Modeling ‘ilities’ in early Product-Service Systems design

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Abstract

Product-Service Systems, like all complex systems, are vulnerable to unpredictable environmental changes that can seriously undermine their ability to continuously deliver value to customers. The long-term consequences of volatile markets, unanticipated technologies, and unpredictable changes in society must be captured, modeled and communicated to decision makers since the earliest stages of the design, so to identify sustainable PSS solutions able to deliver value for years or decades to come. The paper analyses the problem of PSS changeability from the perspective of established medium-large product manufacturers facing the transition toward result-oriented PSS offers. Building on established literature in the systems engineering field, the paper proposes the definition of the changeability criteria, also named ‘ilities’, that are relevant to consider for PSS engineers in the early stages of design. Furthermore, the paper describes a systematic framework for assessing ilities in early PSS design, elaborating on technological enablers for ilities modeling.

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1. Introduction

The transition to Product-Service Systems (PSS) represents a paradigm shift for traditional manufacturers. Not only it transforms the way products are offered to customers, but also how they are iteratively conceived, developed and assessed [1,2]. In the last decade, research has investigated how to build industrial capability for PSS design [2,3,4,5], resulting in a variety of methods and tools to support practitioners in the definition and selection of the most value-adding product-service bundles. Yet, several studies show that manufacturing companies struggle to capitalize on the PSS opportunity [6], especially when moving towards use-oriented and result-oriented PSS models [7]. From a design perspective, the PSS transition shakes the traditional basis for decision-making. While the members of the engineering team are typically familiar with hardware-based value propositions, PSS design brings them outside the comfort zone, mainly because it introduces new dimensions when evaluating the risk vs. opportunity trade-off [6]. The long-term consequences of volatile markets, unanticipated technologies, and unpredictable changes in society need to be captured, modeled and communicated to decision makers since the earliest stages of the design, so that PSS solutions, able to deliver value for years or decades to come, can be identified and further detailed in later stages.

Research in systems engineering (SE) has been debating about how a system shall be designed to minimize the impact of finite-duration disturbances on its ability to deliver value to customers and stakeholders. The SE community has proposed since the late 2000s several approaches supporting the identification and selection of ‘value robust’ solutions [8,9]. Those imply the ability to deliver the highest possible value both under ‘normal’ (i.e., expected) circumstances and in the presence of “changes” in the super-system that may asymmetrically degrade the performance of the solutions. In recent years, SE research has increasingly regarded non-traditional design criteria – commonly referred to as “ilities” [10,11] – as critical system properties to ensure the ability of a system to deliver value to stakeholder and customer. Ilities are...
defined as “desired properties of systems that often manifest themselves after a system has been put to its initial use” [11, p66]. Hence, a design criterion can be classified as ility if it captures the ability of a system to adapt to change “at an acceptable level of resource expenditure” [12, p3]. The definition, the quantification, and the visualization of “ilities” are discussed in literature mainly from the perspective of aerospace and satellite systems design. Yet, many parallelisms can be drawn between SE and PSS research. Both PSS and SE deals with complex systems, with PSS being arguably more ‘complex’ due to its even larger cross-disciplinarity. Both PSS and SE deal with highly unpredictable environments, requiring careful back-up strategies. Furthermore, they both feature the involvement of a (possibly) large network of third parties (suppliers, subcontractors, dealers, and retailers) when defining the requirements for a solution. Hence, the expectations and preferences of many stakeholders need to be captured and modeled, pushing decision makers to exit their comfort zone to gather the necessary information for design decisions to be made. The main aim of this paper is to define the set of ilities that shall be leveraged during early stage design decision making and to define a model-based approach for their quantification, so to raise engineers’ awareness about the long-term value provision of a PSS.

1.1. Research approach

The findings presented in the paper emerge from the application of case study research [13] in a cross-company setting. Case study research is a qualitative research method that aims at deriving new theory by examining contemporary real-life situations. The list of ilities for PSS design proposed in this paper is based on empirical data collected by the authors through the direct participation in research activities on the topic of PSS. Those have involved both academic researchers and design process owners from companies operating in the aerospace, construction equipment, and food packaging sectors, with experience in the field of PSS design and systems engineering. Data were triangulated by means of regular co-creation workshops, as well as through the analysis of internal company documents. Demonstrators have been applied in the research to verify the proposed modeling concepts. These demonstrators have then been discussed with company stakeholders as a verification means.

2. Systems engineering and the definition of ‘ilities’

In order to successfully identify valuable design concepts, SE research highlights the need to introduce ‘proxies’ able to capture the ability of a system to deliver value in the presence of changing operational environments, economic markets, and technological developments [14]. According to Rhodes [10], value-adding systems are those that are capable of adapting to changes in mission and requirements and be effectively/affordably sustainable over their lifecycle. These systems shall be expandable and scalable, and designed to accommodate growth in capability. They shall further be developed using hardware designed for use in various platforms, and its sub-systems shall modifiable to a high degree to accommodate future new technologies.

The discussion about the different ilities that determines the value of a system has recently grown in Value Driven Design (VDD) [8], Value Engineering [15] and TradeSpace exploration [9] literature. McManus et al [12, p.3] presented a set of “ilities” for complex systems in a VDD framework, defining them as follow:

- **Changeability**: the overarching principle defined as the ability of a system to alter its form or function at an acceptable level of resource expenditure.
- **Robustness**: the ability of a system to maintain its level and set of specification parameters in the context of changing system external and internal forces. Such a concept is particularly linked to the Value Robustness, defined as the ability to maintain value delivery in the context of changing system external or internal forces.
- **Versatility**: the ability of a system to satisfy diverse expectations on the system without the need for changing form.
- **Flexibility**: the ability of a system to be changed by a system-external change agent. Such characteristic takes the name of Adaptability if the change agent is internal to the system.
- **Scalability**: the ability of a system to change the current level of a system specification parameter. Such characteristic takes the name of Modifiability if a set of systems specification parameters can be changed.
- **Survivability**: the ability to avoid or withstand a hostile environment (definition traditionally used for military systems).

The work by Ross et al. [16] proposed the use of TradeSpace exploration, parametrizing the system under consideration, to create TradeSpace model(s) to quantify the ilities. However, such work remains quite unique in its kind and specific for the aerospace context.

3. Modelling PSS ilities: opportunities and challenges

Previous authors have already touched upon the aspects of changeability in a PSS concept. Richter et al. [17] have discussed the flexibility of industrial PSS highlighting four aspects of changeability, namely, adaptability, robustness, agility, and flexibility. However, their work focused on user-oriented business models, presenting modularization as a “reasonable idea” to be applied in designing industrial PSS architecture [17, p131]. Differently, Wang et al. [18] saw changeability as one of the common characteristics of modularity, together with combinability, substitutability and standardization of modules. They described modularity, and thus changeability, as a means to standardize production and provide customized services to better satisfy the customers. The work presented in this paper interprets the concept of changeability as related to the system capability to change in response to an unexpected variation of the overall context. It mimics the definition given in SE literature, thus it excludes aspects such as modularity in production or flexibility of the business offer. Moreover, the work stresses the necessity of modeling and assessing changeability in the early stage of
design, in order to enable increased engineers’ awareness in the decision-making process.

An important trigger to study ilities in a PSS context is the emergence of cyber-physical systems and the advent of the Internet of Things. The ability to monitor hardware use, service performance and human-product interactions (e.g., using smart devices to collect feedback from customers and stakeholders) opens unprecedented opportunities to customize the PSS, adapting it to changing customer needs, user preferences, market conditions and more. The ability to configure the PSS in a way to tap into these opportunities (or to, conversely, reconfiguring the offer to abandon less valuable streams) is an important aspect to be considered during the idea generation and subsystem embodiment phases [19]. While a number of case studies and conceptual frameworks are available dealing with the integration of data science as an enabler of better design decisions in PSS design [20], research dealing with the definition of metrics or ‘proxies’ able to represent this value-generation opportunity is less developed.

4. A systematic framework for modeling “ilities” in PSS design

The research brought to the development of a systematic framework to support decision-makers in identifying and modeling ilities for PSS design, with particular emphasis on the early design stages. Importantly, it shall be noticed that the concept of “systems ilities” discussed in the paper shall not be confused with the concept of “Product Lifecycle ilities” such as used by Aydin et al. [21].

The framework features a list of ilities that are derived from the criteria described in SE research (left in figure 1). Yet, the results of the empirical studies spotlight the need to capture other ‘changeability’ aspects for PSS solution that are not considered today in existing frameworks (right of Figure 1). These are positioned at different organizational layers (i.e., strategic, tactical and operational), rendering a framework composed of a total of 10 parameters.

![Fig. 1. PSS ilities: newly introduced (in teal on the right-hand side of the figure) and derived from SE literature (in striped grey on the left-hand side of the figure).](image)

4.1. Translating SE ilities into PSS research

Changeability in SE is declined into the following ilities, which are:

- **Value Robustness.** From a PSS perspective, robustness in ‘value’ can be seen as the ability of the PSS to continue to provide value in the presence of an internal and/or external change in value scales. “Internal changes” refers to the PSS provider, and may concern a shift in the strategic orientation of the organization (e.g. ownership structure, KPI at a tactical level). For example, an established manufacturing company shifting toward PSS would need to consider how many business models the organization would be capable to deal with at the same time. External changes could be represented by economic trends, changes in legislation or political conditions. For instance, an EU based construction machinery company, that relies on extensive result-oriented PSS contracts in developing countries, cannot neglect to consider the risk for commercial and political instability that could seriously undermine the periodic PSS cash flow.

- **Versatility.** This classical SE parameter can be interpreted in the PSS domain as the ability of solutions to smoothly react to a change in the customer needs and expectations. PSS versatility can be seen as the latent value embedded either in the product side or in the service side of the PSS. A highly versatile PSS is a combination of product and services that, even taken standalone, would generate value for the customer. In an extreme example, the capability of a construction equipment provider to drop the service aspects and “come back” to a pure product selling, while still being perceived as highly valuable by the customer, is a measure of high versatility.

- **Scalability.** The scalability of a PSS can be seen as the ability to scale up (or down) the form (e.g. in terms of the number of hardware) or the function of the PSS (e.g. in terms of increased productivity). For instance, in the case of a generic vehicle sharing system, the typical questions reflecting the PSS scalability would be: To what extent can I increase the number of vehicles available without introducing criticalities in the system? Can I sensibly increase the results delivered (e.g. mobility, productivity, efficiency), in response to a customer need, without encountering a product or service-related problem?

- **Flexibility (Adaptability).** The term flexibility in PSS has been used with different meanings (see for instance [17]). This paper considers it as an integral part of the PSS changeability assessment. Flexibility is defined as the ability of a PSS to be changed by either internal or external change agents. Such definition does not differentiate between flexibility and adaptability as it happens in the SE literature. This is done to avoid the ambiguity introduced by a potentially unclear definition of the boundaries of the system in a PSS context. The introduction of a new technology can be a typical change agent upon which to verify the PSS flexibility. For instance, building on the previous example of a construction equipment PSS provider, the introduction of electrical engines to substitute diesel engines can represent a challenge in term of PSS flexibility. The understanding of how much the PSS is capable of integrating such new technology (encompassing, among
others, new hardware design, new supply chains, new maintenance process, new logistics, etc.) is critical to be assessed in early design stages.

4.2. Defining new ilities for PSS design decision making

In PSS design decision making, the traditional ilities that characterize SE are not enough to cover all aspects of product-service bundles. The first set of ilities aims at capturing the ability of a PSS to continuously deliver value under changing market and business conditions. Two main categories of ilities for PSS have been identified at a ‘strategic’ level, which go under the keywords ‘win-win-ability’ and ‘ecosystem plugin-ability’.

Win-win-ability is defined as the ability of a PSS solution to maintain fruitful win-win situation between two or more parties in the PSS consortium, even in case of contextual, environmental, or operational conditions changes. Previous research [22] has highlighted the need for establishing win-win collaborations across the value creation network as a major prerequisite for the successful deployment of a PSS strategy. The PSS shall be designed, therefore, in a way to contrast or avoid opportunistic behaviors when environmental conditions change. Also, early stage assessment shall provide feedback on how resilient incentive models are against changes in the market and business landscape. For instance, a PSS may feature poor win-win-ability if one party (e.g., a battery provider for an electric vehicle) experiences lower profit due to the innovations introduced by the other party in the win-win agreement. (e.g., a vehicle design that makes more difficult to perform battery swap activities).

Ecosystem plugin-ability is an additional ility at the strategic level that aims to capture the ability for a PSS solution to enable the network of suppliers to ‘plug-in’ or ‘plug-out’ of the PSS network as soon as an opportunity for value generation appears, or conversely extinguishes. The main purpose of this parameter is to provide decision-makers with a measure of how much ‘open’ the PSS ecosystem is towards new competencies, skills, and complimentary offers. This dimension considers both hindrances in terms of the working process and enabling technologies. For instance, a PSS solution features a poor ecosystem plugin-ability when mobility product providers are unable to collaborate and ‘tap in’ the existing PSS network to provide customer enhancing solutions, due to, for instance, proprietary data exchange standards or protocols that cannot be open by third parties.

Another category of ilities looks into the Tactical layer, to identify the ability of a solution to integrate into the customer process for continuous value delivery. Seamlessness and Reconfigurability summarize the level to which the PSS can change and transform itself without impacting the Key Performance Indicators (KPI) of the customer process.

Seamlessness is defined as the ability of a PSS solution to be seamlessly absorbed by the customer operational process, ensuring continuous value delivery. For instance, a PSS features a poor absorbability if the introduction of the new PSS causes an interruption in the revenue-flows for the customer company (e.g., due to the need to suspend operations during the set-up process) or additional costs.

Reconfigurability is another dimension overlooking operational KPI. It specifically measures the ability to reconfigure the network of actors providing the solution in a way that the PSS increases its ability to deliver value to customers. This means that it shall be possible for the system integrator to reconfigure its network of dealers/suppliers in a way to meet increasingly sophisticated customer expectations and values, without the PSS customer being (negatively) affected by such a change. A PSS features poor reconfigurability if the provider is locked to a certain supplier/dealer by strict contractual requirements. Even though this partnership is believed to be the optimal one at present, it might be too costly, or not optimal, to sustain in the long run.

Additional ilities have been proposed to highlight value creation at an Operational level. Supportability and Monitorability deal with specific procedures and processes that occur within the lowest levels of the PSS provider organization.

Supportability in this respect refers to the ability of the underlying service process for the PSS (i.e., the process below the ‘line of sight’ of the customer) to support continuous delivery of value to the customer. For instance, a PSS features a poor supportability if the resources allocated for the back-office operations (such as repairing bikes in a ‘bike sharing’ system) are undersized compared to other processes (such as the maintenance of the bike sharing app), being then unable to cope with changes in customer behaviors (such as peaks in the demand).

Monitorability, on the other end, can be defined as the ability for a PSS provider to monitor processes above and below the ‘line of sight’. This means being able to access and analyze data to continuously plan for innovation and propose an improvement to raise value generation along the PSS lifecycle. There is nowadays a shared agreement about the importance of being able to collect and analyze PSS lifecycle data. However, getting access to those can often be problematic, especially when the PSS transition is done in established product-based industries. Problems can arise from technological issues in dealing with a large amount of data, but also from legislation or company business structure. Taking again the example of the construction machinery industry, legislative problems can raise when the data collected are linked to specific individuals or workers, for instance allowing the identification of the driver of a machine. Problems might also be present when different companies are working in synergy in the same system. For instance, in the mining industry, it is not uncommon to have situations in which different stakeholders respectively own the mine, the machine, the personnel, the additional services, and the mine data, making cumbersome for the PSS provider to monitor and manage data access among multiple actors.

5. A model-driven approach for assessing ‘ilities’ in PSS design

The evaluation of ilities in a PSS environment foresees a 3-step process, characterized by increased complexity and data intensity, and summarized in Figure 2.
Thanks to those who foresee the operational timeframe. For performances of a given hardware design an overall score used as a proxy for PSS solution, in a way that resembles value environmental changes.

The first step is driven by a qualitative scale which aims at gathering feedback from the cross-functional design team on the ability of a PSS to deal with changing conditions in market, technology and/or environment. Here, decision makers are asked to set a score to each parameter based on their own experience with the hardware/service, as well as on the base of lessons learned gathered from previous projects. The main function of this phase is that of highlighting ‘hotspots’, which are the main hinders in adapting to changing conditions. The work shall be directed than in configuring the product-service bundle in a way to become more value-resilient. Such a qualitative scale for ilities assessment acts as a boundary object [23], facilitating coordination and negotiation among the cross-functional design team.

The second step foresees the development of a more systematic approach to link PSS features to the list of ilities. Multi-Criteria Decision Making (MCDM) research provides several tools to raise consistency during the assessment process. While this evaluation remains mostly qualitative (uncertainty and lack of data still dominate this step), decision-makers can explore with more granularity which PSS function/component lowers the ability of the PSS to capitalize on (or survive) changes. The EVOKE model, proposed by Bertoni et al [24], is one of such MCDM models to systematically capture how specific characteristics of the solution impact the ability of the PSS system to adapt to environmental changes. Ilities are introduced in the EVOKE as value criteria and assessed against a list of so-called ‘characteristics’ for the PSS solution, in a way that resembles and extends Quality Function Deployment. A design ‘merit’ score is generated for each criterion and further aggregated in an overall score used as a proxy to communicate the value of a design concept.

The third step involves the development of models for scenario-based analysis. These models consider evolving contextual conditions in the scenario and evaluate the performances of a given hardware-service package in a given timeframe. For instance, Discrete Event simulations are used to foresee the operational behaviors of a proposed PSS concept. Thanks to those it is possible, for instance, to estimate the impact on new engine technologies on product performances and operations. The data collected from these models are then used to provide a more fact-based evaluation of the different ilities. Physical models can also be exploited to further complement such simulations and clarify the meaning of the different ilities, trying to move the qualitative evaluation from the previous steps into a monetary-related dimension.

6. Discussion

The findings from the cross-company study highlighted a need to inform decision makers, since an early design stage, about the ability of PSS design concept to be more/less resilient to change compared to alternative options. This brought to the development of a new set of ilities for PSS design, emerging from previous work in the SE domain. The concept of ilities is closely related to risk and strives to introduce measurable and negotiable proxies for PSS engineers to discuss and converge upon, so to discover the most value-adding solutions from a lifecycle perspective. Ilities are designed in a way to facilitate benchmarking with more traditional performance criteria. For instance, they can be exploited in the MCDM exercise to identify and evaluate trade-offs among a wide range of value-related parameters for the PSS solution. A main property of the ilities construct is that their definition is consistent throughout the entire PSS design process. Ilities are intended as actionable and measurable criteria, which can be exploited already in the earliest phases of PSS design. Yet, they can be systematically followed up and assessed – by means of increasingly fine-grained models - as far as the description of PSS solutions becomes more mature.

An integral part of the ilities assessment framework is also the development of an ad-hoc environment (named Model-Driven Decision Arena or MDDA [25]) where the information gathered in step 3 and 4 is displayed to the decision-making team. The MDDA consists of a high-speed server with large fixed screens, as well as a touch screen in the center of the room, on which to display complex data, models and simulation results. Its main function is that of facilitating discussion and negotiation about PSS design trade-offs: here the team can benchmark results, control input variables, manipulate models and decide to iterate the process in case all the explored PSS concepts are eventually rejected.

The systematic framework proposed in Figure 2 shall be considered an attempt to picture the systematic process guiding the cross-functional design team in monitoring ilities along the entire PSS design process. Noticeably, the approach is currently under development and is rather immature for what concerns the instantiation of the assessment models during the different proposed steps. Furthermore, the context of the empirical studies from which the framework originates limits the generalizability of the findings. Hence the authors do not claim the list of ilities, and the associated assessment process, to be applicable to all PSS transitions. Rather the proposed ilities should be seen as a contribution to assess the PSS value in established medium-large manufacturing companies. Additionally, even though the proposed framework builds on components (i.e., qualitative assessment scales, MCDM matrices, DES) previously applied in early PSS design, their
integration in a unique process has not been fully tested yet and remains at a rather theoretical level.

7. Conclusions and future work

Product-Service Systems are vulnerable to unpredictable changes in the super-system, which can seriously undermine their ability to continuously deliver value to the customer. In turn, solution providers need to grow their understanding already in the earliest stages of the design about how the PSS shall be configured to adapt to change, so to be ‘fluid’ enough to capitalize on emerging opportunities.

The proposed set of ilities for PSS design, and the associated framework for assessment, is intended as a major enabler for the PSS cross-functional teams to deepen the exploration of the feasible design space since an early stage. By monitoring and measuring ilities, decision-makers can raise awareness of the risks and opportunities linked to radical vs. incremental PSS design concepts, and elaborate on the dynamic nature of PSS value contribution along the lifecycle.

The definition of a systematic framework to assess PSS ilities can be seen as a step toward modeling uncertain systems dynamics in early PSS design. To this concern, the advent of Industry 4.0, and the increased accessibility and utilization of computational methods based on data science, is seen as the development frontier to allow prediction models to forecast the behavior of the system. The application of such techniques is however still in the infancy in the PSS design context. The definition of changeability aspects provided in the paper supports the creation of a shared understanding of what needs to be measured and quantified, given the higher accessibility of data granted by Industry 4.0.

Future research will also aim at defining more specific guidelines indicating when a PSS concept is mature enough to move from step 1 to step 2 and finally to step 3 of the ilities assessment process. The definition of a minimum level of detail requested for such a transition would be necessary, together with a preliminary assessment of the level of reliability of the results of the ilities assessment models.

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References


