PROTOTYPING FOR PRODUCT-SERVICE SYSTEMS INNOVATION: INSIGHTS FROM THE CONSTRUCTION EQUIPMENT INDUSTRY

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The scientist builds in order to study

The engineer studies in order to build
ABSTRACT

To radically increase the value delivered to the customers in the construction industry a concerted effort is needed to develop solutions beyond incremental adjustments. Simply providing add-on services to existing products does not effectively create solutions with enough gains in core customer values. Designing and developing a product service system (PSS) through the adjustment or reconfiguration of existing elements is a challenge on its own and adding the design of new elements serves to confound the process even further. By realigning all components of a PSS from inception towards a function provides an opportunity to escape current product limitations and explore new solutions with potentially higher value. Designing a new PSS solution from scratch comes with added ambiguity in an expanded solution space. The ability to conduct early phase exploration of a wide range of potential solution proposals is of importance for companies that want to deliver impactful PSS offers.

The aim of this thesis is to investigate early conceptual phases of PSS innovation within the domain of construction equipment manufacturing. The research included the development and testing of a prototyping method to foster customer co-creation and transdisciplinary design which are considered primary impact factors increasing the value of final PSS solutions.

The work was performed in collaboration with a construction equipment manufacturer, conducting a demonstrator project on an electric and autonomous production site. The thesis first depicts how the prototyping method can be implemented to enable insights from stakeholders that were previously not accessible through current practices. This leads to the testing of the method in a broader perspective to represent tangible and intangible elements in a way that facilitates concept design decisions in multi-disciplinary settings. The thesis concludes by exploring the limitations on current practices in relation to the adoption and potential use of the method.

**Keywords:** Product-Service System Design, Design Thinking, Prototypes, Boundary Objects, Transdisciplinarity
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LIST OF PAPERS

This thesis is based on the following studies, referred to in the text by their Roman numerals.


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INTRODUCTION

Emerging Technology Enabling Innovation

Over the last 60 years, global increases in productivity for construction-based industries have lagged behind similar industries such as agriculture (by a factor of 15) and manufacturing (by a factor of 8). A key component of this lag stemming from a lack of innovative mindsets and investments into transformative technology (Barbosa, et al. 2017). This is not to say that the products being developed are not technologically advanced. They have seen decades of constant development, but two factors are converging to drive manufacturers to look towards more drastically new solutions. Firstly, the customer expectations of value are constantly growing and, secondly, these expectations cannot solely be achieved through the constant addition of features to what is essentially the same basic product. The current transformational shift in technology is both enabling and emboldening traditional construction equipment manufacturing firms to explore new technologies such as; electrification, automation, 5G, and IoT towards a radical innovation of products, services, and systems.

The Rise of Product-Service Systems

As a way to achieve added value beyond the core product, additional services are being sold to augment the solution provided to the customer. This type of servitization approach is known as Product-Service System (PSS) solutions, which enables manufacturers to achieve differentiation of products in the market by creating additional value to customers via packaging of products, services and systems. PSS solutions fall into three fundamental categories, Product-oriented, Use-oriented, and Result-oriented. These categories indicate that the primary driver for bringing value to the customer is on a continuum from product-centered to service-centered. As solutions approach the result-oriented end of scale, the ownership of the product is retained by the manufacturer thus incentivizing them to develop the most efficient products to solve the customer need.

This has translated to methods, frameworks and tools coming from academia to support the design and development of these solutions. For example, Service CAD (Komoto and Tomiyama 2009), Service model and Service Explorer (Sakao and Shimomura 2007), Integrated Product and Service Design (Aurich et al. 2006), Fast-Track Total Care Design (Alonso-Rasgado et al. 2004), PSS
Design (Maussang et al. 2009), Heterogeneous IPSS concept modelling (Meier and Massberg 2004) and The dimensions of PSS design (Tan et al. 2010). Initially, approaches would isolate the individual components of a PSS for design or development with much of the effort being invested into services for existing products. Due to existing infrastructure, knowledge and experience in place for the existing products, this is the logical place to start. More support has been developed and tested in case studies and action research towards holistic PSS design (i.e., integrated design, parallel design, etc.) of products, services and systems either individually or in parallel. The original product-centric solutions still limit the overall potential value to be delivered by a PSS, since the same artifacts (e.g., products, infrastructure, etc.) can only be reorganized in a finite number of configurations and carry forward ownership transfer designs. What we see from industry is a desire to seize the available technological opportunities to create entirely new products with expressed intent to operate most efficiently as a component of a PSS solution.

**PSS Design Challenges**

The opportunity of radically different products and customized services being packaged into result-oriented solutions comes with specific challenges. PSS design in general is already challenging due to the vast array of disciplines needing to cooperate and comprehend each other’s concepts to efficiently create the tangible and intangible components of coherent PSS solutions (Isaksson et al. 2009). These challenges are further compounded considering the inherent need in PSS design to include external stakeholders (customers and other solution providers across the value chain) earlier into the design process, known as co-creation (Boukhris et al. 2017). This required collaboration, of diverse internal and external stakeholders, towards concept generation and design decisions is a substantial challenge. Focusing on the design decisions at the beginning of the design process is where the most impact on the final value is possible because the solution space is at its largest (Boukhris et al. 2017). At this stage designers struggle with high levels of ambiguity because they have the least amount of knowledge about anything related to the problem or solution other than organizational knowledge and individual tacit knowledge (Carleton et al. 2008). Design space exploration in a high ambiguity setting requires rapid iteration of concepts and shared visions of success between designers. Yet, at this juncture these diverse stakeholders are separated by disciplinary boundaries lacking a common language with which to explore these ambiguous design opportunities.
**Prototyping in PSS Design**

To address the mentioned challenges, the design thinking framework (Brown 2008) proposes prototypes as an effective mechanism to explore ambiguity in early design. Additionally, literature also notes that tangible prototypes can act as effective boundary objects to enable the engagement of diverse stakeholders through a “common language” which eases concept cognition (Exner 2016). While prototypes and prototyping are not new to PSS design or development, the methods and frameworks primarily place them later in the design and development process based on the perceived resource investment vs value gained. When PSS solutions are being developed based on preexisting products or established product elements much is known about their behavior and performance to frame the initial design requirements and goals. But if a company is attempting to disrupt the market through radically new offerings including new products or elements, the feedback and data from which the early design decisions are made is limited. What is needed is a way to generate this feedback as early as possible in the design process to help inform these decisions. Feedback data comes in many forms depending on the prototype and many prototyping methods exist to handle a variety of situations (Menold et al. 2018). To explore this need, a greater understanding of prototypes and prototyping will be explained in later sections.

**Research Motivation**

This research has its origins in working with paradigm-shifting solutions for an industry primarily devoted to incremental innovations wanting to move towards a triple zero goal of zero carbon emissions, zero accidents, and zero down time while achieving 10x increase in efficiency. The primary explicit strategies to achieving these goals are through automation and electrification of purpose-built equipment. An emergent property of this approach is to redesign how their customer’s facilities operate to best achieve the potential gains available through these approaches. Previous research has not focused on this type of radical innovation within PSS design and the role of prototyping to support this technology paradigm shift.
**AIM**

**Research Aim**
This research aims to explore the early phases of PSS design where ambiguity is highest, and the design decisions made have critical impact on the final solution value. With this aim, there is a specific interest in how to use prototyping as an approach to generate data that better informs early-stage design decisions of radical PSS solutions.

**Research Questions:**
1) How can ambiguity be managed in the early phases of PSS design for traditional manufacturing industry transitioning from pure product solutions?
   a) How can prototypes facilitate customer co-creation and transdisciplinary design in such transitions?
METHODS

Research Methodology

Design research is unique in the scientific field as it struggles from a lack of ability to utilize true control groups as is the traditional standard other fields. Design specific phenomenon observed are cognitive processes occurring within a specific ontological and temporal context. In order to structure the research process, Blessing and Chakrabarti (2009) Design Research Methodology (DRM) was implemented as systematic guidance for planning and aligning the research approach with the research questions. This method is particularly relevant in industrial collaboration research where the balance needs to be struck between research objectives and actionable outcomes for industry.

The DRM prescribes four discrete stages in guidance, yet these stages are not required to be completed sequentially and to be used at the discretion of the researcher based on the findings emerging from them. These stages are: Research Clarification, Descriptive Study I, Prescriptive Study and Descriptive Study II. The overall framework flow can be seen in figure 1 below:

- Research Clarification (RC): At this stage the researchers try to find some evidence or at least indications that support their assumptions in order to formulate a realistic and worthwhile research goal. They do so mainly by searching the literature for factors that influence task clarification and product success, in particular those factors that link the two together.
• Descriptive Study I (DS-I): At this stage, the researchers, now having a clear goal and focus, review the literature for more influencing factors to elaborate the initial description of the existing situation. The intention is to make the description detailed enough to determine which factor(s) should be addressed to improve task clarification as effectively and efficiently as possible.
• Prescriptive Study (PS): At this stage, the researchers use their increased understanding of the existing situation to correct and elaborate on their initial description of the desired situation. This description represents their vision on how addressing one or more factors in the existing situation would lead to the realization of the desired, improved situation.
• Descriptive Study II (DS-II): At this stage the researchers proceed to investigate the impact of the support and its ability to realize the desired situation. The study is used to evaluate the applicability, usefulness and success of the support.

Many of these stages overlap in this thesis and each paper's relevance to each is portrayed in figure 2. As the approach is clarified by Blessing and Chakrabarti (2009) to be iterative and the phenomenon to be understood is not addressed directly in this context by previous literature, the depth of each stage varies between Review-based, Comprehensive or Initial, each of which is described as follows:

- Review-based: is based only on the review of the literature.
- Comprehensive study: includes a literature review, as well as a study in which the results are produced by the researcher, i.e., the researcher undertakes an empirical study, develops support, or evaluates support.
- Initial study: closes a project and involves the first few steps of a particular stage to show the consequences of the results and prepare the results for use by others.

Figure 2. Thesis papers' focus in DRM framework
Data Collection

The collection of data for this research was primarily conducted through interviews and observations with a survey being included in one paper to better triangulate the qualitative data. The interviews and observations were primarily focused around a specific prototype created as part of the overall case-study conducted in this research. The prototype will be described below in the next section.

Scale Site

To assess a phenomenon consisting of the impact of a tangible artifact's effect on design conversations and decisions that has previously not been utilized in the desired context it is necessary to develop said artifact. This speaks to the heart of DRM as a solution-based research approach in aiming at creating support for design engineering practice. The site concept was centered around generic scenarios that could be relevant for a broad audience of potential customers. The generic scenarios included the human operation of machines in collaboration with autonomous machines to reflect the reality of the current. The developed prototype platform consisted of a 5m x 5m scaled-down site including two autonomous haulers in loading and dumping interactions (figure 3) typical of a quarry or mine operation.

The machines were 1:11 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.
THEORETICAL FRAMEWORK

PSS Design

The term PSS was first coined in a report from the Dutch government by Goedkoop et al. who defined a PSS as "a marketable set of products and services capable of jointly fulfilling a user’s need" (Pg. 3, 1999). According to Mont "PSS are defined as systems of products, services, supporting networks and infrastructure that are designed to be competitive, satisfy customer needs, and have a lower environmental impact than traditional business models" (Pg. 239, 2002). Haase et al. (2017) and Boehm and Thomas (2013) have conducted extensive quantitative analysis of over 265 PSS articles in literature across three separate disciplines including information systems, business management, and engineering and design to find no common PSS definition. However, Cook (2006) was able to reduce the breadth of definitions by categorizing PSS solutions into three main types differentiated by product ownership and type of service provided:

- **Product-oriented PSS**: The product is sold in a traditional manner and the service is added, e.g. in form of after-sales services.
- **Use-oriented PSS**: The provider does not sell the product but the use or availability of it and therefore he keeps the ownership. Products are leased, rented or shared.
- **Result-oriented PSS**: The result or capability is sold instead of a product. This is the most sophisticated business model because a washing machine is not sold, but clothes are laundered, for example.

Tukker and Tischner (2006) further refined the categorizations into 8 types of PSS solutions as seen below in figure 4.

![Figure 4. 8 types of PSS (Tukker and Tischner, 2006)](image-url)
As we can see in figure 4 and reconcile from the generally accepted definitions, all PSS solutions consist of variable combination of products and services. This expansion of tangible and intangible elements provides designers with new degrees of freedom not addressed in the traditional design of pure physical products (Sakao 2011). Designing requires a goal to be aimed for, in the case of PSS design the two primary opportunities are increasing customer value and/or ecological sustainability (Boehm and Thomas 2013).

In current PSS design methodologies, the emphasis is paid primarily to the service element of the solution and thus retains the standard products (Sundin et al. 2009). Vasantha et al. (2012) found in their review that the methods could be differentiated by how the term 'service' was classified. The two classifications are either 'traditional' or 'broader'.

- Traditional Perspective: A service is a set of activities which intends to keep products functionally available. Such services can be maintenance, repair, overhaul, upgrade or other technical services.
- Broader Perspective: A service is a set of activities which intends to satisfy customer value.

The later of these two perspectives pairs more with a product in the early stages of design as the former is aimed at mature products. Though a mention of products is included here, the emphasis is still on innovation through service development also known as servitization. Sundin et al. (2009) take a different view, instead focusing the methodology on product design for product-services systems. This type of methodology is rarer. Vasantha et al. (2012) conclude upon 20 important issues within PSS design and assessing the relative maturity of available models shows only four of these (Lifecycle Planning, Definition of Elements, Product and Service Integration) have been addressed to an adequate degree.

Product and service design methodologies tend to converge in agreement that early phases of design have the highest impact on the final solution where design freedom is the highest (Bertoni et al 2019a). Two unavoidable and value generating issues arise in these early stages of PSS design. First, transdisciplinarity is abundant as these solutions include products, services, infrastructure, extended lifecycles, extended value-chains, internal and external stakeholders, etc. (Sundin et al 2009). Their design demands specialists of vastly different domains to collaborate early and often (Exner 2016). Each domain and/or discipline tends to have its own methods, tools and 'languages' with minimal overlap. In order to conduct transdisciplinary design these boundaries between internal stakeholders must be managed and crossed to arrive at a unified solution (Bertoni et al 2016).

Secondly, by extending the value-chain and creating intangible value, external stakeholders (e.g., Customers or Suppliers) must be included in the design process as co-creators (Bertoni et al. 2019). External stakeholders of a PSS solution are
either stakeholders in the supply chain who will contribute to the functionality of the end solution or stakeholders who will be the customers of the solution. Co-creation goes beyond simply asking for their input, rather integrating them as active participants who generate concepts and bring downstream knowledge to the 'fuzzy' front end of design.

**Design Thinking**

PSS design contains high levels of ambiguity in the early phases due to expanding both the problem and solution space. Design thinking (DT) as defined by Brown (2008) is a human-centered approach to innovation that draws from the designer’s toolkit to integrate the needs of people, the possibilities of technology, and the requirements for business success. DT serves as a framework to explore early design phase ambiguity while building empathy between internal and external stakeholders. This concept of shared empathy is at the core of managing transdisciplinarity and enabling co-creation. DT is also known as a prototype-driven approach meaning problem and solutions spaces are explored iteratively through the creation of prototypes to represent concepts. In this context prototypes are not meant to represent final products, instead they are used to learn about the strengths and weaknesses of the idea and to identify new directions that further prototypes might take (Brown 2008). The knowledge and empathy are gained through both the process of prototyping (construction of the prototype) as well as the feedback from testing the prototype with relevant stakeholders.

**Prototyping**

Overall, the venture of prototyping is to gather information to help in the decision-making process of design. Designers at IDEO have a saying, “if a picture is worth a thousand words, a prototype is worth a thousand meetings” (Pg.56 Fredman 2002). They provide opportunities for fast feedback, new inputs and a hands-on user experience. Furr and Dyer assert that rapid prototypes have a fundamental role in hypotheses validation (2014). They also discovered that in some cases it can be beneficial to fake the capability of a product if the experience is your key point of investigation (Furr and Dyer 2014). Experiential prototyping techniques endeavor to accomplish three goals towards addressing the problem: understanding existing user experiences and context, exploring and evaluating design ideas, and communicating ideas to an audience (Buchenau et al. 2000).

Towards enabling co-creation and transdisciplinary design, prototypes have a unique capability for enabling sensemaking between stakeholders with differing domain vocabularies by creating a “common language” (Exner 2016). Prototypes enable this phenomenon via the following properties (Exner 2016):

- A prototype visualizes mental ideas
• A prototype supports the comprehension of complexity
• A prototype enables communication, thus removing cultural and linguistic barriers
• A prototype always contains a specific question and is limited due to given constraints
• A prototype tests functionalities and requirements.

Prototype fidelity increases as phases mature in the design process from initial concept to feature testing. Fidelity should be augmented to 'fit' the desired objective and the audience (Exner 2016). In order to strategically achieve this balance, Menold (2017) developed a prototyping framework known as Prototype for X (PFX). The PFX framework organizes prototyping into three phases: (1) Frame, (2) Build, and (3) Test. Through these phases, PFX helps designers focus their effort and resources on building prototypes that test core assumptions and lead to deeper and richer insights about specific aspects of the design at the time of testing (Menold 2017). Camburn et al. (2017) provided additional justifications, strategies and opportunities available through prototyping as seen in figure 5 below, connecting prototyping objectives with individual techniques.

![Figure 5. Prototyping Objective and Technique Matrix (Camburn et al. 2017)](image)

**Prototyping at the boundaries**

In innovative development, actors often come from different practices, functions, or organizational worlds (Carlile 2002) and must collaborate to solve problems and develop solutions (Morelli 2006) together across the boundary or shared area (a boundary is not at the periphery, but rather dead-center between the collaborators) that separates them. To effectively cross that boundary, they need to facilitate this collaboration, share knowledge and information and solve problems together even though they are not automatically equipped with the same language, understanding of the vocabulary employed, or understanding of what is described (Carlile 2002). A remedy to this is to utilize a boundary object (Morelli
2006) as a mediating artifact between the social worlds. The boundary object is defined by Star and Griesemer as “...objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them.” (p.393 1989).

According to Star there are three fundamental aspects to the class description of the boundary object; interpretive flexibility, material structure, and granularity, which corresponds to the information and work requirements of the groups utilizing the object, that is what is needed to represent and take the knowledge base from as-is to to-be (i.e. the work) (Star 2010).

A boundary object is not about achieving consensus among the actors (Star 2010) the boundary object as such may mean different things to different people. Important is that it facilitates users to employ a shared syntax, learn about differences across the boundary, and transform their knowledge together (Carlile 2002).

Derivatives of the original definition have stressed on additional aspects that are important for practice, and which could be supported by the mediating object. Boujut and Blanco (2003) use the term intermediary objects as a way of depicting these objects as representations of intermediate states of the future product, acting as mediators as a prescription from one actor to the next, transformations of the product from one state to the next, and as a representation of the future product. The intermediary objects can provide a frame for collaboration along the development process. Essentially, as more information and knowledge are created the intermediary object evolves (Boujut and Blanco 2003). Lee (2007) introduce the concept of the boundary negotiating artifact as having the role to not only traverse boundaries, but also to renegotiate these boundaries to establish new ones. By doing so the focus is on synthesis and innovation across different practices. In a similar vein, Subrahmanian et al. (2003) frame the prototype as a boundary object, to stress the constant dynamic (i.e., “prototypical understanding”) that goes on at the interfaces between developers. Design is seen as a theory-building activity where designers create prototypes as representations of their current understanding of the product (Subrahmanian et al. 2003).
SUMMARY OF APPENDED PAPERS

Paper A


Summary

The objective of the paper was to investigate how experiential prototyping could function as a contextualized platform from which to build empathy with users and secure specific feedback on the feasibility of Human Machine Interaction (HMI) to modulate trust between humans and autonomous machines. The activities aimed to identify how scaled-down experiential prototypes on a scale site mock-up replica of a real construction site could serve to function as data generators for designers looking to design complete PSS solution by providing the ability to test intangible components. Within the construction manufacturing industry these approaches were uncommon if at all attempted because building tangible prototypes of machines was only seen as valuable in full scale and functionality. While the results were mixed concerning the site it was able to provide feedback for the HMI concept with marginally positive responses considering the site as a contextualizing platform.

Relation to Thesis

This paper was a step into realm of exploring ambiguity specifically within early PSS design. It introduced the scale site prototype as a platform from which to test other concepts. This use of the site to provide contextualize experience of an HMI prototype meant it served primarily as a descriptive study I and exploratory prescriptive study where the HMI was tested utilizing the site as a support tool. The emergent finding was the perception of the site as a potential boundary object to abet co-creation of the larger PSS solution and not just to test individual concepts. The testing group's technological competence was relevant for the HMI feedback, but lacked contextual industry knowledge necessary to more accurately assess the deeper intentions of the site's capability for making decisions about the PSS as a whole.

Author's Contribution

The author configured the equipment in the scale site prototype while the AR prototype was built by master thesis students. Data was collected by the author through interviews, observations and survey. The writing of the paper was
conducted by the author and co-author Martin Frank with reviews, feedback and help in structuring the research work from the co-author team.

**Paper B**

https://doi.org/10.1016/j.procir.2019.03.099

**Summary**

This paper explicitly targeted investigating how boundary objects could serve as a vehicle to promote co-creation with customers earlier in the process. Within PSS design literature much of the boundary management objects were more two-dimensional representations of the system components interacting in service blueprints or stakeholder maps. The scale site intended to act as a tangible boundary object between the designers and other internal stakeholders and potential future customers. The experiment was conducted by running the equipment on the scale site as a demonstration for specific audiences coupled with project leaders giving a verbal narrative to the concept. Operating the site as a demonstration allowed the entire PSS solution to be in focus with the core elements of the solution acting out their roles collaboratively and independently. Again, this style of prototyping was not common in construction equipment industry giving an opportunity for exposing new concepts to the public in a lower risk environment.

Qualitative data was gathered in the form of interviews with the project leaders and customer representatives and questions fielded from the audiences during the demonstration. Responses highlighted the increased tangibility of the discussions for co-creative design purposes and concept cognition by all parties matched similar levels compared to seeing the full-scale site in person.

**Relation to Thesis**

This paper leveraged the concept of boundary objects as the theoretical underpinning for the functioning scale site. Building from emergent results in the previous paper, instead of testing a specific prototype concept using the site as a contextualized background, the site in operation was the prototype concept. Deploying functional scaled down equipment as a boundary object functioned to satisfy the Descriptive Study II. The support tool (i.e., the functioning scale site) was introduced to highly relevant stakeholders (internal management, potential customer representative, and the media) at an official event and the experience with the site was guided by real designers and project leaders within the company.
Author’s Contribution

The author conducted the research investigation and wrote the paper with reviews, feedback and help in structuring the research work from his co-author team.

Paper C

(Submitted to DESIGN 2020)

Summary

This paper explored the gap between prototyping as prescribed by literature and the current application in practice within the traditional construction equipment industry. Interviews were conducted with relevant stakeholders in the industry in search of the how, why and when they are implementing prototyping. Interview respondents spanned engineers, service designers and innovation managers of emerging technology departments. The themes identified in practice were set against the context of innovative PSS design and a current prototyping support tool.

Relation to Thesis

As an investigation into the current practices and a literature review this paper functioned primarily as a Descriptive Study I to map out the current situation around prototyping usage in practice. The questions asked were the result of the cumulative knowledge acquired through the other research phases described in this thesis. With positive results from the previous phases, the larger ambition is to generate support to influence design in practice. This paper functioned to identify the deficiencies in need of support if the industry is to reach the desired radically innovative future with PSS solutions. The paper results in the desire to modify a current prototyping support tool into an innovative PSS design tool.

Author’s Contribution

The researcher drove the research investigation by conducting the interviews and was assisted by Johansson in analyzing the responses. Paper was written in conjunction with Larsson as a co-author. Further support in the form reviews, feedback and help in structuring the research work was provided by Johansson and Bertoni.
SUMMARY OF RESULTS

The empirical studies focused on identifying when, how, and where strategies around the use of prototypes can be supported to better address the accelerating ambiguity of radical PSS design and development. The literature shows as the industry starts leveraging the technological revolution to transition towards radical solutions, current designers'/engineers' ability to manage ambiguity has been eroded over time through a focus on incremental improvement, thus designers are less inclined or informed on how to seek alternate hills with higher potential radical innovation. This thesis, in line with the Design Thinking theory, emphasizes prototypes as a means for exploring early design phase ambiguity and sees prototypes as an enabler of radical innovations.

The results of the research presented in Paper C revealed that prototypes are dominantly applied on late stage verification and validation of physical performance. Even when designers/engineers perceived the prototypes they engaged with to be in an early phase it was clear problem/solution space boundaries had already been defined. This led to the interviewees' perceived applications for prototyping reflecting those successfully implemented in previous experiences. The omission of the explorative applications implied to the author that in practice a narrower interpretation of a prototype's function, compared to literature, can occur.

Paper C also shows that related to the practice of developing prototypes, there is a recurring theme concerning risk. The risks can be classified as potential failure modes of a physical product, unforeseen issues navigating a Human Machine Interface (HMI) in the machine, and/or safety concerns. These risks are identified well after ambiguous problems and solutions have been predetermined and reflect uncertainty of specific aspects of a well-defined concept. This view results in each discipline or department building prototypes that allow them to assess the relevant criteria for them. This utilization of the prototyping mechanism is more restrictive than what is discussed in prototyping literature (see for instance, (Camburn 2017, Menold et al 2018). Paper C also shows a disconnection, in the current AS-IS situation, between the development of prototypes and their use in decision making. This raises the need for prototypes to become more effective boundary objects for multi-disciplinary teams to be able to exploit their value in decision making.

The results from a number of applications in the case studies as presented in the appended papers (A, B and C) to this thesis are summarized in the following subsections. They describe emerging phenomena observed by the use of physical prototypes in different moments of a PSS innovation process featuring the
participation of different stakeholders (e.g. from customers to development engineers)

**Contextualized Prototyping Platform**

Initially, the work was driven by the desire to explore concepts for implementation on the case project electric autonomous equipment. Early in the project, only full-scale prototypes of the equipment were available in limited numbers mainly for testing of overall functionality. Envisioning the future scenario compared to traditional operation (seen in figure 6) of autonomous machines sharing the same worksite as humans raised several questions. The one this research aimed to investigate was the question of how humans will trust their autonomous counterparts on the worksite, given traditional communication methods were absent due to the loss of the (human) machine operator.

![Traditional Operation (left) vs Autonomous & Electric Solution (right)](image)

Needfinding and research guided the team towards a concept for building this trust with a communication link between the autonomous machine and the human via an Augmented Reality (AR) interface. Testing this concept following the design thinking framework meant rapid iterative building, but an integral element for users to provide quality feedback was missing. Because trust is an emotional response the missing element was context. To achieve this context, paper A discusses how a scaled-down site and the corresponding machines were built to recreate the most generalizable scenarios of equipment operation. Alongside the site, a prototype AR interface was created capable of voice and gesture commands to control the autonomous machines as well as displaying basic information about the machine. Examples of the display and site are visible in fig 7 below.
The prototypes confirmed the scaled-down site's capability to provide a contextualized experience for user feedback on new concepts. Paper A's emergent findings revolved around just how well the physical site was able to provoke questions like "where and how do they charge up?" and "How long can the real ones run for?" from the rather diverse group of users and observers. While experiential prototyping is a common tool for providing feedback on specific concepts this is not the case within construction equipment manufacturers. Paper A's findings sparked further research into the site as a potential boundary object to represent the entire new system solution being the focus, as opposed to its use as primarily a background context setting mechanism.

**Boundary objects for shared experience**

As a part of an official event of the partner company, the scale site was provided the opportunity to serve as the primary discussion piece representing the automation and electrification project. In this setting, the prototype was able to be exposed to highly relevant users in the construction, mining and quarry industries. The following quote from paper B embodies the result of the site at the event:

"Scale prototypes like the site enable visualization of the operations and systems of machines where the true gains in efficiency are realized."

By running the site (seen in figure 8) as a demonstration, it functioned as a boundary object for the shared experience of the live system with moment-by-moment granularity. The value of the functional site as a boundary object is multi-layered from the individual machines to the overall solution. On the highest level, it provides an easily comprehensible overview of how the system components will interact to provide the functional result, which in this case was "moving dirt". By observing the whole operation, stakeholders from different groups were able to inquire in a meaningful way on the impacts compared to their current solutions.
Through this lens the site supports transdisciplinary teams to build empathy around the future scenario concept, resulting from both a shared cognition of the system and the subjective impact on their disciplinary context.

On the component level, the individual prototypes that comprise the system solution can be discussed and highlighted. PSS design recognizes a new solution may consist of new and existing products. So, by having them represented, even in the scale system function context, the individual capabilities and differentiation from current products at full scale is apparent to observers. Perhaps underpinning the above layers is the temporal factor in the live demonstration. 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. This was a critical result in paper B of the prototype as a PSS boundary object. By 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.

**Tangibility enabling co-creation**

Another less tangible result of the prototype was the power of the scaled-down functional machines to convey a sense of full-scale feasibility. The prototype machines were performing simple magnetic line-following with the magnetic strip hidden under the site surface and the sensor was incorporated in the autonomous haulers' build. In both paper A and B, before this was explained, the fact that these were functional machines running 'autonomously' provided enough reality to suspend their disbelief in an autonomous future to provoke exploratory inquiry.
For example, with autonomous material haulers, there is no need for a human operator cab thus changing the overall design of the machine. Observers of the site began to discuss what other machines could be designed differently if autonomous. The discussion expanded towards products with increased performance efficiency of a specific task in contrast with the traditional trend of designing machines with multiple less efficient capabilities. The following quote from paper B further emphasized the benefit of the tangibility: "...it is something three-dimensional and for real (people can see, hear and feel) it is just a very good illustration of what will happen and with the automation it triggers process questions and helps explaining". This cemented the sense that this is happening in front of me so it cannot be faked or exaggerated compared to a movie, poster or pictures.

**Supporting prototyping practices**

Reflecting on the strengths of the scale site as a boundary object prototype, it is part of design research to investigate how to transition the use of this tool type into practice. Perspectives on prototypes (i.e., how, when and why to use them) are highly contextual to the given discipline, department, company or industry utilizing them. Putting boundary objects to work for PSS design requires support as this is a transitional process from pure product manufacturer to PSS solution provider. Investigating how to support the transition starts through an assessment of the current perspectives within this industry towards prototypes and prototyping.

From the top-down approach, managers overwhelmingly supported the use of prototypes as early as possible for many of the core benefits they provide. Primarily from the innovation point of view to catch product issues early and make adjustments prior to sunken costs and design fixation occurs. Additionally, the managerial level and the designers interviewed conveyed an astute understanding of the value prototypes can provide during the inclusion of external stakeholders. The attitude all around was positive to the use of prototypes, however defining their function illuminated a narrower utilization in practice. The primary motivation expressed concerning usage was to identify risk and eliminate deficiencies in the product prior to manufacturing.

Eliminating risk in the stated cases occurs later into the design phase when the design freedom has already been reduced. In contrast, PSS design and particularly PSS innovation being discussed in this thesis requires the designers to manage much higher levels of ambiguity. Here exploring opportunities from a wider solution set becomes the focus of prototyping rather than risk mitigation. Accomplishing PSS design increases the difficulty as it involves diverse disciplines managing this ambiguity together. The boundary artifact prototype is effective in these conditions to create a shared language. However, like any good
tool, if nobody knows how to use it, how good is it? To support the tool usage, this thesis points to an effective existing support tool, 'the prototyping canvas' (Lauff et al. 2019), as a starting point. Through the addition of elements unique to PSS design, it is a potential that prototyping could be used as an explorative tool, not just a risk mitigator.
CONCLUSIONS

This thesis was aimed at exploring how to manage ambiguity in the early phases of PSS design. Early phases were targeted to create the largest impact on final value of the solution. Within the early phases, customer co-creation and transdisciplinary work were identified as primary drivers affecting a design team's ability to navigate ambiguity towards innovative solutions. Design thinking literature provided foundational guidance in the identification of prototypes as a previously under-utilized means to support these activities particularly in a PSS context.

Results reflect the PSS context as the underlying difference in the application of prototyping in this research. In order to begin using prototypes as ambiguity navigation tools, designers in these traditional industries need to reframe their perspectives concerning the utilization of prototypes towards earlier learning, not just pre-production risk elimination. Through this adjustment they can become boundary crossing objects that are capable of providing a shared context from which to conduct design. The shared context provided by the functional site enabled the diverse stakeholders to partake in transdisciplinary inquiry regarding the products, services and system comprising the overall solution concept. It was also discovered that by designing tangible and functional boundary objects, customers were able to suspend disbelief in full scale feasibility of the underlying technology to better articulate their concepts during co-creation. The other defining facet of the site was the ability for professionals to participate in productive play by controlling the machines manually and experiencing the moment to moment human-machine interaction on a personal level. While these individual insights are expected results of the individual approaches, when put together in the PSS design context the cumulative concept is a nuanced method to enable a transition towards desired future solutions.

Future work

The implications of the conducted research require additional investigation into supporting the creation of these boundary object prototypes. Additionally, conducting experiments and/or workshops with participants more well versed in the area of PSS design will test the validity of the underlying hypothesis and assumptions.
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Paper A

Abstract: The construction industry is ripe for disruption through innovative solutions that provide added productivity. Equipment manufacturers are attempting to disrupt their industry with investments in autonomy, electrification and product-service system business models. Designing solutions that will operate in completely new systems or modify an existing complex system require new approaches to address the uncertainty of system impacts. An iterative approach can help tackle ambiguity through cyclical validation of design decisions. Data mining in each cycle adds a quantitative dimension to the rationale of decision making, but data is sparse and difficult to collect in parallel with design of theoretical product-service systems operating in future scenarios. This can be combated using experiential prototyping techniques to design flexible infrastructure that supports contextualized data gathering in a variety of focused design sprints using Design, Build and Test approach. The intricacy of designing innovative solutions to increase productivity in the construction industry can be untangled by framing aspects of the problem in small sprints and testing them in a contextualized setting built to generate functional data to drive design.

Keywords: Product Service System, Data Mining, Experience Prototyping, New Machine Development

1 Introduction:

Over the last 60 years, global increases in productivity for construction based industries have lagged behind similar industries such as agriculture (by a factor of 15) and manufacturing (by a factor of 8) particularly due to a lack of innovation (Barbosa, et al. (2017)). Much of this deficit in innovation can be attributed to construction’s level of operational complexity when compared to agriculture and its constantly changing operational environment in contrast to manufacturing’s static workflows (Abderrahim and Balauge (2008)). Yet, as technological capability continues to increase, opportunities exist to be the best smart construction equipment supplier.

Attempting to expand into a non-existing market reveals a plethora of ambiguity concerning the form and function of new products, services and systems. Compounding the challenges associated with ambiguity is the difficulty of gathering data to drive design when addressing hypothetical future scenarios and environments. For instance, a Swedish Construction Equipment Manufacturer is developing autonomous and full electric machines as part of their commitment to a 10x increase in efficiency (Volvo Concept Lab (2017)). But, introducing autonomous construction equipment results in an unknown hybrid interaction of new and original artifacts consisting of complex and dynamic interactions with converging hardware and software, products and services, humans and machines.

By integrating the system components toward the provision of a functional solution rather than individual products, manufacturers can arrive at Product Service System (PSS) solutions (Tukker (2004)). When purposefully designed, PSS’ provide increased customer value, improved long-term return on investment, built-in environmental-friendly aspects and possible, spare part and waste reductions (Tukker (2004)). However, focusing on the functional integration of products and services affects the manufacturer’s development process i.e. how development work is organised and which tools and methods are used.

Engineering design thinking provides sets of tools and methods capable of unpacking the ambiguity in PSS development through a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients’ objectives or users’ needs while satisfying a specified set of constraints (Dym et al. (2005)).

Generation and evaluation of concepts can be accelerated through the incorporation of data-mining to drive design decision rationale. This concept is engendered by the emerging field of data driven design (Bertoni and Larsson...
The objective of this paper is to explore data driven design for the purpose of guiding product-service system development in the construction industry via flexible experiential prototyping infrastructure.

2. Scientific Background:

2.1 PSS Design

Complexity in product development is emphasized when hardware, software and services are packaged into a single “total offer” (Alonso-Rasgado et al. 2004). Product-Service Systems (Mont, 2002) is one of the industrial trends representing the shift in manufacturers’ strategic focus from selling a physical product to providing performance and availability, as a way to satisfy more sophisticated needs and expectations (Baines et al. 2007; Williams, 2007). Eight types of PSS are proposed by Tukker (2006), which have been further synthesized by Cook et al. (2006) in:

- Product-oriented PSS: the ownership of the physical artifact is transferred to the customer and services are offered to ensure the “utility of the product”, such as warranties and maintenance.
- Use-oriented PSS: the service provider retains the ownership of the physical artifact and the customer pays for its use over a period of time or units of service.
- Result-oriented PSS: the service provider, as in use-oriented PSS, retains the ownership rights of the physical artifact, and the customer pays a fee proportional to the expected outcome rather than for the mere usage of the product. For instance, instead of leasing or buying a haul truck the customer can sign an agreement for material transport by mass with an full service provider.

Compared to the traditional one-sale model, designing these PSS types challenges engineers to raise their awareness on customer and stakeholders needs along the entire product lifecycle, so to realize solutions that are value adding for all the actors involved (Isaksson et al. 2009). Furthermore, PSS development is known as functional product development, where the solution of any combination of hardware, software and services is developed in a coordinated development effort.

2.2 Data Mining:

Data mining is defined as the discovery of non-trivial, implicit, previously unknown, and potentially useful and understandable patterns from large datasets (Anand and Buchner, 1998). When it comes to application of data mining in industrial environments, the term is often associated with the concept of machine learning, i.e. the study of computer algorithms that improve automatically through experience (Mitchell, 1997). Data mining and machine learning are used in engineering both with the predictive goal of forecasting the value of a variable and with the descriptive goal of understanding and discovering patterns in the available data (Anand and Buchner, 1998). Data mining can thus be used to support data driven rationale during a design process.

2.3 Experiential Prototyping

Overall, the venture of prototyping is to gather information to help in the decision-making process of design. The designers at IDEO have a saying, “if a picture is worth a thousand words, a prototype is worth a thousand meetings”. They provide opportunities for fast feedback, new inputs and a hands on user experience readily available. Furr and Dyer (2014) assert that rapid prototypes have a fundamental role in hypotheses validation. They also discovered that in some cases it can be beneficial to fake the capability of a product if the experience is your key point of investigation (Furr and Dyer (2014)).

Experiential Prototyping techniques endeavor to accomplish three goals towards addressing the problem: Understanding existing user experiences and context, Exploring and evaluating design ideas, and Communicating ideas to an audience Buchenau and Suri (2000).
2.4 HRI

Vaussard et al. (2014) had been able to split the direct and indirect interaction between human and robot into three main parts:

1. how users operate and give commands to the robot,
2. how the systems gives feedback to the user and
3. indirect interaction with the users and robots shred environment.

It has been stated that users wish to understand how the robot is working, what could be described as transparency. The study also revealed, that an inadequate information sharing is decreasing the long-term acceptance of the robotic system, what was also stated by Lynas and Horberry (2011). It has been indicated, that a user-centered design approach is likely to overcome collaboration issues with a parallel focus on system automation rather than component automation by Lynas and Horberry (2011).

Brezeal et al. (2013) as well as Jung et al. (2013) highlight the importance of the human–robot interface, and especially its design, as key success factor for the human-robot teamwork. In their study about resilient autonomous systems, Matthews et al. (2016) pinpoint the challenges for the teaming between human operators and autonomous systems. The study suggest to design an interface that enables the autonomous system to effectively signal its capabilities and its intent to the human operator.

3. Results:

3.1 Prototype Results

To construct an effective prototype experience flexible enough to test a variety of interface functionalities, generic scenarios from real construction operations were needed. Collaborating with a Swedish construction manufacturing company’s marketing department provided the necessary relevant activities to be included in the prototype.

As large scale organizations (such as: Uber and University of Michigan) heavily invest in autonomous transport they have recognized the importance creating models of cities to test and simulate their specific concept’s operation in realistic context. Most other high fidelity investigations into autonomous vehicle intention communication and pedestrian interaction, create scaled functional machines based on golf carts or smaller vehicles [e.g., Matthews et al. (2017), Florentine et al. (2016), St.Claire et al. (2011)] in order to have an artifact for testing a range of interfaces or interaction techniques. In contrast, an autonomous construction site will involve multiple machines collaborating to complete specific tasks (Ameen and Safawizadeh (2017)), requiring humans to process information from multiple sources simultaneously.

To address this distinct difference, the developed prototype platform consisted of a 5m x 5m scaled down site including two autonomous haulers’ loading and dumping interactions (figure 3.1) typical of a quarry or mine operation.

Figure 3.1: Hauler and excavator loading operation on scale site.

The machines were 1:11 scale remote control versions of Volvo CE’s currently available EX01 excavator and LX01 wheel loader concepts, with the addition of the prototype HX02 autonomous hauler. To best reflect the reality of the operation, loading machines (excavator and wheel loader) were left as remotely controlled machines, while the HX02s were fitted with sensors, control boards and communication devices to enable an autonomous experience for the user.

A Microsoft HoloLens was acquired to build a functional prototype of an AR interface resulting in an application transmitting voice commands to haulers and display an information panel with fictional data. (fig 3.2)

Figure 3.2: Deployed Hololens interface testing layout

3.2 Data Generation

Experiential Prototyping is not normally found in the construction industry, but it is essential when the goal is generating/gathering feedback data from a large number of diverse users interacting with a limited production prototype designed for a hypothetical construction site. With the scale site constructed as a research platform the stage was set to generate testing data on the HRI prototype’s feasibility to meet the needs of future construction scenarios including manually operated machines, autonomous machines and human laborers.
In testing with the infrastructure, data gathered consisted of quantitative responses to a questionnaire aimed to confirm desired emotional responses to the inclusion of user interface elements. To complement the questionnaire and broaden the scope of potential learnings, qualitative observations and interviews were conducted of users and non-user observers.

The questionnaire were designed to measure emotional responses to the drivers identified in a previous case study Winqvist (2016). The range of available response variables was intentionally narrowed so data gathered indicated a binary presence of the desired emotional components rather than the degree which is less reliable at the designed fidelity.

The response prompts were:
1. HoloLens app made me feel connected to the machines
2. HoloLens app increased my trust of the haulers
3. Voice commands made me feel in control
4. The AR display was more helpful than distracting
5. Overall site experience felt realistic in its operation

The responses of 15 respondents are gathered in the Graph 3.3 below.

![Liker Scale Prototype Feedback Survey](image)

**Figure 3.3: Questionnaire responses to AR experience**

The 15 respondents do not make for statistically significant quantitative data, but basic trends in the response create useful qualitative data. Lowest scores were found in the perceived realism of the scale site. Interview questions confirmed this stemmed from the RC controllers connected to the scale wheel loader and excavator being seen as "toys" more so when combined with low skilled drivers demonstrating “unrealistic operations” that would create “unsafe and inefficient performance”. Responses to questions 1-4 indicated an optimistic attitude towards the HoloLens AR platform as an interface.

Interviews, in the unstructured format they were conducted, more resembled conversations. Not shockingly, most conversations started with the question, “what is it?” The researcher answered this question the same to all who asked, describing it as “A scaled site demonstration platform for autonomous vehicles in construction operations, currently being used to test HMIs with the autonomous haulers”.

Following this description people either totally disengaged or became curious at the word “currently”. Suddenly, people began to give their own interpretations for its potential function.

One such quote include the concept of aligning the user involvement with collaborative actions between humans and autonomous machines not just other humans, “you should find ways to include more users interchangeably, like an MMO game”. This would allow more people to craft more unique individual experiences with the same equipment. Expansion and immersion of the user experience was addressed by the following two quotes, “okay, well how will people in the machines communicate with those autonomous ones?”, “It would be more interesting to drive the manual machines from that simulator” (referring to a Volvo CE wheel loader operator simulator). While this functionality would create functional training mechanisms they also enrich the context of the user experience. Adding these dimensions to the site could serve as a bridge to acclimate humans to the collaborative nature of future semi-autonomous sites.

Some key quotes revolved around the autonomous demonstration site activities and features. While watching the machines perform tasks, someone logically scanned to see who was controlling them, they asked, “So, nobody’s driving that right now?” in reference to the hauler running its route. The answer was no and to their delight the concept of the site became one of the future, not just a playground with fancy toys. Additionally, while observing HMI testing a spectator was curious about the verbal command over the haulers, they were not aware of how much control or when the connection was active in their question, “Is the machine listening to me?”. These questions reflected the designed features for testing trust derived from the functionality in the HMI features.

Other’s statements captured the observer’s perception of the real operations being simulated. Due to the scaled down nature of the demo site, perspectives were automatically shifted to reflect theorized future collaborative roles captured in this quote, “I feel like a site manager staring down at the operation”. This theme gained traction building off the genuine interest in the future scenarios of construction. Curiosity about the infrastructure requirements came in questions like, “How long can the real ones run for?” and “where and how do they charge up?”. This even expanded to the HMI potential with feedback about its real roll out features in the quote, “If they were real I’d like to see more granular data on the interface”. This kind of comment shows the users immersing themselves in the future usage.

4. Discussion:

Over the last decade, data mining has been recognised for its potential to profoundly shift decision making to be more transparent, informed and autonomous, and with less bias. While this has become a reality for the design of certain artifacts in the construction industry, the same cannot be said...
for PSS or functional solution development. The work conducted in this case study aimed to address the issue of creating adequate user context for generating feedback on the human element in future scenarios. In this way, future PSS scenarios can be dissected and tested with minimal effort compared to construction of full scale machines and test sites.

The scale infrastructure in this case study was built to recreate the key interactions identified in foresighting of future autonomous construction sites. Although the data generated from the conducted testing was primarily qualitative in nature, the components of the site (i.e., machines and interface devices) are entirely capable of producing quantitative data similar to that collected by Akhavian and Behzadan (2013) who highlight the importance of factual data for as input for a construction simulation model.

It is claimed, that there is a trend in the simulation of construction fleet activities on estimating input parameters using expert judgments and assumptions. To have a reliable source of simulation input parameters, the authors used a model site and laboratory environment to validate their statement that a construction fleet operation can benefit from knowledge-based data-driven simulation model generation.

By streaming equipment data (such as position, weight and angle) and subsequently applying fusion and reasoning algorithms, Akhavian and Behzadan (2013) show promising trends in simulation quality of site operations. Based on this, equipment manufacturers have begun to take steps to include data gathering capability on active machines, yet this data serves to improve mainly maintenance and use phase services. This can lead to the sub-optimization of system elements when the goal is actually functional solution or PSS.

The application of new technologies in the construction and mining sectors is very much dependent on the productivity of the solution and how well it fits into the existing operation. Isolating the impact of individual changes in a complex system can be difficult which is why in engineering design, prototyping as a verb is an essential philosophy to finding flaws in concepts early when investment is low and design freedom is still broad (Furr and Dyer (2014)).

An overarching principle behind the scaled down site operations rests on the following theorem. Through a tangible experiential prototype platform embodying the idealized PSS concept environment, designers could backcast a series of iterative development missions for the five stages of PSS design: Planning, Idea generation, Sub-System, Detailed Design, Deliver and Use-Phase. With a scale site, more variations of PSS scenarios can be explored at an increased pace leading to more informal early phase decision making.

An important aspect is the flexibility of the prototype platform elements to support investigations into the various interactions engendered by functional system solutions. Furthermore flexibility extending to the customizable fidelity of the elements can focus the data gathering to answer specific design questions avoiding irrelevant feedback on external components. This can benefit the parallel development processes required for successful PSS design by creating a shared foundational vision of the future scenario across all perspectives during inquiry.

5. Conclusions:

Through targeted inquiry, a cyclical approach can be applied to generate/mine data on future scenarios to drive their development. Beginning with designing the future PSS scenarios to explore before applying experiential prototyping techniques to create a holistic interaction exposing users to tangible artifacts set in the desired context. Data is generated from the user engagement with the scenario and its artifactual components, then mined to provide input for design decisions.

Thus, data driven design, as it is defined by the authors, is the deployment of data, generated through data mining activities, during all design process stages of a product or a specific service as well as product service systems. In that context, the data can have different characteristics such as temporal physical machine and / or process data, contextual data, factual data, user feedback etc. but adds to generate a basic knowledge about the nature of the observed system.

7. Future Work:

Taking the next logical step with this research is to add more granular data capturing devices to the site equipment while at the same time finding the conversion factors for translating the scaled down data to full scale operational inputs. Additionally, converging this quantitative data with qualitative user feedback as a holistic way to drive design decisions.

8. References:


Paper B

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A role for physical prototyping in Product-Service System design: Case study in construction equipment

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Abstract

Using a case study methodology to exploring an ambitious experimental combination of a construction equipment manufacturer’s products tailored to provide exponential increases in efficiency and reductions in CO2. The products and system represent a relevant example of new technology being the foundation upon which a functional offering IPSS can be designed. The researcher constructed a scaled down functional experiential prototype reflecting a full scale experimental all electric quarry site in under operation outside of Goteborg, Sweden. The prototype site represented the primary equipment and system functionality, to act as a boundary object around which relevant stakeholders both internal and external could share the vision of an electric autonomous future. This was confirmed via observation at an event where the scale site was used for this purpose and verified with follow up interviews to dig deeper into the impact this tangible representation could have in increasing the perceived viability of the full scale technology’s potential on display thousands of miles from the event.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Globalization and the high pace technology innovation, have radically changed the industrial strategies pursued to create value [8]. Companies have shifted from a product-centric thinking to the increasing provision of services. The results of the “servitization” process are commonly referred to by the term “Product-Service systems” (PSS) [1]. Large and established product manufacturer shifting toward PSS-provision, need to rethink the way in which complex products are designed and developed since the early stages of development [11] the creation of robust design solutions while encompassing, at the same time, radical changes in the product operating system and unprecedented technological innovations [2]. In the case of traditional industries such as construction machinery and mining, the advent of new technologies and industry 4.0 capabilities enable more tailored and efficient solution offerings. However, the concentration of knowledge needed to operate the transition toward PSS also lie with the capability to generate innovation and effectively communicate it to relevant stakeholders.

The research presented in this paper focuses on the conceptual design stage of PSS, where cognitive, social and technical challenges abound [9], and explore how the creation of innovative systems solutions can be supported in a complex industrial context dominated by established product development and systems engineering practices. Authors have largely explored the application of methods to exploit the creativity and innovation in product development, building a consistent research stream dealing with the so-called Design Thinking approach [4]. However, only in recent years authors have started to explore the potential to apply Design Thinking method to engineering new complex systems [9], not directly addressing the context of PSS development.

This paper focuses on one of the aspects of Design Thinking, which is the use of early prototypes to convey information and raise discussion and understanding of new concepts in the very early design stages. 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. The research presented in this paper is based on the hypothesis that in the context of PSS design, physical prototyping (from small scale systems to full scale individual equipment) can create boundary objects which act as effective tools for engaging relevant stakeholders in meaningful dialog around small details or the entire physical system. Tools like this could enable design teams and companies to better tailor a PSS to add the more value and be more easily accepted as potential alternative to traditional offerings.

The aim of the paper is to raise the discussion about how physical prototyping can create boundary objects for engaging customer stakeholders in early phase PSS design discussions. This is achieved by presenting the findings of a case study run in the construction equipment industry, where the use of a small-scale prototype of a construction site as a boundary object for multi-stakeholder discussions has been tested.

2. Context of the Case Study

The case study was run in collaboration with a construction equipment manufacturer aiming to develop the world’s first ‘emission-free’ quarry. Drawing on the electromobility and automation expertise, the research project, dubbed Electric Site, aims to electrify each transport stage in a quarry from excavation to primary crushing, and transport to secondary crushing. The system’s efficiency, safety and environmental benefits are set to impact both customers and society at large.

Such new solutions with machines, technologies and operations consisting of complex products and systems are functionally different compared to traditional equipment manufacturer offerings. This raises the potential to obfuscate the advantages of these new solutions from the internal and external stakeholders. In any product-service system development process it is necessary to garner feedback to inform the design as early as possible. A challenge arises here due to PSS design methods relying solely or heavily on two-dimensional service blueprinting techniques as the medium for conveying complete solutions until fully functional products and systems take a physical form towards the end of the design phase.

It was the intention of VCE to create a functional physical instantiation of the electric site in a small scale prototype form to provide tangibility to their feasibility claims about the full scale operation before it was constructed. The corporate interest was to reduce the need for transporting equipment to Sweden to observe the testing of the machines, as well as to support the testing of the machines by creating an interactive display that could, in essence, bring the site to them. From a research perspective, the intent was to demonstrate and test how the physical prototyping of functional system components in a small scale construction environment could act as an effective boundary object to drive a deeper dialog with all interested parties whom are vital to the full scale successful implementation in the early design phases.

3. Prototypes as Boundary Objects

Overall, the venture of prototyping is to gather information to help in the decision-making process of design. The designers at IDEO have a saying, “if a picture is worth a thousand words, a prototype is worth a thousand meetings”. They provide opportunities for fast feedback, new inputs and a hands-on user experience readily available. Furr and Dyer assert that rapid prototypes have a fundamental role in hypotheses validation[7]. They also discovered that in some cases it can be beneficial to fake the capability of a product if the experience is your key point of investigation [7]. Experiential Prototyping techniques endeavor to accomplish three goals towards addressing the problem: Understanding existing user experiences and context, Exploring and evaluating design ideas, and Communicating ideas to an audience [4].

In innovative development, actors often come from different practices, functions, or organizational worlds [6] and must collaborate to solve problems and develop solutions [12] together across the boundary or shared area (a boundary is not at the periphery, but rather dead-center between the collaborators) that separates them. To effectively cross that boundary, they need to facilitate this collaboration, share knowledge and information and solve problems together even though they are not automatically equipped with the same language, understanding of the vocabulary employed, or understanding of what is described [6]. A remedy to this is to utilize a boundary object [12] as a mediating artefact between the social worlds. The boundary object is defined by Star and Griesemer as “…objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them.” (p.393)[12].

According to Star there are three fundamental aspects to the class description of the boundary object; interpretive flexibility, material structure, and granularity, which corresponds to the information and work requirements of the groups utilizing the object, that is what is needed to represent and take the knowledge base from as-is to to-be (i.e. the work) [14].

A boundary object is not about achieving consensus among the actors [13], and the boundary object as such may mean different things to different people. Important is that it facilitates users to employ a shared syntax, learn about differences across the boundary, and transform their knowledge together [6]. Derivatives of the original definition have stressed on additional aspects that are important for practice, and which could be supported by the mediating object. Boujut and Blanco [3] use the term intermediary objects as a way of depicting these objects as representations of intermediate states of the future product, acting as mediators as a prescription from one actor to the next, transformations of the product from one state to the next, and as a representation of the future product. The intermediary objects can provide a frame for collaboration along the development process. Essentially, as more information and knowledge are created the intermediary object evolves[3].

Lee [10] introduce the concept of the boundary negotiating artefact as having the role of not only traverse boundaries, but also to renegotiate these boundaries to establish new ones. By
doing so the focus is on synthesis and innovation across different practices. In a similar vein, Subrahmanian et al. [15] frame the prototype as a boundary object, to stress the constant dynamic (i.e., “prototypical understanding”) that goes on at the interfaces between developers. Design is seen as a theory-building activity where designers create prototypes as representations of their current understanding of the product [15].

4. Results

The setting for the demonstration of the prototype site took place over a 3-day event around emerging technology and products from Volvo CE (VCE), Volvo Cars and Volvo Trucks. Attending audience included members of Volvo management, key customers and the press. 3 different groups representing each of these were guided through multiple stations with presentations at each station. The station including the prototype site was focused on communicating VCE’s work on the semi-autonomous electric site aimed at a 10x improvement in efficiency of quarry operations while reducing on-site emissions by nearly 100%.

As seen in figure 1 the research team constructed a 1:14 scale prototype of the new autonomous electrified machines working on a 5m x 5m model of a generalized quarry site, consisting of two loading/dumping scenarios. The loading machines were manually operated, and the electric haulers were autonomously controlled.

![Figure 1. Scale Site at The Volvo Event](image)

This scale site was operated by the research team during the culmination of a presentation by the project leaders from both Volvo CE and Skanska, responsible for the full-scale experiment site operation taking place in Sweden. They discuss the need to redefine how the operational dynamics of site functionality must be redesigned in tandem to take full advantage of the electric and autonomous equipment on display. This translates to a move away from equipment designed to be broadly capable of many tasks and more towards product service system solutions consisting of equipment that can perform purpose-built tasks exponentially better.

4.1. Observations

During the demonstration of the site the project leaders fielded questions from the audience while a member of the research team recorded the questions asked by each group observers. Each group asked distinctly different types of questions illustrating their unique areas of interest. The observers posed numerous questions, but for display purposes they are organized by group and category with embodying samples (as seen in table 1) to avoid the irrelevant and non-unique questions.

<table>
<thead>
<tr>
<th>Group</th>
<th>Question Category</th>
<th>Question Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Readiness</td>
<td>Is it reliable and safe enough to match our brand?</td>
<td></td>
</tr>
<tr>
<td>Technology Bleed</td>
<td>What other areas of the company can benefit?</td>
<td></td>
</tr>
<tr>
<td>Manufacturability</td>
<td>How and where can we cost effectively make this equipment?</td>
<td></td>
</tr>
<tr>
<td>Operational Changes</td>
<td>How many to equal my current operation’s production?</td>
<td></td>
</tr>
<tr>
<td>Availability</td>
<td>When will these machines be publicly available?</td>
<td></td>
</tr>
<tr>
<td>Feasibility/Flexibility</td>
<td>How can this be adapted to fit my industrial operation?</td>
<td></td>
</tr>
<tr>
<td>Functionality</td>
<td>How do they work? (small and full scale)</td>
<td></td>
</tr>
<tr>
<td>Delivery</td>
<td>When will these go into production?</td>
<td></td>
</tr>
<tr>
<td>Future Vision</td>
<td>What is next in the innovation pipeline?</td>
<td></td>
</tr>
</tbody>
</table>

A more detailed analysis of the content of the questions is found in the discussion section, but briefly we can highlight how these examples demonstrate an ability for the prototype site to act as an effective boundary object. Highlighting the amount of questions that had to do with more than the functionality of the scale site versus how much focus was translated into inquiries relating to the full scale site demonstrates the ability for people to see demonstration for more than a collection of toys and more like a representation of a real situation. The categorical differences in question substance also bodes well for the perspective that each group was able to see it through their own lens without having to change anything about the site itself, the elasticity of their viewpoints was entirely related to the observer further reinforcing the scale site’s classification as an effective boundary object.

4.2. Interviews

The results from the observations were complemented with open-ended interviews with experts, two of whom were part of the customer observation group and two were with the project leaders for the Electric Site (representing Skanska and VCE). Due to the low number of interviews conducted, the results here are used for the triangulation of the data collected to derive more solid and reinforce reliable conclusions. The questions
are stated with the most relevant quotes from the respondents displayed below.

Interviews held as semi-structured discussions around two main questions:

a) How observing the scale prototype in action impacted their perception of the Autonomous/Electric site solution’s feasibility within their industrial context?

“Scale prototypes like the site enable visualization of the operations and systems of machines where the true gains in efficiency are realized. Expands the conversation beyond individual machines questions to more operational level questions about manpower changes and machine-to-machine interactions.”

“Site serves as an excellent communication initiation tool. Provides a way to more tangibly visualize the new products and their interactions.”

“As I see this just as another media to explain our future plans next to already existing posters, ppts and videos I think there is no drawback and only positive additional impact. As it is something three-dimensional and for real (people can see, hear and feel) it is just a very good illustration of what will happen and with the automation it triggers process questions and helps explaining. As also on batteries it is also a nice catch to always refer easily to the real solution so from a communication standpoint it is easy to fit into a presentation and talk around it.”

b) What kind of opportunities do you see with new technology within your operations?

“Creating solutions for a demand and that demand is efficiency and safety. Contrary to generalized very capable machines that are inherently less efficient at conducting specialized tasks. The future is focusing on combinations of machines to satisfy the operational needs. Means a need to look at operation more abstractly in order to broaden the potential solution space of combinations. Automation allows for more structured workflows as opposed to individual workers being real time decision makers. This enables a better modeling of the operational and safety risk.”

“Biggest wish from a customer perspective is to have some sort of standardization of traffic/production control to allow for pairing of different manufacturers machines in the same system. Don’t want to be locked in like apple but more like android with ability to put different machines on the same network. Or more like telecoms in general where the network is built by everyone and allows all devices to connect.”

“At Waste Management we are interested in autonomy and remote operation for different reasons that normal. They have trouble both hiring people and maintaining them as employees due to the environment. Interested in creating remote operation stations for millennials to run multiple machines from.”

5. Discussion

Scale experiential and non-functional prototypes served as effective Boundary Objects allowing customers (and internal stakeholders) to envision how these new products as a system solution can be implemented across a range of industries. Design thinking and by extension the act of prototyping is an approach for addressing design complexity and as products are phased into PSS solutions they continue to increase in technological complexity and interdependency between other system components. Long [11] connects engineering systems thinking as a necessary skill for design thinking which carries over to how to use of tangible and experiential prototypes as boundary objects to convey system concepts as well as the new products enabling the new design.

The statements captured during the showing of the prototypes made evident an attitude of not caring what the machines look like if they can accomplish a specific task better than those currently available. However, skepticism exists around the feasibility of the components adding up to be more capable than their current operations in place now. The scale prototype was able to bring this front and center with questions while also enabling the hosts to explain in more detail how this is actually possible by pointing at the artifact interactions and extrapolating how the components could be customized to best suit the a target customer’s operations.

A key feature of prototypes is to allow to identify gaps otherwise difficult to observe. Some of the gaps can be caused from observers not grasping the level of fidelity on display is not a 1:1 of what happens in real life and other gaps are legitimate concerns that without the “realness” of the boundary object might not be brought into the design discussion until it is too late or much more expensive.

6. Conclusion

PSS solutions that lean closer to function and result oriented category must offer significant advantages whether it be in safety or sustainability the advantages need to match the values of the manufacturer and their customers. The paper has discussed the role of Experiential prototypes and functional prototypes as boundary objects creating shared visions between customers and manufacturers garnering valuable feedback data to guide design decisions. The case study of a construction equipment company investigating the transition toward PSS by means of early prototypes has been presented framing the findings in the field of design thinking and complex systems design.

Future work will focus into formalizing a functional requirement guided and innovative product centered PSS design methodology that includes early phase physical prototyping enabling data-driven design. Through the development of an established methodology it would be possible to run multiple case studies validation in different industrial context, to verify the presence of similar benefits in different context. This would contribute to the generalization of a PSS design approach including early stage experiential and
functional prototypes.

7. Future Work

In the interviews the customers want interoperability between different manufacturers and not to be locked into using only Volvo Equipment for everything to function properly. These concerns are coming into the forefront while the maturity of new technologies such as AI, Autonomy and Electrification is increasing to a point where it may be deployed in previously unrefined industries. Handling such compatibility issues will potentially become service offering requiring manufacturers to play together if they expect to meet customer requirements of the future. Again, the use of tangible and experiential prototypes to enable immersive design discussions across trans-disciplinary and trans-corporate partnerships may a potent tool to drive this level of collaboration by allowing shared vision of the system and catching valuable feedback from customer stakeholders in the earliest phases of design.

References


Paper C

(Submitted to DESIGN 2020)
PSS DESIGN INNOVATION: PROTOTYPING IN PRACTICE

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Abstract
Heavy equipment manufacturers recognise an opportunity to realise customer value gains through offering new Product-Service Systems. Such transition implies a radical shift in how new systems are designed. Based on a set of interviews the paper investigates how radical PSS innovation can be enabled by the use of physical prototypes as boundary object to navigate early PSS design ambiguity. On such basis, suggestions for augmenting existing support tools are made in relation to the existing literature.

(Product-Service Systems, Prototypes, Design Support)

1. Introduction
Equipment manufacturers supplying incumbent construction industries (e.g. construction, quarry and mining operations) are currently operating in saturated markets where product differentiation is relatively low between manufacturers. Simultaneously, customers' constantly increasing expectations of the value provided by the equipment creates a pressure for manufacturers to innovate beyond incremental efficiency gains and feature additions. This can be categorized as 'radical' or 'transformative' innovation corresponding to increases in efficiency, sustainability, performance, safety or whatever the customer defines as their core values (Norman et al. 2013). Achieving substantial gains across these core values cannot be realized by pure product innovation or the addition of aftermarket service contracts alone but rather on addressing multiple 'ilities' in the development process (Bertoni et al. 2019).
An approach equipment manufacturers are increasingly adopting to achieve this radical innovation effort is the coupling of equipment and services into integrated Product-Service System (PSS) solutions (2). A PSS solution can comprise of a combination of existing and/or new to the world artifacts; coupled with services and new business models, all operating in a system tailorable for individual clients. Additional value beyond the pure artifact sale is created through the development of customized products and services to meet the customer's needs. For example, Rolls Royce's 'power by the hour' offer where they sell the uptime of the engines to the airlines instead of simply selling an engine to the aircraft manufacturer (Smith 2013). The utilization of PSS has been shown to enhance competitiveness and economic goals, as well as attract and retain new customers (tran et al. 2015).
Academia has created many methods, tools and frameworks to design and develop each component of a PSS individually or in parallel as readily applicable support (Rosa et al. 2017). When reviewing these approaches through the lens of actionable support, it makes logical sense their focus is on leveraging the individual company’s knowledge, experience and investment into the design, development and manufacturing of their product (Norman et al. 2013). By conducting PSS design in this manner, the end solutions trend primarily towards a restructuring of existing elements (products) with the addition of product enhancing service components into a new business model. This is referred to as Servitization, a
term coined by Vandermerwe and Rada in the 1980's to reflect a product-oriented PSS under Tukker's categorization model (Vandermerwe 1988, Tukker 2003). Although these strategies have been successful over previous decades to satisfy customers and edge out competitors, technological advances (AI, Electrification, Automation, IoT, 5G, Global WIFI) have the potential to disrupt industries in a similar way to manufacturing and other industries (Barbosa, et al. 2017). Riding this technological wave, heavy equipment manufacturing companies are eager to take advantage of the opportunity by leveraging new technologies to realize drastic (10x) increases in productivity or efficiency for their customers. The panacea of opportunity comes with the challenge of ambiguity in design. It is difficult enough to design a new product, or new business model. Previously a company's focus was building better machines, but now they want to deliver a better outcome to the customer. For example, a bigger diesel dump truck was originally considered an improved solution for moving material, but now it could be 20 smaller electric and autonomous dump trucks without cabs achieving the same outcome of moving material. This addition of variables into the design space accelerates the ambiguity of the solutions available. Established methods from the field of design thinking (DT) manage early ambiguity through the use of prototypes, paying particular attention to tangible prototypes' ability to facilitate exploration and communication across the disciplinary domains at the core of PSS design(Carleton et al. 2009). Within established literature on PSS design, few references to tangible prototypes are made. In a recent review of currently available PSS design methods/processes conducted by Ilg et. al. only one of the fourteen methods even mention tangible prototypes (Ilg 2018). Other case studies and action research studies (Marques et. al. 2013, Blomkvist 2016, Ilg 2018, Exner 2016, Exner et al. 2014) have also explored different prototyping methods within industry, but they primarily deal with much less ambiguous scenarios where the products, services or systems resemble already established concepts or elements. Creating new to the world products (artefacts) coupled with new services to operate within a new system requires management of higher amounts of solution space ambiguity than previously addressed in PSS design. Prototypes are a flexible vehicle of exploration for all the relevant disciplines to communicate across their boundaries and PSS value chain (Exner et. AI 2016). They can take many different forms depending on their purpose. Whether it be to answer specific questions or explore solution and problem spaces, a well-designed prototype can act as an effective boundary object to achieve engagement across disciplines and stakeholders boundaries (Bertoni et al 2016). To develop these boundary object prototypes many elements and perspectives need to be balanced in order to realize maximum benefit from the resources invested. This balance requires the designer to be aware of and attentive to all the pertinent elements during the development and testing of the prototype. Current support tools such as the 'prototyping canvas' are aimed to increase the designer's simultaneous cognition of these elements for product design (Lauff et. al 2019). Considering the additional elements persistent in radical PSS design, current designers need supplemental support to manage accelerated early phase ambiguity. In order to create a support tool for traditional equipment manufacturing companies to strategically design radical PSS solutions through prototyping it is necessary to map and understand how designers from the relevant disciplines view the what, why and when around prototypes and prototyping

1.1. Objective

The primary objective of this paper is to identify how practitioners responsible for design and development of products, services or systems currently utilize prototypes. These insights will be summarized and used for further research to enable a deeper understanding of the gap between current practices and potential best practices in the future, and to provide guidelines for the development of suitable support tools.

2. Scientific Background

2.1. Ambiguity in Practice
Within the incumbent construction industry, designers and engineers in practice are less likely to encounter high levels of ambiguity. While some ambiguity exists, more of what the designers/engineers encounter is uncertainty. Ambiguity refers to 'unknown unknowns' and Uncertainty is 'known unknowns'. This differentiation originates from Carleton et al.'s (2008) work on complex problem solving. Figure 1 visualizes in general how these two concepts change throughout the process although they do make clear that they fluctuate more discreetly than that graph reflects and that the phases overlap in practice.

![Uncertainty and Ambiguity Curve in complex problem solving (Carleton et. al. 2008)](image)

2.2. PSS and Prototyping and Boundary Objects

Within PSS design, boundaries exist between the required stakeholders and disciplines that must be overcome to attain a shared cognitive model for the concept and the customer perspective within the design team. Typically, attempts to address this challenge refer to artifacts or models that represent the concept as boundary objects. Djelassi and Decoopman (2016) define a boundary object as something that facilitates the exchange of knowledge and expertise between disparate actors in a network. Existing literature has highlighted the ability for prototypes to serve as effective boundary objects, but not all prototypes accomplish this goal due to the variety of prototyping methods available (Subrahmanian et al. 2003). Menold (2018) addresses the range of prototypes available to fit the desired function. Here they ground they process of prototyping into a systematized activity targeted at having a higher correlation between the artifact and the needs of the designer required to make the next decision. The state-of-the-art review in PSS design processes done by Rosa et. al. (2017) showed the 14 most common process out of which only one used physical prototyping as an activity. Instead the processes all lean heavily on service blueprinting and frameworks for conveying concepts. The challenge here is that when we explore the Design Thinking (Leifer et al. 2011) literature, it heavily emphasizes the use of physical prototypes to convey the concept in a manner which has a higher rate of concept cognition especially when taking into account new to the world and radically different products and services. This lines up with the desire to engage and enable humans in their exploration of the problem and solution space in order to produce the right solution for the right customer. This is in essence the core of PSS design, attempting to satisfy customer’s needs in a manner that derives value beyond just the tangible product.

3. Research approach

The research presented in this paper can be framed as one of the activities conducted during the Descriptive Study I phase of the Design Research Methodology (DRM) proposed by Blessing and Chakrabati (2009). In this respect, interviews were identified to be a highly suitable method to answer the research questions related to the identification of the current as-is situation concerning utilization of prototypes. The interviews have been used to create and refine a reference model of the current status of the industry as it relates to the implementation of prototypes and identify themes to be addressed in a future PSS innovation support tool. Six interviews were conducted with five being employees of
Company A and one from company B. Company A was chosen due to their strides in innovation towards bold goals and are a rare actor in their industry with an emerging technology department exploring radical solutions. Company B was included since both the interviewee and the company have extensive experience in design and development of products across a broad spectrum. Neither of the companies are assumed to be atypical within their industry in the same manner as Herriott (2017). Interviewees were chosen specifically because they represented different positions within the company relevant to the design and development of products, services or systems. Each had at a minimum of five years experience in their field (sans interviewee 5 in position 2 years) and a background with research around innovation and design thinking.

The results of the interviews were subjected to thematic coding independently between two of the authors then the relevant topics were converged upon together. This analysis and relation to the objective of the paper is organized by interview with specific quotes highlighting the identified themes. Each interview began with a short background discussion covering the research area context being PSS design to provide logical boundaries and guide the responses towards more relevant feedback. Then the interviewees were all asked the same following set of questions in a semi-structured interview process with more intricate dialog explored when appropriate:

1. How do you define a prototype? What are they? What are they used for?
2. When designing/developing new products & services, how are the trade-offs identified and communicated between departments (internal stakeholders)?
3. How does a New Product/Service design project run? (what are the phases)
4. At what phases are prototypes used? How do they lead to improvements?
5. What methods are used to engage customers during the design phases?

4. Results

To present the data captured from interviews with conceptual coherence the results and analysis will be presented together. In this way, the discrete facts will better connect be grouped into comprehensible sub-patterns while simultaneously linking them to the overall objective proposed in this paper.

4.1. Prototyping Interview 1

This interviewee has been previously involved in small to medium organizations running product and service development for a wide range of products. Currently, they work at company B which operates as a middle-man between individuals and SME organizations desiring to take their product concepts through industrialization in preparation for mass manufacturing. The following quote reflects the bulk of the topic discussed in the interview relating to the overall design and development process:

“we’ve been doing design for years, but our official process and phases is continually changing”

They recognized having advantage as a smaller company more agile company when compared to larger companies with more rigid process flows. The interviewee continued to highlight over the course of the conversation how within an organization skills, capability, knowledge, and maturity all play a central role in when and why prototypes are created:

“We physically prototype certain interfaces or sub-systems until we know our modelling skills and knowledge have been validated and confirmed”

In the context of prototyping, an organization may utilize one strategy based on their current human and technological capability and organizational knowledge, but using each project as a learning opportunity, the rules for prototyping decisions should change. By rules, it was intended to mean the reasoning for the why to prototype. The term risk dominated the reasoning behind the bulk of decisions to go ahead with tangible prototypes. The final quote addresses each time a prototype is created, the organization's confidence in its ability to create a specific type of part or surface to reach certain physical requirement grows:
This inversely affects the likelihood to prototype it in the future for the purposes of saving time and materials. Here a link can be made between ambiguity and a need for physical prototyping although not explicitly stated.

4.2. Prototyping Interview 2

This interviewee has been part of an advanced engineering department for company for the last 10 years. Their role is that of a development engineer with broader responsibilities to explore various products beyond the scope of a single department. Having achieved their PhD in engineering, they also have a clear understanding of research and mechanical engineering. The first two quotes below reflect a common disconnection observed between their observed potential for prototypes to communicate across disciplinary boundaries and current perceptions of prototype form/function fit:

“Physical Representations are the least commonly used in multidisciplinary design meetings”

“Testing/understanding for yourself or an audience” and “verification & validation is more than a sketch or CAD, prototypes are tangible”

A clear frustration was expressed when noting that no meetings that include other departments included prototypes, instead opting to base design decisions of the concepts by simplifying them into cost analysis on spreadsheets or at best a CAD drawing. It shows how the mindset and organizational direction still lays heavily at the late stage of production ready prototypes. The issue here is ignoring an entire arsenal of options for iterative development of final fidelity products. This omits the possibility of learning from early prototypes with the potential to uncover unaddressed design assumptions and potentially potent insight that could result in transformative customer satisfaction.

In the discussion they reiterated how they work primarily in the earliest phases of designing new concepts. More information concluded that the company's official development process is a stage-gate model which starts at the end of their conceptual phase where it is then handed off manufacturing for industrialization. Unfortunately, this conceptual work is not prescribed with any formal process, guidance or design support tools. Instead the company allows their highly experienced designer/engineer to utilize their skills creatively. Finally, the interviewee perceived themselves as working in the earliest stages of the design process, from a design thinking context their provided initial design prompts primitively bound the design space. This limiting of ambiguity enables them to lean on previously successful ad-hoc methods familiar to the engineer instead of potentially more successful approaches.

4.3. Prototyping Interview 3

This interview was conducted with another advanced engineer at company A. This engineer works at a facility in a different country than interviewee 2 that focuses on different equipment. Another critical difference is they are well versed in the language of innovation and design thinking resulting from being a current industrial PhD candidate in the area and working with innovation methods development with the emerging technologies department of the company.

The following quote from the interview is pertinent to a specific topic:

"for sure a prototype is a tool to support conveying a message or a new type of working on your system solution product in some way that people or the typical users can
interact with your idea more than it is in the way that you just draw a picture or you have a sketch at hand or something like that.”

This quote reflects a particularly interesting view on the power of physical vs two-dimensional (2D) prototyping or sketching. Expanding on this was a side conversation about whether CAD models count as 2D although they can be perceived as 3D. The interviewee's professional experience suggested nothing is 3D until it can be held and manipulated in your hands. Although if a CAD model was distributed to other engineers it could be interpreted as intended, but beyond the boundaries of the same discipline or department it served as more of a sketch needing direction to be correctly understood.

Following are the additional quotes from the interview:

"We then utilize another way of working. So we bring all the different stakeholders together in one big open space office...we are bringing all people together in one open space office and there the engineers the aftermarket people manufacturing guys supply chain, they in purchasing they working all or sitting all together. So here it's more that they have all information available and they have short distances to the people having the information that is needed in each time step”

"They meet at the Prototype ... and one technician was more or less constantly there to manufacture or to bolt this stuff together. And so all these meetings had happened at that machine.”

This situation being described is the company has had success in terms of demand from customers with a new machine concept unique to the market and want to capitalize quickly. The company concentrated all of the relevant internal stakeholders in one floor of a building primarily centred around a flexible prototype of the developing machine. With the quotes in context it can be inferred that there is a recognition of the value gained from having a tangible prototype enabling all internal stakeholders to more easily grasp the new concept and how it was evolving. Further information revealed a positive response from this department exhibited via reduction in time to make design decisions. This described 'strategy' reflects more of a scrum mentality implemented to take advantage of an opportunity and enabled in this case because the machine was small enough to bring into an office building where all domain stakeholders are conveniently co-located. The primary takeaway is the company succeeded in building a prototype capable of facilitating concept cognition across disciplinary and departmental boundaries with positive effects. Another caveat, to address is in terms of innovation, this project would not be considered radically different in overall function of the machine, but drastically different subsystems to accomplish this capability. Related to managing ambiguity this anecdotally successful scenario discussed in the interview is still also bounded at the existing machine level limiting the solution space.

4.4. Prototyping Interview 4

This interviewee has been an Innovation manager at their previous company and in their current role in company A. Given their work and background they are versed in the academic prototyping language, producing a concise conversation with direct answers. The following quotes are the highlights from the interview:

“it's about utilizing the right, the appropriate prototype fidelity for the right purpose in order to get the right feedback”

“They could envision how this would fit within their lifestyle or day-to-day and how that would provide value to them and they were asking when can I have it and that a completely different conversation”

These two quotes are in direct reference to the interviewee's experiences with tangible prototypes in their capacity with new concept development. The examples given were those of added functionality or sub-systems within a machine and particularly Human Machine Interfaces (HMI) systems. This respondent's capacity within their organization puts them in a unique position to be more frequently meeting customers and potential users of the under-development products. HMI systems are more
portable again and software-based so the prototypes are more easily manipulated and changed than what other engineers may consider tangible or physical prototypes.

The primary take-aways from this interview are firstly, this was the only direct reference to the term fidelity, although it is a primary consideration during any prototyping activity. Secondly, the concept of “fit” is important to note because it has direct implications with respect to consideration of the various elements present in any prototype development. The final quote below reflects the discussion of partnerships with customers being invaluable in the new concept development process and even more when considering products, services and systems:

“if you don't work with partners, you are working in a black box and you will suffer the consequences for doing that ultimately when reality happens”

This mention of co-creation here is another vitally important strategy particularly when developing new to the world solutions as the customer input is a primary diver of the final value of a PSS solution.

4.5. Prototyping Interview 5

The interviewee was a service designer at company A with nearly two years’ experience in the position. Their primary responsibilities being to design additional services for new equipment. Verbiage used in the interview questions did not translate as well into this individual’s colloquial work language, so more stories were exchanged. The first quote is centred around one of the few times where a tangible prototyping entered their workflow:

“we have those prototypes if the issue is really crucial ... or if it's something completely new”

As a department, the interviewee’s interaction with tangible prototypes only occurred when uniquely new or critical products were developed. This was done to understand the impacts and potential new (emergent) behaviors of the sub-system or machine level. The final two quotes are anecdotes summarizing a frustration originating from a lack of real interface with customers limiting empathy for how the overall solutions are perceived

“it can be really surprising actually to meet them and to hear their real-life experiences with the machine. It can be really surprising, but I would love to do it actually more often. I did it in my first year when I was a trainee”

“you develop something together and they see it in a completely different way. You spend time, like hours or days or weeks on something, then when they see it, they might say why did you do this?”

Within these narratives the interviewee highlights typically customer visits for service designers only occur once when they are being initially trained even though they left a positive impression. To further accentuate the issue, their final story showed an enduring perception of increased performance being misconstrued as a more desirable solution from the customer. This story consisted of investing hundreds of hours into the design and production of a better engineered filter solution before customer feedback being introduced. This resulted in the unveiling of the solution being rejected by customers due their trust in the previous solution even with the reduced performance. The overall sentiment conveyed in this interview is a disconnection between designers/engineers and their customers leading to a misconstruing value drivers in solutions at an early phase of design.

4.6. Prototyping Interview 6

This interviewee was in a role as an innovation manager and previously a department manager responsible for strategic innovation research projects at company A. This was a necessary perspective to gather as those responsible for managing innovation have a greater impact on strategies, methods and tools used during design and development than individual engineers or designers. This respondent has extensive experience working towards shifting the organizational mindset to be an innovation generator. During the interview the manager, who is also a researcher aware of best practices existing, they pointed
out the current processes within the company limits the fostering of innovation. As exemplified in the following quote a primary barrier identified was an entrenched mindset of existing engineers:

“... the question is also is it possible to change, can existing experienced engineers unlearn or is it that we need new types of engineers ...?”

This mindset included a tendency to devalue customers as a source for input towards designing better machines and only producing prototypes as means to test physical characteristics with nearly complete final machines. The interviewee made it clear to delineate between prototyping for functional testing and prototyping for new innovative concepts. The following quotes coupled the company engineers' collective mindset on prototyping with their established process as an issue:

“The only problem is because of all those processes have the prototypes much too late and too much similar to the final product... you didn't allow yourself to question your prototypes enough...”

“it's almost like pre-production even with the first prototype. So, it's more to test the function than actually drive the conversation typically”

The need always exists to test and reduce risk before bringing equipment to market, but the newer mantra in innovation is the maker sure you're designing the right it before you design it right. This is where the concept of tackling ambiguity arose in the conversation as something engineers and designers trained in traditional PD methodologies have only dealt with in the area of feasibility. The interview concluded on the concept of how to support engineers and designers with massive amounts of tacit knowledge from experience in tackling the accelerating ambiguous challenges of coupled radical Products, services and systems.

5. Discussion

The interviews note a few particular themes to expand on when considering how and where strategies around the use of prototypes in practice can be supported to better address the accelerating ambiguity of radical PSS design and development.

Deriving from interviews and observations related to the practice of developing prototypes, there is a recurring theme concerning risk. The risks can be classified as potential failure modes of a physical product, unforeseen issues navigating an Human Machine Interface (HMI) in the machine, and/or safety concerns. These risks are identified well after ambiguous problems and solutions have been predetermined and reflect uncertainty of specific aspects of a well-defined concept (Carleton 2008).

This view results in each discipline or department building prototypes that allow them to assess the relevant criteria for them. This utilization of the prototyping mechanism is more restrictive than what is discussed in prototyping literature (Camburn 2017). For instance, Menold et al.’s (2018) prototype for X framework emphasises flexibility in application and a fit between the desired knowledge and the prototype itself.

Interviewee 6, as a manager, perceived a lack of flexibility within the designers to grow their interpretation of prototypes and follow Camburn’s (2017) cited research showing that the majority of prototypes should take place in the first 30% of a project (Elsen et al. 2012). Interviews with the designers/developers themselves reflected an understanding of the expanded role of prototypes in the design process. The disconnect arose in how they presented their examples of prototypes not being used in design decision meetings. What they needed to build were boundary object prototypes for other departments and disciplines to be able to extract the same value from their prototypes. Support exists to augment this disconnect by Lauff (2019) in the form of a prototyping canvas. The canvas enables designers to incorporate the broader elements of a prototype of audience, material, driving questions, etc. By forcing the designer to think through these elements they are more informed with their choice of prototyping method resulting in better connection between the prototyping efforts and the questions answered.

As industry starts leveraging the technological revolution to transition towards radical solutions, current designers/engineers ability to manage ambiguity has been eroded over time through a focus on...
incremental improvement. As Norman and Verganti (2013) point out, focusing on the incremental innovation of the current hill (or ‘known’ solution) designers are less inclined or informed on how to seek alternate hills with higher potential radical innovation. Leifer et al. (2011) emphasise prototypes as a means for exploring early design phase ambiguity. Yet, a central narrative of the interviews revealed their dominant application in practice centred primarily on late stage verification and validation of physical performance. Even when designers/engineers perceived the prototypes they engaged with to be in an early phase it was clear problem/solution space boundaries had already been defined. This led to the interviewee's perceived applications for prototyping reflecting those successfully implemented in previous experiences. The omission of the explorative applications implied to the authors that in practice a narrower interpretation of a prototype's function compared to literature can occur (Menold et al. 2018, Camburn et al. 2017).

Stepping into the PSS frame beyond pure product development even more transdisciplinarity is needed to create these solutions. To date, the Prototyping Canvas does not address these additional elements of service and system. Adding these elements may result in an effective tool to support the creation of boundary crossing prototypes towards enabling designers/developers to better explore the added ambiguity they will face. It could be useful for future work to attempt a workshop centred around PSS design from which we may see differing results. However, this does not discount the observation that support for these activities is needed to ease the transition from one working mode to another.

From a methodological perspective the paper sees some limitation in relation to the number of interviews and lack of triangulation in data analysis. This is less relevant in qualitative research, it was more important that the interviewees represented highly relevant actors with experience in both their specialty and research around innovation. Nevertheless, the work contributed to build a clearer as-is description of the current situation by identifying critical challenges, issues, and requirements to enable the research process to enter an initial prescriptive study phase. In other words, the findings represent the first necessary knowledge to be used to generate initial support ideas. That knowledge will be further improved and updated in combination with more detailed investigations of the current situation, in line with the iterative nature of the DRM.

6. Conclusions

The objective of this paper was to identify where and how prototypes are being used in practice within a specific industry attempting to make a transition towards radically innovative PSS design. The resulting themes were set against the backdrop of literature-based guidance on the use of prototypes and radical innovation towards input for a future support tool. Concerning the concept of addressing ambiguity, it was clear that in practice the majority of designers are not typically currently participating in the phases of projects where the ambiguity was what literature would define as high. The counterintuitive aspect of this is that while the interviewees interpreted their own work as containing high levels of ambiguity, academics would more aptly define this as uncertainty. This contention between perspectives might lead designers/engineers with a lot of experience to retain a fixed mindset towards the use of prototypes.

Connecting all of the interviews, a common issue of addressing 'known unknowns' is persistent, but also solving these unknowns in known ways with little guidance on the breadth of methods and tools available. Currently, support tools such as the 'prototyping canvas' enable designers to better visualize the connections between prototype approach, features, needs and audiences for product development. To address the additional tangible and intangible components in future radical PSS design more elements need to be included. These additional elements should aim to address the broader stakeholder network and cross the boundaries of the growing number of disciplines required to holistically design/develop a PSS.
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8. References


