



HAL
open science

A Framework to Address Complexity and Changeability in the Design of Circular Product-Service Systems

Alessandro Bertoni, Raj Jiten Machchhar

► **To cite this version:**

Alessandro Bertoni, Raj Jiten Machchhar. A Framework to Address Complexity and Changeability in the Design of Circular Product-Service Systems. IFIP International Conference on Advances in Production Management Systems (APMS), Sep 2022, Gyeongju, South Korea. pp.19-25, 10.1007/978-3-031-16411-8_3. hal-04768963

HAL Id: hal-04768963

<https://inria.hal.science/hal-04768963v1>

Submitted on 6 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



This document is the original author manuscript of a paper submitted to an IFIP conference proceedings or other IFIP publication by Springer Nature. As such, there may be some differences in the official published version of the paper. Such differences, if any, are usually due to reformatting during preparation for publication or minor corrections made by the author(s) during final proofreading of the publication manuscript.

A framework to address complexity and changeability in the design of circular product-service systems

Alessandro Bertoni¹^[0000-0001-5114-4811] and Raj Jiten Machchhar¹^[0000-0001-7581-439X]

¹ Department of Mechanical Engineering, Blekinge Institute of Technology, Karlskrona, 37179, Sweden

Abstract. The design of a circular PSS solution goes beyond the traditional perspective of circular product design encompassing multiple complexity dimensions that need to be considered and addressed in the early stages of design. The paper provides a literature-based outlook on the levels of complexity to be faced when making decisions in early PSS design by positioning the concept of changeability inherited from the systems engineering literature into the context of the design of circular PSS. The paper ultimately stresses the need to consider the changeability of PSS as a relevant dimension in the assessment of its circularity potential. It does so by proposing a framework for the design of circular PSS solutions, summarizing the main design strategies and approaches currently described in the literature to mitigate the uncertainties generated by PSS complexity.

Keywords: Changeability, product-service systems, complexity, circularity.

1 Introduction

Governmental institutions and researchers agree that a move toward circular economy systems would contribute to the achieving of the sustainable development goals defined by the United Nations [1]. Manufacturing companies play a key role in realizing sustainability ambitions and a consistent research effort has been spent on identifying what are the fundamental criteria upon which circular economy is defined and measured in the industry (e.g., [2]). From a product development perspective, circularity consideration makes early decisions more and more difficult, increasing the level of complexity of the design problem, now addressing the development of a complex system featuring the combination of product and service components (i.e., developing Product-Service Systems solutions or PSS) to be delivered in a lifespan that could, in some cases, extend over several decades. In such contexts, the translation of high-level circularity considerations into specific product requirements that guide design decisions is a challenging task. Methods to promote the development of circular systems have been proposed in literature both from a business development and a product development perspective (e.g. [3][4]). However, the literature still does not provide a comprehensive outlook on how to deal with the new uncertainties introduced by circularity considerations during the early engineering design of PSS. In this regard, one of the challenges is the lack of

literature elucidating the complexities that exist in and around the inferred PSS. To bridge this knowledge gap, the paper aims to provide a comprehensive outlook on the level of complexity introduced by PSS, stressing the need to consider the changeability of PSS as a relevant dimension in the assessment of its circularity potential. As a result, the paper positions the concept of changeability in relation to the available literature about the design of circular solutions and in relation to the literature concerning systems complexity and changeability in systems engineering. Ultimately the paper summarizes the main available design strategies and approaches currently described in the literature to mitigate the uncertainties generated by PSS complexity.

The definition of the research problem and objective is the results of a participatory action research approach in collaboration with two major Swedish companies operating in the aerospace and construction machinery industry. Qualitative data were gathered through semi-structured interviews, workshops, and focus groups, initially to compile a comprehensive descriptive analysis, although the contribution of this paper shall be seen as largely based on literature review and synthesis. A narrative-styled literature review, complemented by a snowballing technique, was performed in the field of PSS and systems engineering. The choice of not performing a more structured and formalized systematic review was driven by the acknowledgment of the high variety of synonyms of changeability, flexibility and adaptability available in literature, that led, in a first step, to an unmanageable number of publications from multiple research fields.

2 Literature review

2.1 Design of Circular PSS solutions

The academic discussion about how to design circular products can be framed into the broader research effort of developing and implementing methods for sustainability quantification. In product design, this translates into the capability of integrating new methods and approaches into the current well-established engineering practices. In such a context a broad range of engineering methods have flourished under the umbrella of Eco-design (e.g. [5]), Design for Sustainability (e.g. [6]), Design for environment (e.g. [7]), Sustainable Product development (e.g. [8]) and Design for Circularity (e.g. [4]). The latter has focused on understanding what the features of a circular economy system are, and therefore, what kind of circular economy indicators can be introduced to measure the circularity of a product or a system. To enable this, the Ellen McArthur Foundation published a list of material circularity indicators at the product level and at the company level [3]. Pauliuk [9] stressed the importance of circular strategies to be monitored from a higher system perspective, to avoid defining indicators that would bring companies' decisions in the wrong direction. This highlights the need to have the right indicators used in the correct context and with a suitable level of granularity based on the specific focus of the design activity. Den Hollander et al. [4] argued that circular product design is guided by the Inertia Principle, prescribing product integrity to be the main design objective to be pursued and to be preferred to product recyclability. Based on this they defined circular product design as the combination of both design for

integrity (i.e. aiming at resisting, postponing, and reversing obsolescence at the product and component level), and design for recycling, aiming at preventing and reversing obsolescence at a material level.

2.2 Complexity and changeability in systems design

In the realm of systems engineering, Magee and de Weck [10 p2] defined a complex system as “a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change”. Further, Gaspar et al. [11] defined the complexity of a system as the quantity of information necessary to define a system, understand the interdependencies, and predict future scenarios. In such a context, five essential aspects for engineering a complex system were proposed by Rhodes and Ross [12], namely, structural, behavioral, contextual, temporal, and perceptual complexity. Addressing such complexities reflects the primary need to deliver desired value to all the associated stakeholders throughout the lifecycle [12]. In such a context changeability is a property of the system to reach various conceivable states to allow a robust value delivery during the operational stage while embracing changes in the operational context [13]. Changeability is a collection of many change-related “ilities” such as adaptability, flexibility, scalability, etc. and it is acknowledged as an over-arching property of the system of being able to either change the “form” or “function” of the system to bring about a change in the operation as a response to changes in the context [13]. Changeability is highly related to the complexity of the system; however, changeability excludes change-related ilities outside the operational life of the system thus excluding factors such as “remanufacturing” or “recycling”, that fall inside the “traditional” boundaries of design for remanufacturing and recyclability.

3 Defining changeability in the design of circular PSS solutions

The existing literature shows some limitations in supporting the design of circular PSS solutions. Firstly, limited methods and tools are capable of identifying and assessing circularity in early design phases, which requires linking PSS circularity with stakeholder needs, as well as potential business implications, that may change over time. Secondly, when working on the conceptual design of PSS components (or sub-systems), engineers work with requirements that seldom reflect the overall design rationale of circular solutions. Thirdly, even if circularity-related product requirements are in place there is a lack of understanding about the value robustness of a circularity solution along its lifecycle, that is, about how the PSS solution will deal with the behavioral, structural, contextual, perceptual, and temporal complexity, or, in other words, about how “changeable” a PSS solution will be.

Based on such considerations Fig. 1 proposes a framework for design of circular PSS solutions, positioning design for PSS changeability as a complementary dimension to design for integrity and recycling. The framework adds the “Design for PSS changeability” dimension (bottom part of Fig. 1) listing potential design strategies and

potential methods to mitigate the negative impact of five levels of system complexity. The complexity levels are derived from the work by Rhodes and Ross [12] further investigated by authors in the field of aerospace and maritime engineering (e.g. [11][13][14][15]), while the potential design strategies and methods to mitigate the negative effect of complexity in design decision making are derived from the available scientific literature in the field. In detail the five levels of complexity are:

Structural complexity. Defined by the system components and their relationship. The structural complexity is determined by the decision made by engineers and designers in PSS design; thus, it is normally in the control of decision-makers. Structural complexity is often addressed and reduced by applying strategies for modular product and service design, that are claimed to be able to mitigate changes and conflicting requirements. In this regard, an example of concept selection for elevators provided as PSS is presented in literature by [16]. Here the selection of proper PSS module instances which are a function of product and service modules combined into a solution under relevant constraints is the design strategy to address the structural complexity of the product while developing as PSS solution [16].

Behavioral complexity. Defined as the complexity given by the multiple parts of the designed system that concurrently operate to deliver the intended value. Such definition does not encompass external factors that can influence the system under design, thus also the behavioral complexity can be considered as a parameter in the control of the decision-makers. Model-based systems engineering (MBSE) is one of the known approaches to simulate such behavior while systems are still in the design stage. Based on the use of “executable” models (often based on SysML or UML language), MBSE is increasingly adopted in industry to address the behavioral complexity of complex systems.

Contextual complexity includes all external factors that can influence the behavior of the system. Contextual complexity is focused on understanding the influence of external stimuli and it has been the focus of research for many decades. The challenge is that the decision-makers can manage the uncertainties internal to the system to a certain level, but the external uncertainties are beyond the control of the decision-makers, thus making it cumbersome to build a system capable of handling these uncertainties. This viewpoint is preserved in PSS design, where many researchers have actively acknowledged the changing context and its influence on the lifecycle of the [17]. Emerging design strategies dealing with PSS contextual complexity encompass the use of scenario simulations based on agent-based and discrete event modeling (e.g. [18]) or the creation of environmental interaction models [19].

Temporal complexity. Temporal complexity escalates the concept of contextual complexity by introducing a time dimension in the system-context interaction. Researchers agree on the unexploited potential of the PSS value delivery given by the lack of integration of long-term thinking during the design, stating that PSS must include a lifecycle or through-life perspective, (e.g. [20]). In such a context, scenario-based simulations linked to the development of digital twins are seen as the potential strategies to deal with temporal complexity in PSS design. In particular, the literature identifies as a potential future scenario the use of virtual “beta prototypes” of PSS (also defined as “fake twins” [21]) capable of simulating radical changes in the PSS hardware while running in parallel with the entity that exists in reality. This is based on the idea that, through the accumulation of data, the virtual models will reach a tipping point showing when a

fake twin (i.e., a radical redesign of the original PSS concept) will become more value-adding for both the provider and its customers, considering investments, switching costs, risks and more in the equation.

Perceptual complexity. Such complexity is generated by the differences in the opinion of the stakeholders about the value of a system. The essence of perceptual complexity is the dynamics of expectations from the system through time [11]. Work in the field of PSS prototyping has focused on PSS perception by crating shared stakeholders' experiences and providing a sense of full scalability of PSS solutions [22]. Additionally, virtual reality applications have been proposed to replicate intangible and subjective customers' experiences during PSS testing [23], although the use of such technology to address the perceptual complexity in PSS design is still in its infancy.

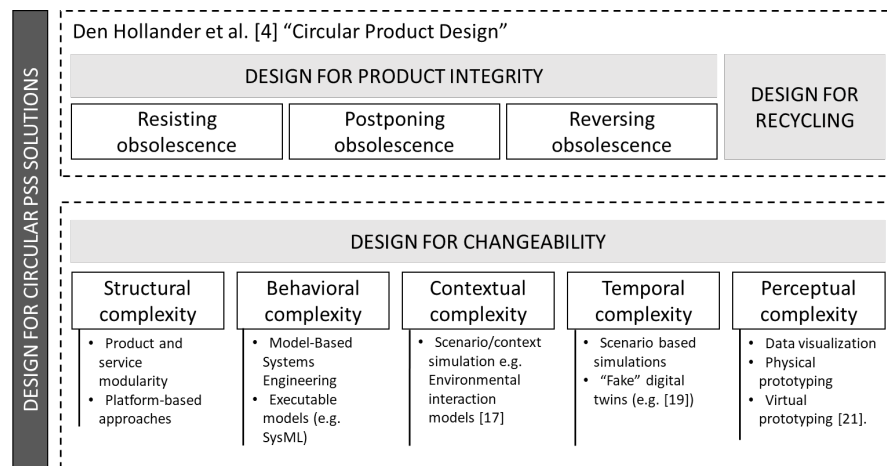


Fig. 1. Framework for Design for PSS circular solution positioning "Design for PSS changeability" in relation to circular product design.

4 Conclusions

The design of a circular PSS solution goes beyond the traditional perspective of circular product design encompassing multiple complexity dimensions that need to be considered and addressed in the early stages of design. The paper has presented an outlook on various levels of complexities that affect PSS design stressing the need to consider the changeability of PSS as an integral part of the effort toward designing new circular solutions, complementing the established approach for circular product design available in literature. The paper positions its contribution in between the field of PSS design and systems engineering and shall be seen as a tentative to provide a framework of reference around which to further develop future research efforts in the field.

References

1. United Nations General Assembly: Transforming our world: The 2030 agenda for sustainable development (2015). Available at: <https://www.unfpa.org/resources/transforming-our-world-2030-agenda-sustainable-development> accessed on April 29, 2022.
2. EASAC European Academies' Science Advisory Council: Indicators for circular economy. The Clyvedon Press Ltd, Cardiff, United Kingdom (2016).
3. MacArthur, E., Zumwinkel, K., Stuchtey M.R.: Growth within: a circular economy vision for a competitive Europe. Ellen MacArthur Foundation (2015).
4. Den Hollander, M. C., Bakker, C. A., Hultink, E. J.: Product design in a circular economy: Development of a typology of key concepts and terms. *Journal of Industrial Ecology*, 21(3), 517-525 (2017).
5. Pigosso, D. C., Rozenfeld, H., & McAloone, T. C.: Ecodesign maturity model: a management framework to support ecodesign implementation into manufacturing companies. *Journal of Cleaner Production*, 59, 160-173 (2013).
6. Bhamra, T., & Lofthouse, V.: Design for sustainability: a practical approach. Routledge (2016)
7. Sroufe, R., Curkovic, S., Montabon, F., & Melnyk, S. A. The new product design process and design for environment. *International Journal of Operations & Production Management* (2000).
8. Byggeth, S., Broman, G., & Robèrt, K. H.: A method for sustainable product development based on a modular system of guiding questions. *Journal of cleaner production*, 15(1), 1-11 (2007).
9. Pauliuk, S.: Critical appraisal of the circular economy standard BS 8001: 2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation and Recycling*, 129, 81-92 (2018).
10. Magee, C., de Weck, O.: Complex System Classification (Working Paper). International Council of Systems Engineering (INCOSE) (2004).
11. Gaspar, H.M., Rhodes, D.H., Ross, A.M., Ove Erikstad, S.: Addressing Complexity Aspects in Conceptual Ship Design: A Systems Engineering Approach. *Journal of Ship Production and Design* 28, 145–159 (2012).
12. Rhodes, D.H., Ross, A.M.: Five aspects of engineering complex systems emerging constructs and methods, in: 2010 IEEE International Systems Conference. pp. 190–195 (2010)
13. Mekdeci, B., Ross, A.M., Rhodes, D.H., Hastings, D.E.: Pliability and Viable Systems: Maintaining Value Under Changing Conditions. *IEEE Systems Journal* 9, 1173–1184 (2015).
14. Gaspar, H.M., Hagen, A., Erikstad, S.O.: On designing a ship for complex value robustness. *Ship Technology Research* 63, 14–25 (2016).
15. Ross, A.M., Rhodes, D.H., Hastings, D.E.: Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value. *Systems Engineering* 11, 246–262 (2008).
16. Song, W., Sakao, T.: A customization-oriented framework for design of sustainable product/service system. *Journal of Cleaner Production*. 140, 1672–1685 (2017).
17. Richter, A., Sadek, T., Steven, M., Flexibility in industrial product-service systems and use-oriented business models. *CIRP J. Manuf. Sci. Technol., Industrial Product-Service Systems* 3, 128–134 (2010).
18. Rondini, A., Tornese, F., Gnoni, M.G., Pezzotta, G., Pinto, R.: Hybrid simulation modelling as a supporting tool for sustainable product service systems: a critical analysis. *International Journal of Production Research* 55, 6932–6945. (2017).

19. Zhang, H., Qin, S., Li, R., Zou, Y., Ding, G.: Environment interaction model-driven smart products through-life design framework. *International Journal of Computer Integrated Manufacturing* 33, 360–376. (2020).
20. Gaiardelli, P., Pezzotta, G., Rondini, A., Romero, D., Jarrahi, F., Bertoni, M., Wiesner, S., Wuest, T., Larsson, T., Zaki, M. and Jussen, P.: Product-service systems evolution in the era of Industry 4.0. *Service Business*, 15(1), pp.177-207 (2021).
21. Bertoni, M., Bertoni, A. Designing solutions with the product-service systems digital twin: What is now and what is next?. *Computers in Industry*, 138, 103629 (2022).
22. Bertoni, A., Ruvald, R.: Physical Prototypes to Foster Value Co-creation in Product-Service Systems Conceptual Design: A Case Study in Construction Equipment. In *Working Conference on Virtual Enterprises* (pp. 382-389). Springer, Cham (2021).
23. Peruzzini, M., Mengoni, M., & Raponi, D.: How to use virtual prototyping to design product-service systems. In *2016 12th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA)* (pp. 1-6). IEEE (2016).