filière de valorisation des batteries de véhicules électriques en fin de vie : contribution à la modélisation d'un système organisationnel complexe en émergence. Ph.D. thesis, Université Paris-Saclay. https://tel.archives-ouvertes.fr/tel-01243863/document.

Ijomah, Winifred L. 2009. Addressing decision making for remanufacturing operations and design-for-remanufacture. *International Journal of Sustainable Engineering* 2(2): 91–102. doi:10.1080/19397030902953080.

ISO. 2002. *Integrating environmental aspects into product design and development. ISO/TR 14062:2002*. http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=33020.

Lund, Robert T. 1984. Remanufacturing. *Technology Review* 87(2): 19–29.

Pigosso, Daniela C.A., Evelyn T. Zanette, Américo Guelere Filho, Aldo R. Ometto, and Henrique Rozenfeld. 2010. Ecodesign methods focused on remanufacturing. The roles of cleaner production in the sustainable development of modern societies. *Journal of Cleaner Production* 18(1): 21–31. doi:10.1016/j.jclepro.2009.09.005.

Sundin, Erik, and Bert Bras. 2005. Making functional sales environmentally and economically beneficial through product remanufacturing. *Journal of Cleaner Production* 13(9): 913–925. doi:10.1016/j.jclepro.2004.04.006.

Tomiyama, T., P. Gu, Y. Jin, D. Lutters, Ch. Kind, and F. Kimura. 2009. Design methodologies: Industrial and educational applications. *CIRP Annals—Manufacturing Technology* 58(2): 543–565. doi:10.1016/j.cirp.2009.09.003.

Zhang, Feng. 2014. *Intégration Des Considérations Environnementales En Entreprise : Une Approche Systémique Pour La Mise En Place de Feuilles de Routes*. Grenoble, France: Université de Grenoble. http://www.theses.fr/s95811.

Zwolinski, Peggy, Miguel-Angel Lopez-Ontiveros, and Daniel Brissaud. 2006. Integrated design of remanufacturable products based on product profiles. *Journal of Cleaner Production* 14(15–16): 1333–1345. doi:10.1016/j.jclepro.2005.11.028.

Target-Driven Sustainable Product Development

Tom Buchert, Anne Pförtner and Rainer Stark

Abstract Figuring in sustainability in product development requires a profound understanding of the cause and effect of engineering decisions along the full spectrum of the product lifecycle and the triple bottomline of sustainability. Sustainability design targets can contribute to mitigating the complexity involved, by means of a formalised problem description. This article discusses how sustainability design targets can be defined and presents methods for systematically implementing these targets into the design process. To that end, different means of decision support mechanisms are presented. They comprise (a) use cases of target breakdowns in subsystems, (b) systematic reduction of solution space and (c) assistance in design activities to ensure achievement of sustainability design targets. This paper explains how interfaces to engineering tools such as Computer Aided Design/Engineering (CAD/CAE) or Product Data/Lifecycle Management (PDM/PLM) can be put in place to make the process of retrieving information and providing decision support more seamless.

Keywords Decision support · Sustainable design · Product development · Sustainability targets

1 Challenges in Sustainable Product Development

The topic of Sustainable Product Development (SPD) has been discussed in academic research since the early nineties with a strong focus on the environmental perspective (e.g. by Allenby 1991). In this context, numerous approaches have been developed, while some success-stories, e.g. the diffusion of LCA into industrial

---

T. Buchert (✉) · A. Pförtner
Technische Universität Berlin, Berlin, Germany
e-mail: Tom.buchert@tu-berlin.de

R. Stark
Chair of Industrial Information Technology, Institute for Machine-tools and Factory Management, Technische Universität Berlin, Berlin, Germany

R. Stark et al. (eds.), *Sustainable Manufacturing*, Sustainable Production, Life Cycle Engineering and Management, DOI 10.1007/978-3-319-48514-0_9

practice (Kara et al. 2014), have been achieved. However, nearly thirty years after the sustainability debate emerged, industrial production remains far from being sustainable [e.g. in the sense of exceeding planetary boundaries (Steffen et al. 2015)]. This insight leads to the question of what specific challenges need to be overcome in product design to improve the overall situation.

From a practical perspective, a range of factors influence the successful implementation process of SPD, such as:

- personal motivation of actors (e.g. incentives for fostering sustainability integration into product design),
- available resources (e.g. time budget for SPD method application) or
- lock-in effects (e.g. existing contracts with suppliers of unsustainable materials).

While these practical barriers can be solved by appropriate managerial oversight in the respective companies, great potential remains untapped in the research on SPD. A major challenge in this context is to find solutions for decreasing the complexity attached to SPD decision-making. Yet a sustainable design can only be achieved if design engineers develop subsystems in accordance with their influence on the triple bottomline (economic, environmental and social sustainability) at each and every step along the way of the entire product lifecycle (see Fig. 1). One approach for coping with this complexity is to break the problem down to smaller sub-problems which are easier to handle (problem modules). Figure 1 gives an example of which modules can be considered in the context of SPD (e.g. environmental impacts of electronic recycling).

Nevertheless, this reductionist approach may not prove to be sufficient due to the diverse interrelations between problem modules (e.g. better recyclable electronics may lead to economic problems in production). A key task of SPD research

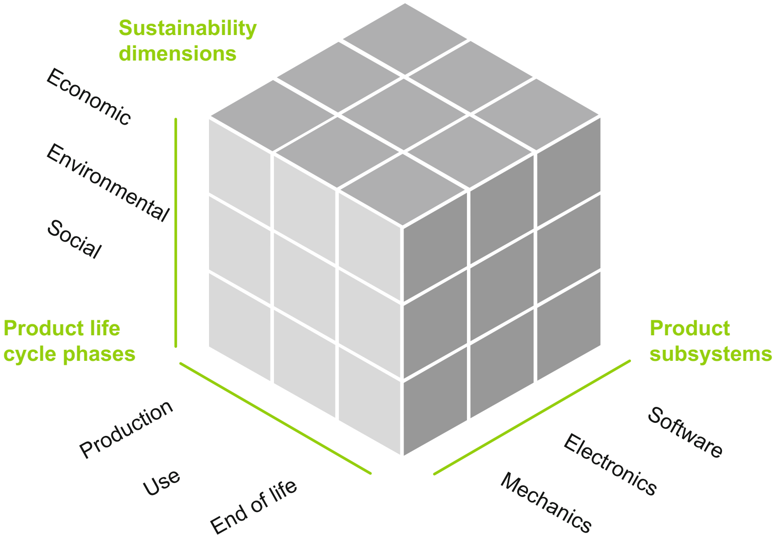


Fig. 1 Modules of sustainable product development problems

therefore lies in enabling engineers to anticipate these dependencies by means of methodological guidance as well as by enhanced knowledge and information supply. Thus, rather than searching for solutions to specific problem modules, this article will focus on providing novels mechanisms for increasing the transparency of decision-making.

2 Methods for Supporting Decision-Making in SPD

A wide variety of approaches for supporting decision-making in SPD have been developed in the last years. Baumann et al. (2002) classify existing approaches for environmental sustainability into six categories which still apply today in the field of SPD:

Analytical tools try to quantify the impact on the three dimensions of sustainability with varying precision. Life Cycle Sustainability Assessment as a combination of Life Cycle Assessment, Life Cycle Costing and Social Life Cycle assessment (Neugebauer et al. 2015) is utilised for more accurate estimations in later design phases, at which point plenty of information about the product is available. More simplified approaches (e.g. by Collado-Ruiz and Ostad-Ahmad-Ghorabi 2013) can be utilised in earlier phases as a form of heuristic prediction of impacts.

Checklists and guidelines provide best practices for guiding engineers along in the design process. They can be utilised in the early phases but are less helpful for decision-making for specific design problems. In the environmental realm, exhaustive collections of design guidelines have long since existed (Telenko et al. 2016). Guidelines for sustainable design are scarce. The most mature approach is based on a modular set of guiding questions which are also referred to as “templates” (Ny et al. 2008).

Rating and ranking tools provide possibilities for the simple but structured comparison of different solution options, based mostly on qualitative or semi-quantitative evaluation (see for example Shuaib et al. 2014).

Organizing tools furthermore help structure the design process by involving multiple stakeholders in the form of workshops or structured interviews.

Software and expert systems assist in applying methods by automating certain steps of the method application or by simplifying the process of researching for information through databases (e.g. LCA software such as GaBi.[1] Furthermore, IT-support of this kind has the potential to enable one’s own methodological approaches like the Eco-Pas software tool by Duflou and Dewulf (2005). The latest approach for IT-based decision support is the integration of SPD methods in engineering tools like CAD (e.g. Solidworks Sustainability Pro[2] and in PDM systems (Ciroth et al. 2013). Nevertheless, these approaches are limited to the

---

[1] https://www.thinkstep.com/software/gabi-lca/.

[2] http://www.solidworks.de/sustainability/.

assessment of the current design progress and the relative comparison to a reference design without actual guidance. Furthermore, the underlying impact model and the dependencies between engineering decisions as well as the sustainability impact have all yet to be made transparent to the engineer. In particular, trade-offs between the sustainability dimensions are not being intensively researched since most of available methods focus on the environmental sustainability perspective. The following three characteristics summarise insights on methods for sustainable product development (see Buchert et al. 2014 and Sect. 4.3):

- Existing methods focus on assessment. There is a lack of engineering approaches that assist engineers in the form of offering support for design synthesis. Guidelines can be utilised for synthesis but are often not sufficient for addressing a specific design problem.
- Availability of information in conceptual design is usually scarce. Analytic approaches require a lot of information and are therefore only utilised once major decisions have already been made.
- Insufficient transparency on system relations between product design decisions, sustainability impacts and product life cycle stages prohibits a systematic examination of the specific trade-offs and side-effects attached to engineering decisions.

3 Integration of Sustainability Targets into the Design Process

The complexity of cause and effect chains presents a major challenge for judgment calls in sustainable product development. One favourable way of reducing the complexity factor in the whole process lies in defining targets which specify the most relevant influencing factors for the problem and which provide a basis from which to develop further decision-making models (Bretzke 1980). Hence, it needs to be clarified how “sustainability design targets” can be formulated in a complimentary fashion to basic technical or functional requirements. A starting point for addressing this problem is to pinpoint the causal relations between engineering decisions and sustainability impact. This is achieved by classifying different types of information to different categories in a fixed order illustrated in Fig. 2. The categories and their respective relationships will be introduced in the following paragraphs. A more detailed description can be found in (Buchert et al. 2016).

The scheme developed is based on the separation of product characteristics (I) and properties (II) as defined by Weber et al. (2003) in the scope of their “Property Driven Product Development (PDD)” approach. Category (III) refers to the sustainability impact of a product on various stakeholders such as the environment, health aspects of employees and customers as well as the financial stability of the company (III). In order to connect the design engineering perspective (I and II) with the sustainability impact view (III), the category *product properties*

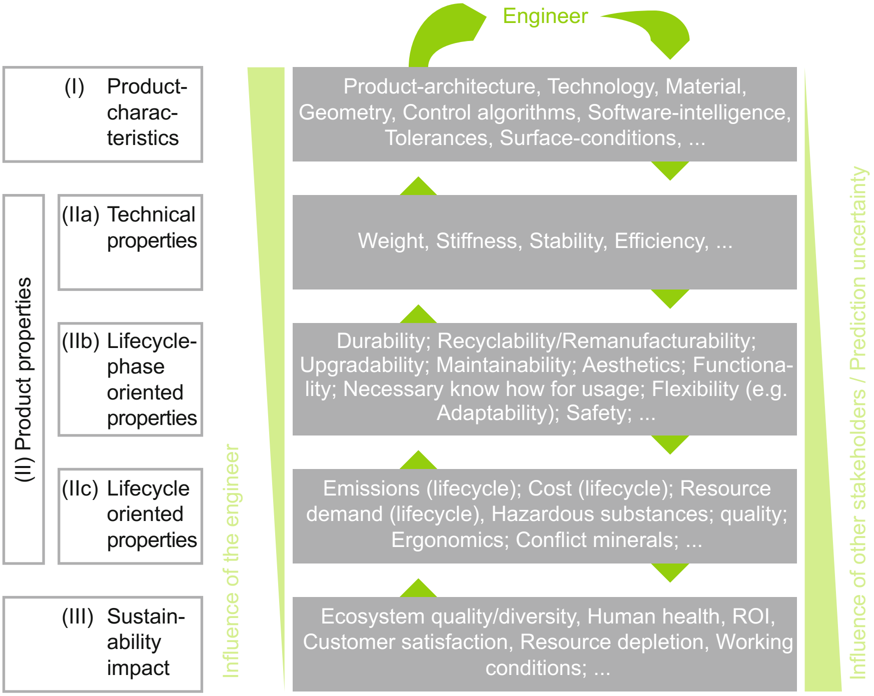


Fig. 2 Scheme for linking design decisions to sustainability impact (Buchert et al. 2016)

was subdivided into three subclasses, each of which takes the perspective of the product life cycle (IIa–IIc) into consideration. Category IIa consists of technical properties that are defined directly as a result of engineering decisions for product characteristics. The definition of the characteristic's material and geometry defines, for example, the technical property weight. When technical properties are combined and enriched with influences from outside the system, boundary lifecycle-phase oriented properties are determined (IIb). The prediction of durability in the usage phase of a pedelec frame is, for example, based on technical properties such as tensile strength or stiffness, but also relies on user behaviour. This type of property defines how a product interacts with its surrounding systems within specific lifecycle phases (e.g. durability, remanufacturability). If all effects of these interactions are aggregated along the product lifecycle, (e.g. in terms of cost or emissions) lifecycle-oriented properties are then derived (IIc). Lifecycle oriented properties can be understood analogous to the term Lifecycle Inventory which is used in the context of Life Cycle Assessment to evaluate environmental sustainability.

By analysing the complete scheme, it becomes evident that the influence of engineering decisions decreases with every level, since other actors in product creation (e.g. sourcing) likewise have a significant influence on overall product sustainability impact. Furthermore, external influences (e.g. user behaviour) may deviate from assumptions stemming from the design process and therefore increase uncertainty of predictions for the whole lifecycle of a product. One conclusion from this analysis is that targets on impact level are less appropriate for design engineers since they are not trained to relate their actions properly to impact indicators. Hence, sustainability experts need to be involved in the design process, which serves to make the most critical lifecycle-oriented properties and the most significant lifecycle phases for engineering target definition identifiable. In addition to sustainability experts, other company roles may also define relevant targets in a sustainability context, in particular from an economic perspective (e.g. product or quality managers).

Figure 3 provides a reference framework for integrating sustainability targets into the design process by differentiating between different stakeholders involved and by identifying challenges for successful target integration. Potential for decision support in the other direction is identified with this framework. Respective challenges are introduced in the following paragraphs.

Once sustainability targets are defined by the respective experts, they then have to be broken down into technical subsystems or assemblies by system engineers (see Fig. 3). This step poses a special challenge, since it is not clear how narrowly a target should be formulated in order to be effective in the sense of sustainability improvement. It can be argued which level of the scheme shown in Fig. 2 is most appropriate for which respective purpose. The more specifically the target is defined (e.g. on the level of technical properties such as weight), the less opportunities remain for domain engineers to find a creative solution to foster sustainability performance. Furthermore, unintended side effects can occur since the domain

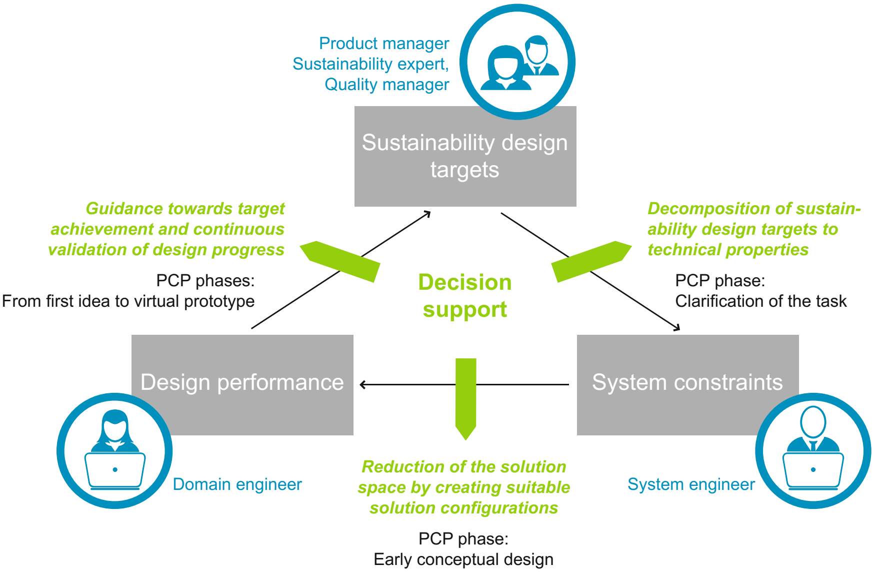


Fig. 3 Framework for decision support based on sustainability design targets

engineers may not be informed about the intended effect of the target in terms of sustainability improvement (e.g. changing to a lighter material to save fuel consumption of a car may shift the environmental burden to material production). In this context, how exactly targets should be allocated to subsystems for establishing the basis for a sustainable solution configuration also needs to be evaluated.

Another challenge which needs to be overcome to properly address sustainability targets in the design process, lies in the identification of sustainable and technically feasible configurations of system elements and inherent product characteristics. This task is troublesome since multiple configurations are possible, and it also needs to be determined which components can be reused and where new developments are necessary. This reduction of the solution space decreases the effort for further design activities and therefore increases efficiency and effectiveness of the design process.

Domain engineers then finally develop suitable solutions according to the given requirements. In that pursuit, it is necessary to evaluate whether the current design process and estimated product performance in different PCP stages are compliant with given sustainability design targets. Furthermore, providing specific advisory tips towards achieving these targets can be beneficial. Hence, a range of activities might be necessary, such as, ideation for new and more sustainable products, comparison of solution concepts, and/or final solution assessment. A broad set of methods has been developed for assisting in these tasks. The challenge therein lies in selecting the right method for each and every task along the way in the product development process.

The challenges described are also summarised in Fig. 3 and are viewed by the authors a handy framework of reference for implementing sustainability targets in the design process. Decision support tools can play a viable role in overcoming these challenges by fostering transparency on sustainability cause and effects and by increasing the availability of information for the engineer. New approaches for decision support to that effect are therefore presented in the following chapters addressing these aspects.

4 Decision Support for Integrating Sustainability Design Targets

This section introduces three concepts for addressing the challenges for integrating sustainability targets into the design process. The respective approaches are explained based on the example of a pedelec (i.e. an electric bicycle) redesign project. Exemplary questions raised within the scope of this project are illustrated in Fig. 4 and will provide use cases for decision support mechanisms which have been developed.

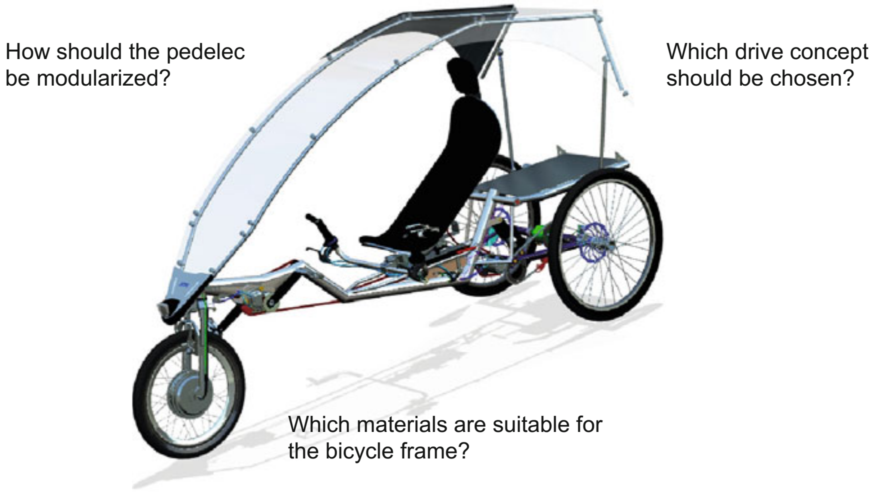


Fig. 4 Exemplary engineering decisions with an influence on pedelec sustainability

4.1 Breakdown of Sustainability Targets for Product Architecture Decisions

Proper breakdown of sustainability targets from desired impacts to technical influencing-factors introduces an array of hurdles for design teams. Yet defining targets at the system level and for respective subsystems can be seen as one of the most crucial tasks in the design process, since the basis for implementing engineering strategies is defined in this step. In many companies, heuristics are followed to define their strategies. Automotive companies choose, for example, “lightweight design” to reduce fuel consumption of their vehicles. The problem with heuristics is that they are often formulated for one specific target without considering side-effects and concomitant relations with other company targets. Thus, it can be helpful to give an overview of which options are available to achieve targets or, on the flip-side, to see which indicators can be affected by design changes. A good example of a missing link in cause and effect chains can be found when considering decision-making on product architecture. The majority of companies modularise their products to limit internal complexity, to decrease their time to market, and to increase external variance for customers at the same time (Gleisberg et al. 2012). Nevertheless, other relevant targets have to be considered, such as flexibility of the product to allow multiple product use-cases and disassembly to provide reuse opportunities or simplification of maintainability.

In order to increase the transparency of relations between modularisation decisions and sustainability targets, a qualitative concept map was developed. An extract of the map is displayed in Fig. 5. The full map contains 77 modularisation drivers (i.e. targets and sub-targets) and 44 modularisation metrics. The map is structured from top to bottom regarding the information categories identified in Fig. 2 and the type of decisions addressed (from strategic to tactic and from tactic to operational level). The grey boxes visualised in Fig. 5 mark one possible way through the map starting with sustainability targets on impact level at the top. This particular way is explained for the example of setting targets for a pedelec architecture definition. At impact level (III), different sustainability indicators may be relevant for a pedelec. In this example, climate change and customer value were chosen as important impact categories. In practice, the selection of indicators relies on legal requirements as well as on company strategy, which may also include

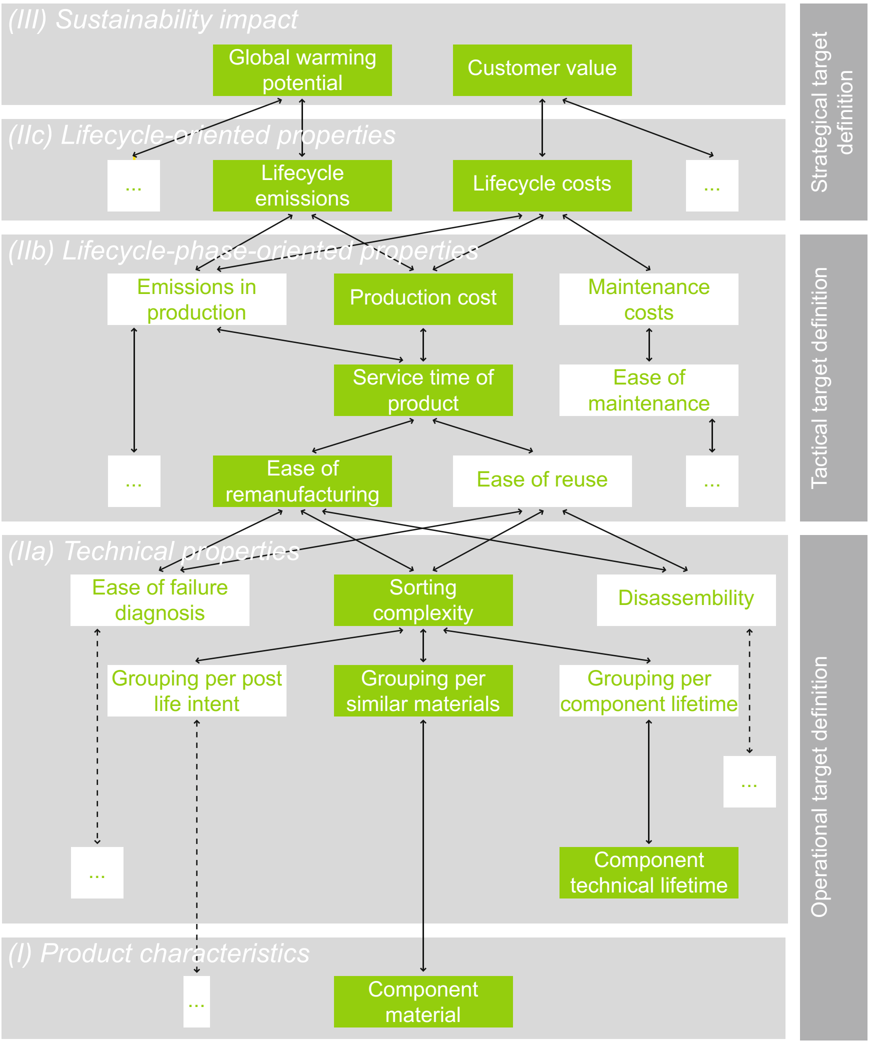


Fig. 5 Concept map for illustrating targets for product architecture definition

voluntary agreements. Customer value relies on the total cost of ownership (lifecycle cost) of the pedelec. Yet, there are also other factors to consider, such as functionality, which can be enhanced by upgradeability of the pedelec (e.g. with a stronger motor or an additional roof). The environmental impact category Climate Change is determined by total greenhouse gas emissions (GHG) along the pedelec lifecycle.

To reduce total emissions, the production phase of the pedelec should be considered since it contributes almost half of the total GHG emissions of a pedelec (Neugebauer et al. 2013). The most important contribution of modularisation at decreasing GHG emissions in production is to increase the time the product can be used (service time), since a longer utilisation period ultimately decreases the amount of products which have to be manufactured. If less products need manufacturing, absolute production cost likewise decreases. Furthermore, remanufacturing or reusing are possible measures for increasing the service time of the product. Both End of Life (EOL) options can be fostered by increasing the ease of disassembly or by grouping components in such a way that the sorting of components can be improved upon (e.g. by clustering components with same materials).

In contrast to other product characteristics, like material or geometry decisions, sustainability targets cannot be broken down to the individual component level (e.g. a targeted efficiency of a motor). Targets for modularisation can only be formulated on a system level since modularisation considers how different components are organised.

By going through the map, it should be noted that the strategic paths chosen may also lead to side effects. Increasing service time may, for example, impact the business model by decreasing sales revenue due to the fact that less products are sold. Furthermore, production could turn out to be less efficient, leading to the necessity of downsizing the production system. Smaller production may lead to personnel shifts, layoffs etc. Due to this multitude of effects, it can be difficult to find a suitable system boundary for strategic modularisation decision-making. Furthermore, missing quantification of relations between targets and modularisation metrics poses a barrier toward the quantitative assessment of modularisation effects. For enhanced decision-making in support roles, new quantified models for modularisation impact will thus have to figure into play (see Sect. 5).

4.2 Model Based Reduction of the Solution Space

Targets which are broken down and formulated as constraints can be used to reduce the solution space and eliminate the design solutions that do not comply with the defined constraints. Calculating the fulfilment of constraints for possible solutions manually is however time-consuming. Each option for all variable characteristics (e.g. each material and geometric parameters) would have to be assessed in order to determine all the viable solutions. If relations between a choice of characteristic and constraints associated with a target are formalised on a quantitative basis, viable solutions can be calculated automatically. Consequently, a formalised model expands the option pool for considering a high amount of configurations and multiple targets. Configuration options from predecessor products can be used as a basis for identifying solution options (Buchert et al. 2016). This model-based approach shall now be demonstrated with the simple example of a pedelec frame.

Based on a previous LCA study, emissions for wrought material production were identified as an important lifecycle phase oriented property (Neugebauer et al. 2013). Hence, the indicator "CO_2 emissions in material production" was selected as a sustainability target for improving the pedelec frame. Furthermore, the durability of the pedelec frame in the use phase was chosen as a second target. The frame-durability determines a part of the value provided to the customer and may contribute to an overall reduction of CO_2 emissions if the lifetime of the pedelec is extended. Another reason for choosing durability as a target is to verify that a decision on material matters does not negatively affect the use-phase of the bicycle frame. Durability is a lifecycle-oriented property implying that influences (load and forces) from the respective lifecycle phase (use phase) are either assumed based on experience or on user studies or empirical studies of similar processes. The accurate determination of the frame durability would require a combination of different models for simulating the material strength under both static and dynamic load as well as for usage behaviour. In that pursuit, durability was examined by means of simplified analysis of axial frame deformation and v. Mises strength in comparison to tensile strength of the material. Figure 6 displays the causal relations between durability and CO_2 emission in material extraction with the product characteristics material and geometry.

Durability is dependent on the stiffness of the frame and on forces applied during use. The relations between material parameters such as young's modulus and stiffness follow principles of physics. The causal relations can thus be captured in

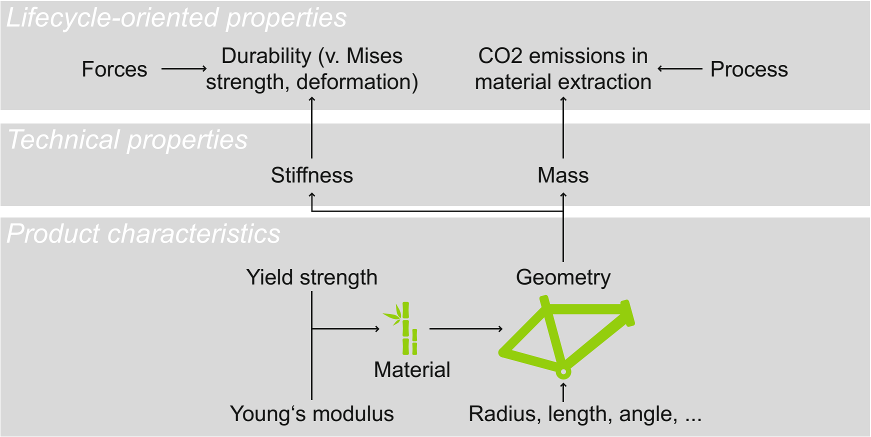


Fig. 6 Relations to calculate lifecycle oriented properties

mathematical equations. The v. Mises strength and the deformation can be calculated by an automatic FEM analysis. An existing frame CAD and FEM model from a predecessor product were utilised as a basis for the respective calculations. Since the new design may deviate from the original frame, the results calculated can only be understood as heuristic. Nevertheless, the process yields valuable insights about which materials are suitable for given requirements already in conceptual design, with the assumption that the frame design does not change significantly.

Figure 7 gives an example of how the data model for a decision support tool can be structured. The classes are instantiated for the selection of a material for the pedelec frame. The following dependencies between different classes of information were formalised:

- Constraints (broken down targets) are associated with product properties.
- Product properties can be calculated based on further properties, constants or characteristics.
- The CO_2 emission for wrought material, for example, can be calculated by the property *mass* times the constant *CO_2 emissions per kg* wrought material.
- The constant *CO_2 emissions per kg* can be derived from an environmental database, e.g. the ELCD database, thus through an IT-interface.
- IT-interfaces require certain data, in this case the ELCD material name, in order to yield the desired information *CO_2 emissions per kg* material.
- *Mass* is calculated by *volume* and *density* for the material.
- The *volume* can be easily calculated by a CAD system.
- Possible values for the characteristic (e.g. specific materials) are automatically derived from a repository which is linked to the model. In the case of the pedelec, all materials from the Siemens NX database were taken into consideration.

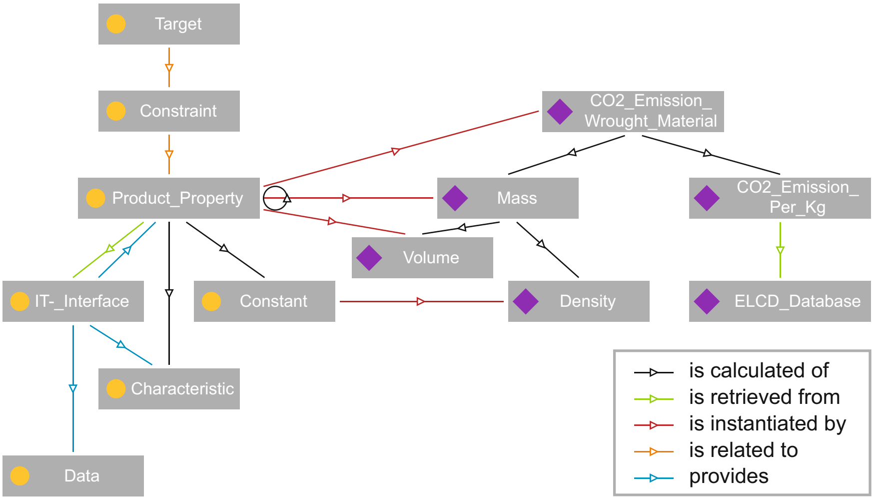


Fig. 7 Meta model for target calculation with exemplary instantiation

The software tool interprets all the interconnected steps independently, starting from a target and proceeding up until the point when it reaches an IT-database. The tool then derives the required information and successively inserts the information derived or calculated until a value for the product property concerning a selected constraint can then be calculated. The benefit of this approach is that all (discrete) values for a characteristic can be automatically iteratively assessed even if the required information is dispersed among different IT-tools. The IT-tools are accessed by respective interfaces e.g. a Service Oriented Architecture (SOA) interface. If all relevant relations are modelled according to the meta-model, the software tool can automatically calculate viable values for a characteristic and thus exclude unfitting solution options and reduce the solution space.

In the case of the pedelec frame, the tool proposed 5 different steel versions which fulfill the CO_2 emission and the deformation and strength constraints as a proof of concept. However, not all materials were listed in the ELCD database and were therefore excluded. Otherwise more suitable options could have been derived. The mapping of different material databases moreover remains imprecise and requires further research in order to boost accuracy. A more detailed description of this first model prototype can be found in the publication of Stark and Pförtner (2015).

A discussion of how the use case can be extended to assemblies and entire product systems can be found in Sect. 5.

4.3 *Guidance for Achieving and Proving Compliance with Sustainability Targets*

When sustainability design targets are formulated, engineers have to take action to prove that compliance with these targets in all stages of the PCP. Furthermore, guidance is necessary for assisting engineers in achieving the respective targets. These activities can be steered and supported by design methods. Since many methods for Sustainable Product Development (at least concerning environmental sustainability) are available, Ernzer and Birkhofer stated already in (2002) that: “the difficulty […] is not the development of design methods anymore, but rather the ability to select the relevant methods.” Hence, a scheme for selecting and combining methods was developed, which allocates a suitable approach to designing activities necessary for achieving or proving adherence with a sustainability target. The approach consists of a taxonomy of SPD methods and a method repository including 29 design methods. Figure 8 shows the three major steps for method selection and application. Step 1 characterises the definition of milestones. Milestones constitute a point of time in a design project where the achievement of a sustainability design target has to be proven.

A relevant sustainability target for a pedelec redesign process could be, for example, to decrease cost and CO_2 emissions in the usage phase with reference to what specific elements could be broken down into various alternatives for a drive

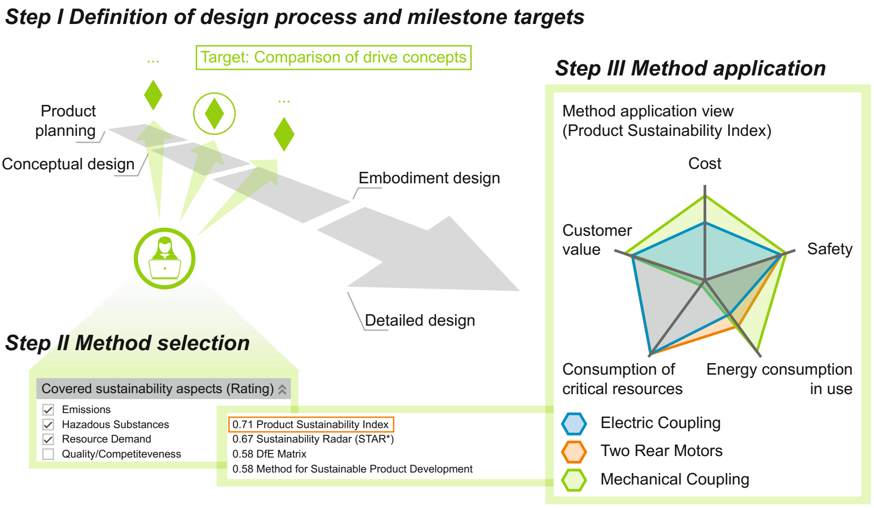


Fig. 8 Method selection and application feature for guiding engineers and to validate design performance against sustainability design targets

concept. Hence, a comparison of variants for the drive concepts regarding CO_2 emission and cost is necessary for the process of reporting results at a milestone towards the end of the conceptual design phase.

The second step (see Fig. 8) aims at selecting a suitable method for achieving targets defined in step 1. To that end, a taxonomy of design methods was put together (see Table 1).

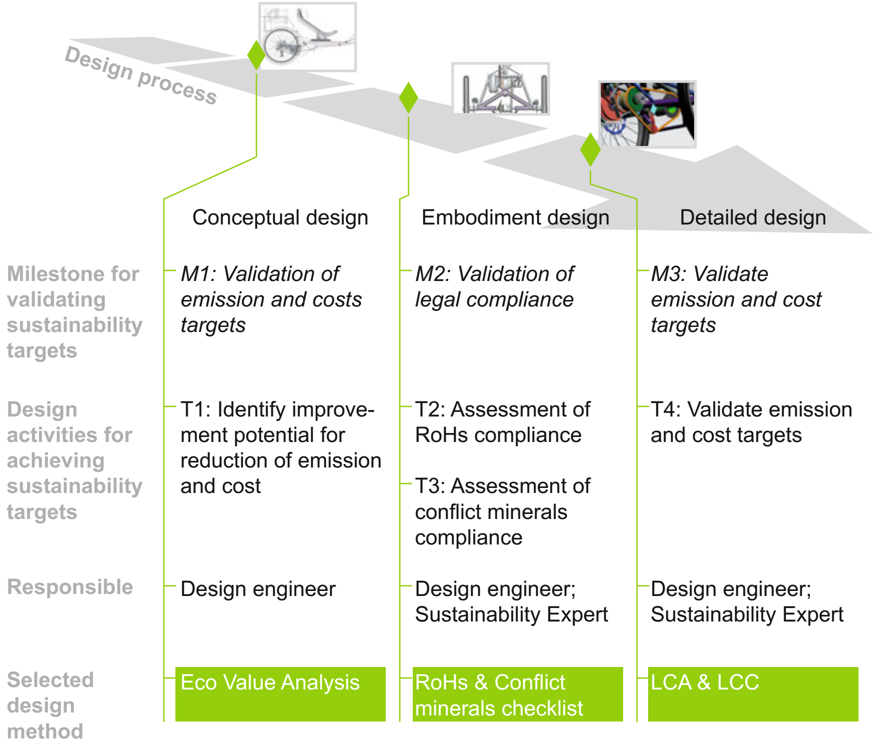
The taxonomy outlines the design activity which the method supports (e.g. assessment), as well as information about the effort and information inputs required. Furthermore, it considers the type of targets which can be addressed by the method (e.g. addressed sustainability aspects or quantification of the target).

Complimentary to the taxonomy development, 29 SPD methods were successfully identified which were found to be compliant with predefined criteria (e.g. coverage of the whole product lifecycle, accessibility or a focus on technical products). Figure 9 shows an example for proving achievement of sustainability targets by selecting appropriate methods for the pedelec drive concept.

In addition to improved method selection, a concept for fostering application of methods was also implemented for three different methods (Pförtner et al. 2016). The main idea behind this approach was the development of an information platform which stores sustainability relevant information for a product and makes it available for the application of various methods. Only by following this approach does a combination of different SPD methods become attractive, since effort for information search can therein be reduced. Both the selection scheme and the information platform were implemented in the PDM system Siemens Teamcenter. Hence, necessary product-information (e.g. product structure, weight) can be imported. Further drawbacks and advantages of the approach are presented in Sect. 5.

Table 1 Taxonomy criteria for method selection

Criterion	Options
Method purpose	Identification of improvement measures, comparison, assessment, direct selection of product characteristics based on targets
Quantification	Qualitative, quantitative, semi-quantitative
Covered sustainability targets	Emissions, hazardous substances, resource demand, quality/competitiveness, safety, material origin, cost
User of the method	Product manager, product designer, sustainability expert
Effort for application	1 = low, 2 = middle, 3 = high
Necessary information for application	Requirements/functions, solution concepts, product architecture, CAD files/EBOM, production process/MBOM, auxiliary information
Redesign focus	Yes/no



	Conceptual design	Embodiment design	Detailed design
Milestone for validating sustainability targets	*M1: Validation of emission and costs targets*	*M2: Validation of legal compliance*	*M3: Validate emission and cost targets*
Design activities for achieving sustainability targets	T1: Identify improvement potential for reduction of emission and cost	T2: Assessment of RoHs compliance T3: Assessment of conflict minerals compliance	T4: Validate emission and cost targets
Responsible	Design engineer	Design engineer; Sustainability Expert	Design engineer; Sustainability Expert
Selected design method	Eco Value Analysis	RoHs & Conflict minerals checklist	LCA & LCC

Fig. 9 Exemplary method selection results for a pedelec redesign process

5 Conclusion and Outlook

The last chapters presented different approaches on how the challenges for integrating sustainability targets into the design process (summarised in Fig. 3) can be addressed. For the specific case of modularisation, it was shown how the breaking down of sustainability design targets can be supported by qualitative causal diagrams (see Sect. 4.1). Nevertheless, qualitative visualisation of decision pathways can only be a first step towards decision support based on facts and data. What remains a challenge however, lies, in defining scenarios on how multiple sustainability design targets can be achieved by varying sub-targets for assemblies or subsystems. A lifecycle CO_2 reduction target could be, for example, achieved by material substitution of a pedelec frame or the more costly development of an efficient motor. To properly take stock of these side effects and trade-offs, a parametric model becomes necessary, which serves to establish connections between the decision criteria of the three sustainability dimensions. These “dependency models” can be utilised for setting targets but also for minimizing the solution spectrum of possible design solutions.

In Sect. 4.2, a first prototype of a dependency model was presented with the simple example of a pedelec frame material selection regarding technical targets and a CO_2 emission limits. The dependency model was represented in an ontological map and interpreted by a self-developed software tool. The model-prototype developed showed satisfying results, yet remains limited to a single component. In order to allow consideration of assemblies and complete products, more comprehensive models are necessary which comprise libraries of components from previous design projects that contain sustainability relevant information (e.g. material composition, GHG emissions, cost etc. (see Buchert et al. 2016). By following this approach, solution configurations can be identified which are compliant with a set of sustainability targets. In this context, model design must be simplified due to the fact that the effort for coupling different models in dispersed IT systems stands quite high.

In that pursuit of deeper understanding of the product’s interrelation with sustainability impact, Sect. 4.3 presented a more process-oriented perspective on achieving sustainability design targets. By providing a selection scheme for SPD methods, the best suitable approach can be assigned to the tasks which are necessary for proving that sustainability design targets were achieved. In addition to the main findings of a corresponding literature analysis (see end of Sect. 2), a lack of methods considering all three sustainability dimensions was observed. While several methods focusing on environmental sustainability exist, approaches concerning social sustainability remain scarce. An integrated view of all three dimensions is indeed nearly non-existent. Furthermore, descriptions of several existing methods have only scratched the surface, while use cases for successful implementation are hard to come by. Nevertheless, the developed selection scheme and information platform presents the opportunity for combining heterogeneous approaches (such as qualitative guidelines and quantitative assessment methods) which allow for an overall more holistic perspective on the product.

References

Allenby, Braden R. 1991. Design for environment: A tool whose time has come. *SSA Journal* 12(9): 5–9.

Baumann, H., F. Boons, and A. Bragd. 2002. Mapping the green product development field: engineering, policy and business perspectives. *Journal of Cleaner Production* 10(5): 409–425. doi:10.1016/S0959-6526(02)00015-X.

Bretzke, Wolf-Rüdiger. 1980. Der Problembezug von Entscheidungsmodellen. 29: Mohr Siebeck.

Buchert, T., A. Kaluza, F.A. Halstenberg, K. Lindow, H. Hayka, and R. Stark. 2014. Enabling product development engineers to select and combine methods for sustainable design. *Procedia CIRP* 15: 413–418. doi:10.1016/j.procir.2014.06.025.

Buchert, T., A. Pförtner, J. Bonvoisin, K. Lindow, and R. Stark. 2016. Model-based sustainable product development. In *Proceedings of the 14th International Design Conference*, ed. Dorian Marjanovic, Mario Storga, and Neven Pavkovic, 145–154. Stanko Skec: Nenad Bojcetic.

Ciroth, Andreas, Jean-Pierre Theret, Mario Fliegner, Michael Srocka, Volker Bläsig, and Özlem Duyan. 2013. Integrating life cycle assessment tools and information with product life cycle management. In *Proceedings of the 11th Global Conference on Sustainable Manufacturing*, ed. Günther Seliger, 210–212. Universitätsverlag der TU Berlin.

Collado-Ruiz, Daniel, and Hesamedin Ostad-Ahmad-Ghorabi. 2013. Estimating environmental behavior without performing a life cycle assessment. *Journal of Industrial Ecology* 17(1): 31–42. doi:10.1111/j.1530-9290.2012.00510.x.

Duflou, Joost, and Wim Dewulf. 2005. Eco-impact anticipation by parametric screening of machine system components: An introduction to the EcoPaS methodology. In *Product engineering: Eco-design, technologies and green energy*, ed. Doru Talaba, and Thomas Roche, 17–30. Dordrecht: Springer Science + Business Media Inc.

Ernzer, M., and H. Birkhofer. 2002. Selecting methods for life cycle design based on the needs of a company. In *Proceedings of the 7th International Design Conference*, ed. Dorian Marjanovic, 145–154.

Gleisberg, Jochen, Oliver Knapp, Stefan Pötzl, and Michael Becker. 2012. Modular products—how to leverage modular product kits for growth and globalization. http://www.rolandberger.fr/publications/publications_monde/2012-04-10-Modular_Products.html.

Kara, Sami, Suphunnika Ibbotson, and Berman Kayis. 2014. Sustainable product development in practice: an international survey. *International Journal of Manufacturing Technology Management* 25(6): 848–872. doi:10.1108/JMTM-09-2012-0082.

Neugebauer, Sabrina, Julia Martinez-Blanco, René Scheumann, and Matthias Finkbeiner. 2015. Enhancing the practical implementation of life cycle sustainability assessment—proposal of a Tiered approach. *Journal of Cleaner Production* 102: 165–176. doi:10.1016/j.jclepro.2015.04.053.

Neugebauer, Sabrina, Ya-Ju Chang, Markus Maliszewski, Kai Lindow, Rainer Stark, and Matthias Finkbeiner. 2013. Life cycle sustainability assessment & sustainable product development: A case study on pedal electric cycles (Pedelec). In *Proceedings of the 14th Global Conference on Sustainable Manufacturing*, ed. Günther Seliger, 549–554. Universitätsverlag der TU Berlin.

Ny, Henrik, Sophie Hallstedt, Karl-Henrik Robèrt, and Göran Broman. 2008. Introducing templates for sustainable product development. *Journal of Industrial Ecology* 12(4): 600–623. doi:10.1111/j.1530-9290.2008.00061.x.

Pförtner, A., T. Buchert, K. Lindow, R. Stark, H. Hayka. 2016. Information management platform for the application of sustainable product development methods. *Procedia CIRP* 48: 437–442. doi:10.1016/j.procir.2016.04.091.

Shuaib, Mohannad, Daniel Seevers, Xiangxue Zhang, Fazleena Badurdeen, Keith E. Rouch, and I. S. Jawahir. 2014. Product sustainability index (ProdSI). *Journal of Industrial Ecology* 18(4): 491–507. doi:10.1111/jiec.12179.

Stark, Rainer, and Anne Pförtner. 2015. Integrating ontology into PLM-tools to improve sustainable product development. *CIRP Annals-Manufacturing Technology* 64(1): 157–160. doi:10.1016/j.cirp.2015.04.018.

Steffen, Will, Katherine Richardson, Johan Rockström, Sarah E. Cornell, Ingo Fetzer, Elena M. Bennett, Reinette Biggs, Stephen R. Carpenter, Wim de Vries, and Cynthia A. de Wit. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223): 1259855. doi:10.1126/science.1259855.

Telenko, Cassandra, Julia M. O'Rourke, Carolyn C. Seepersad, and Michael E. Webber. 2016. A compilation of design for environment guidelines. *Journal of Mechanical Design* 138(3): 31102. doi:10.1115/1.4032095.

Weber, Christian, Horst Werner, and Till Deubel. 2003. A different view on product data management/product life-cycle management and its future potentials. *Journal of Engineering Design* 14(4): 447–464. doi:10.1080/0954482031000160687б.