MODEL-DRIVEN PRODUCT SERVICE SYSTEMS DESIGN: THE MODEL-DRIVEN DEVELOPMENT AND DECISION SUPPORT (MD3S) APPROACH

Bertoni, Alessandro;
Larsson, Tobias;
Wall, Johan;
Johansson Askling, Christian

Blekinge Institute of Technology, Department of Mechanical Engineering

ABSTRACT

The paper presents a Model-Driven approach for Product-Service System (PSS) Design promoting an increased digitalization of the PSS design process based on the combination of data-driven design (DDD) activities and value-driven design (VDD) methods. The approach is the results of an 8-year long research profile named (omitted for blind review) featuring the collaboration between (omitted for blind review) and nine industrial companies, in the field of PSS Design. It combines VDD models and the supporting data-driven activities in the frame of PSS design and aligns with the product value stream and the knowledge value stream in the product innovation process as described by Kennedy et al. (2008). The paper provides a high-level overview of the approach describing the different stages and activities, and provides references to external scientific contributions for more exhaustive descriptions of the research rationale and validity. The approach is meant to ultimately drive the development and implementation of a simulation environment for cross-functional and multi-disciplinary decision making in PSS, named Model-Driven Decision Arena, describe in the concluding part of the paper.

Keywords: Product-Service Systems (PSS), Data Driven Design, Model-Driven Development, Decision making, Early design phases

Contact:
Bertoni, Alessandro
Blekinge Institute of Technology
Mechanical Engineering
Sweden
alessandro.bertoni@bth.se

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1 INTRODUCTION

Solving problems in engineering product development becomes increasingly expensive and time-consuming as development projects progress, and financial commitments are made and production started (Ullman 2002, Ulrich and Eppinger, 2012). Mechanical and knowledge engineering models are important means to predict hardware properties at an early stage of design. In the process of an increasing transition towards Product-Service Systems (PSS) offerings, such models shall also be used in a broader business perspective to design the entire ecosystem of products and services (Mahut et al. 2017). The exponential evolution of computational hardware (enabling also software development) has brought also increased growth in the use of virtual models for performance analysis and optimization (e.g., Computational Fluid Dynamics, Multibody Dynamics, etc.). Vallhagen et al. (2013) show how virtual modeling methods are becoming a commodity in the domain of structural mechanics, aerodynamics, and fluid mechanics. The same cannot be said for PSS design support, where early design decisions are driven by a larger and heterogeneous set of needs including lifecycle implications, supply chain impact, and more high-level global challenges. Computational modeling has not reached the level of maturity to compute such dimensions, often referred to as “ilities” in the scientific literature (McManus et al., 2007; Bertoni and Bertoni, 2019).

The transition from product seller to PSS provider implies fundamental changes in both value creation for customers and value capture by the provider (Matschewsky et al. 2018). Hence researchers have turned to the value concept to structure design approaches and provide new ways of measuring the viability and expected success of such offerings (Bertoni et al., 2016; Kimita et al., 2009a; Sakao and Lindahl, 2012). This has renewed interest in Value Centric Design (VCD) and Value Driven Design (VDD) (see: Vengadasalam et al. 2017).

At the same time, one success factor in engineering design is the ability to make effective and risk-managed decisions in a timely manner. The ability to do so relies on the availability of knowledge, hence, a major quest in PSS design is search for information and subsequent build of knowledge. This search comes down to the availability of data to populate early PSS design models and simulations, while the creation of knowledge is subjected to the interpretation and the analysis of data, dealing with ingrained uncertainties and the need to validate prediction models. The term Data-Driven Design (DDD) is being consistently used to refer to the opportunities for data collection and analysis granted by the advent of cyber-physical systems and the Internet of Things (Kim et al., 2017). By exploiting connectedness in cyber-physical systems, explorative models can be created and used as a foundation for more informed decisions. Literature shows three major areas of application for data-driven design models for PSS, respectively focusing on customer needs identification, design synthesis, and more recently, early design concept assessment (Bertoni and Larsson, 2017).

The research presented in this paper is grounded on the idea that multidisciplinary simulations become of foremost importance for PSS design. Those need to emphasize value creation along the entire lifecycle by confronting the shift toward digitalization and circular economy challenges (Lugnet et al., 2020). On such a basis the paper presents an approach promoting an increased digitalization of the PSS design process based on the combination of DDD activities and VDD, ultimately driving the development and implementation of a simulation environment for cross-functional and multi-disciplinary decision making. The paper summarizes the results of multiple research contributions in the field of PSS design, formalizing them in a process model (namely the Model-Driven Product Service Systems Design approach) with related data-driven activities, ultimately aiming to support the design of PSS in the light of the increased availability of product and service data.

The paper summarizes the results of an 8-year long research profile named Model-Driven Development and Decision Support (MD3S) featuring the collaboration between Blekinge Institute of Technology and nine industrial companies. The research environment and the research approach are described in detail in section 2. Section 3 presents a brief review of DDD and VDD models in PSS design. Section 4 provides a high-level overview of the approach for model-driven PSS design developed during the research profile, describing the different stages and activities, and providing references to external scientific contributions for more exhaustive descriptions of research rationale and validity of the different processes included in the approach. Section 5 discusses the findings in light of the current literature highlighting relevant questions for further research in the field.

2 RESEARCH APPROACH AND ENVIRONMENT

The research presented in this paper has been performed in the frame of the MD3S research profile at Blekinge Institute of Technology. The profile is a research initiative dedicated to sustainable Product-Service Systems (PSS) innovation which has the main objective to develop, disseminate, and integrate relevant, user-friendly, and efficient computer-aided support methods and tools for sustainable PSS innovation into business leaders', business developers' and product developers' working environments. The applied research was performed to support and enable industry to thrive in the changing global context, supported by both simulated and real data using the internet of things and AI/machine learning. The research was performed through a combination of participatory action research and case study analysis in collaboration with nine industrial partners operating in the aerospace, construction machinery, packaging, fixtures, and sealing industry. Despite operating in different sectors the partner companies shared some key features making them relevant as research subjects: they were all active in the business-to-business sector, most of them were familiar with systems engineering and set-based concurrent engineering, they had experience with cross-functional design teams; they had grown lessons learned on the need to facilitate a participatory process in the design; their business was facing rapid transformations largely driven by the same macro trends, i.e. servitization, digitalization, connectivity, artificial intelligence, and resource scarcity. Figure 1 shows the partner structure of the MD3S research profile.

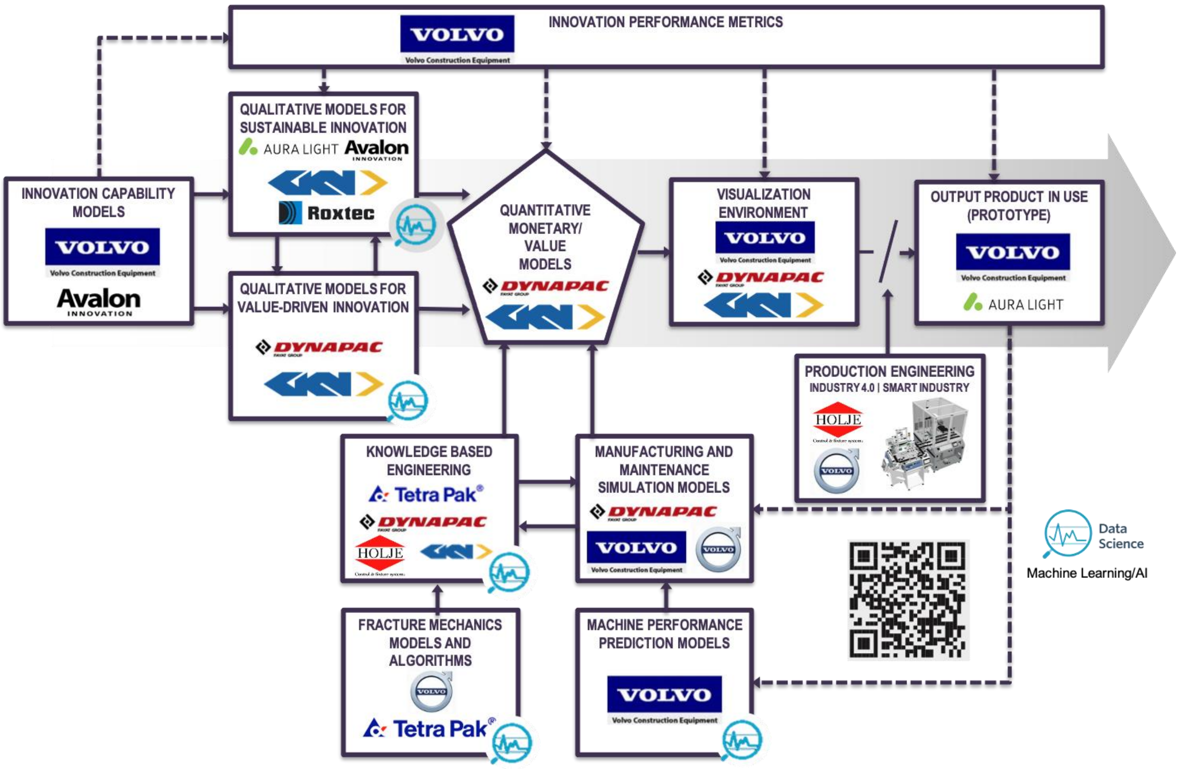

Figure 1. Partner structure of the MD3S research profile at Blekinge Institute of Technology

3 VALUE-DRIVEN AND DATA-DRIVEN PSS DESIGN

More than a decade ago, Isaksson et al., (2009) in their paper on challenges and opportunities for product-service systems development published in the Journal of Engineering Design, highlighted the need for an integrated effort of engineering, marketing, and sales to develop PSS offering. They described a situation in which services and physical products were largely developed independently, arguing the need for a development process, called Functional Product Development (FPD) process, to address the new needs introduced by the PSS transition. They identified four main constituents of the FPD process, namely:

- Being highly driven by the focus on customer needs.
- Include a high degree of customer involvement during the development process.

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- Enlarge the stakeholder collaboration network to include customers partners and suppliers.
- Being capable of modeling and simulating all aspects of PSS in the early phases of design.

When the Isaksson et al. (2009) paper was published, the academic discussion on the concept of Value-Driven Design was very much in its infancy, mostly limited to some use case applications in the field of aerospace systems engineering. At the same time the term Data-Driven Design, despite being already coined (Domazet 1995), had not gained momentum in research and the application of data science in engineering design counted only a few examples and prototyped applications (see Kusiak and Tseng, 2000; Agard and Kusiak, 2004; Kusiak and Smith, 2007).

The VDD term was popularized by Collopy and Hollingsworth (2011) in the Journal of Aircraft and collects methods/tools for design decision support that uses generated value (rather than requirements) as the main design objective to orient trade-off resolution for complex systems and ecosystems (Isaksson et al. 2013). VDD features two main approaches to increases awareness of how much customers value certain capabilities against each other, namely deterministic optimization models and qualitative models.

Intuitively, mathematical optimization models are used to identify the “best system solution” for the maximization of a given monetary function for value. Several case studies in the aerospace sector proposed variations of Net Present Value (NPV) and Surplus Value (SV) equations to perform such an optimization (see: Curran et al. 2010; Cheung et al., 2012). NPV is a widely adopted method for the analysis of investments based on the cash flow generated by different investment strategies over the years; it uses a yearly “discount rate” making cash flows less and less valuable the farther they happen in the future. The SV is instead based on the assumption that seeking optimization of the profit of a whole industry (including all the actors in the supply chain) will render design decisions that will maximize the profit for each company involved. Thus SV should be easier to compute as a subset of NPV since it is not affected by competition (Cheung et al., 2012). Critique has however been raised on the use of monetary functions (Soban et al., 2012) and proposes the use of more qualitative models. The lack of trustworthiness in deterministic models, induced by uncertainty and lack of data, is claimed to hinder communication among the decision-makers (Collopy, 2012, Monceaux et al. 2014), thus calling for the implementation of VDD models based on Multi-Attribute Decision Making to support early-stage system design. The EVOKE model (Bertoni et al., 2018) and the EVA model (Rondini et al., 2018) are two examples of such models developed in the field of PSS design decision making.

Additionally, current VDD research shows that in situations where the ‘system’ to be engineered is becoming increasingly large and complex, value models are the main enablers to support a value orientation in requirement management. Furthermore, the availability of data from the usage phase, granted by the increased access to information communication technologies, enables the development of more reliable assessment models based on quantitative measurement rather than qualitative assessment. For instance, the ability to record data about hardware use, service performances, and human-product interactions (e.g., using smart devices to collect feedback from customers and stakeholders) is believed by many to sensibly improve the early-stage design decision making, hence the above-mentioned ‘frontloading’ exercise. The qualitative value analysis loop is also believed to be a necessary complement of more deterministic analysis, creating awareness and consensus among decision-makers on possible solution directions even before starting to engineer the PSS.

The interest in integrating data science as an enabler of better design decisions has radically increased in the last years from both researchers and industrial practitioners. Nevertheless, due to its novelty, the research field still lacks consistent methodologies and approaches generalizable in different industrial areas and implemented into the established design processes (Bertoni, 2018). While some case studies and conceptual frameworks are available dealing with the very early planning of a new product, limited contributions are available integrating data-driven models in traditionally engineering-oriented product or service development projects, encompassing idea generation and sub-system embodiment (Bertoni and Larsson, 2017). Recently, the idea to support PSS as a whole has been addressed by the proposal of a Data-Driven Product-Service Systems Design and Delivery methodology (Sala et al., 2020) developed to leverage the benefits of data collection and analysis both in the PSS design and in the delivery process of PSS. Such methodology is partially based on the PSS Lean Design Methodology (Pezzotta et al., 2018), which proposes a comprehensive approach focusing on the whole PSS life from the identification of customer needs to the monitoring of performances on the market.

The model-driven PSS design approach presented in this paper builds on the theory here described taking as a standpoint the specific issues emerging in the early stages of PSS design. It does not aim to

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provide a comprehensive picture of PSS lifecycle design and management, rather it proposes an approach encompassing processes and deterministic and probabilistic models to be applied at a lower level of process granularity.

4 THE MODEL-DRIVEN PRODUCT SERVICE SYSTEMS DESIGN APPROACH

This section provides a summary of the approach for model-driven PSS design developed in the frame of the MD3S research profile. The text does not go into the details of the case studies implementation, rather it presents the overview of the processes and methods applied all along the product innovation process, providing references to the specific cases to further investigate the applications in detail. Finally, the section describes the cross-disciplinary simulation environment for multi-disciplinary decision-making that has been developed and tested to operationalize the proposed design approach. Figure 2 summarizes the steps of the Model-Driven PSS Design process (in orange) framed in the generic activities of a VDD process adapted from the work by Bertoni and Bertoni (2019a) (in green) and in relation to the knowledge value stream and the product value stream as defined by Kennedy et al. (2008).

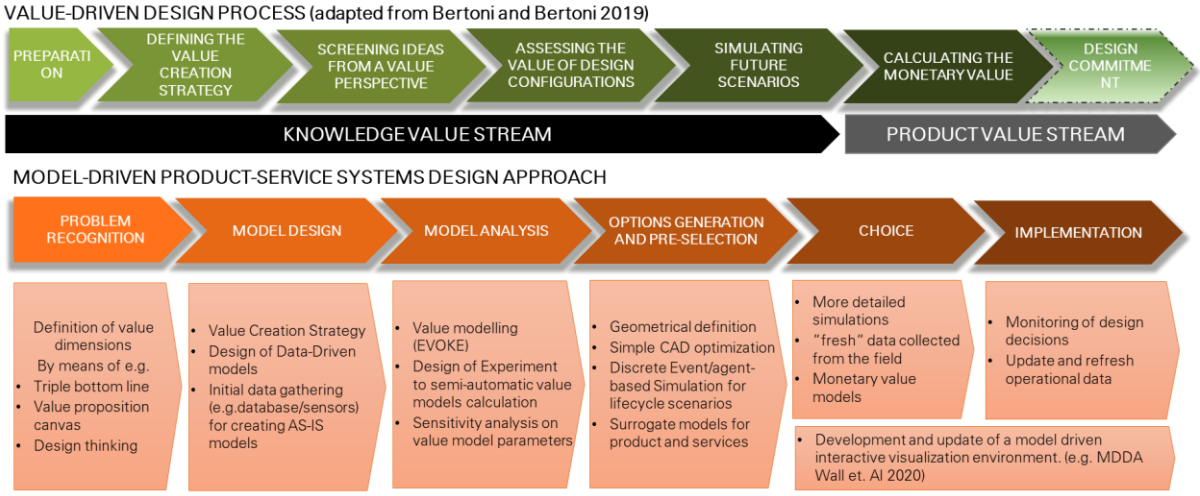

Figure 2. The model driven PSS design approach and its relationship with value-driven design process and data-driven design activities framed in the product innovation process by Kennedy et al. (2008).

4.1 Stage 1: Problem recognition

This is the initial phase of the PSS design process and it is where a problem to be solved or a set of needs to be satisfied are identified. This step wants to provide an understanding of the main dimensions of 'value' that are relevant for PSS engineering and design. The Triple Bottom Line (Norman and MacDonald, 2004), Value Proposition Canvas (Osterwalder et al., 2014) and the Design Thinking methodology (Brown, 2008) frameworks are the main references in this respect. From a DDD perspective, this step provides an understanding of what problem needs to be investigated, setting the boundaries of what data are relevant. It answers the question: "What would you need to know if you could have all the data you want?".

4.2 Stage 2: Model design

In this stage, the first simulation and assessment models are developed. The work starts with the definition of a Value Creation Strategy (VCS) (Bertoni and Bertoni, 2019a). The VCS provides a detailed description of the characteristics, motivators, and preferences of different markets and customers for the PSS. The VCS also helps the design team in defining a complete and customized list of value criteria for a new PSS solution. These criteria are further prioritized to mirror the preferences of a given market and consider both a customer and provider perspective. Customer Tier Analysis, Personas, and Value Strategy Canvas are the main tools used here to inform the creation of the VCS. Here is also where a data collection strategy is formulated and where DDD models are designed to support the quantification of value drivers. Initial data gathering can happen out of historical databases

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or live measurements with the intent to create an understanding of the AS-IS situation in terms of data availability and structure.

4.3 Stage 3: Model analysis

This stage provides a more granular, detailed assessment of the value of alternative PSS design concept configurations. The EVOKE model (Bertoni et al., 2018) is a major support tool for this task. It exploits value functions of different shapes and sizes to map the engineering characteristics of a product against the value criteria. This mapping process matrix is informed by an IBIS map. The EVOKE model is initially used for a high-level screening of the concept ideas from a value perspective, and it is extended in a second step for a more detailed assessment of specific pre-selected concepts. Such extension is possible when a shared agreement on an overall concept definition is reached, thus when specific design features of the new PSS are defined at a high level. The extension consists of enhancing the EVOKE computation by the estimation of the EVOKE parameters through Design of Experiment (DOE) allowing for the automatic computation of multiple EVOKE results inside the design space boundaries of a specific concept (see Bertoni and Bertoni, 2019b). As a last step sensitivity analysis is run on the model parameters to identify the needed improvement in terms of data availability and reliability, this is done to provide the most consistent and reliable models to be used in stage 4 when quantitative simulations are run.

4.4 Stage 4: Options generation and pre-selection

At this stage, the PSS concept starts to take a more defined shape both in terms of more detailed geometry definition and service systems simulations. In other words, this stage brings the design team from the realm of qualitative assessment to the domain of quantitative analysis. A basic geometrical definition of the product allows for simple optimization models utilizing Computer-Aided Engineering simulations. From the service systems design side, process models are used to simulate the operational life of the PSS and Discrete Event Simulations are used here to calculate the performances of a design concept in alternative lifecycle scenarios. The individual behaviors of customers or relevant agents can also be modeled when relevant by the use of agent-based simulations. The increased use of quantitative simulations requires models to be populated by data derived from historical databases, collected on the field, or based on assumptions and expertise of the design teams. Scenario simulations are allowed by the creation of surrogate models for both product and service behaviors, those are enhanced using data science algorithms (see for instance Bertoni et al., 2020). A critical aspect to be considered for the DDD activity in this stage is the necessity to keep "transparency" on the collection, use, and application of data science algorithms. This is because of the heterogeneous nature of the computed data that own different reliability and maturity level. Failing to keep transparency on data sources and reliability might give a false impression of models' reliability to the decision-makers.

4.5 Stage 5: Choice

In this stage, the final design decision on the PSS design is taken. More advanced simulations are developed based on the increased understanding of what needs to be modeled and what data need to be collected, awareness respectively obtained as follow-up of the "model design" and "model analysis" stage. The new simulation can be now complemented by the new "fresh" data collected from the field. Choices are made to improve the simulations and the design concepts. In parallel VDD models focus now on calculating the monetary value of design solutions no longer encompassing qualitative measurement. This brings VDD models to be used in the same fashion as in the definition of VDD by Collopy and Hollingsworth (2011) and iterated in a number of examples by (Castagne et al., 2009; Cheug et al., 2012). In this way, based on the information provided by the previous simulations, the design team can estimate the monetary value (representing long-term profitability) of a proposed PSS solution, both from a provider and customer viewpoint.

4.6 Stage 6: Implementation

This stage goes beyond the product development process and concerns the practical implementation and delivery of the PSS. Although the development being formally closed such a stage is relevant to monitor the effects of design decisions. Based on the information available, delivery decisions are implemented, new data are stored, and the DDD models are kept up to date. This creates a virtuous

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loop in which a constant update and refresh of operational data improve the reliability of the design models and support the constant development of innovative PSS solutions. The resulting design support takes the form of a digital twin featuring constant updates based on the data from the usage phase. A methodology for the continuous design and delivery of PSS has been proposed as complementary research to the proposed process by Sala et al. (2020) but it is not described in this paper.

4.7 The Model-Driven Decision Arena: an enabler for model-driven PSS design

Even if the outcome of the model analysis stage contains the necessary information to support the sought decision, it is still hard for a diverse group of stakeholders to navigate through and make sense of the generated data. Key enablers for exploration and negotiation in a multi-stakeholder decision scenario are constructs and practices aiding interaction with model-generated data. A major challenge in this exercise is how to exploit human judgment to deal with situations where the data set is both very large but also incomplete and inconsistent. In this situation, the visualization strategy shall consider the need to empower the human component and augment its ability to recognize patterns and relationships in the data set. Visualization is an important part of the intended workflow as it may augment problem-solving capabilities by enabling the processing of more data without overloading the user. Cognitive tools propel users into far more effective thinkers and computer-based tools with visual interfaces may be the most powerful and flexible cognitive systems (Ware, 2005).

The research leading to the model-driven PSS design process described in this paper has identified in the Model-Driven Decision Arena (MDDA) a suitable enabler for PSS development. The MDDA is a simulation and decision-making environment where PSS models are visualized at decision gate events. Those models include the 3D geometry for the given design case, the results of the qualitative and quantitative value assessment models, the color-coded visualization of the latter, and the control panel for parameters selection in the DoE. The MDDA provides decision-makers with ad-hoc interfaces to explore the behavior of given configurations under varying assumptions. These interfaces allow the design team participants to play with some of the model inputs and other relevant scenario parameters. A detailed description of the MDDA environment is available in Wall et al. (2020).

5 CONCLUDING DISCUSSION

The transition toward the PSS business model generates cascading effects on the design and development process. Engineers need to keep the focus on value creation from the perspective of the whole lifecycle, thus access to multidisciplinary models and simulations becomes a key competitive advantage. The approach presented in this paper is the result of applied research in multiple industrial contexts facing the design challenges introduced by the transition to PSS.

The challenge of the co-existence of multidisciplinary models in complex development projects is not new. Researchers in model-based systems engineering have stressed the need for multiple and heterogeneous models to communicate and share data and information. Model-based systems engineering environments have been developed together with specific modeling languages (such as UML or SysML) to manage the complexity of the concurrent design of multiple sub-systems driven by the cascading definition of requirements. In such a context, the concept of VDD has challenged the requirements-driven approach for system development, based on the idea that to develop new innovative solutions engineers should focus on the maximization of value rather than on the fulfillment of requirements.

The approach presented in this paper concerns the design of a PSS, which is an effort that lay in-between a traditional product development process and a systems engineering project. In specific the approach contributes to the early stages of the design (aligning with the Knowledge Value Stream definition by Kennedy et al. 2009). Here the consideration of a service-dominant logic requires the definition of a common denominator upon which solution alternatives can be benchmarked. To this purpose, the concept of value, as proposed by VDD, has been identified as such a common denominator to ease engineers' decision-making. Nevertheless, the concept of 'value' itself is a context-dependent and multi-faceted notion, which needs to be reduced (i.e., rendered in more practical and actionable terms), to guide the decisions along the different stages of a development project. To make VDD models more "actionable" in the context of early PSS design, the proposed approach leverages the increased possibility of product ownership and control introduced by PSS, opening to a spectrum of opportunities for data collection.

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In the engineering design field, the concept of DDD has been often discussed and several applications have been presented with the intent to solve problems identified "ad-hoc" (see Kim et al. 2017). Fewer contributions are instead focusing on how to integrate a full spectrum of data-driven activities in the current development process, to proactively design a development process that would exploit the benefit of increased data availability in early engineering design. The novelty of the proposed Mode-Driven Product Service Systems Design approach relies on complementing the VDD approach by formalizing a number of data-driven activities that enable a more consistent and reliable development of models to support decision making. In particular, the approach adds a clear indication on when, how, and for which purpose data-driven activities shall be introduced in the development process, to become effectively integrated into a model-driven approach for the design of PSS. Data can then be used to support the creation, population, and operationalization, of the VDD models. In this way, the "static" view of VDD models can be overcome by a smoother integration of data-driven methods (and data science) in traditional engineering working practices, making a transition from low-fidelity value models to deterministic functions as the PSS design process proceeds.

When using the proposed approach engineers and decision-makers shall be aware that a reason for applying it is that of staging discussions about the value contribution of a design, rather than to identify the best possible concept via optimization. Triggering discussion forces cross-functional design teams to converge to a common view of what the value of a new PSS is and resolve conflicts. Gut feeling and personal experience still play a key role in engineering decision making and the complexity of the PSS design requires the ability to foresee how product and service features will mutually interact and how they will impact the final value delivery. The development and the implementation of the Model-Driven Decision Arena described in section 4.7 supports such cross-disciplinary discussion in early design. This is obtained by leveraging the role of visualization in an engineering context in which multiple competencies concur to define the overall design of the future PSS architecture, and in which the integration of data-driven models introduces the need for data science knowledge, which is often outside the portfolio of competencies of engineers and innovation experts. Such problem of understanding the logic and reliability of specific models in a cross-disciplinary decision-making environment is not new to the literature in engineering design (e.g., Johansson et al., 2011), thus the improvement of the understanding through suitable visualization techniques becomes a necessary part of a Model-Driven PSS design process.

The further development of the proposed approach can be promoted from several perspectives. Among those, a challenge is not only about producing data or results, but rather to make the data accessible and understandable in a wider community. This reflects the need to generate guidelines on how to best interact with the environment without the need for expert knowledge. At the same time robustness and speed of execution are also main challenges: failing in providing almost instantaneous feedback to a decision-making team might compromise the effectiveness of the models to work as a "boundary object", thus acting as a support for facilitating discussions and negotiations between diverse stakeholders from different backgrounds to negotiate value contributions in the light of design changes (Panarotto et al., 2019). From another angle, the verification activities run with the partner companies have highlighted the need for the measurement of a Model Maturity Level (MML) as a promising concept to deal with the uncertainty of the knowledge base in early PSS design. The first version of an MML has been proposed by Johansson et al (Johansson et al., 2017) computing the distance between the current and ideal value of maturity to be expected from a given model, displaying it using a five-level scale. Such a notion would need to be further developed to assess the degree to which a lack of maturity will impact the development process activities.

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