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Bertoni A., Ruvald R. (2021) Physical Prototypes to Foster Value Co-creation in Product-Service Systems Conceptual Design: A Case Study in Construction Equipment. In: Camarinha-Matos L.M., Boucher X., Afsarmanesh H. (eds) Smart and Sustainable Collaborative Networks 4.0. PRO-VE 2021. IFIP Advances in Information and Communication Technology, vol 629. Springer, Cham. https://doi.org/10.1007/978-3-030-85969-5_35

Physical Prototypes to Foster Value Co-creation in Product-service Systems Conceptual Design: A Case Study in Construction Equipment

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Abstract. The paper presents the experience collected in a case study in the construction equipment concerning the use of physical prototypes for the development of product-service systems (PSS) enabled by new digital technologies. The paper firstly presents how a scaled physical prototype has been deployed to foster value co-creation with customers about the cross-disciplinary opportunity of the transition toward autonomous and electrical construction sites. Secondly, the paper presents the lessons learned during the empirical study.

Keywords: Product-service systems, digitalization, prototypes, design thinking, co-creation, value, case study, construction equipment.

1 Introduction

Engineering design and systems engineering practices are centered around the collection of the customers' needs followed by a series of activities that culminate in the creation of prototypes to validate and test a final solution (e.g. [1]). The use of early prototyping for quick learning circles through trial and error is a recurrent topic in the literature on design thinking [2]. Traditionally design thinking has been related to the human-centered and creative part of the design, slightly in contrast with the established analytical approaches for systems engineering [3]. In addition to this, the digitalization of manufacturing industries is increasingly seen as an opportunity to differentiate and create customer value. Digital technologies have been identified as a major instrument to build knowledge about product-service systems (PSS) solutions that could drive innovation from both a business strategy and an engineering capabilities perspective [4]. However, PSS brings new challenges for those design teams that have been historically predominantly built with mechanical engineering competencies at their core. The research presented in this paper focuses on the early design stage of the PSS and builds on the potential synergies in using design thinking principles in systems engineering to address design complexity by recognizing systems interdependences and interactions [5]. In particular, the research focused on how can physical prototypes facilitate customer co-creation and transdisciplinary collaboration in the early phases of PSS design in the context of a traditional manufacturing industry transitioning from pure product to PSS provision.

The paper presents the findings from a case study in the construction equipment industry featuring the use of physical prototypes in PSS conceptual design as an instrument to foster customer value co-creation. The PSS context is introduced by the transition toward autonomous and electrical construction sites that forces construction equipment companies to consider the possibility to retain the ownership of the physical products along its life to grant data accessibility and hardware and software updates. The paper presents how a scaled physical prototype has been deployed with customers to investigate the uncertainties in customer value creation and to co-define opportunities and challenges of the PSS. Finally, the paper describes the lessons learned from the empirical study reflecting on their generalizability and on the opportunity for future research.

2 Research Approach

The research presented in this paper has been performed in the frame of the Model-Driven Development and Decision Support Research Profile at Blekinge Institute of Technology. The research was performed through a combination of participatory action research and case study analysis partially in collaboration with an industrial partner operating in the construction equipment industry.

During participatory action research, data were gathered by means of open-ended and semi-structured interviews, company presentations, and concurrent development of demonstrators. During the case study, data were qualitative and were collected through interviews and observations that were later triangulated with surveys. The data collection about value co-creation and prototyping was supported by the use of a physical replica of a construction site (described in section 3.1). Data from potential customers about emerging needs and expectations of future solutions were collected on the occasion of a national exhibition at the university facilities and 3 international exhibitions in the US, China, and India sponsored by the partner company.

3 Case Study: Context, Focus, and Limitation

The case study focused on the transition toward autonomy and electromobility in the construction equipment industry. Such a future scenario raised several challenges in the design that goes beyond machine development, stressing the need for the re-design of a whole PSS with a related supporting ecosystem [7]. The new PSS solution aims at drastically reducing air pollutants, increase workers' safety, and create value for customers by reducing the cost of operations. However, while the possibility to drive fully electrically and autonomously on a single machine is nowadays a reality, there is still a low understanding of the implications of scaling this innovation up to a network of machines and a large collaborating system. Among those uncertainties the results presented in this paper focus on two aspects: the uncertainty of the customer perception of such innovation and the uncertainties introduced by the increased availability of machines and ecosystem data.

To clarify the positioning of the case study in relation to the current literature, the work can be seen as targeting the technology trade-off phase in the Product Innovation Process framework proposed by Kennedy et al. [8]. Such a framework describes the innovation process as divided into a knowledge value stream and a product value stream. The knowledge value stream represents the capture and reuse of knowledge about markets, customers, technologies, products, and manufacturing capabilities, which is general across projects and organizations. The product value stream is instead specific for each project and consists of the flow of tasks, people, and equipment needed for creating, for example, drawings, bills of materials, and manufacturing systems. This model is increasingly proposed as a lean enabler for systems development and has been further contextualized by Isaksson et al. [9] as a framework to support value and sustainability decision models, with different needs observable progressing along the two streams. The main activities along the value streams can be summarized as:

- Concept/technology Screening (Scoping): when possible solutions need to be screened quickly and with limited effort and time, typically in the order of hours.
- Concept/technology trade-off: where a set of the most promising solutions is selected for further analysis. Here the solution space is more limited but the trade-off is still driven by simple models with low maturity and dependent on variable input.
- Emerging Design (product commitment): here decisions are made to enable the design team to confine the design space and down select a limited number of concepts from the previous set.
- Concept development: here the knowledge value stream is abandoned to commit to a specific product value stream. Product and process definitions are refined to minimize risks and costs.

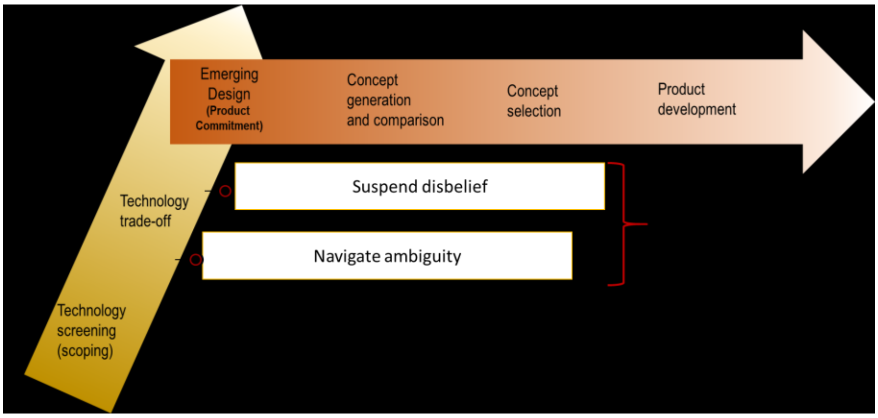

Fig.1 The focus of the case study in promoting customer co-creation framed in the Product Innovation Process (adapted from [8])

As shown in Fig. 1 the research performed in the case study targeted specifically the role of physical prototyping as support for value co-creation limited to the technology trade-off stage, that is, when preliminary ideas of the most promising PSS solutions were already identified, but uncertainties about different dimensions of customers and stakeholders' value were still present.

3.1 The Physical Prototype - The Small Scale Site

The physical prototype deployed in the case study, and named "small-scale site", is a concept centered around generic scenarios that could be relevant for a broad audience of potential customers and engineers. The small-scale site consisted of a 5m x 5m scaled-down site including two autonomous haulers in loading and dumping interactions (Fig. 2) typical of a quarry or mine operation. The machines were 1:14 scale remote control versions of electric excavator and hybrid wheel loader concepts, with the addition of the prototype autonomous haulers. To best reflect the reality of the current transition period from manual operation to a fully autonomous future, loading machines (excavator and wheel loader) were left as remotely (human) controlled machines, while the haulers were fitted with sensors, control boards, and communication devices to enable an autonomous experience for the user. Alongside the site, a prototype of an augmented reality interface was created capable of voice and gesture commands to control the autonomous machines as well as displaying basic information about the machine. Such a feature was initially introduced as an add-on to the physical prototype to attract customer attention to it.

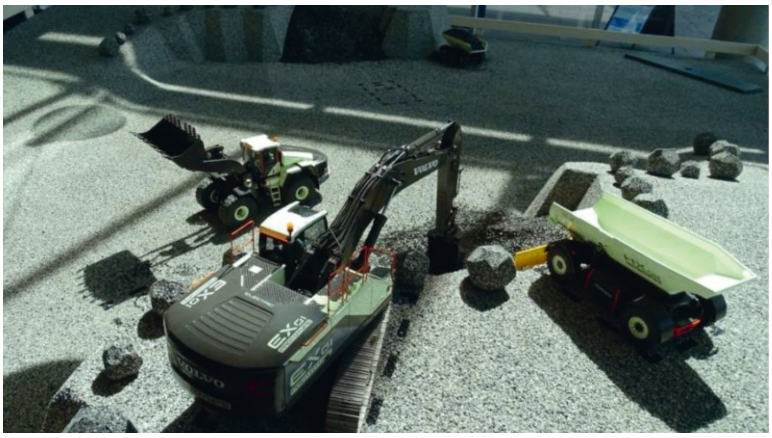

Fig.2 The small scale site during a loading operation with autonomous wheel loader [6]

3.2 Findings of the Case Study

Physical prototypes are at the core of traditional product development, validation and testing activities are run both internally and with customers to test verify e.g., functionalities, aesthetics, and systems integrations. Customer needs and "first-impressions" are often gathered through prototyping to improve the final product before production and ramp-up. Modern innovative product development processes stress the importance of creating tangible prototypes for their ability to communicate complexity, enable rapid feedback and provide guidance on design changes in the early stages of the process [6].

In the case study, the physical prototype was meant to be used as an effective tool for engaging relevant stakeholders in meaningful dialog around small details or the entire physical system, ultimately expanding the focus of the conceptual design activities to operational questions that might not be directly visible for the company developing the new PSS. In such a context the small-scale site was used to convey information and raise discussion and understanding about the new PSS. The scaled site provided tangibility to the feasibility claims about the full-scale operation and engage customers in conceptual value co-creation design activities. Here customers could raise concerns, evaluations, and wishes about the future PSS.

The collection and post-analysis of customers feedback and interactions allowed for the formalization of new needs and expectation that not only concerns product features (e.g. dimensions and or productivity of a machine) but encompass general reflection of the PSS system as a whole with the related support infrastructure and physical and digital ecosystem, In the case study, the co-creation activities with customers generated design feedback related to operational changes, flexibility, availability, and feasibility of the systems, while the same activities run internally at the development company focused more on technology readiness, technology bleed, and manufacturability of the machines (results also presented in [6]). In relation to the aim of the research two main benefits from the case study concerning the use of physical prototypes for customer co-creation of PSS were identified and are summarized as follows.

The physical prototype provided a sense of full-scale feasibility. The small-scale site worked effectively in suspending customer disbelief in the new technologies encouraging explorative enquiring. For instance, customers started inquiring how other machines could be designed differently rather than arguing about the feasibility of the presented solution.

The physical prototype worked as boundary objects for a shared experience. The value of the functional site as a boundary object was multilayered from the individual machines to the overall solution. On the system level, it provided an easily comprehensible overview of how the system components will interact to provide the functional result. Stakeholders from different groups were able to inquire in a meaningful way on the impacts compared to their current solutions building empathy around the future scenario concept, resulting from both a shared cognition of the system and the subjective impact on their disciplinary context.

In addition to such results, the use of an augmented reality interface emerged as an interesting source of qualitative data concerning human-autonomous machine interaction and trust. The qualitative observation suggested that:

The augmented reality interface helped to build trust in human-autonomous machine interaction. This happened because envisioning the future scenario of autonomous machines sharing the same worksite as humans raised several questions. One of those concerned how humans would trust their autonomous counterparts on the worksite, given traditional communication methods were absent due to the loss of the (human) machine operator. The prototype of the augmented reality interface integrated into the small-scale site allowed to create a contextualized experience for users and customers and gather additional feedback on new the new PSS concepts including individual perceptions and personal trust in the technology.

4 Discussion

While in traditional product development, customer needs are translated into functional requirements mainly focusing on the product as a physical entity, in a PSS context, the physical entity is only a part of the complete solution, thus, more inferences can be made about the PSS by analyzing the behaviors in its surrounding. Both PSS and systems engineering literature (e.g. [10]) highlight the challenge in identifying the impact of a change in a design variable at the sub-system level on the *performance requirements* of the overall system. When it comes to the design of smart PSS that will operate in a digital ecosystem it is not straightforward to define what corresponds to such *performance requirements*, mainly because needs and expectations for a system that is not yet existing are poorly defined.

The case study focused on the opportunities linked to the use of physical prototypes of a PSS, and related ecosystems, to collect the customer needs concerning both the configuration of the future PSS solutions and the potential value added by digitalization and data acquisition from the PSS operations. In the context of the new PSS, the small-scale site was used to convey information and raise discussion and understanding. Besides the findings described in section 3.1. lessons learned gathered during the work can be summarized as follows:

Lesson learned 1. We as humans experience the world as a series of events so it makes sense to have live prototypes, especially in the PSS context. These new products will interact, move and communicate in unexpected ways. Providing all relevant stakeholders with the ability to comprehend and inquire about the system solution at multiple layers of the concept, enables designers to collaborate more effectively with customers and other stakeholders up and down the value chain.

Lesson learned 2. In the process of design, enabling informed decisions early has shown to greatly impact the value of the final solution. The fidelity level of the scale site elements and system shown in the case study reflects the needs of the designers at that stage, as such this is not generally applicable to all situations. Zooming out we see the site concept as part of a larger framework for rapidly growing impossible ideas into nearly improbable solutions. To generate the desired level of feedback and input from stakeholders a concerted effort must be expended in the decisions of the designers to convey the uniqueness in a clear and interactive experience.

Lesson learned 3. By creating a physical representation to capture the complexity of a PSS we capture people's desire to feel and touch the future in a way that videos or 3D models cannot. There is a threshold that allows the observer to properly suspend disbelief enough to engage in generative questions that otherwise are less likely to occur or seem relevant based on the horizon distance of the new technology. New

PSS solutions that utilize unrecognizable technology benefit by finding ways of conveying their possibility to potential users to find partners for case studies of deeper applications.

5 Conclusion, Generalization, and Future Research

The paper has presented the rationale, the setting, the findings, and the lessons learned of a case study run in the construction equipment industry with the intent to promote customer value co-creation in the conceptual design stage of the development of a PSS featuring a future scenario based on machine autonomy and electromobility. The findings presented in this paper concerned the experimentation of the use of a physical prototype in conceptual PSS design to capitalize on potential synergies in using design thinking principles in a system engineering setting, by supporting the recognition of systems interdependencies and interactions.

The prototype showed to be useful as a boundary object for cross-disciplinary communication, giving at the same time a sense of system feasibility and building trust in the interaction between the human and the autonomous machine. However, the data collection concerning customer co-creation might suffer from intrinsic biases given the context in which the feedback from the customers was collected, that is, on the occasion of events sponsored by the partner company under the partner company brand. Based on this the generalizability and validity of the findings cannot be confirmed and further validation activities need to be run in future research. Similarly, the lessons learned collected would benefit from further verification in contexts other than construction equipment. This calls for future research concerning the definition of case studies with multiple industrial partners. Based on the experience emerged while integration augmented reality in physical prototyping, future research will focus on recreating more advance augmented reality setting with a larger capability of interaction with the physical machines. Concurrently, further validation on the benefits of using physical prototypes for early PSS design will need to be performed by comparing those with the use of 3D models in a virtual reality setting. Although the latter not being currently at a level of maturity to be used for comparison, it can be expected that virtual reality solutions will soon be available to a degree that will allow comparative research evaluating the benefits and the drawbacks of the two different settings.

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Acknowledgment

The authors would like to acknowledge the industrial partners and Swedish Knowledge and Competence Development Foundation for providing financial support through the Model-Driven Development and Decision Support research profile at Blekinge Institute of Technology.