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A Failure Analysis Method for Designing Highly Reliable Product-Service Systems

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Abstract

Recently, Product-Service Systems (PSSs), which create value by integrating a physical product and a service, have been attracting attention. In PSSs, it is critical for a provider to offer highly reliable products and services. To do so, the provider needs to effectively and efficiently detect possible failures, and then, take adequate measures against them in the conceptual design stage. However, in current studies on product failure analysis, service aspects are not covered in analyzing failure causes and developing measures. On the other hand, product aspects are hardly considered in existing methods of service failure analysis. To fill the gap, this paper proposes a method for failure analysis in PSS design called PSS Failure Mode and Effect Analysis (PSS FMEA). Especially, this paper extends the framework of FMEA, and then, a procedure for PSS FMEA is introduced so that designers can analyze failures and develop measures in consideration of both product and service aspects. Furthermore, the proposed method supports designers in finding new business opportunities. The proposed method was applied to a real offering of products and services by a cleaning machine provider and found effective.

Keywords

Product-Service Systems, Design, Reliability, FMEA, Business opportunity

1. Introduction

As our economy matured, most manufacturing companies in developed countries have struggled to differentiate their products by pursuing improvement of product technologies (Neely et al. 2011). Because of this predicament, Product-Service Systems (PSSs) (Baines et al. 2007; Goedkoop 1999; Mont 2002; Tukker and Tischner 2006) have received attention as a promising option for differentiating products and increasing revenue for manufacturers. A PSS is a marketable set of products and services jointly capable of fulfilling users' needs (Goedkoop 1999). For fulfilling users' needs in a highly competitive business environment, it is critical that a product and/or service is highly reliable. This holds especially true in providing a PSS that is often driven by users' high reliability demands; for instance, in the telecom, aircraft, and construction machine sectors. To provide the reliability demanded, it is both effective and efficient to detect possible failures, and then, take adequate measures against them in the conceptual design stage. While many researchers have proposed general methods for analyzing failures in design (Kurtoglu et al. 2010; Stone et al. 2005), such methods are not suitable for PSS design. Since a PSS is an integrated system of products and services for fulfilling users' needs, product failures could be caused by the product itself as well as services. Furthermore, measures taken against these failures should be designed in consideration of both product and service aspects. In previous methods, however, missing links exist with regard to (1) analyzing the cause of failures and (2) developing measures against failures.

To fill the gap, this paper proposes a method for failure analysis in PSS design called *PSS Failure Mode and Effect Analysis* (PSS FMEA). This method enables designers to conduct an integrated analysis of product failures and service failures in PSS design. Especially, the paper extends the framework of FMEA (MIL-STD-1629 1980), which is widely used in the product and service field (Kurtoglu et al. 2010; Stone et al. 2005). In the proposed method, design object models for PSSs (Hara et al. 2009; Shimomura and Tomiyama 2005) are adopted so that designers can analyze product and service failures. Furthermore, these failures are prioritized from the viewpoint of their influence on users' needs. The measures taken against high-priority failures may imply new business opportunities. To verify the proposed method, it has been applied to a real offering of products and services by a cleaning machine provider.

The remainder of the paper consists of the following sections: Section 2 presents the literature review, while Section 3 proposes the new method; Section 4 presents the case study; and Sections 5 and 6 present the discussion and conclusion, respectively.

2. Failure analysis for products and services

2.1. Failure analysis in the product design

Failure Mode and Effect Analysis (FMEA), which was originally developed by the US military (MIL-STD-1629 1980), is an engineering technique used to identify, prioritize, and eliminate potential failures from systems under design before a product is released. In general, it is a challenge for designers to predict possible failures exhaustively in the conceptual design stage, especially in new product or service design. To address this problem, in FMEA, a failure is analyzed from the viewpoint of *failure mode*, which is defined as "the way in which a product or process could fail to perform its desired function" (Lange et al. 2001). An example of a product failure mode is disconnection in an electrical circuit. Even though it is difficult to list possible failures exhaustively in a new system, it is predictable that disconnection causing some failures could be happen in the case of the system including electrical circuit. Therefore, by extracting possible failure modes and taking measures against them, FMEA enables designers to prevent failures and enhance the reliability of the system.

In the product design field, many researchers have proposed methods that adopt FMEA to address product reliability. For instance, Stock et al. proposed the function-failure design method (FFDM) (Stock et al. 2003), which aims to provide designers with a methodology for performing failure analysis in conceptual design. For the FFDM, Stone et al. (2005) investigated the process of populating function-failure knowledge bases with actual failure occurrences. Eubanks et al. (1997) developed an advanced FMEA that uses behavior modeling to simulate device operations and helps identify failures. This method can be applied to the early stages of design and captures failure modes normally missed by conventional FMEA. Kurtoglu et al. (2010) also proposed a method for evaluating potential failures and the resulting functional losses during early stages of conceptual design. In this method, functional descriptions are adopted to describe early concepts, and then, Function-Failure Identification and Propagation (FFIP) analysis, which was originally introduced in Kurtoglu and Tumer (2008), is conducted to simulate functional failure propagation. Kmenta et al. (1999) furthermore extended the advanced FMEA to identify problems that might occur within a manufacturing process.

2.2. Failure analysis in product maintenance

Some researchers have used FMEA to analyze failures with respect to product maintenance requirements. Kimura et al. (2002) proposed a computer-aided FMEA to conduct product behavior simulations, and then, FMEA process can be performed in a computer-aided manner. In addition, based on the results, maintenance planning can be evaluated by simulating life cycle operations of machines and predicting their reliability during operation. Zhang et al. (2010) applied FMEA for supporting the conceptual design of product and maintenance (P&M). This method uses Quality Function Deployment (QFD) to translate customer requirements into product concepts and maintenance strategies; FMEA is then utilized to identify and analyze failure modes and their effects on the product concept. Based on the results of QFD and FMEA, maintenance concepts are generated. Rhee and Ishii (2003) developed Life Cost-Based FMEA, which measures risk in terms of cost. This method adopts a Monte Carlo simulation in order to consider uncertainties in detection time, fixing time, and so on. The results can help designers select design alternatives that can reduce the overall life cycle cost and plan preventive and scheduled maintenance of

components. Kmenta and Ishii (2004) highlighted inconsistencies in the risk prioritization of traditional FMEA, and then, proposed a new measure of risk based on expected cost. Furthermore, a failure scenario, which represents a cause-and-effect chain, was adopted to analyze product failures comprehensively throughout a product life cycle.

2.3. Failure analysis in service design

Since the reliability of a service is crucial to its quality and for customer satisfaction, several researchers have applied FMEA to service designs, including Chuang et al. (2007). In their proposed approach, a blueprint representing the service process is used to identify potential failure modes, and then, FMEA is applied to prioritize critical potential failure modes and take the actions required to ensure service design performance. In addition, Chuang (2010) proposed a method for calculating the adverse effect of service failures on quality perceptions. FMEA is also employed to reduce medical errors by identifying risk rankings of health care failure modes and taking priority actions to improve safety (Reiling et al. 2003). Geum et al. (2011) proposed a systematic framework for improving service productivity using an FMEA-based portfolio approach. This framework identifies a failure mode as well as an innovation mode that can provide opportunities for innovation to increase productivity. For each mode, a portfolio matrix is constructed in order to choose the most effective solutions for productivity.

2.4. Failure and reliability analysis in Product-Service Systems

In PSSs, designers need to focus not only on the product itself but also on man/machine interaction, such as training and working conditions, as well as the product utilization process, including its productivity and the occurrence of failure (McAloone and Andreasen 2002). Furthermore, business models tend to transfer responsibilities for these phases from the customer to the supplier, which means that the financial risk caused by a system failure is transferred to the supplier as well (Richter et al. 2010). Therefore, many researchers have investigated evaluating PSS business models in consideration of system failures. Erkoyuncu et al. (2009) proposed a cost estimation method that considered the mean time between failure (MTBF) and the mean time to repair (MTTR). Legnani et al. (2010) assessed how the introduction of preventive maintenance contracts can influence the overall service performance of a manufacturer. For the assessment, the model was developed based on component malfunctions and the failure rate of parts. Bianchi et al. (2009) developed a simulation method to analyze the possible evolution of a PSS strategy from a traditional product-oriented market. In this method, criteria for evaluating the success or failure of the PSS consist of compliance to stakeholders in meeting their needs, efficiency, and the effectiveness of the PSS solution.

Additionally, in the PSS design field, several studies have explored uncertainty, risk, and reliability with the goal of designing a high-reliability PSS. From a review of the literature pertaining to uncertainties in service delivery, Erkoyuncu et al. (2011) classified service uncertainties from the perspectives of demand and supply sources. Based on these uncertainties, uncertainty-modeling methods were proposed for service cost estimation. Sakao et al. (2013) proposed a theoretical and generic framework, called *the PCP* (Provider - Customer - Product) *triangle*, in which various types of benefits and risks associated with a PSS are classified on the basis of information flow and uncertainty. Wang and Durugbo (2013) proposed a hybrid fuzzy methodology for evaluating the uncertainty of service networks. This method concomitantly adopts fuzzy methodologies, leveraging the knowledge of domain experts to evaluate network uncertainty for transitions from traditional product-focused operations to service-oriented operations. Sun et al. (2012) developed a method of evaluating the reliability of a PSS based on service providers' interrelationships, determining whether it is reliable for fulfilling multiple product-service requirements associated with a complex product. As reviewed briefly in this section, PSS failure analysis has not been well researched; in particular, FMEA for PSS design has hardly been represented in the literature thus far.

2.5. Knowledge gap to be filled

As mentioned in the previous sections, many researchers have proposed general methods for analyzing failures in design. From the viewpoint of failure analysis in PSS design, however, missing links exist with regard to (1) analyzing the cause of failures and (2) developing measures against such failures. As introduced earlier, in existing methods in product design, the causes of product failures are analyzed from

the product aspect (Zhang and Chu 2010). Namely, service aspects are not covered as causes of product failures (missing link (a) in Fig. 1). Furthermore, measures taken against product failures are mainly realized by the product itself, and therefore, service measures are limited to maintenance (missing link (b) in Fig. 1). On the other hand, in existing methods for service failure analysis, product aspects are hardly considered (missing link (c) and (d) in Fig. 1). However, since a PSS is an integrated system of products and services for fulfilling users' needs, product failures could be caused by the product itself as well as by services, such as operations and maintenance. Furthermore, for the development of measures against these failures, designers need to consider not only product aspects but also service aspects. In order to enhance the reliability of services in a PSS, it is also essential to consider product aspects against service failures.

Fig. 1 Missing links in failure analysis for PSS design

3. Failure mode and effect analysis for PSS design

3.1. Approach of the proposed method

To solve the problems mentioned in the previous section, this paper extends the framework of FMEA so that designers can analyze failures and develop measures in consideration of both product and service aspects. Especially, the proposed FMEA focuses on the conceptual design stage of PSS redesign for finding new business opportunities where new services could be provided. As mentioned in Section 2.1, FMEA analyzes failures from the viewpoint of failure modes. Therefore, it is necessary to extract constituent elements of a PSS and these failure modes exhaustively. To do so, in the proposed method, design object models for PSSs (Hara et al. 2009; Shimomura and Tomiyama 2005) are adopted to define the target scope of failure analysis and to extract constituent elements and failure modes exhaustively. This is a strength of the proposed method and can be seen as a scientific contribution of the paper. Furthermore, since one of the important objectives of offering a PSS is to fulfill users' needs, extracted failure modes are prioritized from the viewpoint of their influence on such needs. Developing measures against high-priority failures will also be effective for finding new business opportunities where new services could be provided as commercial offerings by taking advantage of greater freedom than in the product or service design.

Below, the definition and scope of PSS failure in this paper is introduced. Subsequently, in Section 3.3, the framework of PSS FMEA is proposed to address the missing links introduced in the previous section. Finally, a procedure for PSS FMEA is introduced in Section 3.4.

3.2. Definition of PSS failure

As compared to the product field, the PSS literature lacks discussions on failure. In particular, there is no widely accepted definition of service failure. This study assumes that the fundamental interpretation of product failure and service failure is essentially the same. Since products and services are produced to provide users with required functions, failures with respect to both can be defined in terms of an event that disables the provision of required functions. Therefore, this study defines a *PSS failure* in a way similar to the definition offered by Lange et al. (2001) in the product field: "the termination of the ability of an item to perform a required function."

This definition implies two differences in how PSS failures and product failures should be addressed. The first difference involves the understanding of the term *item* in this definition. In PSSs, a required function is realized by either product behavior or service activity. Therefore, the *item* here refers not only

to product components but also to actors who conduct service activities, such as employees, organizations, and users. The other difference concerns the perspective for evaluating the required function. As mentioned previously, an objective of offering a PSS is to fulfill users' needs (Goedkoop 1999); therefore, the required function must be evaluated from the perspective of users. According to this definition, this study defines *failure mode* as "the way in which a component's behavior or an actor's activity could fail to perform its desired function."

3.3. Framework of PSS FMEA

Table 1 shows the proposed worksheet for FMEA in PSS design. This framework is extended from the original one in order to analyze product failures and service failures simultaneously and identify critical failures in fulfilling a user's requirement. Columns represented by bold and italic characters are points extended from the original FMEA. The rest of this section introduces characteristics of this worksheet that are different from those of worksheets in existing studies.

Table 1 A worksheet for PSS FMEA with some example descriptions

Item (component or actor)		Characteristic of failure				Rating				<i>Recommendation</i>
<i>Component name /actor's name</i>	<i>Component behavior /actor's activity</i>	<i>Failure mode</i>	<i>Causes of failure</i>	<i>User requirement affected</i>	<i>Current Process and Organization Controls</i>	Probability	Severity	Detection	Priority	
Product component A	Warning of lack of battery power	Fail to warn of lack of battery power	Degradation of the sensor	Reducing machine downtime	Daily check in cleaning service company	1	3	3	9	Increasing frequency of inspection
			Fault in daily check	Reducing machine downtime	None	3	3	3	27	Improving reliability of the sensor
			Fault in daily check	Reducing machine downtime	None	3	3	3	27	Improving management of the daily check
Actor B	Conducting maintenance	Oversight of cracks	Fault in daily check	Reducing machine downtime	None	3	5	3	45	Improving education for Actor B

Note: Causes of failures shaded blue describe causes of service aspects
Recommendations in boxes shaded blue are measures from a service viewpoint

Item (component or actor)

An item here is considered as a fundamental unit for analyzing PSS failures. According to the definition of a PSS failure outlined above, items here include not only product components but also actors who conduct service activities. In addition, the actors include the provider as well as the user, since a user can be regarded as a coproducer of value in services (Vargo and Lusch 2004). In this column, product components and actors, both of which realize required functions in the PSS, are identified; then, their names are listed. For each product component, behaviors are described for detecting failure modes. In the same way, activities are associated with each actor.

Characteristic of failure

In the same manner as in the product field (Lange et al. 2001), this method defines *failure mode* as "the way in which a process could fail to perform its desired function." Note that this process is performed through component behavior as well as through actor's activity. In this column, failure modes are detected from the perspective of the component behaviors or actor's activities described in the items. For each failure mode, subsequently, causes of failure are clarified. These causes include both product and service aspects. For instance, with regard to the failure mode, "fail to warn of lack of battery power," shown in Table 1, its causes include "degradation of the sensor" (product aspect) and "fault in daily check" (service aspect).

Finally, an effect of each failure is evaluated. As mentioned above, in this method, a PSS failure is defined as the inability of an item to perform a required function. Furthermore, this required function is evaluated from the perspective of the user. In the proposed PSS FMEA, therefore, a user requirement affected by each failure is listed in this column. This requirement corresponds to a functional requirement as well as one related to the experience, knowledge, and emotion of the user. Finally, designers fill in current organizations and processes that control and detect failures.

Rating

This rating shows the priority of PSS failures that should be addressed in the PSS design. Priority is calculated by the product of probability, severity, and detection. Probability is evaluated by the occurrence frequency of the failure mode. On the other hand, severity is calculated on the basis of the influence on a user's requirement, as described in the column "characteristic of failure," so that designers can identify critical failures in fulfilling a user's requirement. Additionally, detection is evaluated from the viewpoint of abilities to detect the occurrence of failures.

Recommendation

This column shows measures for guarding against a PSS failure. In PSS FMEA, it is important to consider measures related to both the product and service. One measure that could be taken to guard against product failure could be changing the product structure itself; another measure could offer support service. For instance, as shown in Table 1, "improving reliability of the sensor" (product viewpoint) could be used as a measure against "degradation of the sensor"; another measure could involve "increasing frequency of inspection" (service viewpoint). This is based on the notion articulated as *exchangeability* by Sakao and Lindahl (2015); *exchangeability* refers to the ability to exchange efforts for service and product design to improve the overall PSS characteristics of interdependent products and services.

3.4. Procedure for PSS FMEA

3.4.1. Step 1: Description of PSS design models

A PSS consists of a complex system of products, services, and networks of various stakeholders. Therefore, in order to define the target scope of failure analysis, this procedure begins with a description of PSS design models. Since an objective of offering a PSS is to fulfill users' needs (Goedkoop 1999), PSS FMEA defines the target scope of failure analysis from the viewpoint of a user's requirement. To do so, in this step, designers describe a flow model (Shimomura and Tomiyama 2005) in order to define the target user. Furthermore, for extracting failures that affect the target user's requirement, a view model and extended service blueprint are described (Hara et al. 2009; Shimomura and Tomiyama 2005). Details of each model are as follows.

● Flow model

A PSS involves various kinds of stakeholders. Between a user and a provider, there may be many intermediate stakeholders. As shown in Fig. 2, the flow model represents stakeholders involved in the PSS and their relationships (Shimomura and Tomiyama 2005).

Fig. 2 A flow model example (modified from Shimomura and Tomiyama 2005)

● View model

The view model represents functional relationships among a user's requirement, functions, and entities (Shimomura and Tomiyama 2005). Entities in the view model represent not only product components but also actors for services, such as employees and organizations. As shown in Fig. 3, the view model works as

a bridge from a user's requirement to entities, and thus, it is useful for designers to identify product components and actors for services that perform required functions.

Fig. 3 A view model example (modified from Shimomura and Tomiyama 2005)

- Extended service blueprint

Fig. 4 An extended service blueprint example (modified from Hara et al. 2009)

While the original service blueprint illustrates the activity-oriented aspects of a service (Shostack 1982), the extended service blueprint consists of an interrelated activity blueprint and a behavior blueprint (Hara et al. 2009). The activity blueprint specifies the service delivery process and the interactions between the user and the provider. On the other hand, the behavior blueprint specifies processes of product components to realize functions. For describing both blueprints, Business Process Modeling Notation (BPMN) (White 2004) is adopted for the service blueprint so as to have consistent semantics. As shown in Fig. 4, the extended service blueprint represents necessary behaviors for product components as well as requisite activities for actors.

3.4.2. Step 2: Determination of items (components and actors)

As mentioned above, PSS FMEA defines the target scope of failure analysis from the perspective of a user's requirement. To define the scope, designers first determine a stakeholder corresponding to the user from the stakeholders described in the flow model. With reference to the requirements of the user, a target

requirement is selected. In accordance with the scope, designers subsequently determine the items. In PSS FMEA, the items consist of product components and actors for services that perform required functions. To determine the items, therefore, designers select the view model that describes a structure for fulfilling the target requirement. With reference to entities in the view model, product components and actors for services are listed as items in PSS FMEA.

As mentioned before, in this method, a failure mode is defined as “the way in which a component behavior or actor’s activity could fail to perform its desired function.” In order to detect failure modes, in this step, component behaviors and actors’ activities are clarified based on the extended service blueprint. In the blueprint as shown in Fig. 4, tasks of product components correspond to component behaviors; tasks of actors, such as a user and provider, correspond to actors’ activities.

3.4.3. Step 3: Analysis of PSS failures

In this step, designers first detect failure modes. With reference to component behaviors and actors’ activities described in the previous step, designers detect failure modes in which these behaviors or activities could fail to perform their desired functions. For each failure mode, causes of the failure mode are subsequently clarified. As mentioned above, these causes are analyzed from the viewpoint of product and service aspects. For example, with regard to the oversight of component damage in a periodic inspection, this failure mode might be caused by a product aspect—because of the component’s structure, the damage was difficult to find during inspection. It might also be caused by a service aspect, such as a fault in the checking process by maintenance staff. Subsequently, designers describe the user’s requirement as influenced by each failure. With reference to the view model selected in Step 2, the requirement that is influenced by the failure can be identified. Lastly, with reference to the extended service blueprint, designers fill in current organizations and processes that control the causes of failures. These organizations and processes could belong to the provider as well as to the user. If there are no relevant organizations and processes, nothing is entered in this column.

3.4.4. Step 4: Prioritization

Designers subsequently determine the rate that indicates the priority of failure modes that should be addressed in the PSS design. This rate is calculated by the product of probability, severity, and detection. With regard to probability, frequency of occurrence is evaluated for each cause of failure by using a five-point scale ranging from “rarely occurs” to “frequently occurs.”

Receiver requirements	Importance of requirements	Functions in the first layer		
		F_{11}	F_{12}	...
R_1	W_{R1}	$S^{F_{11}}_{R1}$	$S^{F_{12}}_{R1}$	...
R_2	W_{R2}	$S^{F_{11}}_{R2}$	$S^{F_{12}}_{R2}$	...
...	...	.. co-relational strength		
Influence of functions		I_{F11}	I_{F12}	...

Functions in n^{th} layer	Influence of functions	Functions in the $n+1^{th}$ layer		
		$F_{(n+1)1}$	$F_{(n+1)2}$	...
F_{n1}	$I_{F_{n1}}$	$S^{F_{(n+1)1}}_{F_{n1}}$	$S^{F_{(n+1)2}}_{F_{n1}}$	...
F_{n2}	$I_{F_{n2}}$	$S^{F_{(n+1)1}}_{F_{n2}}$	$S^{F_{(n+1)2}}_{F_{n2}}$	...
...	...	.. co-relational strength		
Influence of functions		$I_{F_{(n+1)1}}$	$I_{F_{(n+1)2}}$	...

Functions in the lowest layer	Influence of functions	Behaviors or activities		
		b_1	a_1	...
F_{lest1}	$I_{F_{lest1}}$	$S^{b_1}_{F_{lest1}}$	$S^{a_1}_{F_{lest1}}$	...
F_{lest2}	$I_{F_{lest2}}$	$S^{b_1}_{F_{lest2}}$	$S^{a_1}_{F_{lest2}}$	...
...	...	.. co-relational strength		
Influence of behaviors or activities		I_{b1}	I_{a1}	...

Fig. 5 Procedure for calculating influence on a user's requirement using Quality Function Deployment (QFD)

Severity is calculated on the basis of the influence of relevant component behaviors or actor's activities on the user's requirement. To calculate the influence, Quality Function Deployment (QFD) (Akao et al. 1990) is applied to the view model in the same manner as in Shimomura et al. (2008). As shown in Fig. 5, at first, tables are prepared that depend on the number of layers between the user's requirement and the lowest functions in the view model. In each table, designers determine co-relational strength between elements in the vertical column and elements in the horizontal row (S); these values are then normalized in each row. Subsequently, designers determine the importance of each requirement in the view model (W_R). Influence of functions (I_{FI}) in the first layer is calculated by the summation of the product of co-relational strength (S) and the importance of requirements (W_R). In the same way, the influence of functions in the following layers is calculated. Finally, designers prepare the table that represents the co-relational strength between the lowest functions in the view model and component behaviors or actor activities; then, the influence of behaviors or activities is calculated in the same manner as calculating the influence of functions. This process should be conducted with multiple designers so that they can compensate for each other's relative levels of knowledge. Detection indicates the abilities of control processes and organizations in order to detect the occurrence of failure causes. With reference to "Current Process and Organization Controls," the likelihood of detecting a failure cause is evaluated using a five-point scale ranging from "almost certain" to "absolute uncertainty."

3.4.5. Step 5: Developing recommendations and finding new business opportunities

In this step, designers finally develop measures against each failure mode. To enhance quality and efficiency for realizing required functions in a PSS, these measures should be developed from the viewpoint of both the product and service; exchangeability between the product and service should be fully utilized here as well. For example, with regard to a failure that has occurred in product operation, from the perspective of the product, failure can be prevented by changing the product structure itself, such as improving the user interface. From the perspective of service, on the other hand, failure can also be prevented by offering adequate services, such as dispatching support technicians.

Furthermore, in this step, designers seek new business opportunities based on the results thus far, because new services can lead to new offerings and, therefore, to new businesses. This is impossible via FMEA for a product, where service is not addressed as part of an offering. With regard to failures caused by the user's activities, for example, if it is difficult for a user to address these failures by itself, then the provider could offer new services to support the user's activities.

4. Application

4.1. Overview of a PSS case

This company is a provider of cleaning machines with a certain level of complexity. One of their product models is shown in Fig. 6. In this application, the proposed method was applied to the conceptual design of PSS redesign, where the cleaning machine corresponded to the core product. The cleaning machine is used to polish concrete floors of buildings such as department stores, museums, and warehouses. A polished concrete floor provides several benefits for the users of a building, such as making exhibits look more attractive and making the floor easier to clean. Furthermore, the company also provides various kinds of services, such as repair, training, and furnishing of tools. The company possesses world-leading technologies and applies the latest technologies to their products and services. Their products are used on every continent, and some services are provided through the company's certified service garages. Before this application, they had utilized a traditional FMEA for their products within a cross-functional group and had already begun to incorporate the service aspect without modifying the method as such. They had perceived the method time consuming. Especially, agreeing on where and how a discussed issue should be described was regarded as time consuming. Their fundamental motivation for using this newly proposed PSS FMEA was based on their continuous efforts to provide their users with higher value. The objectives of this application were to analyze whether the new method enabled the company the followings effectively and efficiently.

- To address both product failures and service failures.
- To develop measures against the failures as well as to find new business opportunities for the company.

Fig. 6 Overview of a floor-cleaning machine

Table 2. Results of applying PSS FMEA to the case (excerpt from the section “Reducing machine downtime”)

Component name/ Actor name	Component behavior/Actor's activity	Characteristic of failure				Rating				Recommendation
		Failure mode	Causes of failure	User requirement affected	Current Process and Organization Controls	Probability	Severity	Detection	Priority	
Electricity box (Fig. 6 (e))	Warning of loss of suction power	Fail to warn of loss of suction power	Degradation of the sensor	Reducing machine downtime	Daily check in cleaning service company	1	4	3	12	Increasing frequency of inspection
			Inadequacy of the maintenance cycle	Reducing machine downtime	None	4	4	5	80	Improving reliability of the sensor
			Failure of alarm adjustment (initialization)	Reducing machine downtime	Daily check in cleaning service company	2	4	3	24	Identifying maintenance schedule based on machine use data
										Improving reliability of the sensor
										Providing an installation service
										Improving the warning system for easy to initialize
Operator (from cleaning service company)	Conducting daily check	Oversight of alert	Fault in daily check	Reducing machine downtime	None	4	3	5	60	Installing sensing devices for independent monitoring center
			Difficulty noticing the alert sound	Reducing machine downtime	Product quality control in machine manufacturer	1	3	1	3	Improving design of the alert
		Oversight of leaks in a garbage bag (Fig.6 (d))	Fault in daily check	Reducing machine downtime	None	5	3	5	75	Installing sensing devices for independent monitoring center
			Difficulty finding leaks	Reducing machine downtime	Product quality control in machine manufacturer	4	3	1	12	Improving design of garbage bags
Service technician (from machine manufacturer)	Checking the pre-separator (Fig.6 (c))	Oversight of cracks in the cover	Lack of knowledge about cracks	Reducing machine downtime	Education for service technicians	1	1	3	3	Improving education for service technicians
			Difficulty finding cracks visually	Reducing machine downtime	Product quality control in machine manufacturer	2	1	1	2	Improving design of the pre-separator
	Checking the sealing (Fig.6 (b))	Oversight of leaks in seal surfaces	Fault in check	Reducing machine downtime	Service management in machine manufacturer	2	1	3	6	Improving management of service technicians
			Difficulty finding leaks visually	Reducing machine downtime	Product quality control in machine manufacturer	2	1	1	2	Improving design of the dust extractor
	Checking hoses (Fig.6 (a))	Oversight of blockages in hoses	Fault in check	Reducing machine downtime	Service management in machine manufacturer	1	1	3	3	Improving management of service technicians
			Difficulty finding blockages visually	Reducing machine downtime	Product quality control in machine manufacturer	3	1	1	3	Improving design of internal hoses
	Repairing machine	Fail to fix problems	Difficulty finding causes	Reducing machine downtime	Service management in machine manufacturer	3	5	3	45	Determining causes based on machine use data

Note: Causes of failures shaded blue describe causes of service aspects
Recommendations in boxes shaded blue are measures from a service viewpoint
Recommendations in boxes shaded red are measures that combine product and service viewpoints

4.2. Results of the application

Table 2 shows some of the results of applying the proposed PSS FMEA. In the following sections, these results are explained in more detail in accordance with the proposed procedure.

4.2.1. Step 1: Description of PSS design models

In this application, a flow model was first described to define the target scope of the failure analysis. Fig. 7 shows the description of the flow model. This PSS consisted of three stakeholders: a cleaning machine manufacturer, a cleaning service company, and building users. The manufacturer provides a cleaning machine and services the machine. The cleaning service company operates the cleaning machine to polish the building's floor. This application focused on the relationship between the cleaning machine manufacturer and cleaning service company. The manufacturer corresponds to the PSS provider; the cleaning service company is regarded as the target user.

Fig. 7 Flow model of a PSS with regard to a floor-cleaning machine

In order to extract failures systematically, a view model and extended service blueprint were subsequently described. First, view models were described to clarify the necessary product components and actors for the required functions. Due to the business hours of clients, the cleaning service company has a limited amount of time to clean floors. As a result, downtime for the cleaning machine is crucial for the company to clean floors within the available time. Therefore, this application focused on the requirement of the company: reducing machine downtime. Fig. 8 shows the view model for the requirement of reducing machine downtime. In this view model, an abstract function, “preventing failures,” was associated with the requirement, and then, decomposed into detailed functions, such as “monitoring operating conditions” and “conducting a shutdown inspection.” These functions were finally associated with product components, such as an electricity box (see Fig. 6 (e)), as well as actors, including an operator and a service technician. Here, the operator corresponds to an actor of the user, i.e., the cleaning service company. On the other hand, the service technician belongs to the PSS provider.

Fig. 8 View model for reducing machine downtime

To analyze PSS failures in the following step, the extended service blueprint was subsequently described to clarify the behaviors and activities of the items in the FMEA. Fig. 9 shows the extended service blueprint. This blueprint describes the activities of the operator (daily check of the machine) as well as those of the service technician (periodic maintenance). Furthermore, this blueprint includes the behavior of the cleaning machine (monitoring and detecting problems).

Fig. 9 Extended service blueprint of daily check and periodic maintenance

4.2.2. Step 2: Determination of items (components and actors)

Next, components and actors in the view model were listed as the items in the FMEA, as shown in the left column of Table 2. In this application, “electricity box” was listed as a product component item; “operator” and “service technician” were listed as actor items. With reference to the extended service blueprint, behaviors and activities were subsequently associated with items in the FMEA. For example, from tasks of the electricity box in Fig. 9, “warning of loss of suction power” was a behavior associated with the electricity box. On the other hand, “conducting daily check” was an activity associated with the operator, and “checking the pre-separator” was described as an activity of the service technician.

4.2.3. Step 3: Analysis of PSS failures

In this step, failure modes were detected based on component behaviors and actor’s activities. The center column in Table 2 shows an example of the detected failure modes. For example, “fail to warn of loss of suction power” was detected as a failure mode with regard to the electricity box’s behavior—“warning of loss of suction power.” On the other hand, “oversight of cracks in the cover” was detected as the failure mode of an activity of the service technician—“checking the pre-separator.” Furthermore, as failure modes caused by the user’s activity, “oversight of alert” and “oversight of leaks in a garbage bag” were extracted as failure modes of the operator’s activity—“conducting daily check.” For each failure mode, causes of failure were subsequently clarified from the perspectives of product and service aspects. Boxes shaded blue in Table 2 describe cause of service aspects. For example, “degradation of the sensor” was identified as a cause of a failure mode of the electricity box, i.e., “fail to warn of loss of suction power.” With regard to failure modes of the operator such as “oversight of alert,” “difficulty noticing the alert sound” was identified as a cause of failure from product aspects. In addition, “fault in daily check” was detected as one caused by a service aspect. Subsequently, “reducing machine downtime” was described as a user’s requirement that was influenced by these failures. Finally, with reference to the extended service blueprint, current organizations and processes that controlled causes of failures were filled in. For example, “daily check in cleaning service company” was described as a control process for “degradation of the sensor,” “failure of

alarm adjustment,” and so on. “Service management in machine manufacturer” was described as a control process for fault in check in periodic maintenance. Furthermore, no organizations and processes existed for some failures, such as “inadequacy of the maintenance cycle” and “fault in daily check.”

4.2.4. Step 4: Prioritization

Fig. 10 Tables of the user’s requirement and functions

Table 3 Tables of functions and component behaviors/actor activities

Functions in the lowest layer in the view model	Influence of Functions	Component behaviors or actor activities					
		Warning of loss of suction power	Conducting daily check	Checking the pre-separator	Checking the sealing	Checking hoses	Repairing machine
Monitoring operating condition	0.31	1					
Conducting daily check	0.20		1				
Conducting periodic maintenance	0.12			1	1	1	
Addressing failures on-site	0.14						1
Addressing failures in the service center	0.23						1
Influence of behaviors or activities		0.31	0.20	0.04	0.04	0.04	0.37

Subsequently, the rate was determined so as to indicate the priority of failure modes to be addressed. Based on an interview with the manufacturing company, the probability was first evaluated using a five-point scale ranging from “1: rarely occurs” to “5: frequently occurs.” Second, using QFD, the severity was

calculated based on its influence on the requirement. First, as shown in Fig. 10, tables were prepared that depended on the number of layers between the user's requirement and the lowest functions in the view model; in each table, the co-relational strength was determined. In the same way, as shown in Table 3, a table was developed to determine the co-relational strength between functions and component behaviors/actor activities. Based on these tables, the influence of component behaviors or actor's activities on the user's requirement was calculated; then, the severity was determined according to the influence score. In this study, values of the influence were normalized, where the maximum value corresponded to 5 and the minimum value corresponded to 0. Furthermore, detection was evaluated using a five-point scale ranging from "1: almost certain" to "5: absolute uncertainty."

Then, the priority was calculated using the product of probability, severity, and detection. As a result, high-priority failure modes included "fail to warn of loss of suction power" caused by "inadequacy of maintenance cycle" and "oversight of leaks in a garbage bag" caused by "fault in daily check."

4.2.5. Step 5: Developing recommendations and finding new business opportunities

Finally, measures against each failure mode were developed from the perspective of both the product and service. Recommendations in boxes shaded blue in Table 2 are measures from a service viewpoint. For example, to counter the failure mode of the electricity box, i.e., "fail to warn of loss of suction power," "increasing frequency of inspection" was developed as a service measure. On the other hand, "improving reliability of the sensor" was determined as a product measure. Furthermore, recommendations in boxes shaded red correspond to measures that combine product and service viewpoints. As a measure against failure modes of the operator, the recommendation of "installing sensing devices for independent monitoring center" was developed. This measure could be realized by sensing devices (product) as well as monitoring (service).

Based on the results, a new business opportunity was recognized. In this application, "oversight of alert" and "oversight of leaks in a garbage bag" were detected as failures caused by an operator's activities. These failures were caused by the operator's "fault in daily check." In addition, the priority of these failures was relatively high as compared with those of other failures. Therefore, a measure taken to guard against these failures could be a new service for the cleaning company. By installing and using the sensing devices on the cleaning machine, the manufacturer would be able to monitor the machine's condition and conduct a daily check instead of the cleaning service company's operator.

4.3. Feedback from the case company

The results of applying the proposed method have been regarded as both useful and interesting. First, the method's systematic manner of description was found to allow them to effectively describe and analyze both product and service aspects, but with clear distinctions from each other. This could contribute to shortening the time needed to perform FMEA. Second, use of FMEA-based methods to find new business opportunities was new and interesting to them. Furthermore, they regarded the proposed method as an effective way to incorporate service-related issues into the traditional FMEA, which they were familiar with. For example, the case company has analyzed product failures from the viewpoint of components of the floor-cleaning machine, such as the electricity box. This existing knowledge can be utilized as inputs for the product viewpoint in the proposed PSS FMEA, as shown in Fig. 1.

5. Discussion

5.1. Effectiveness of the proposed method

This paper proposed a framework of FMEA that enables designers to conduct an integrated analysis of product and service failures. According to the framework, the procedure was introduced, and then, applied to a real offering of products and services by a cleaning machine provider. The results of its application revealed that the proposed method enabled designers to analyze causes of failures from the perspectives of both product and service aspects. As a novelty of the proposed method, causes of product failure modes were detected from service aspects (corresponding to Fig. 1 (a)), while causes of service failure modes were detected from product aspects (corresponding to Fig. 1 (c)). For example, "fail to warn of loss of suction power" was detected as a product failure mode of the electricity box. As a cause of this failure, "degradation

of the sensor” was detected from product aspects. Furthermore, “inadequacy of the maintenance cycle” was detected as a cause from service aspects (corresponding to Fig. 1 (a)). With regard to service failures such as “oversight of leaks in a garbage bag,” “fault in daily check” was detected as a cause from service aspects. Furthermore, “difficulty finding leaks” was detected as a cause from product aspects (corresponding to Fig. 1 (c)).

The application also demonstrated that the proposed method enabled designers to develop measures against these failures from the perspective of both the product and service. As a novelty of the proposed method, service measures were developed for causes of product failures (corresponding to Fig. 1 (b)), while product measures were developed for causes of service failures (corresponding to Fig. 1 (d)). For example, with regard to a cause from a product aspect such as “degradation of the sensor,” “improve reliability of the sensor” was determined as a product measure. Furthermore, “increase frequency of inspection” was developed as a service measure (corresponding to Fig. 1 (b)). With regard to a cause from a service aspect such as “fault in daily check” of the operator, “install sensing devices for independent monitoring center” was developed as a measure that combined product and service viewpoints. This result includes a product measure that addresses a cause of failure from a service aspect (corresponding to Fig. 1 (d)).

The proposed method includes a procedure for describing PSS design models. Especially, the flow model was described to define the target user, and then, the view model and extended service blueprint were developed to extract components, actors, and their failure modes exhaustively. Furthermore, according to the models, extracted failures were prioritized based on their influence on the requirement of the user. By applying these results, a new service was developed —monitoring of the machine’s condition by the provider using sensing devices and conducting daily checks rather than relying solely upon the cleaning service company’s operator. Reflecting this information in the design solution enables designers to find new business opportunities to provide a more reliable PSS. For example, Fig. 11 shows the view model and extended service blueprint that were improved based on the recommendation, “install sensing devices for independent monitoring center.” In the current business, the cleaning service company’s operator takes responsibility for the daily maintenance of the cleaning machine, such as checking alerts and the garbage bag. However, it is sometimes difficult for the cleaning service company to manage operator skills to ensure the quality of the daily check. Faults in the daily check may cause significant troubles with the cleaning machines, resulting in increased machine downtime. Since reducing machine downtime is a crucial requirement for the company, the newly developed service offers new potential. This is an example of the proposed method’s usefulness for designers in finding new business opportunities.

Fig. 11 An improved design solution based on the recommendation in the PSS FMEA

Based on feedback from the case company, practical contributions of the method can be summarized as

follows. First, the method can be used to understand and document influences and opportunities to address services as a part of a company's offerings. Second, the method can be applied to a potential offering as well as to an existing one. Third, the method provides great potential for implementation at a manufacturing company because FMEA is a widely utilized method in industry; what is needed is to implement additional, service-related components to enhance the utility of using FMEA-based methods.

5.2. Possible improvements of the proposed method

In the proposed method, product and service failure modes are extracted based on design object models for PSSs, i.e., a view model and an extended service blueprint. However, doing so depends on designers' knowledge about how to extract possible causes of failures, which they might fail to do exhaustively. To solve this problem as future work nonetheless, one could integrate the proposed method with a process simulation tool (Kimita et al. 2012) in order to predict failures and detect their causes. This simulation tool could also adopt the extended service blueprint, and therefore, outputs of the simulation could be compatible with inputs of the proposed FMEA. Furthermore, the development of measures against these failures is also largely dependent on the knowledge and experience of designers. To address this problem, developing software that stores existing knowledge about failures and countermeasures in the database could be a solution. The authors have developed computer-aided design software for PSSs that supports designers in creating solutions based on an analogy with existing solutions (Sakao et al. 2009). Furthermore, this software offers several functions that evaluate design solutions from the viewpoints of cost, customer satisfaction, and so on. Therefore, future work could include implementing the proposed FMEA in the software so that designers can develop measures against failures.

This application focused on the functional requirement "reducing machine downtime" because of characteristics of the case company. In order to achieve a successful PSS, however, designers need to consider not only functional requirements but also experiential requirements. Since the view model adopted in the proposed FMEA enables designers to consider such kinds of requirements, additional applications are required to conduct failure analysis in consideration of experiential requirements. Additionally, the application revealed that the proposed method is especially useful for designing a product-oriented PSS, in which the provider sells products and offers some extra services (Mont 2002). In order to enhance the reliability of products and services, however, designers need to consider failures caused by the combination of products and services. These kinds of failures are more relevant in result-oriented PSS, where products and services are highly integrated to offer outcomes for customers (Mont 2002). Therefore, future work could include extending the proposed method for analyzing failures caused by the combination of products and services.

6. Conclusion

This paper proposed a method for failure analysis in PSS design. Especially, the PSS FMEA was proposed so that designers can conduct integrated analysis of product and service failures. Based on the results of the case study, the proposed method was found to be effective for helping designers detect both product and service failures, and then, develop measures from the perspectives of products and services. Furthermore, it was also effective for finding new business opportunities where manufacturers could offer new services with products. Future research could include the implementation of the proposed method in software to increase its efficiency.

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