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An Approach to Reveal Starting Points for PSS Design Support with Dynamic Models

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Abstract

The concept of product-service systems (PSS) combines classical products with additional services. Consequences are, e.g. due to a strong customer integration, various challenges with dynamic, behavioral and uncertainty aspects. This publication clarifies the importance of these aspects by a literature review. Existing approaches to model and cope with dynamic are revealed and assigned to a structural PSS model. This model is based on an e-bike sharing system and highlights important domains for PSS development. Different starting points for dynamic modeling are discussed in the PSS model to support PSS developers in the selection of a sufficient dynamic model.

1. Introduction

As the name implies, a Product-Service System (PSS) integrates product and service components to fulfill a customer’s need [1]. Reference [2] defines three major categories to classify PSS depending on the service level of the system: Product-oriented PSS are customer owned products where a company adds additional services that are offered to the customer throughout the entire life cycle. Use-oriented PSS are products that remain on provider’s side while its use or availability is for sale, whereas result-oriented PSS sell capabilities. As the additional services offer higher customer value and therewith justify higher prices, PSS offer a competitive advantage against low-cost manufacturing [3].

With the growing importance of PSS, especially in the western world, new methods are required to ensure the success of these new business concepts. The chance of success can be increased through the use of modeling and simulating methods in the development [4, 5]. Especially the dynamic aspects of PSS are important as PSS are characterized by a high uncertainty. This uncertainty arises out of the system’s complexity as well as its dynamic behavior [6]. Nevertheless, only a few methods have been discussed in literature so far. Consequently, there are new approaches required that focus on dynamic modeling of PSS.

The focus of this paper is on the analysis of the suitability of dynamic modeling approaches for PSS development to reveal starting points for PSS design support. To fulfill these objectives, the paper is structured as follows: For a future consideration of PSS specific difficulties, challenges with dynamic in PSS development are named, followed by an introduction into structural and dynamic modeling (section 2). Section 3 starts with a presentation of a concrete PSS model. Afterwards, a literature review is carried out to identify methods that can be potentially applied to support dynamic modeling in PSS development. Based on the review, the identified methods are assigned to specific subsets of the modeled PSS. These assumptions are verified in cases. The results are discussed in section 4, followed by a conclusion in section 5.
2. Consideration of dynamic in PSS Development

2.1. Challenges with dynamic in PSS Development

According to literature PSS offer several challenges due to dynamic aspects. So, generally innovative and long-lasting business models for PSS require not only a static but also a dynamic perspective on PSS [7]. Due to [8] PSS are during their entire lifecycle socio-technical systems and have a highly dynamic nature. In comparison to a single physical product or service, PSS are characterized by a very high degree of dynamic changes not only during their planning, but also throughout their entire life cycle [9]. Moreover, [10] propagate that an integrated understanding of the PSS lifecycle is crucial to be able to consider dynamics along the lifecycle. According to [11], especially the service design is extremely dynamic in the PSS development process. Reference [11] states that understanding the interconnections among all kinds of dynamics and the individual phases helps to avoid developing less successful PSS or introducing a PSS to the market at the wrong time. These challenges in PSS development lead to several approaches and methodologies coping with dynamic.

2.2. Dynamic modeling in PSS development

Several researchers use system dynamics in the PSS development basically to support business model development. Exemplarily [13] use a system dynamic model to analyze the impact of changes within the innovation process of PSS. [4] see system dynamics as a suitable tool for analyzing PSS and their business models. They further mention “discrete event modeling” and “agent-based modeling” for analyzing and simulating dynamic systems.

[14] propose a simulation method used in the scenario design process, which can deal with a scenario model with various resolutions by combining simulation methods studied on system dynamics and agent-based modeling.

The exemplarily mentioned approaches use some dynamic models for special applications in the PSS development. However, the approaches are not structured. This publications aims to assign different dynamic models to a general PSS model to reveal starting points for PSS design support with dynamic models. Therefore a structural PSS model is developed.

2.3. Structural Modeling in the context of PSS

Methods for structural modeling use matrices or graphs to model and analyze systems, to get better system understanding. The structural model consists of domains, elements and relations. A domain is a superordinate class and includes several elements, which are linked by relations. The first matrix type, a design-structure matrix (DSM) [15], represents a subset of a single domain. Two different domains are mapped by a domain-mapping matrix (DMM) [16]. A multiple-domain matrix (MDM) includes at least two domains and the affiliated subsets represented by DSMs and DMMs [17].

3. Modeling and Simulation of a PSS

While using the above-mentioned matrices from structural complexity management, a structural model of a PSS is created. It is developed on the basis of the PSScycle – an e-bike sharing system developed as part of the SFB768 (see acknowledgment).

3.1. Structural Model of a PSS

The MDM for the PSScycle contains of the four generally needed product-related domains ‘requirement’, ‘function’, ‘hardware’ and ‘software’ as well as a service-related domain called ‘service’ [18]. However, by only incorporating these five domains, an important aspect in PSS development is neglected: the stakeholders. Consequently, another MDM comprising relevant stakeholders is created and attached to the existing MDM. The resultant system graph is depicted in figure 1.

![Fig. 1. System graph of the PSScycle.](image_url)

The MDM of the present system graph includes five product-related domains and seven stakeholder-related domains. This results in twelve different domains with 25 different subsets. To simplify the MDM, the seven stakeholder-related domains were reduced to the domain ‘user’. This domain is linked to the others via an added domain called ‘use cases’ (see grey-highlighted subsets in chapter 3.3). Additionally, it is not necessary to consider all remaining subsets. Only the DMMs, which state the relations between the domain ‘function’ and the product- and service-related domains, are taken into account. With these domains, the existing DSMs can be derived by matrix multiplication (see [17]).

3.2. Literature Review of Dynamic Modeling

The search strategy for this paper began with a review of literature identified by the keywords “dynamic modeling” and “multi-method modeling”. The research focused on literature published after 2000 in order to include the most up-to-date data, using the search engines “TUM Library”, “Google Scholar” and “Science Direct”. The aim was to determine the
state of the art in dynamic modeling, and which models can be
potentially transferred into the context of PSS development.

Table 1. The results of the search for existing dynamic modeling approaches

<table>
<thead>
<tr>
<th>Search Engine</th>
<th>Keyword</th>
<th>Viewed Hits</th>
<th>Hits, used in this Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUM Library</td>
<td>Dynamic Modeling</td>
<td>18 of 1412</td>
<td>[19-23]</td>
</tr>
<tr>
<td></td>
<td>Multi-Method Modeling</td>
<td>15 of 503</td>
<td>[24-25]</td>
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<td>Google Scholar</td>
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<td>8 of 22500</td>
<td>[26-29]</td>
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<td>Science Direct</td>
<td>Dynamic Modeling</td>
<td>18 of 16785</td>
<td>[14; 30-35]</td>
</tr>
</tbody>
</table>

With these references, seven promising methodologies were identified:

Table 2. Overview of the selected methods with corresponding references

<table>
<thead>
<tr>
<th>Identified Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Dynamics</td>
<td>[19], [24], [31], [33]</td>
</tr>
<tr>
<td>Discrete Event Simulation</td>
<td>[24], [32], [35]</td>
</tr>
<tr>
<td>Agent-Based Modeling</td>
<td>[24], [26], [30], [33], [34]</td>
</tr>
<tr>
<td>Individual-Based Modeling</td>
<td>[21]</td>
</tr>
<tr>
<td>Petri Net Analysis</td>
<td>[22], [25], [27]</td>
</tr>
<tr>
<td>Bayesian Network Modeling</td>
<td>[28]</td>
</tr>
<tr>
<td>Analysis based on the Element Concept</td>
<td>[29]</td>
</tr>
</tbody>
</table>

System Dynamics (SD) is an already existing and commonly used method to model and analyze the dynamics of a system [19]. It operates at high abstraction levels and is logically mostly used for strategic modeling [24]. The main idea of SD is that the behavior of a system and therewith its dynamics result from the structure of the system, which is represented by stocks for each entity of a system and flows between these entities [20].

Another approach for dynamic modeling is the event-controlled method Discrete Event (DE) simulation. The methodology is mostly graphically represented as a process flow chart, e.g. a sequence of operations [24]. Therefore, DE uses entities, resources and block charts that describe entity flow and resources sharing [23]. This process-centric approach supports medium-low abstraction.

Agent-Based Modeling (ABM) is a recent bottom-up modeling approach. Here, the system is modeled as a collection of autonomous decision-making entities called agents. These agents represent the system components with their own individual set of rules or behavior [34]. In ABM the practitioner defines explicit behavior at individual level, what determines global system behavior by emergence. This allows detailed up to abstract models on global system level [23].

As the name indicates Individual-Based Modeling (IBM) is a special case of ABM where individuals show a social behavior and follow a common goal [21].

A Petri Net (PN) analysis is a mathematical approach to model and simulate discrete events of states and state transitions in a system, which is commonly used in computer science [22, 25, 27]. A PN is depicted as a directed graph, in which nodes represent transitions (signified by bars) and places (circles). The directed edges describe which places are pre- and post-conditions for which transitions (arrows).

Reference [27] has shown that switching operations of transitions as well as the generation of nodes are enough to describe complex processes in dynamic systems with PNs. However, PNs usually operate at a low abstraction level.

Reference [28] mentions Bayesian Networks (BN) as an additional methodology for tactical modeling of dynamic systems. In general, BNs can be regarded as a mean to represent the relation between several random variables. The nodes in the graph represent the random variables, whereas the edges between these nodes stand for the dependencies. BN analyses differentiate in three types: discrete, hybrid and dynamic BNs. As the name indicates, discrete BN are limited to discrete event systems, whereas hybrid ones can also model continuous variables. Only one random variable is available [28], which is not sufficient for all purposes, e.g. for the analysis of time series or dynamic processes where data has to be represented at different points of time. The main idea of dynamic BN modeling is to represent each point of slice by a separate BN. These time-slices are linked by temporal edges.

Modeling of Dynamic Systems (MoDyS) and Simulation of Dynamic Systems (SiDyS) is a new approach to guarantee an integrated dynamic simulation of complex development projects [29]. As this is a relatively new methodology, which is hardly discussed in literature, it will not be further considered in this paper.

3.3. Assignment of dynamic Models to the MDM

After the system graph has been presented in chapter 3.1, now the methods are assigned to specific domains/subsets or respectively to a specific element of the MDM. Figure 2 displays the corresponding meta-model.

According to reference [24] every method serves a particular abstraction level based on a specific abstraction point (e.g. agents, flow, etc.). In this context, [4] mention that DE is more suitable for simulations at operational level, SD as more suitable for simulation at high levels of abstraction and ABM as possible to be used at all levels of abstraction. While the abstraction point can be defined according the objective of the analysis, the abstraction level is mostly given by the available details or the scope of the analysis.

Therefore, first domains/sub-sets with a distinctive dynamic behavior are identified. Here, e.g. the domain ‘service’ is identified as it shows a significant dynamic behavior over the entire lifecycle of the PSS. This can be for example in forms of managing deferred repair services or the supply with an optimum quantity of bikes to guarantee customer’s satisfaction while keeping the provision costs as low as possible. Afterwards the abstraction point is defined, followed by choosing the abstraction level. To pick up the just mentioned example: the optimum quantity of bikes is mainly affected by the amount of people (agents, stock) using them and how they use it (behavior, flow). Logically, the abstraction point can be either the agent with his individual behavior or the stocks and flows of bikes. In both cases, the modeler has little consistent information and consequently, it is considered a high abstraction. Based on these two criteria, the compiled methods can be assigned. Since ABM and SD
are both used for strategic modeling, the method depends on the choice of the abstraction point: ABM (for an agent focused model) and SD (for a stock and flow based model).

The assignment of dynamic models to the MDM is carried out as exemplarily explained above and illustrated in the figure below.

Fig. 2. Starting points for PSS design support with dynamic models

In the following, some models are presented to verify the applicability of the identified methods to support PSS development.

3.4. SD to optimize deferred service processes

Reference [31] uses a SD model to analyze a PSS with a focus on service performance. The case study refers to a company that manufactures and assembles machinery. A considerable profit share is reached through repairing services. Here, a key issue is to improve deferred service processes in order to increase the profits coming from this business. Consequently, a quick repair and maintenance has to be assured. Since these corrective repair services are completely unplanned and difficult to handle it needs strategies which forecast these deferred activities, e.g. in forms of preventive maintenance.

[31] introduce an SD model to analyze the system considering the provider’s perspective (in terms of revenues and costs) and considering a life cycle temporal horizon. In order to run the model, different parameters have been introduced, like the disposal rate, the cycle time of a corrective action, a failure rate as well as costs of repairing and personal. As a result [31] shows in three scenarios that the provider gets benefits from the introduction of a preventive repairing service. Another result regards the reduction of uncertainty in forecasting of personal as well as spare parts.

Summing up, SD is feasible in the area of forecasting and optimizing deferred service processes, e.g. through the implementation of preventive maintenance within a PSS.

3.5. DE for the ideal allocation of bikes during a day

Reference [36] discusses the applicability of DE for supporting the development of different types of PSS. It is mentioned that DE can theoretically evaluate necessary resources depending on customer numbers and time schedules, e.g. rush hours or other peak times in use-oriented PSS. Additionally [32] introduce a DE model that is used to experiment with different system parameters in a car sharing system. In the DE model used by [32], a realistic environment is created to evaluate the impact of changing environmental factors. In one scenario, one of these factors represents the flow of users depending on the daytime. The demonstrated simulations show that DE enables a reasonable selection of potential system configurations under varying boundary conditions.

With these scenarios, it is shown that DE is capable of simulating an ideal allocation of products and services (here: e-bikes) depending on different time schedules within a PSS.

3.6. ABM to provide an optimum quantity of bikes in a PSS

Reference [34] discusses the abilities of ABM to support PSS development. In use-oriented PSS, ABM can be used to model flows of customer and product entities to analyze how products should be distributed in a certain area. [34] analyzes the provision of an optimum quantity of bikes in the PSSyce use case. Primary aim is to ensure customer’s satisfaction while keeping the costs for the bike provision as low as possible. People lose or gain satisfaction linearly from an initially given value at every time step depending on whether they are able to pick up a bike on their way to a subway or not. The particular model is used to compute an appropriate number of bikes. It helps to answer the question of how many bikes are required in a certain area to create a constant or increasing satisfaction. Even though the model is kept simple, [34] shows in several simulations that ABM is able to calculate the critical number of bikes by given input parameters.

Drawing from these results, ABM is most certainly feasible in the area of calculating the optimum amount of bikes within a PSS.
3.7. PN to understand impacts triggered by discrete changes

Even though PN have been used to analyze dynamic systems, it hardly appeared in the context of PSS. Consequently, a simple PN model is developed to test the feasibility of PN for PSS development. As operating tool, the platform independent petri net editor (PIPE 2) is used.

The model (depicted in figure 3) investigates the impact of discrete changes in legal directives based on the availability of the system to its users. The simulation is released through a new legal directive. A probability rate decides whether the restriction affects the PSS or not. If it does affect the PSS, a new legal directive. A probability rate decides whether the restriction affects the PSS or not. If it does affect the PSS, a second process starts, where token represent staff members. The implementation of the restriction is represented as a stochastic timed transition to guarantee a more realistic approach. The restriction can be for example a new safety regulation concerning the motor of the e-bike. In this case, every bike has to be adapted to it. The particular model is used to compute the necessary time to adapt a system to new restrictions. It helps to determine the required effort in terms of personnel and corresponding costs or the outage of the system, meaning the time in which the system is not available to its customers.

The model shows that PN simulations are generally able to analyze PSS if the process is event-controlled.

Fig. 3. PN model of the implementation of new legal directives in a PSS.

4. Discussion and Reflection

4.1. Discussion of the introduced MDM

A major challenge in PSS development is the dynamic environment and the involved stakeholders. The presented system adopted from the PSScycle is modeled with seven domains in a multiple-domain matrix. It is clear that seven domains cannot perfectly display an entire PSS. Consequently, the paper does not proclaim to cover all existing parts of PSS, but gives hints for a general structural PSS model.

The assignment of dynamic models to sub-systems of the PSS followed clear recommendations since choosing the right abstraction level is crucial to modeling success. Nevertheless, in the model development process it is also recommended to periodically reconsider the abstraction level. Consequently, the modeling method can change during the development.

4.2. Reflection of the results of the presented models

SD is already widely discussed in the context of PSS modeling [19, 23, 31, 33]. In the model presented as well as in other diverse cases, SD has shown its potentials in supporting PSS development by handling dynamic behavior. The advantage of SD is a simple development of a qualitative system model. However, quantitative simulation is based on positive and negative feedback loops, which are difficult to discovered.

DE simulation can support PSS development as long as the described process is event-controlled. The major advantage of DE is the capability of simulating uncertainty and the analysis of impacts on future configurations. However, with DE it is only possible to model passive behavior. Meaning that dynamic emerges out of the system’s structure and not through the individuals involved in it. Nevertheless, the presented model verifies the applicability of DE for PSS modeling under certain boundary conditions.

ABM shows high potential for applicability in PSS analysis. Perhaps the major advantage is already given by the name itself – the agents. They enable to use a set of individuals with individual behavior and so they can represent several interactions, e.g. of users, with complex dynamic behavior aligned to reality. However, this complexity is difficult to implement into the model and increases the necessary modeling effort seriously.

With the purpose of a first rapprochement of PN feasibility in the frame of PSS analysis, a basic petri net is created. The PN simulation has shown a general applicability, however, there is a need for improvements. For instance, instead of a basic petri net, colored petri nets could be used, which allow a better modeling of actual existing systems. Moreover, PN show some major similarities to DE simulation, so it has to be discussed more precisely which one is best for different PSS sub-systems.

5. Conclusion and Outlook

In this paper several dynamic modeling approaches for supporting PSS development and thus handle uncertainty are discussed. As uncertainty arises out of a system’s complexity and its dynamic behavior, an introduction in structural modeling is given and completed by challenges with dynamic in PSS development.

Based on an extensive literature review, promising modeling approaches are identified. These methods are assigned to a general MDM (an e-bike sharing system) and are further evaluated. The authors show that there are proven methods for supporting PSS development, e.g. SD, DE and ABM. As their applicability is verified, a promising approach could be to combine these three methods to cover an even wider range of applications in PSS development. This multi-method modeling methodology is mention by [23] and could be the topic of future research.

Furthermore, a simple PN model has shown that PN is generally suitable to support PSS development. For further work it is suggested to test PN applicability with more realistic simulations in order to get a better understanding of
potentials and limitations the approach faces. Additionally, BN could be analyzed in the context of PSS development, as a transfer seems – based on literature – feasible.

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References


