Simulation-Based Risk Management of Product-Service Systems

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SUMMARY & CONCLUSIONS

Products are increasingly accompanied by services such as maintenance or leasing contracts. The share of services of these so-called product-service systems (PSS) is expected to gain. The provider of such PSS-related services needs a comprehensive knowledge of the product properties and service requirements – particularly the product reliability and availability as well as necessary service resources – in order to minimize its financial risk. Hence, powerful methods need to be applied to the risk management of these services.

The reliability and maintenance simulation offers a great potential for the risk management of PSS-related services. The presented powerful modeling methods are able to consider various product and service parameters which are compared in an overview. The conjoint system model yields the maximum modeling power and is able to consider manifold dependencies and reciprocal effects. The Monte Carlo simulation is the established method for the analysis of the operational parameters. A wide range of applications can be covered, considering the complexity as well as the field of application.

The analyzed operational parameters are an integral base for the risk management of PSS-related services as they enable to evaluate the financial risks. The application of fundamental operational parameters to the risk evaluation of several exemplary PSS-related services is summarized. It is explained how the risk management process is integrated into the different stages of the PSS life cycle. Several risk measures which are common in finance are applied to the risk evaluation. The capability of the method is demonstrated by an example: The risk management of a maintenance contract for a production line with guaranteed maximum maintenance time including a bonus malus system.

1! INTRODUCTION

More and more services are offered along with a product, for instance in terms of warranty extensions, maintenance contracts, leasing agreements or build-operate-transfers. Furthermore, services accompanying the product are increasingly offered as part of the product. The share of services of these PSS is expected to gain [1], [2]. An advancement of these product accompanying services toward so called "hybrid performance bundles" is predicted for the future. From this it follows that the importance of PSS-related services will further increase.

The provider of such services needs a comprehensive knowledge of the product properties and service requirements during the planned period of operation, particularly the product reliability and availability, necessary service resources and costs [3] in order to minimize its financial risk. Hence, powerful methods need to be applied to the development and utilization of these PSS-related services and the evaluation and management of the associated risk.

This paper is organized as follows: In chapter 2 the reliability and maintenance simulation is presented, which serves for the analysis of the operational product properties and service requirements. Founded on these simulation results, the risk management of PSS-related services along its life cycle is illustrated in chapter 3 and demonstrated by an example.

2! RELIABILITY AND MAINTENANCE SIMULATION

The reliability and maintenance simulation is a powerful method which facilitates the calculation and prediction of product characteristics concerning reliability, service resources and costs in a substantiated way. The simulation can be divided into two main parts: Modeling and analysis.

2.1! *Modeling*

Numerous aspects have to be taken into account when modeling. The so-called inherent parameters, i.e. those parameters which can be allocated to the product or its service directly, are of crucial importance. The main issues are the inherent properties of reliability, functional logic, maintenance strategy, production process, resources as well as dependencies and cost drivers. These modeling aspects are summarized in Table 1.

Different modeling methods for the analysis of reliability, maintainability and availability are introduced in a general overview below. The main focus is on graphical modeling methods, specifically on state-space oriented methods since they offer great advantages for the description of dependencies and reciprocal effects. Graphical modeling methods can be categorized in combinatorial, queue oriented and state-space oriented. Certain established basic modeling methods can be allocated to these categories:

- Combinatorial models: Reliability block diagram (RBD), fault tree
- Queue oriented models: Queues (Q)

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- State-space oriented models: Markov state graphs (MG), Petri nets

Modeling aspect \ Modeling method	RBD	Q	MG	ESPN	ECSPN	CSM
General						
Concurrency/Synchronization	–	○	–	+	+	+
Chronological sequences	–	○	–	+	+	+
Competition	–	○	○	+	+	+
Queuing behavior	–	+	–	○	+	+
Timed/Stochastical system behavior	–	+	+	+	+	+
Dynamic changing system behavior	–	–	–	–	○	○
Fuzzy input data	–	–	–	–	+	+
Reliability						
Reliability structure	+	–	–	○	○	+
System and component states	–	–	○	+	+	+
Constant failure rates	–	+	+	+	+	+
Time-dependent failure rates	–	–	–	+	+	+
Dynamic changing failure behavior	–	–	–	○	+	+
Aging; Several operative states*	–	–	–	–	+	+
Failure dependencies	–	–	○	○	+	+
Functions						
Functional states	–	–	○	+	+	+
Functional sequences	–	–	–	+	+	+
Functional logics, dependencies	–	–	–	○	+	+
Maintenance						
Corrective maintenance	–	–	○	+	+	+
Preventive maintenance	–	–	○	+	+	+
Inspections	–	–	–	○	+	+
Sensor-based condition monitoring	–	–	–	–	+	+
Time-dependent transition rates	–	–	–	+	+	+
Degree of renewal*	–	–	–	○	+	+
Spare part logistics	–	–	○	+	+	+
Limited maintenance capacities	–	–	○	+	+	+
Maintenance dependencies	–	–	○	+	+	+
Production						
Material flow	–	+	○	+	+	+
Information flow	–	+	○	+	+	+
Production structure	–	+	–	+	+	+
Queuing behavior	–	+	–	○	+	+
Priorities	–	–	–	–	+	+
Production dependencies	–	+	–	+	+	+
Costs						
Duration-/Number-based costs	–	–	–	–	+	+
Variable Costs/Revenues	–	–	–	–	+	+
* with time-dependent failure or transition rates						

Table 1 – Comparison of modeling methods (+ = can be directly modeled; ○ = can be modeled with restrictions; – = cannot be modeled or only with high effort)

Combinatorial models are advantageous for the description of the reliability structure, i.e. how components of the product influence its main function. Queue oriented models allow for describing queuing processes, e.g. the waiting of several faulty components to be repaired by a single service personnel. State-space oriented models have benefits when describing the states of a product and its components as well as transitions between these states, which are often described by stochastic distribution functions. Possible states could be "functioning" and "failed". Petri nets, allocated to the category of state-space oriented models, represent an excellent method for the modeling of reliability and maintenance. Over the course of the last few decades, ordinary Petri nets have been advanced to a series of very powerful higher-level Petri-net categories (an overview is given in [4]).

One variant very suitable for the modeling aspects summarized in Table 1 are the Extended Coloured Stochastic Petri Nets (ECSPN) [4]. Based on the ECSPN, the so-called Conjoint System Model (CSM) has been developed. The CSM is capable to unite the modeling world of Petri nets – i.e. a state-space oriented model, the ECSPN – with the RBD – i.e. a combinatorial model [4]. Certain advancements and supplements are found in the mentioned references in chapter 3, whose preliminary last status is represented by [5].

The modeling methods offer different degrees of complexity and performance which are assessed comparatively in Table 1 [6]. Therefore, the CSM is the most powerful method, which even allows for the incorporation of the reliability structure in the model.

2.2 *Analysis*

For the analysis of models, especially of the more powerful models describing numerous time-dependent stochastic parameters and dependencies, only simulation-based techniques can be applied [3]. The Monte Carlo simulation is the established analysis technique for the simulation of reliability and maintenance [7]. By means of the Monte Carlo simulation, a stochastic "game" is played with the model, with a great number of "matches", i.e. replications. The moves of the playing parties can be interpreted by means of statistical methods. An extensive description of the Monte Carlo algorithm as an analysis technique for the modeling methods introduced in section 2.1 is given in [4].

The analysis of the models provides important parameters which are associated with the operation of the product and the accomplishment of the services, the so-called operational parameters [4]. They take into account all dependencies as well as the reciprocal effects and are usually time- or event-based.

Besides the operational reliability, functionality, productivity and availability of the product these are parameters which describe the quality of the service, which performs maintenance or provides the aligned resources, e.g. maintenance personnel and spare parts. Exemplary operational parameters are:

- Reliability parameters: Lifetime distributions
- Functional parameters: Function state probabilities
- Production parameters: Process time distributions
- Availability parameters: Point or interval availability, operation time or down-time distribution
- Maintenance parameters: Number of maintenance actions

or maintenance time distributions, maintenance delay time distributions
- Spare part and logistic parameters: Number of required spare parts, supply delay times, service level of spare part inventory
- Cost parameters: Operational costs, maintenance costs, spare part costs

These operational parameters can be used as a base for the evaluation of financial risks related to guaranteed performance values, which are an integral part of the PSS contracts. This is an integral part of the risk management of PSS. This topic is described in the next chapter and underlined by the example in section 3.5.

3 RISK MANAGEMENT OF PRODUCT-SERVICE SYSTEMS

The reliability and maintenance simulation offers a great potential for the risk management of PSS. This paper focuses on the PSS-related services.

3.1 *Range of Applications*

The presented method of simulation-based modeling and analysis is able to cover a broad range of application. It can be applied to products with different complexity – from a single component to a comprehensive system – due to its few and general modeling elements (basically two different modeling elements in Petri Nets: places and transitions) and universal analysis possibilities.

Products of most diverse fields of applications can be considered. The products may consist of components of different engineering domains, e.g. mechanical, electrical and electronic components combined with actuators, sensors and information and control technology, generally named as mechatronic systems. Below, several representative examples (references can be found in [6]) with different complexity and from different areas are summarized to underline the performance of the method:

- Automotive and mechanical engineering, e.g. a parallel hybrid power train of a car
- Machine tool or facility engineering, e.g. the axis of a machine tool [5]
- Production and its processes, e.g. a flexible productions system
- Logistics, e.g. a delivery scenario
- Power engineering, e.g. a photovoltaic system
- Aerospace engineering, e.g. a pressure control system of a space laboratory

3.2 *Product-Service Systems*

A product-service system (with the already introduced acronym PSS) is a combination of a product with one or several product-related services [1]. A PSS can be categorized by its product to service ratio [2]:

- Product based: Product related service or consulting
- Operation based: Product leasing, hiring, sharing, or pooling. Frequently pay-on-availability, i.e. the product's availability and operability is guaranteed
- Outcome based: Activity management, pay-per-use or functional results or outcomes. Also, pay-on-production is common, i.e. the revenue results from the number of units produced

The operational parameters – gained by the method in chapter 2 – are a fundamental basis for the risk management of PSS-related services, as they provide the performance values which can be evaluated in terms of their financial risk. An example is a warranty extension of a product which can be assessed based on the analyzed operational reliability.

Table 2 lists, for several exemplary product-service-systems, which fundamental operational analysis parameters can be applied for the risk management. The most important parameters for the evaluation of financial risks are represented accordingly in each case (based on [6]).

Operational analysis parameter / Product-service system	Reliability	Maintainability	Availability	Productivity	Logistics	Spare parts demand	Costs
Warranty extension	+						
Maintenance and repair contract		+	○		+	○	
Operational warranty (e.g. mobility warranty)			+		○	○	
Leasing, hiring, sharing or pooling	+		+		○	○	○
Spare part provisioning						+	
Pay-per-use	+		○	+	○	○	+
Pay-on-production	○		+	+	○	○	+
Build-operate-transfers	+	○	+	+	○	○	+

Table 2 – Risk management based on operational parameters (+ = most important parameter; ○ = secondary parameter)

3.3 *Risk Management*

The reliability and maintenance simulation is applicable for risk assessment throughout various stages in the PSS life cycle. The life cycle is roughly divided in the early development phase, the later development phase and the usage, or operation, period, which is shown in Figure 1.

The early development phase covers the planning, conception and layout of the PSS. In the later development phase, the further definition and validation of the PSS is contained. In the usage period the product is operated and the related services are performed. The evaluation of the financial risk and the comparison with a target risk are the elementary parts of a risk management process. According to the deviation of the actual risk from the target value, several measures can be initiated by this risk management process in order to control the risk.

In the early development phase the simulation enables to predict the operational parameters of the product, which can be used for the conception of the services and early evaluation of the associated financial risk. Depending on the risk, measures can be implemented to adapt the product or service properties.

In the later development phase, when testing results (of the product or the service facilities) are available, the improved information situation can be used to confirm or further improve the service and concretize the risk evaluation. Based on the evaluated risk, further measures might be necessary to improve product or service properties. If the evaluated risk is below the target and might be increased, measures to optimize the product or service (e.g. a higher guaranteed performance value) could be considered.

During the usage period of the product, the warranty and service data can be applied to improve the service accomplishment and to further reduce the risk. The simulation enables one to investigate the effect of variations, e.g. the influence of the increase or the reduction of maintenance personnel on the operational availability. If the evaluated risk is lower than the target, measures can be initiated such as optimizing (i.e. lowering) the service resources or extending maintenance intervals. If the risk is exceeding the target value, measures to reduce the risk need to be initiated, e.g. the service resources need to be increased. If an optimization does not sustainably improve the risk, then a negotiation of contracted performance values might also be considered.

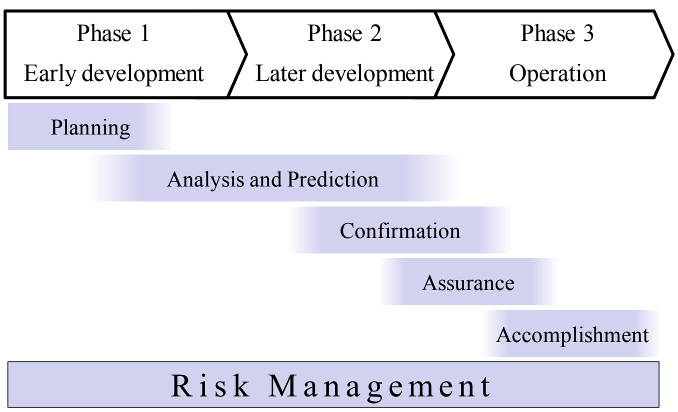

Figure 1 – Simulation-based risk management along the service life cycle

It should be mentioned here, that the aspects of gaining the input data for the risk evaluation is not covered within this paper. It is assumed that the inherent probability distribution functions which describe e.g. the inherent lifetime or maintenance time of a product are provided by a separate appropriate process. This process collects, condensates and analyzes the data along the life cycle of the PSS. In early phases, the data is usually based on expert knowledge, data of predecessors or calculations. In later development phases, test results can be analyzed which provide a higher confidence for the inherent parameters. In the usage period of the product when the offered services are accomplished, warranty and service data can be made available. From this data, the inherent parameters can be further confirmed and the actual operational parameters can be analyzed. Methods for the statistical analysis of data can be found in [3] as well as Bayesian methods for combining data of different sources and lifecycle stages. By combining the simulation analysis method of section 2.2 and the data analysis process described above, the operational parameters can be tracked along the PSS life cycle.

It can be generally stated that the data process mentioned before enlarges considerably the data base of the PSS supplier. The data can be collected from online monitoring (e.g. operation data stored in electronic control units), condition monitoring (e.g. sensor-based data), service-personnel reporting or logging data and spare part orders. Based on the operational data, operation profiles or load collectives can be derived. In doing so, information about the actual properties of products or services (both parts of a PSS), either from in-house production or supplied by third parties, can be gathered and compared. An advantage is that it is relatively easy to get access to this data compared to the situation of "regular" product seller, where the feedback about product properties is normally limited to the warranty period. If the PSS-related services are offered longer than the warranty period lasts, which would often be the case, then the services provide a lot of additional product information in the post-warranty period. In doing so, the actual operational parameters can be analyzed. Based on the analysis, early warnings of potential product weaknesses can be identified. Moreover, all data can be used for the development of predecessor products. All these aspects, as well as the increase of the data base, are a significant additional benefit of the PSS-related services.

3.4! *Financial Risk*

These services constitute a certain economic risk for the offering party, which intends to minimize or exclude this risk as far as possible. The decision for or against a specific service variant contains a specific risk.

The objective is to reach the highest possible profit in combination with a lowest possible risk. For this purpose the decision maker needs to know the probability of unwanted events which leads to risks [8]. Often, one-sided risk measures are applied, so-called shortfall or quantile measures. The shortfall considers the case of falling below a target value. The quantile of a distribution function can be used alternatively as a risk measure. A quantile is defined as the value which is undercut by a given probability (1%, 5%, 10%, …). The α-quantile Q_α of a distribution $F(\bullet)$ is defined as

$$Q_\alpha = F^{-1}(\alpha)\,. \qquad (1)$$

The most established risk measure is the Value at Risk (*VaR*) which is used in banking and finance for risk control (especially for the securitization of risks by equity capital) [9]. For a given portfolio, the profit-and-loss distribution $F_{PL}(x)$ describes the probability that the profit X will be equal or smaller than a value x for a given time horizon. The *VaR* of a given confidence level $1-\alpha$ is defined as the loss value L (often expressed as complement to a negative profit, i.e. $L = -X$) which is not exceeded with probability $1-\alpha$, i.e. *VaR* corresponds to the α-quantile of the profit-and-loss distribution $F_{PL}(x)$,

$$VaR_{\alpha}(X) = F_{PL}{}^{-1}(\alpha) \; . \tag{2}$$

Often the *VaR* is given by a positive number (L) although it represents a loss (profit X has a negative value). The *VaR* is a so-called downside risk measure which enables measurement of potential losses, i.e. the left (negative) side of the profit-and-loss distribution is considered.

A further measure is the Expected Shortfall (*ES*) which evaluates the risk area and describes the average of all *VaR* for $0 \le x \le \alpha$ by

$$ES_{\alpha}(X) = \frac{1}{\alpha}\int_{0}^{\alpha} VaR_{\gamma}(X)d\gamma \; , \tag{3}$$

i.e. the averaged loss with probability α [10].

The operational parameters which are analyzed by the method of chapter 2 are an integral base for the calculation of the financial risk measures related to a product-service system. The decision for a specific service variant or contracted and guaranteed performance value can be taken based on these risk measures. The risk can be considered for decision making by determining the risk measure for an operational parameter, e.g. the *ES* for a contracted production volume. Furthermore, it allows the investigation of improvements and the effect of countermeasures initiated by the risk management process.

3.5! *Example: Maintenance Contract*

The following example shows how the risk management for PSS-related services can be based on the operational parameters.

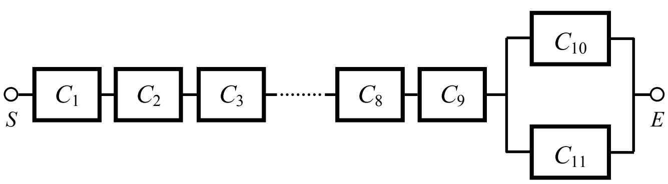

Figure 2 - Reliability block diagram of the production line

The financial risk of a maintenance contract for a production system which is described in detail in [4] shall be evaluated. The production system consists of 11 machines. The RBD of the production line is shown in Figure 2. It is built by a series path out of nine machines, i.e. machine C_1 through C_9, and a parallel path of two machines, i.e. machine C_{10} and C_{11}. The number of maintenance personnel for the entire production line is limited to 3 persons. A repair priority is given to the components of the series path. This means that if a machine in the series part is failed at the same time as a machine of the parallel production path, it will be repaired first. This example focuses on the parallel production path.

For machines C_{10} and C_{11}, a maximum duration of repair is guaranteed by the contract in order to limit the maximum down-time of the entire production line. It is specified by the customer with 336 h. The intended contract contains a penalty if the specified maximum downtime is exceeded. The downtime cost of the system is 20,000 €/h. The penalty (i.e. the malus) is defined as 2 % of the downtime cost, i.e. 400 €/h. Furthermore, a bonus of 400 €/h is granted if the actual repair time is lower than the specified maximum downtime. The contract foresees a yearly determination of the bonus or penalty based on the actual repair times. The contract duration is 8 years. The yearly contracted turnover (i.e. the maintenance costs) amounts to 812,500 € on average.

The provider of the maintenance contract intends to limit its financial risk. Therefore, the financial risk of the contract conditions is evaluated by means of the *VaR*. A maximum value for VaR_{α} with a confidence level of $1 - \alpha = 95\ \%$ is given as a limit, i.e. a loss value L which is not exceeded with probability $1 - \alpha = 95\ \%$. This limit value is 162,500 € per year which is 20 % of the yearly contracted turnover.

The analysis of the operational parameters yields the distribution functions of the operational repair duration which consists of the inherent repair duration, i.e. the duration of the repair activity itself, and the maintenance and logistics delay time, i.e. the waiting time for maintenance personnel and spare parts. In [4] the operational repair duration for machine C_{10} and C_{11} has been analyzed by a *Weibull* distribution [3] with shape parameter $b = 3.1$ and characteristic lifetime $T = 297.2$ h. The mean number of repairs per year has been determined as $N_R = 15.3$.

Based on these analyzed operational parameters and the bonus malus conditions stated above, the profit-loss-distribution F_{PL} is generated, which describes the probability of the yearly bonus or malus (i.e. negative bonus). The risk measures for the required confidence level are determined as $VaR_{\alpha}(X) = -534{,}600$ €. That means, with a probability of 5 % the loss L is higher than 534,600 €. With a probability of 95 % it is lower.

The evaluated financial risk is considerably higher than the target value. Therefore, during the risk management process, a measure to reduce the financial risk needs to be defined. The maximum duration of a repair acceptable to keep the financial risk below the target value is investigated. Considering the maximum value for $VaR_{\alpha} = -162{,}500$ € per year yields a maximum repair duration of 396.8 h. The

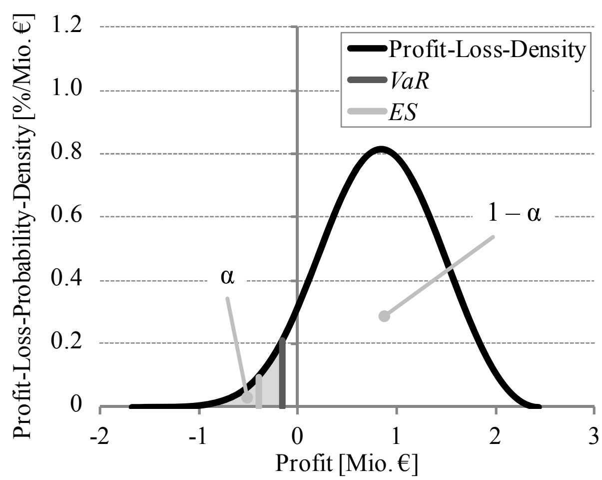

Figure 3 - Density function of the profit-loss-distribution

service provider will negotiate a maximum repair duration of

397 h in order to reduce his financial risk to the intended level.. Based on the increased maximum repair duration, an updated profit-loss-distribution F_{PL} is generated. The corresponding density function f_{PL}, as well as the *VaR* and *ES* are shown in Figure 3. The bright grey area on the left of the *VaR* under the density function represents the probability of $\alpha = 5$ %, whereas the area to the right of the *VaR* is the intended confidence level of $1 - \alpha = 95$ %.

The risk measures for the required confidence level are determined as $VaR_{\alpha}(X) = -161{,}520$ € and the corresponding expected shortfall as $ES_{\alpha}(X) = -397{,}440$ €. That means, with a probability of 5 % the loss L is higher than 161,520 €. If the loss exceeds the value $VaR_{\alpha}(X)$, the average loss will be 397,440 €.

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