Lifecycle Oriented Flexibility Assessment of Customized Solutions in Capital Goods Industry: A State of the Art

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Abstract. The beginning of a Product-Service System´s lifecycle is surrounded by a high degree of uncertainty regarding customers' todays and prospective requirements. Thus, the ability to adapt a Product-Service System to changing customer requirements by providing flexibility becomes an important quality and success criterion along the entire lifecycle. This paper analyzes existing approaches of economic and engineering theory dealing with the assessment of flexibility in the industrial environment. A State of the Art is provided including literature reviews on both the economic assessment, based on NPV and ROA, and the engineering assessment, based on a detailed flexibility analysis that originates from manufacturing systems. The article continues with implications, followed by a recommendation and appoints tasks for further research.

Keywords: Product-Service Systems, Flexibility, Assessment.

1 Introduction

Customers of capital goods no longer demand pure technical products, but customized solutions, consisting of a product enhanced by different services along its life cycle that are generally understood as Product-Service Systems (PSS) in the industrial B2B-area [1-2]. Therefore, capital goods manufacturers enter into long-term business to business relationships with their customers. In particular, at the beginning of these relationships a high degree of uncertainty regarding customers' todays and prospective requirements exists [3].

Thus, the ability to adapt PSS to changing customer requirements becomes an important quality and success criterion along the entire lifecycle. While flexibility of manufacturing systems has been subject of research for many years [4-6], flexibility of service structures and processes is rarely considered. In order to assess and improve flexibility of PSS a flexibility concept is required that contains PSS-specific types of flexibility as well as adequate assessing methods. Against this background, this paper aims at analyzing existing approaches of flexibility assessment that mostly originate from an economic perspective. It also focuses on manufacturing systems

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regarding their suitability for PSS. At first, a conceptual understanding of PSS flexibility is given. Subsequently, requirements regarding a suitable assessment method for PSS flexibility are derived. Finally, these requirements are confronted with existing assessment approaches for assessing flexibility from economic and manufacturing perspective. Therefrom, implications for further research on assessing flexibility of PSS are derived.

2 Flexibility of Product-Service Systems

2.1 Definition

The scientific literature provides a variety of definitions of flexibility in the context of manufacturing systems [4-6]. Due to the fact that most of these definitions are formulated rather generally and refer to systems, they can be used as a basis for developing a flexibility definition for PSS. Besides of manufacturing aspects, it is of particular importance to include flexibility of service structures and processes of a PSS. In this area there is still a lack of definitions and concepts in the literature.

In the following, flexibility of PSS is understood as the ability to adapt to changing customer requirements without significant effort of time and cost. Additionally, an adequate consideration of arising risks is necessary. Thereby, adaptions of the product, of services and external production factors as well as their interplay have to be taken into account. Therefore, a wide range of possible system conditions constitutes a key prerequisite. Moreover, flexibility of PSS is understood as a relative property that depends not only on a PSS but also on the external requirements respectively changing circumstances.

2.2 New Scope of Consideration

In order to assess flexibility, first the scope of consideration has to be defined. PSS can be viewed from a static and a dynamic perspective [7]. From a static, system theoretical point of view, PSS can be differentiated into three subsystems [8, see Figure 1]. Those contain different elements that include the production factors for delivering PSS. The subsystem “product” represents a technical product that is divided by means of a function structure. The subsystem “customer” includes all external production factors the customer contributes to the PSS-realization (e.g. production site, user). The subsystem “service network” comprises the organizational and operational structures that are necessary to produce different services. When having a system theoretical view on PSS, flexibility is considered as system inherent.

In general, the lifecycle of PSS can either be viewed from provider’s or from customer’s perspective [1-2]. In the following, a PSS within customer environment is considered as scope of investigation for flexibility assessment. It starts with an investment phase that can be differentiated into decision making and purchasing. This is followed by a long usage phase of the product that is supported by different services. Finally, the disposal of the product takes place [9-10]. Neither the integrated processes of planning and developing a PSS nor the manufacturing processes are subject of the flexibility assessment. Thus, a suitable flexibility concept for PSS has to cover both system flexibility and the flexibility of the delivery processes from customer's point of view.

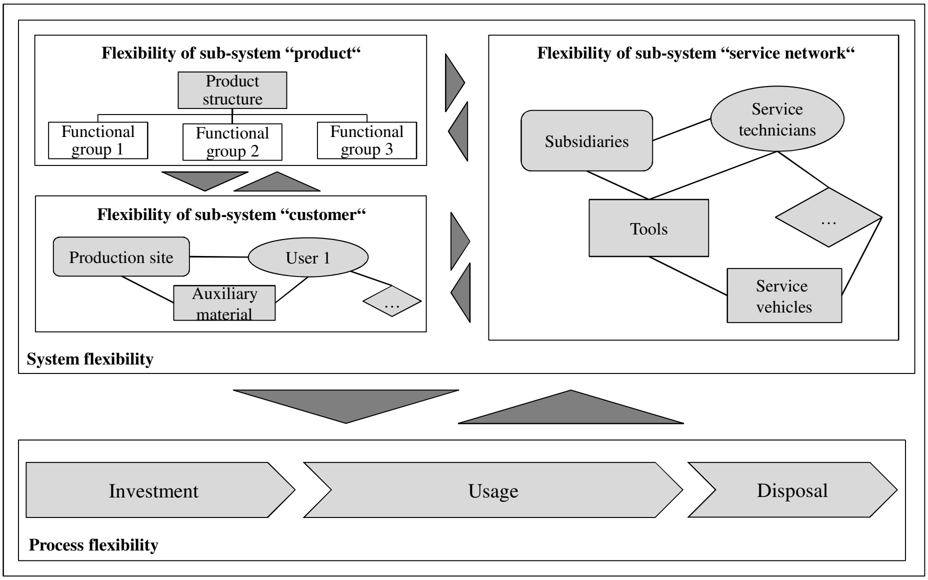

Fig. 1. New scope of flexibility evaluation (following [7])

2.3 Types of Flexibility for Product-Service Systems

In the scientific literature there is agreement that flexibility is a multidimensional phenomenon and determined by numerous influence factors [11]. This can also be transferred to PSS. In order to assess flexibility, different types of flexibility have to be defined that operationalize system and process flexibility of PSS. System flexibility consists of the flexibility of the aforementioned sub-systems. System flexibility is an intrinsic property respectively potential that sets the architecture for process flexibility of PSS. Process flexibility comprehends the ability of adapting process sequences and deployed internal and external production factors within delivery of PSS. Those processes result from the interaction between the sub-systems of a PSS.
In the following, system-oriented types of flexibility are proposed that serve for assessing flexibility of PSS and are mainly based on [4-6]:

Sub-system "product"

- **Product flexibility:** ability of a product to carry out different production tasks economically and with acceptable quality. This also includes the ability for convertibility.
- **Volume flexibility:** ability of a product to produce different production lots economically and with acceptable quality.

- **Operation flexibility:** ability of a product to operate in different production environments (e.g. mobile working machinery) as well as to produce different product variants.
- **Expansion flexibility:** ability of a product to be expanded without noteworthy cost and time (e.g. by additional product modules).

Sub-system "customer"

- **Customer flexibility:** ability of external production factors (customer's personnel, auxiliary material etc.) to adapt to changing circumstances.

Sub-system "service network"

- **Service flexibility:** ability of a service network to perform different types of services economically and with acceptable quality.
- **Volume flexibility:** ability of a service network to perform different numbers of services economically and with acceptable quality.
- **Operation flexibility:** ability to deliver services in different (production) environments as well to deliver different service variants.
- **Expansion flexibility:** ability of a service network to be expanded easily (e.g. additional service technicians).

Process flexibility of PSS can be specified into flexibility of production processes and flexibility of service processes:

- **Production process flexibility:** ability to achieve production goals in different process sequences. Depends on the flexibility of the product and the machine user.
- **Service process flexibility:** ability to generate a customer benefit with different process sequences. Depends on the flexibility of service network as well as on the flexibility of external factors (e.g. customer's personnel).

3 State of the Art in Flexibility Assessment: Review

Flexibility of PSS is analyzed from different points of view. At first, contextual requirements are worked out. In the second place, the assessment process of flexibility is based on an economic perspective. In the third place, flexibility is analyzed from a technical, engineering perspective.

3.1 Identification of Requirements

Regarding the characteristics of PSS in the industrial area (B2B), the following requirements to assess a PSS´s value were identified as working definitions:

- Level of assessment

The level of assessment is subdivided into two hierarchical categories: The PSS´s level considers the generic system and process level. In other words, the generic result can be metered. The second hierarchical level is understood as level of elements. It contains the subsystem and subprocess level and provides a more detailed description of flexibility of product and service parts, as well as the influence of the external factor. This level is far more detailed and gives insight in form of subsystems or subprocesses that are necessary to achieve the generic result.

- Dimensions of assessment

The dimensions of assessment include the categories of cost, time, adaptability and risk. These dimensions help to ensure a PSS´s functionality and productivity and therewith its overall performance. Therefore, they are important factors for an economically significant assessment of PSS in the industrial area and necessary to support technical decisions by economic values.

- Time of assessment

As far as PSS are considered, their attention is devoted to a long-term orientation and therewith to a lifecycle centered point of view. The long-term influence of decisions made in this context reverts to the underlying processes that are in charge of running the PSS successfully. Going on to an assessment that is conducted during the whole lifecycle and several times, effects of changes over time become obvious. This enables decision makers to adapt decisions formerly made to maintain the effectiveness of the underlying PSS and to react properly to changes in customer requirements or market needs.

But why is the assessment of flexibility important for PSS and how it can be done? In today´s economic environment the importance of long-term success is more and more under pressure by rising competition mostly from BRIC-countries. Anyway, the rising competition is accompanied by an increased appreciation of lifecycle costs by decision makers mostly from Eastern countries [12]. Even if some decision makers still rely on acquisition costs, their portion is decreasing because decision makers from emerging countries overcome this traditional, short-term thinking and switch to a lifecycle orientation [12].

In the following, the state of the art in evaluating flexibility of PSS is provided.

3.2 Assessment of Product-Service Systems as Investment Projects

PSS in the industrial area can be characterized as investment projects, because of the need for investments under uncertainty at the beginning of their development [13]. Hence, the approaches to be introduced in 3.2.1 originate from an investment point of view.

3.2.1 Literature Review Regarding Flexibility Assessment of Product-Service Systems

In reference [14] it is argued that use of the Real Options Analysis (ROA) can be a useful tool to determine a situation specific and appropriate degree of provided and inherent flexibility of a PSS. The whole purpose is to offer and understand flexibility as an option to improve the measurability of flexibility´s economic value in monetary terms [3]. Richter, Sadek and Steven [3] dealt with the concept of modularization [15] and observed that modularization may be a helpful tool to increase flexibility. They concluded that the approach of Baldwin and Clark [15] - when used for PSS in the industrial area - is of limited use, because of assuming additivity in value of modules. In contrast, PSS used in an industrial environment are characterized by interdependent parts of products and services that influence each other. This is due to the concerted development process regarding products and services [3].

Rese, Karger and Strotmann [16] tried to implement flexibility by determining the net present value, followed by a decision tree that is based on real options for prospective changes. In order to choose the best possible decision, the different option values are determined by using a recursive approach. By using a combination of NPV and ROA in the way of [16], a possible solution with and without flexibility is provided.

Karger et al. [17] valued flexibility according to the requirements of industrial PSS. On the one hand, the authors conducted the customer´s willingness to pay for additional flexibility and interpreted the result as value of the underlying option. On the other hand, the net value of the provided flexibility is conducted by including the provider´s costs for offering this flexibility and assessed by using the NPV approach. It is concluded that the supplier´s choice how to implement flexibility depends on the resulting value with regard to its amount in monetary terms.

Table 1. Literature review regarding assessment of flexibility of PSS

	Assessment level				Assessment dimension				Assessment type			Assessment approach	
	Product-Service System	Subsystem product	Subsystem service network	Subsystem external factor	Costs	Time	Adaptability	Risk	Ex ante	Lifecycle	Ex post	NPV	ROA
Abele et al. (2006)	○	●	○	○	◑	◑	◑	◑	◑	○	○	◑	◑
Steven et al. (2008)	●	○	○	○	○	○	○	◑	○	○	○	◑	◑
Rese/Karger/Strotmann (2009)	●	○	○	○	◑	◑	◑	○	○	◑	○	◑	◑
Karger et al. (2010)	●	○	○	○	◑	◑	◑	◑	◑	●	○	◑	◑
Richter/Sadek/Steven (2010)	●	○	○	○	◑	○	◑	◑	◑	◑	○	○	◑

completely fullfilled ● partially fullfilled ◑ not fulfilled ○

Abele et al. [18] created a concept to use the ROA on product centered manufacturing systems in order to insert flexibility including its contribution to create value. As the authors dealt with practical problems regarding different manufacturing systems, their proposal of using the Black-Scholes formula [19] is to be discussed briefly. The approach seems to be attractive for the focal scope as the authors focused on different kinds of manufacturing systems and tried to assess some kinds of flexibility.

Especially, the use of the Black-Scholes formula limits the focal analysis to only one kind of uncertainty. Furthermore, the Black-Scholes assumptions of a known market price in combination with a European option are quite unrealistic [20] for real assets in the B2B-area.

In the industrial environment of PSS, an option may also be an American option. This means that the option can be drawn at any time before maturity. Hence, the use of the Black-Scholes-Formula is insufficient with regard to the requirements of PSS and a multitude of different kinds of uncertainty. Furthermore, practitioners claim that a complexity reduction, as it is done by financial options using the Black-Scholes formula, may be risky because of the nonobservance of a multitude of variables that influence the underlying option(s) [21-22].

Table 1 unfolds that there is still a great potential for research regarding the measurability of flexibility by using Real Options in context of PSS. These articles are mainly based on the topic of industrial PSS but do not implement a formalized Real Options analysis capable to quantify a chosen flexibility option.

In the following, approaches for valuing Real Options are presented. Those are realistic but focus on valuing investment decisions with Real Options in general. Nonetheless, using these approaches seems to be an adequate way to enhance the measurability of flexibility for PSS in the B2B-area.

3.2.2 Evolution towards the Applicability on Product-Service Systems

The aforementioned approaches tried to implement flexibility into the context of PSS in the industrial B2B-area. These approaches can be understood as effective but still remain rudimentary in assessing real options and their value contribution.

As a first step to extend the adequacy of assessing the value of flexibility, the evaluation process of Copeland and Antikarov [20] is discussed. They argued, that the best comparable for the object of investigation is an adequate approximation of itself. The traditional approach of NPV is used on the investment project and constitutes the starting point for the further analysis. The NPV approach can normally be used as a static or dynamic version. Copeland and Antikarov use a Monte-Carlo simulation to determine an adequate approximation of prospective present values in different points of time. The assumption of a random walk of changes in the underlying present values supports the use of Monte-Carlo simulation in the evaluation approach. Due to this assumption, it is possible to consider a variety of uncertainties. This is an advantage compared to the Black-Scholes formula that is only capable to consider one kind of uncertainty.

But, the problem of an increase in complexity, because of a variety of different kinds of uncertainty is to narrow down. The complexity reduction is solved by combining different kinds of uncertainty - by using a Monte-Carlo simulation - and treating them like one. Therefore, the estimation of volatility is a key element to receive a satisfying result. This procedure may lead to falsification if the underlying uncertainties cannot be combined due to e.g. interdependencies. Even if statistical difficulties occur, an accompanying event tree can be constructed. It displays surrounding forms of uncertainty and the evolution of the present value in distinctive points of time in a binominal lattice. Until now, options to deal with underlying uncertainty are neither considered nor assessed.

By implementing specific kinds of flexibility, the event tree is transformed into a decision tree including a converted risk scheme and additional costs because of the provision of additional flexibility. For the first time, a difference between the values with and without flexibility results. Until now, the value of incorporated options is not evaluated separately. The approach concludes with valuing the different revenues from step to step of the decision tree and therewith the added Real Options.

3.2.3 Boundaries for the Applicability

As this approach seems to be feasible, some critics are noticeable. The problem is, that every time a decision tree is built up, assumptions have to be made, e.g. about future values of options etc., that are based primarily on uncertain and asymmetric information [21]. Haathela [23] constitutes that the approach of Copeland and Antikarov [20] leads to a bias in the estimated volatility and is therefore to be adapted according to the underlying focus of a particular analysis. Furthermore, the approach of Copeland and Antikarov [20] is not built up to value Real Options in (industrial) PSS. The special characteristic of an integrated development of product and service parts is difficult to measure. The value contribution of a technical part is measurable quite easily because of the existence of appropriate data. It becomes much more complicated to measure the value contribution of services like training courses or a technician's personnel skill. But the main problem to be solved in future research is to determine the value that evolves from the collaboration of provider and customer.

The similarities to the approaches analyzed in 3.2.1 are pointed out in the following:

An exclusive and separated usage of the approaches mentioned above, limits the focal scope to chosen, localized applications. Changes over time are not considered adequately. In case of using only a static NPV approach without considering flexibility options, the consequence will be a permanent underestimation of the project´s real value [16]. The resulting bias may lead to incorrect managerial decisions. Using ROA separately is extremely difficult to solve due to a significant rise in complexity and effort in computing option values. The approach of Copeland and Antikarov [20] including critics of Haathela [23] can be understood as a feasible starting point for the valuation of flexibility of (industrial) PSS.

3.3 Flexibility Assessment of Product-Service Systems Based on Approaches from a Manufacturing Perspective

3.3.1 Literature Review Regarding Flexibility of Manufacturing Systems

Flexibility assessments in manufacturing environments refer either to technical or to socio-technical systems. This includes approaches on different system levels (plant level, production line level, and machine level). In this context, numerous assessment approaches were developed. In the following section selected approaches for flexibility assessment on machine level are analyzed and evaluated against the defined requirements of PSS (see chapter 3.1).

Most approaches for assessing flexibility refer to manufacturing systems respectively machine level. Mandelbaum and Brill [24] developed a mathematical description of flexibility that is based on theory of probability. They defined measures in order to quantify the notion of how well a machine or group of machines can absorb changed requirements. They recommended measuring the efficiency of the manufacturing equipment in performing its tasks to evaluate manufacturing flexibility. Chang et al. [25] described flexibility of manufacturing systems as a function of range of operations, time, and cost. They propose different equations that are based on entropy approach, which was extended from information theory, and the Data Envelopment Analysis (DEA) for the measurement of manufacturing flexibility [25].

Table 2. Classification of selected approaches for flexibility assessment

	Assessment level				Assessment dimension				Assessment type		
	Product-Service System	Subsystem product	Subsystem service network	Subsystem external factor	Costs	Time	Adaptability	Risk	Ex ante	Lifecycle	Ex post
Mandelbaum et al. (1989)	○	●	○	○	○	◑	●	●	●	○	○
Chang et al. (2001)	○	●	○	○	●	○	◑	◑	●	●	○
Reinhart et al. (2007)	○	●	○	○	◑	◑	●	○	◑	●	●
Baykasoglu et al. (2008)	○	●	○	○	●	●	●	●	●	○	○
Lanza et al. (2010)	○	●	○	○	●	○	◑	◑	●	●	○

completely fullfilled ● partially fullfilled ◑ not fulfilled ○

Reinhart et al. [26] understand flexibility as a potential of a manufacturing system that is determined in the early phases of its design. Thereby, they considered volume and variant flexibility. In order to measure and assess flexibility of manufacturing systems they developed indicators for each flexibility type. These indicators are supposed to be monitored within so called flexibility corridors [26-27]. Baykasoglu et al. [28] the theory of permanents is applied to measure the flexibility of manufacturing systems. They developed a flexibility diagraph that comprehends different states that a system is able to work in and its possibility to move from one state to another. Flexibility is determined by assessing the efficiency of the current state as well as the efficiency of moving from one state to another. Moreover, flexibility depends on the probability of operating in one state as well as the probability of changing states [28]. Lanza et al. [29] propose an assessment approach for flexible quantities (volume) and product variants in production. It aims at forecasting production costs by a simulation algorithm that allows a comparison between different production scenarios.

Table 2 shows a scheme for classifying the approaches for flexibility assessment against the requirements derived from the characteristics of PSS. It serves as summarizing overview of the discussed approaches of flexibility assessment in manufacturing environments.

3.3.2 Implications to Flexibility Assessment of Product-Service Systems

Research on flexibility of manufacturing systems goes back to the early 1980s. Thus, numerous flexibility types and assessment methodologies were developed and discussed in this area. With regard to PSS it can be captured that these approaches are transferable to the sub-system "product" of a PSS. However, there is still a lack of approaches for flexibility assessment of service networks and the influences of external factors. Moreover, the interdependencies between product and services that occur within PSS delivery process are not covered by the existing approaches. In order to fill this gap, investigating the existing approaches regarding their expandability to assess flexibility of service network and external factor seems promising. Therefore, approaches have to be appropriate to measure and assess the flexibility types for PSS defined in chapter 2.3.

There is wide agreement in the scientific literature that flexibility of manufacturing systems can be assessed regarding the dimensions cost, time, and amount of possibilities for adaption. These dimensions are also included in the aforementioned flexibility definition for PSS. Among the analyzed approaches only [28] considers these three dimensions equally. Most of the approaches focus only on one dimension and consider the others indirectly. With regards to PSS the system-oriented flexibility types should be measured by indicators concerning possibilities for adaption. The process-oriented types of flexibility should be measured by indicators in terms of effort of cost and time needed for adaptions. For visualizing and monitoring these indicators, the flexibility corridor according to [26] is applicable. It has to be noted that system flexibility of PSS constitutes a key influence factor on process flexibility. These interdependencies between flexibility types exist and have to be revealed and included in the flexibility assessment of PSS.

Most of the analyzed approaches are based on ex ante assessments that use different scenarios and simulation algorithms to forecast flexibility. This is caused by the fact that flexibility is viewed as an inherent property of a system that is determined before its usage. But these simulation-based approaches seem problematic when transferring them to service processes. In particular, customer contributions in service processes are highly individual and therefore difficult to predict and hard to simulate [30]. Rather, a lifecycle oriented approach is necessary that allows a measurement of flexibility indicators at defined measuring times during delivery of PSS. At this point it can be concluded that new indicators have to be developed that are able to operationalize all flexibility types for PSS. In particular, indicators for measuring and assessing the flexibility types of service networks, customer influences on PSS flexibility as well as the interdependencies between products and services are required.

4 Summary and Further Research

This article focused on both the economic and the engineering point of view. From the economic perspective, the assessment of flexibility was analyzed by using approaches of investment theory. The technical assessment was conducted by focusing on a detailed description of flexibility types and appropriate indicators on a subsystem level. The authors conclude that a comprehensive flexibility assessment is required. It is recommended to assess a PSS´s value by using a combination of NPV and ROA that is to be combined with an indicator based approach in order to link strategic and operative needs by monitoring and control flexibility and its monetary impact along its lifecycle. Due to the special properties of PSS, the existing approaches cannot be transferred easily. For example, the influences of customers on process flexibility of PSS (production process flexibility, service process flexibility) have to be considered by using adequate indicators. From the technical perspective, an adapted definition of data gathering is needed for computing problem specific indicators as a task for further research. In the economic assessment of flexibility, the focus of future research lies on an adequate adaptation of the introduced approaches in order to implement specific characteristics and problems of industrial PSS.

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