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Design Guidelines towards Absolute Sustainability for technical Product-Service Systems

Jan C. Aurich[a]*, Max Werrel[a], Moritz Glatt[a]

[a]*Institute for Manufacturing Technology and Production Systems (FBK), TU Kaiserslautern, P.O. Box 3049 Kaiserslautern, Germany*
* Corresponding author. Tel.: +49-631-205-2618; fax: +49-631-205-3238. *E-mail address:* jan.aurich@mv.uni-kl.de

Abstract

The concept of product-service systems (PSS), established around the turn of the millennium, was coined by the realization of increased sustainability potentials compared to offering products alone. As the concept of PSS was further developed, technical PSS became a successful variation, exploiting economical and technical potentials in industrial settings. The recent shift towards an absolute perspective of sustainability changes the understanding of sustainable life cycle engineering and design. This new understanding challenges designers to create PSS that not only offer incremental environmental advantages but actively contribute to a sustainable development. In PSS design, which comprises PSS planning and development, around 80% of the environmental performance throughout the life cycle are defined. Therefore, the design phase offers strong potentials to achieve significant improvements of the environmental performance of a PSS. In this article, guidelines to design technical PSS in the context of absolute sustainability are presented. The guidelines include measures to achieve a high level of customer satisfaction, while simultaneously aiming to achieve environmental impact targets along the entire life cycle. The application of the guidelines enables the development of economically successful and sustainable technical PSS.

Keywords: Product-Service Systems; Design Guidelines; Absolute Sustainability

1. Introduction

Facing the ongoing climate crisis while fulfilling the needs of a growing population are the major challenges for society today [1]. Addressing these challenges requires efforts in all areas of society, aiming to “meet the needs of the present without compromising the ability of future generations to meet their own needs”, as defined by the United Nations Brundtland Commission in 1897 [2]. The needs are commonly split up in an ecological, an economical, and a social dimension [3]. These dimensions are reflected in the 17 Sustainable Development Goals, which include actions towards industry, innovation and infrastructure [4]. Sustainability in the context of industrial manufacturing predominantly addresses the ecological dimension, but increasing attention focuses on social impacts as well [5].

Engineers and designers aim to create products, which can maximize the intended output while minimizing inputs and costs, ergo creating efficient products. In sight of ecological sustainability, creating efficient products may be determined as energy efficient or resource efficient, or, in a broader sense, eco efficient. The ISO 14045 standard defines eco-efficiency as an “aspect of sustainability relating the environmental performance of a product system to its product system value” [6]. Following this definition, many design approaches aim to improve this efficiency, leading to an understanding of sustainability in a relative context.

In recent years, the understanding of sustainability started to shift from a relative view to absolute sustainability [7]. Absolute sustainability considers the planetary boundaries proposed by Rockström et al. [8] as well as the minimum social standards derived by the Sustainable Developments Goals [4]. This understanding can be illustrated by the “doughnut of social and planetary boundaries” by Raworth, shown in Figure 1 [1].

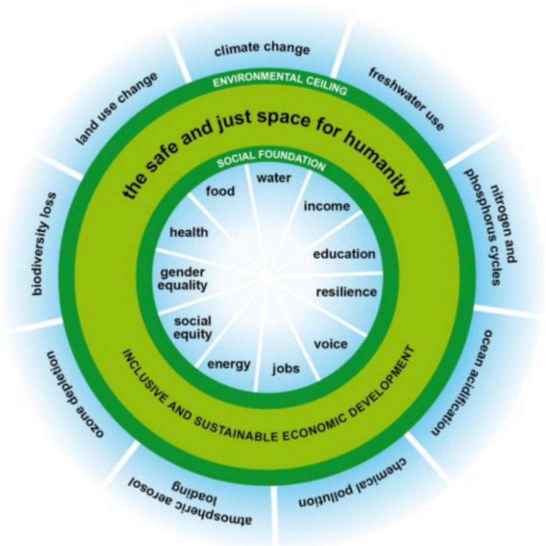

Figure 1: Doughnut of social and planetary boundaries [1]

This change in understanding entered product development and life cycle engineering (LCE). Hauschild et al. proposed a LCE framework, linking manufacturing to absolute sustainability [9]. Subsequently, several challenges were identified to ensure that the targets of absolute sustainability are met through LCE, e.g., the quantification of boundaries, tailoring tools of LCE or developing new tools and approaches if efficiency-focused approaches are insufficient [10].

Approaches towards eco-efficiency are well established and widespread in production research [11] and comprise tools to support selecting among different processes and products [12]. Following the comparative and relative understanding of sustainability, the concept of Product-Service Systems (PSS), established around the turn of the millennium, shows a potential to deliver customer benefits with lower environmental impacts compared to the sale of products alone [13]. By the definition of Mont, PSS comprise of physical products, non-physical products (services), and a network of companies together with supporting infrastructure to deliver customer benefits, as illustrated in Figure 2 [14]. Despite these potentials, several studies indicate that PSS do not per se lead to sustainable solutions and instead, the sustainability extent has to be evaluated individually [15].

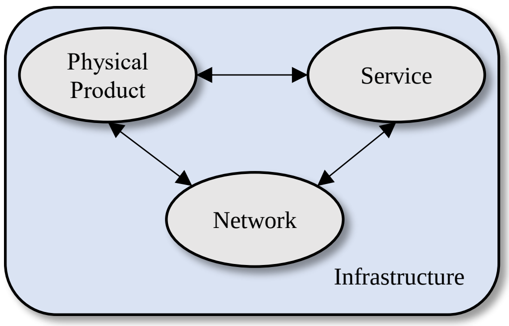

Figure 2: Product-Service System according to Mont [14]

Recent changes in customer demands towards sustainable and sustainably manufactured goods [16] as well as legal provisions such as the European green deal [17] or eco-design requirements [18] have strengthened a development towards sustainable production. An additional factor is the technological development of the last years. Foremost, the availability of data used for improvement both during production and operation has increased, as well as the capabilities of data analysis (e.g., machine learning). Those developments create conditions that enable PSS providers to finally achieve the sustainability advantages that PSS were originally intended for [19]. In present research, numerous authors identify the need to develop methods and tools to achieve absolute sustainability. Kara et al. point out that means promoted as pathways to sustainable growth like material circularity need to take a broader, whole-systems approach [20]. There also is a need to develop products and services with a life cycle view to realize their true environmental impact reduction potential [20]. To further drive this development and move in the direction of absolute sustainability, the design and LCE of PSS needs to be revisited in sight of absolute sustainability targets.

This article contributes to this development with the inclusion of these targets into PSS design processes by offering universal guidelines for practitioners and scholars.

2. State of the Art

Motivated by the broad dissemination in industrial practice, PSS are a widely investigated research object resulting in a variety of concepts, principles, and approaches regarding their design. These approaches set their focus differently, ranging from exploiting economical potentials, integrating PSS in corporate structures, fostering innovations, to enhancing sustainability.

PSS are conceptualized in various settings and business models. Regarding the adaption of PSS in the area of capital goods, the term *technical* PSS was coined [21], which comprises the following characteristic aspects:

- Both, physical and non-physical components have an investment character
- The monetary value and importance of the physical product exceeds the value and importance of the non-physical components
- PSS-provider and customer engage in a business-to-business relationship

In the remainder of this article, the term PSS is used to address technical PSS. The proposed guidelines are directed but not limited to technical PSS. In the remaining section, several approaches are described to outline the current state of research and to highlight approaches towards sustainability.

One of the earliest works concerning sustainability in PSS design was given by McAloone and Andreasen in 2004, arguing that the development of PSS needs to consider socio-economic factors to be offered successfully and thereby achieving improvements in sustainability. Also, the authors postulate that the behavior of customers or users might be the greatest barrier for PSS realization [22].

An approach focusing on closed resource loops is given by van der Laan and Aurisicchio, who propose a set of guidelines for the design of closed-loop PSS addressing design requirements, composition and organization and operating mechanisms [23].

The approach by Aurich et al. contains a model for technical service design as well as a life cycle oriented model for process design and was successfully implemented in industrial practice [21]. Subsequently the development of business models for life cycle oriented PSS is proposed as part of a PSS oriented life cycle management [24].

Salazar et al. suggest eco-design of PSS by degrading functions, ergo cutting off unnecessary elements, and maintaining user satisfaction. This is achieved by introducing user-oriented design elements in PSS development as well as substituting products and services [25].

Fargnoli et al. developed a framework to enhance sustainability and customer satisfaction for PSS. The framework consists of an integrated approach based on tools like life cycle assessment (LCA), life cycle costing or quality function deployment and is based on customers' needs and demands [26].

In addition to the mentioned approaches, numerous other contributions have been made, such as reviews and textbooks, e.g. from Richter et al. [27], Vasantha et al. [28], Vezzoli et al. [29], Pieroni et al. [30] or Boehm and Thomas [31], comprehensive frameworks, e.g. from Song and Sakao [32], Bertoni et al. [33] or Cibat et al. [34], and other work such as the contributions from Kjear et al. [35], [36] or Fernandes et al. [37], examining PSS in the context of sustainability and circular economy.

In a recently published review of literature and practice, Brissaud et al. suggest future characteristics for PSS and adequate design processes. They propose a design framework for PSS, which intends to design assets working longer, better, and more economically. The authors also give recommendations for future PSS design research, suggesting five main domains: science-based, systemic, value-centric, context-aware, and dynamic design. The domain of context-aware design should invent methods that enable responsible consumption and production patterns [38].

Despite the numerous valuable approaches which are paralleled by the successful application of the PSS concept in industry, the perspective of absolute sustainability is insufficiently considered in PSS design approaches. However, this perspective creates new opportunities to design PSS which not only are environmentally *better than* products alone but create solutions which are *good enough* and contribute to a safe and just transition of economies. Nevertheless, it can be expected that several measures of existing approaches can be adopted to design PSS towards absolute sustainability.

3. Research Approach

To incorporate absolute sustainability targets in the PSS life cycle, the design phase of PSS provides a crucial point of application. PSS design provides opportunities to integrate measures that affect the entire life cycle and to consequently shape PSS in sight of absolute sustainability.

As outlined in Section 2, there is a lack of PSS design approaches towards absolute sustainability. To address this gap, general design guidelines can initiate a shift towards absolute sustainable PSS design. A research approach with two steps was chosen to compose these guidelines.

The first step comprises the examination of existing PSS design approaches in sight of their consideration of absolute sustainability aspects. Even if none of the existing approaches cover all aspects of absolute sustainability, several measures can be adopted and reinterpreted. Approaches were examined to determine whether they address the challenges Hauschild et al. identify with regards to absolute sustainability in LCE [10]. Adopted to LCE for PSS these are:

- C1: Quantifying boundaries and distributing the space between them among different activities and elements
- C2: Enabling a global perspective to a product's life cycle and offer improvements to become eco-effective
- C3: Adapting the "toolbox" of LCE towards absolute sustainability
- C4: Developing approaches to support function or system innovation
- C5: Achieving a just distribution and use of limited resources
- C6: Consideration and avoidance of rebound effects

Only those design approaches were considered which address at least on challenge for absolute sustainability in LCE. They either offer tools to directly overcome a challenge (requirement 1) or lay the groundwork to be further adopted and address challenges indirectly (requirement 2). Those two gradations are reflected by either filled (requirement 1) or half-filled (requirement 2) circles in Table 1. An additional prerequisite for approaches to be considered is the successful implementation either in use cases or industrial practice (requirement 3). This successful implementation can lead to a more solid social foundation (compare Figure 1) by offering jobs and income. implemented PSS can deliver their benefits towards the transformation to absolute sustainability while unimplemented solutions remain hypothetical. Overall, 14 design approaches were identified which meet the three requirements.

Table 1. Analyzed PSS design approaches and their extent of considered absolute sustainability

Reference	C1	C2	C3	C4	C5	C6
McAloone and Andreasen 2004 [22]	○	○	◑	◑	◑	○
Aurich et al. 2006 [21]	○	●	●	◑	○	◑
Aurich et al. 2010 [24]	○	◑	◑	◑	○	○
Pigosso et al. 2013 [39]	○	○	●	◑	○	○
Kuo 2013 [40]	○	○	◑	◑	○	○
Vezzoli et al. 2014 [29]	○	◑	◑	◑	○	◑
Salazar et al. 2015 [25]	◑	○	●	◑	○	○
Bertoni et al. 2017 [33]	○	○	○	◑	○	○
Cibat et al. 2017 [34]	○	◑	◑	◑	○	○
Song and Sakao 2017 [32]	○	◑	◑	●	○	○
Fargnoli et al. 2018 [26]	○	◑	●	◑	○	○
Kjaer et al. 2019 [35]	○	◑	●	○	◑	●
van der Laan and Aurisicchio 2019 [23]	○	◑	◑	●	◑	○
Neramballi et al. 2020 [41]	○	○	◑	●	◑	○

The second step of the research approach is the formulation of guidelines. For this purpose, the different measures which directly address challenges were composed in as few guidelines as possible to rule out duplications but include all different measures. Subsequently, indirect measures were adjusted to either complement and enhance the direct solutions or were composed to new guidelines elements.

Also, the guidelines themselves are formulated to contribute to C2 and C3 by providing new tools for LCE and offering improvements to become eco-effective.

4. Design Guidelines

Following the research approach described in Section 3, a total of eight guidelines are formulated. They are intentionally conceptualized at a high and overarching level to enable a broad application in various industries of technical PSS. The guidelines address procedures along the entire life cycle and are composed to enable a systemic view on PSS by including value-adding networks, requirements of stakeholders and customers, and technological innovations. They can be classified in three categories. The first category comprises four guidelines and is primarily aimed at basic requirements in the planning and development phases of the PSS life cycle. The second category addresses lifelong improvements, while the third category focuses on the End-of-Life (EOL) of the PSS.

Figure 3 gives an overview and a brief description of the guidelines. The arrangement in a circular form illustrates the transition between different PSS solutions and generations as well as the entirety of the life cycle.In the remainder of this section, the guidelines are explained in detail, starting with the

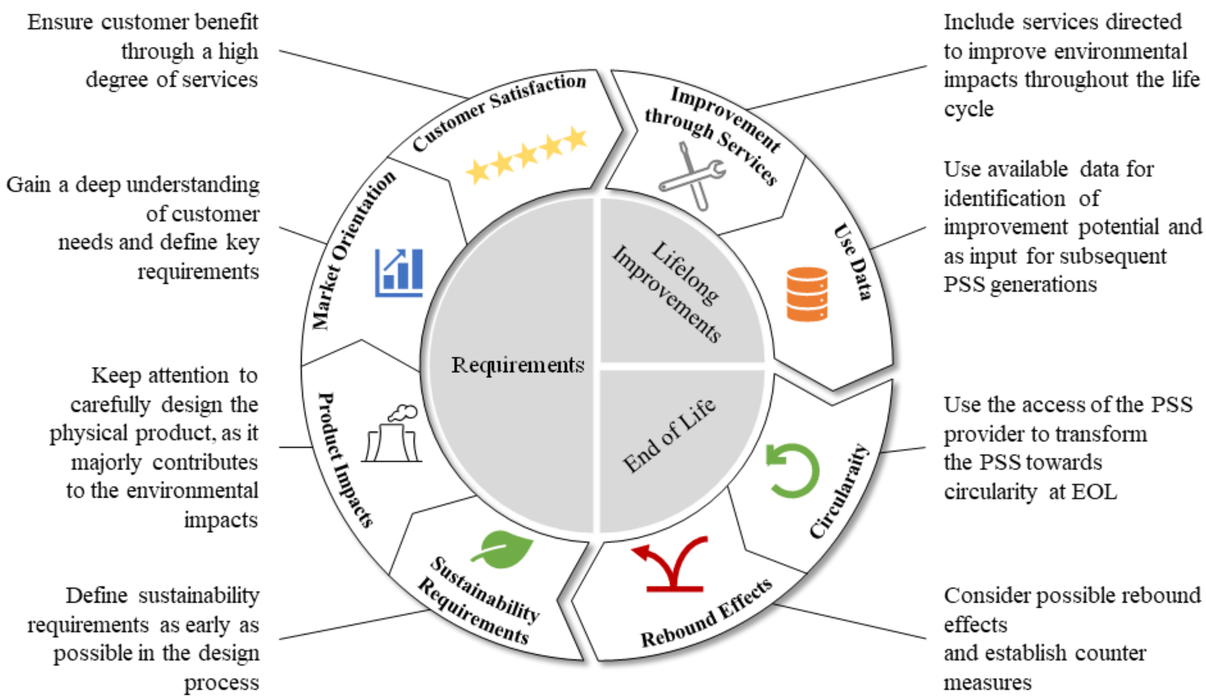

Figure 3: Design guidelines for sustainable PSS

guidelines for basic requirements in PSS design, followed by the guidelines for lifelong improvement and finalized with the guidelines regarding the EOL.

4.1. Define Sustainability Requirements early in Design Processes

The first guideline is concerned with the definition of sustainability requirements at the beginning of design processes. These processes usually start with technical specifications, customer requirements, and basic functions, whereas sustainability requirements play an inferior role. However, sustainability aspects need to be addressed early in the PSS life cycle, as around 80% of the environmental impacts are defined in PSS design [42]. Also, the limited ability and high costs to implement changes in later life cycle phases (Figure 4), suggest an early integration. The integration can be achieved in several ways but is heavily depending on the respective PSS development strategy.

Sustainability requirements need to be derived from planetary boundaries to set absolute targets. Once these targets are determined, they can be simply added to the list of requirements which have to be met in the ongoing development process. This is particularly suitable for requirements concerning the physical product, e.g., material selection or energy intensive manufacturing processes.

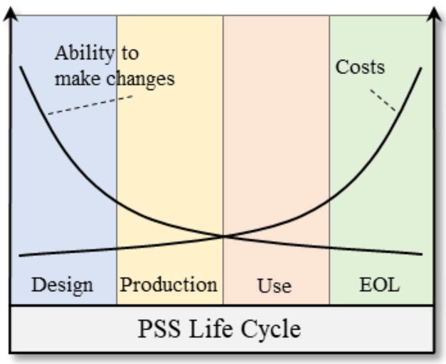

Figure 4: Ability to make changes and costs over PSS Life Cycle

Sustainability requirements concerning the non-physical parts of PSS are more difficult to integrate due to uncertainties quantifying their environmental impacts and dependance on user behavior [43]. Nevertheless, resources required should be used by as many services as possible to create synergy effects. When new services or service modules are designed, the existing services should be screened for commonly usable resources.

4.2. Reduce Product Impacts

The physical components of PSS majorly contribute to the overall environmental impacts in production, use, and disposal. The overall impacts of products embedded in PSS might be lower compared to products alone, nevertheless PSS designers should collaborate closely with product designers to adopt measures of sustainable product design.

For this purpose, numerous approaches and principles for sustainable product design can be utilized. One of the most commonly used is the principle of eco-design, which includes efficiency in material use and energy consumption, reduction of waste, repairability, or reduction of logistics. Another approach is Design for Environment, which combines design for environmental processing and manufacturing, design for environmental packaging, design for disposal or reuse, and design for energy efficiency. The choice for design principles heavily depends on the product type as well as on preconditions in companies, wherefore a general suggestion is not applicable.

Designing products in the context of PSS should include measures to keep the product adaptable and adjustable during its use to prolong its lifetime. Therefore, a modular approach is favorable. Another measure should be the integration of sensors and monitoring to gather data which can be further used for optimization (compare Guideline 6). Lastly, benefits result from designing the product in a way that services can be easily and efficiently performed, which is fostered if collaboration with future service providers during the design is performed.

4.3. Create a market-oriented PSS

A deep understanding of customer needs and defining key requirements is crucial, because each fulfilled function of a PSS is connected to certain environmental impacts. Consequently, the impacts of functions and PSS elements that do not align with the intended use of the customer can be considered as wasted.

Therefore, the efforts taken to clearly identify the customer needs can help to limit the PSS' environmental impacts to activities that are perceived useful to the customer.

This aspect of PSS can be achieved through a modular and reconfigurable structure, as customer demands, and requirements might be subject to change within the life cycle. A modular approach also might extend the market segment the PSS is suitable for, by addressing additional groups of customers with a different configuration. Furthermore, constant re-evaluation of the customers usage behavior is crucial to continuously focus the PSS operation on what the customer actually needs.

4.4. Achieve Customer Satisfaction through Services

PSS are intended to deliver high customer benefits with lower resource consumption compared to products alone. Following this aim, the core aspect of customer satisfaction needs to be preserved when designing PSS in sight of absolute sustainability. Only with high customer satisfaction, PSS can be offered successfully while exploiting individual sustainability potentials.

To ensure high customer satisfaction, early involvement of customers in design processes beyond commonly applied generic customer requirements is needed. For instance, through using an integrated design approach involving key customers for testing and feedback [44]. Additionally, maintaining a close cooperation with customers throughout the use of the PSS can improve the customer satisfaction. Furthermore, PSS should be designed to be rather easily adaptable to new user requirements in the scope of the PSS functions, providing additional benefit and prolonging use times.

Considering sustainability targets, achieving customer satisfaction with a high degree of services should be aimed for. As stated in the previous guideline, services can fulfill functions with comparably low environmental impacts.

4.5. Gain environmental Improvements through Services

Previous research suggests the existence of an energetic leverage effect of the service part of a PSS [45]. Particularly, while services themselves usually only cause minor amounts of the environmental impacts of a PSS, they bear potential to significantly lower the overall impacts of other elements. For instance, a maintenance service that reduces friction of certain moving parts of the PSS' product element might account for very little environmental impacts, yet it will contribute to lower the overall impact.

The guideline therefore suggests identifying and offering services with similar potential. This can be based on an analysis of the PSS' product components with the biggest contribution to the PSS' environmental impacts. Those contributions can be assessed and quantified through LCA, even if some assumptions need to be made because of uncertainties during the design phase. Subsequently, services need to be designed and offered, which influence these heavily contributing elements, possibly providing advice on sustainable operation (e.g., proposing suitable parameters to operators) Additionally, services can be rather easily adjusted to changes occurring in the use phase and can thus reduce the risk associated with uncertainties.

4.6. Use Data for improved Operation and Design

Technological advancements provide new opportunities for data collection, processing, evaluation, and analysis. PSS designers should use available data for continuous improvement and identification of improvement potential and input for subsequent PSS generations, as shown in Figure 5.

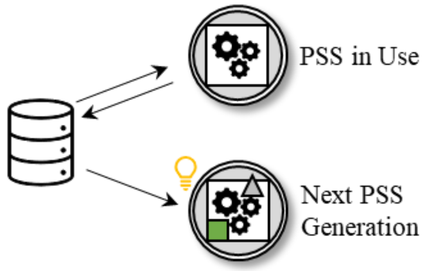

Figure 5: Use of Data in PSS Design

Gathering data in the use phase of the PSS life cycle is the foundation for many improvements concerning sustainability. For instance, the wear of parts and thereby optimal time for maintenance can be determined individually for each PSS, possibly preventing downtimes. Thus, data can provide insights in the operation of the physical product, leading to potential improvements in efficiency due to better set ups in use. For instance, with the help of experts via remote support, commercial vehicles can be better adjusted to attachments to fulfill different tasks, possibly leading to reduced fuel consumption.

The amount of data collected over the long use time of PSS not only serves as foundation for improvement but should be carefully analyzed for the design of subsequent PSS generations. The data can provide information of parts proven to be weak points, e.g., parts responsible for many failures or downtimes, during operation and need to be designed differently in the future, for instance for a longer lifetime. The data can also give indications about elements which are rarely used or parts which are over dimensioned. Thereby, overengineering can be avoided and leading to a leaner, more resource-efficient, and customer-oriented PSS.

This guideline implies the need for designers to include the necessary sensors and access points as well as the infrastructure to gather and provide data to partners in the network. As digital technologies evolve rapidly, PSS should be designed to enable the continuous integration of novel technologies in the use of the PSS. Important data interfaces need to be accessible and replaceable to take advantage of technological developments. Furthermore, the gathered data should be reevaluated regularly to find new potentials with emerging approaches such as machine learning.

4.7. Enable Circularity

PSS offered in business-to-business relations between the PSS provider and its customers usually entail a long-lasting cooperation. The form of this cooperation heavily depends on the specific case. It can vary from maintenance contracts, extended long time service agreements, leasing models, up to shared responsibility for production. These forms have in common, that the PSS provider has access to the physical product after it has been manufactured. The extend of the access typically depends on the business model and the form of cooperation. In accordance with the previous guideline, this access can be used to gather information about the condition of the physical product in use and, more importantly, about the condition at the end of its lifetime. The knowledge about this aspect can initiate different loops, where parts can be reused, refurbished, or remanufactured and subsequently reintegrated in production processes.

For designers, this results in several challenges addressed in this guideline. First, it must be determined which product parts are suitable for circularity. Parts with relatively low wear during use or standardized parts can be indicators. Second, the condition of the parts necessary to direct them in the correct circles must be identified. Parts in better conditions might be suitable for light refurbishment whereas strongly worn parts need to be recycled. Therefore, the data required to map the conditions as well as the optimal time to return the physical product to the PSS provider is crucial. Third, production processes must be designed open to the integration of parts from the different loops. The ability of functions as logistics, job scheduling or quality need to be assessed and adjusted.

If the challenges of traceability of parts, data collection and analysis, return, and reintegration are addressed, designers should conceptualize as many parts as possible with regards to circularity (e.g., through easy access for replacements). In this way, a lower consumption of primary resources can be achieved. Designing the services regarding circularity, focus need to be set on the creation of ways on how the products can be returned, with the respective partners, so a circular approach is economically beneficial for all parties.

However, attention must be paid to the effort required for return and reprocessing to achieve comprehensive improvements in sustainability. Also, the resulting additional complexity in the value-adding network needs to be considered.

4.8. Consider and mitigate Rebound Effects

Rebound effects describe a reduction of the effectiveness of improvements in resource and energy efficiency due to secondary effects [46]. Rebound effects can be further subdivided into direct and indirect effects with numerous respective subcategories [46]. It is generally accepted that rebound effects cannot be fully avoided. Thus, the purpose of this guideline is to raise awareness for this phenomenon in design processes.

Initially, designers need to be educated to know about the characteristics and the origin of rebound effects. Special attention is set on effects that can outweigh the intended positive impact of certain improvements, so the overall sustainability performance deteriorates and possibly threatens sustainability targets. When the necessary attention is created, measures regarding sustainability improvement should be checked for potential rebounds. Even if the rebound effect cannot be avoided, actions for mitigation can be taken. For instance, Kjear et al. propose the incentivization of customers to spend money saved through resource efficiency on services rather than products [35]. Subsequently, rebound effects should be considered as a possible downside to all improvement measures. Nevertheless, they should not be an obstacle on the way to continuous improvements.

To include the knowledge about rebound effects in PSS, designers can impact user behaviors in the product’s use phase. First, standard settings of the physical product should be set in an eco-friendly way. Second, the awareness of the user towards his behavior should be increased, e.g., by including information in frequently used displays. The biggest opportunity to counter rebound effects is the creation of incentives for the customer to behave in an eco-friendly way, e.g., by prolonging maintenance intervals if machines are used correctly.

5. Discussion

The guidelines were composed to address the challenges created by the adoption of an absolute sustainability perspective in LCE.

The challenge of quantifying suitable boundaries (C1) is addressed by the guidelines 1 and 2. Guideline 1 suggests the inclusion of absolute targets as requirements in the early stages of PSS design. Subsequently, in guideline 2 measures are taken to improve the environmental performance of the product, as it majorly contributes to the overall environmental impacts.

The development of tools to support function- and system innovation (C4) is covered by guidelines 5 and 6, where a continuous improvement and the use of data enables designers to include innovations over the entire life cycle. Also, following the guidelines 5 and 6 provides the possibility to address changes and the associated uncertainties over the lifecycle.

The challenge of a just distribution of resource is manly covered (C5) by guideline 7, where circularity serves as the foundation and a tool to save resources.

Guideline 8 was formulated to cover the challenge of avoidance of rebound effects (C6). Even if rebound effects still endanger the achievement of absolute sustainability, mitigation of the rebound effects is mandatory in PSS design.

The challenges of enabling a global perspective to a product's life cycle and offer improvements to become eco-effective (C2), and the challenge adapting the toolbox for LCE (C3) are addressed by the composition of the guidelines overall, as those challenges majorly inspired this contribution.

The guidelines 3 and 4 were created to support the successful implementation of absolute sustainability in design processes in industries by ensuring high customer satisfaction and market orientation. Furthermore, they can provide benefits towards the social foundations to create jobs through services and create constant revenue streams and thereby address the challenge of economies that support a sustainable transition. To quantify the improvements gained by the application of the proposed guidelines, designers need to implement measurements of the most important indicators for absolute sustainability. These indicators can be derived from the impact indicators of an LCA, as suggested by [47].

Lastly, the high level and overarching guidelines were formulated so that they can be easily adopted in explicit design approaches for different business models or PSS concepts. Although the guidelines mainly address the design of technical PSS, they serve as a foundation for the design of PSS used in business-to-customer relations or outside the investment goods sector.

6. Conclusion and final Remarks

The concept of absolute sustainability challenges approaches on how to design and manufacture products and PSS by setting new boundaries, derived from planetary limits and social foundations. Within these new boundaries, novel ways of LCE need to be examined.

Adopting the perspective of absolute sustainability into PSS design, six challenges were introduced. In sight of these challenges, current PSS design approaches were examined, showing potential for further enhancement for the field PSS design research. This contribution takes a first step to initiate further research by formulation general design guidelines towards absolute sustainability in PSS design. The guidelines contribute to context-aware PSS design research in sight of absolute sustainability requirements.

Future research needs to set the boundaries for corporate activities and examine methods, of how to break those boundaries down to specific requirements for products and PSS. In addition, frameworks and specific approaches on how to strictly comply these limits throughout an entire life cycle, different business models, and PSS configurations need to be developed.

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References

[1] Raworth, Kate, 'A safe and just Space for Humanity', *Oxfam Discussion Papers*, 2012, [Online]. Available: https://policy-practice.oxfam.org/resources/a-safe-and-just-space-for-humanity-can-we-live-within-the-doughnut-210490/

[2] United Nations Brundtland Commission, 'Report of the World Commission on Environment and Development: Our Common Future', 1987.

[3] J. Elkington, 'Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development', *California Management Review*, vol. 36, no. 2, pp. 90–100, Jan. 1994.

[4] United Nations, 'Sustainable Development Goals'. [Online]. Available: https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[5] C. Herrmann, S. Blume, D. Kurle, C. Schmidt, and S. Thiede, 'The Positive Impact Factory–Transition from Eco-efficiency to Eco–effectiveness Strategies in Manufacturing', *Procedia CIRP*, vol. 29, pp. 19–27, 2015.

[6] *DIN EN ISO 14045 - Environmental management - Eco-efficiency assessment of product systems - Principles, requirements and guidelines*. 2012.

[7] A. Bjørn and M. Z. Hauschild, 'Absolute versus Relative Environmental Sustainability: What can the Cradle-to-Cradle and Eco-efficiency Concepts Learn from Each Other?', *Journal of Industrial Ecology*, vol. 17, no. 2, pp. 321–332, Apr. 2013.

[8] J. Rockström *et al.*, 'A safe operating space for humanity', *Nature*, vol. 461, no. 7263, pp. 472–475, Sep. 2009.

[9] M. Z. Hauschild, C. Herrmann, and S. Kara, 'An Integrated Framework for Life Cycle Engineering', *Procedia CIRP*, vol. 61, pp. 2–9, 2017.

[10] M. Z. Hauschild, S. Kara, and I. Røpke, 'Absolute sustainability: Challenges to life cycle engineering', *CIRP Annals*, vol. 69, no. 2, pp. 533–553, 2020.

[11] R. G. G. Caiado, R. de Freitas Dias, L. V. Mattos, O. L. G. Quelhas, and W. Leal Filho, 'Towards sustainable development through the perspective of eco-efficiency - A systematic literature review', *Journal of Cleaner Production*, vol. 165, pp. 890–904, Nov. 2017.

[12] J. Ehrenfeld, 'Eco-efficiency: Philosophy, Theory, and Tools', *Journal of Industrial Ecology*, vol. 9, no. 4, pp. 6–8, 2005.

[13] A. Tukker, 'Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet', *Bus. Strat. Env.*, vol. 13, no. 4, pp. 246–260, Jul. 2004.

[14] O. K. Mont, 'Clarifying the concept of product–service system', *Journal of Cleaner Production*, vol. 10, no. 3, pp. 237–245, Jun. 2002.

[15] A. Tukker, 'Product services for a resource-efficient and circular economy – a review', *Journal of Cleaner Production*, vol. 97, pp. 76–91, Jun. 2015.

[16] S. Pastoors, 'Einleitung', in *Praxishandbuch Nachhaltige Produktentwicklung*, Berlin, Heidelberg: Springer Berlin Heidelberg, 2018, pp. 1–8. Accessed: Jun. 24, 2022. [Online]. Available: http://link.springer.com/10.1007/978-3-662-57320-4_1

[17] European Union, 'A European Green Deal - Striving to be the first climate-neutral continent', *European Union*, 2022. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[18] European Union, 'Rules and requirements for energy labelling and ecodesign', 2021. https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/rules-and-requirements_en

[19] T. C. McAloone and D. C. A. Pigosso, 'From Ecodesign to Sustainable Product/Service-Systems: A Journey Through Research Contributions over Recent Decades', in *Sustainable Manufacturing*, R. Stark, G. Seliger, and J. Bonvoisin, Eds. Cham: Springer International Publishing, 2017, pp. 99–111.

[20] S. Kara, M. Hauschild, J. Sutherland, and T. McAloone, 'Closed-loop systems to circular economy: A pathway to environmental sustainability?', *CIRP Annals*, vol. 71, no. 2, pp. 505–528, 2022.

[21] J. C. Aurich, C. Fuchs, and C. Wagenknecht, 'Life cycle oriented design of technical Product-Service Systems', *Journal of Cleaner Production*, vol. 14, no. 17, pp. 1480–1494, Jan. 2006.

[22] T. C. McAloone and Andreasen, M.M., 'Design for utility, sustainability and societal virtues: developing product service systems', presented at the the 8th International Design Conference, 2004.

[23] A. Z. van der Laan and M. Aurisicchio, 'Designing Product-Service Systems to Close Resource Loops: Circular Design Guidelines', *Procedia CIRP*, vol. 80, pp. 631–636, 2019.

[24] J. C. Aurich, C. Mannweiler, and E. Schweitzer, 'How to design and offer services successfully', *CIRP Journal of Manufacturing Science and Technology*, vol. 2, no. 3, pp. 136–143, Jan. 2010.

[25] C. Salazar, A. Lelah, and D. Brissaud, 'Eco-designing Product Service Systems by degrading functions while maintaining user satisfaction', *Journal of Cleaner Production*, vol. 87, pp. 452–462, Jan. 2015.

[26] M. Fargnoli, F. Costantino, G. Di Gravio, and M. Tronci, 'Product service-systems implementation: A customized framework to enhance sustainability and customer satisfaction', *Journal of Cleaner Production*, vol. 188, pp. 387–401, Jul. 2018.

[27] A. Richter, P. Glaser, B. Kölmel, L. Waidelich, and R. Bulander, 'A Review of Product-service System Design Methodologies':, in *Proceedings of the 16th International Joint Conference on e-Business and Telecommunications*, Prague, Czech Republic, 2019, pp. 115–126.

[28] G. V. A. Vasantha, R. Roy, A. Lelah, and D. Brissaud, 'A review of product–service systems design methodologies', *Journal of Engineering Design*, vol. 23, no. 9, pp. 635–659, Sep. 2012.

[29] C. Vezzoli, C. Kohtala, and A. Srinivasan, Eds., *Product-service system design for sustainability*. Sheffield: Greenleaf Publishing, 2014.

[30] M. de P. Pieroni, C. A. N. Marques, R. N. Moraes, H. Rozenfeld, and A. R. Ometto, 'PSS Design Process Models: Are They Sustainability-oriented?', *Procedia CIRP*, vol. 64, pp. 67–72, 2017.

[31] M. Boehm and O. Thomas, 'Looking beyond the rim of one's teacup: a multidisciplinary literature review of Product-Service Systems in Information Systems, Business Management, and Engineering & Design', *Journal of Cleaner Production*, vol. 51, pp. 245–260, Jul. 2013.

[32] W. Song and T. Sakao, 'A customization-oriented framework for design of sustainable product/service system', *Journal of Cleaner Production*, vol. 140, pp. 1672–1685, Jan. 2017.

[33] M. Bertoni, A. Rondini, and G. Pezzotta, 'A Systematic Review of Value Metrics for PSS Design', *Procedia CIRP*, vol. 64, pp. 289–294, 2017.

[34] J. Cibat, T. Süße, and U. Wilkens, 'An Ecosystem Approach as a Design Principle for a PSS-Specific Business Simulation', *Procedia CIRP*, vol. 64, pp. 223–228, 2017.

[35] L. L. Kjaer, D. C. A. Pigosso, M. Niero, N. M. Bech, and T. C. McAloone, 'Product/Service-Systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption?', *Journal of Industrial Ecology*, vol. 23, no. 1, pp. 22–35, Feb. 2019, doi: 10.1111/jiec.12747.

[36] L. L. Kjaer, D. C. A. Pigosso, T. C. McAloone, and M. Birkved, 'Guidelines for evaluating the environmental performance of Product/Service-Systems through life cycle assessment', *Journal of Cleaner Production*, vol. 190, pp. 666–678, Jul. 2018.

[37] S. da C. Fernandes, D. C. A. Pigosso, T. C. McAloone, and H. Rozenfeld, 'Towards product-service system oriented to circular economy: A systematic review of value proposition design approaches', *Journal of Cleaner Production*, vol. 257, p. 120507, Jun. 2020.

[38] D. Brissaud, T. Sakao, A. Riel, and J. A. Erkoyuncu, 'Designing value-driven solutions: The evolution of industrial product-service systems', *CIRP Annals*, vol. 71, no. 2, pp. 553–575, 2022.

[39] D. C. A. Pigosso, H. Rozenfeld, and T. C. McAloone, 'Ecodesign maturity model: a management framework to support ecodesign implementation into manufacturing companies', *Journal of Cleaner Production*, vol. 59, pp. 160–173, Nov. 2013.

[40] T. C. Kuo, 'Mass customization and personalization software development: a case study eco-design product service system', *J Intell Manuf*, vol. 24, no. 5, pp. 1019–1031, Oct. 2013.

[41] A. Neramballi, T. Sakao, S. Willskytt, and A.-M. Tillman, 'A design navigator to guide the transition towards environmentally benign product/service systems based on LCA results', *Journal of Cleaner Production*, vol. 277, p. 124074, Dec. 2020.

[42] T. McAloone, N. Bey, Danmark, and Milj??styrelsen, *Environmental improvement through product development: a guide*. Environmental Protection Agency, 2009.

[43] L. L. Kjaer, A. Pagoropoulos, J. H. Schmidt, and T. C. McAloone, 'Challenges when evaluating Product/Service-Systems through Life Cycle Assessment', *Journal of Cleaner Production*, vol. 120, pp. 95–104, May 2016.

[44] M. Werrel, L. Yi, P. Kölsch, and J. C. Aurich, 'Customer-Driven Eco-design for Technical Product-Service Systems', in *Production at the Leading Edge of Technology*, B.-A. Behrens, A. Brosius, W.-G. Drossel, W. Hintze, S. Ihlenfeldt, and P. Nyhuis, Eds. Cham: Springer International Publishing, 2022, pp. 592–600.

[45] M. F. Glatt, L. Yi, G. Mert, B. S. Linke, and J. C. Aurich, 'Technical Product-Service Systems: Analysis and reduction of the Cumulative Energy Demand', *Journal of Cleaner Production*, vol. 206, pp. 727–740, Jan. 2019.

[46] L. A. Greening, D. L. Greene, and C. Difiglio, 'Energy efficiency and consumption — the rebound effect — a survey', *Energy Policy*, vol. 28, no. 6–7, pp. 389–401, Jun. 2000.

[47] A. Bjørn and M. Z. Hauschild, 'Introducing carrying capacity-based normalisation in LCA: framework and development of references at midpoint level', *Int J Life Cycle Assess*, vol. 20, no. 7, pp. 1005–1018, Jul. 2015.