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Paper:

Ontological Descriptions for Integrating Design Information of Product-Service Systems

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Product-service systems (PSS), which create value by integrating physical products and services, have received much attention as a promising option to increase manufacturers' revenue and reduce environmental impact. The process of designing a PSS requires collaboration among various experts who use domain-specific knowledge. Therefore, several researches have been investigated for developing design tools tailored to their expertise. However, while the specialization of design tools can be useful for experts, it hinders companies from ensuring the integrity of design information in different design elements. This results in the failure in achieving expected benefits. To address these issues, this study applies the concept of interoperability to PSS design to integrate design information from different domains. In particular, ontological descriptions is adopted to achieve semantic interoperability in different design elements. The application of the proposed ontology to a lecture on PSS design highlights that the proposed method is effective for integrating information on PSS design elements and those between value creation and capture.

Keywords: product-service systems, design, interoperability, ontology

1. Introduction

In a maturing economy, most manufacturing companies, particularly in developed countries, struggle to distinguish their products by pursuing improved product technologies [1, 2]. Furthermore, the limitations of the current linear economic model (i.e., the take-make-use-dispose model) have pushed society toward a circular economy, which is restorative by design and aims to keep products, components and materials at their highest utility and value at all times [3]. Against this background, product-service systems (PSS), which create value by integrating physical products and services, have received attention as a promising option to both increase manufacturers' revenue and reduce environmental impacts [4]. In PSS, customers pay for product utilization instead of the products themselves, such as paying for mobility instead of cars and cleaning services instead of washing powders. The role of manufacturers has shifted toward service provision aimed at creating the highest possible value derived from product use with the lowest possible costs of the lifecycle by prolonging a product's life, minimizing resource loss, and so on. This enables manufacturers to improve resource efficiency and generate a new revenue stream [5]. From an economic viewpoint, Wise and Baumgartner highlight that moving downstream in the value chain allows manufacturers to discover new revenue sources [6]. According to Neely, manufacturing companies that offer services generate higher revenues [1]. Eggert et al. reveal that services supporting clients' actions (SSC) directly impact revenue and profit streams, while services supporting suppliers' products (SSP) indirectly affect financial performance mediated through SSCs [2]. Despite the high expectations for PSS, in practical terms, many companies have struggled to achieve the expected benefits. Many researchers have provided the evidence that investment in extending the service business does not necessarily result in generating the expected corresponding higher returns [7]. For example, Fang et al. revealed that the impact of a company's transition to services on firm value remains relatively flat or slightly negative until the firm reaches a critical mass of service sales [8]. For achieving the expected benefits, many researchers have emphasized on the importance of ensuring the integrity among various design elements, such as products, services [9, 10], organizations [11, 12], and partner networks [13, 14]. However, existing methods and tools focused on particular elements that are described with domain specific knowledge, terminologies, and representations. This situation hinders companies from evaluating the integrity of design information on these elements. For addressing this problem, this study develops ontological descriptions for PSS design aimed at integrating design information in different design elements. The proposed ontology is verified through an application to a lecture on PSS design.

The remainder of this paper is organized as follows. Section 2 discusses the motivation underpinning this re-

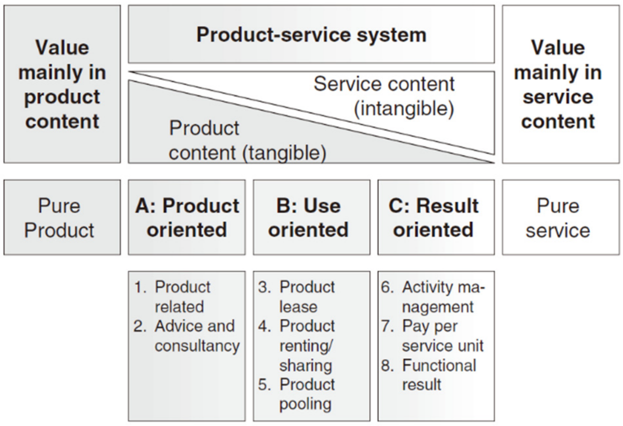

Fig. 1. PSS categories and sub-classifications [4].

search while reviewing the extant literature. Section 3 proposes the ontology and Section 4 presents its application. Sections 5 and 6 present the discussion and conclusions.

2. Literature Review and Research Motivation

2.1. Product-Service Systems (PSS) Design

PSS is classified into product-, use-, and result-oriented PSS [4] (see **Fig. 1**). In a product-oriented PSS, providers sell products and offer additional services needed during the product use phase, such as maintenance, guidance, and consultation. In a use-oriented PSS, providers own the products and make them available to users in various forms. The products may be shared by multiple users through, for example, leasing, renting, sharing, or pooling. In a result-oriented PSS, clients and providers agree on a result in principle, and there is no pre-determined product. In this case, providers generally focus on activity management, pay-per-service units, and functional results.

The PSS design process requires the collaboration of various experts such as managers, product engineers, and service designers. Since these experts design PSS on the basis of their domain-specific knowledge, several studies have discussed the development and customization of design tools suited for each expert. For example, persona [15] is frequently used by service designers to understand customer needs. Persona is a virtual representation of customers' portraits, demographics, beliefs and values, and lifestyles. Pezzotta et al. highlight persona as a useful tool in PSS design [16]. The business model canvas is a practical framework used to design an overview of business model [17]. To apply it to PSS design, Kwon et al. specified possible strategies for each of the nine dimensions in the business model canvas [18]. The literature presents several tools for solution design, including a function block diagram [19], a view model [20], and a product service concept tree [21]. These tools aid designers in organizing a structure of relations between value propositions and resources. Service blueprint [22] is one of the most popular tools to design PSS from a process viewpoint. PSS design studies have extended it to represent product behaviors and human activities in a unified scheme (e.g., [20, 23]). The systemic aspect of PSS requires the configuration of actors involved in PSS. Interactive [24] and system [25] maps have been proposed to design a network of actors and exchanges between each couple of them.

2.2. Integration of Design Information

In the field of product design, several studies have been investigated for the integrity of design information based on the concept of interoperability. Interoperability is the ability of different types of computers, networks, operating systems, and applications to work together effectively, without prior communication, in order to exchange information in a useful and meaningful manner [26]. To incorporate interoperability in product design, several modeling languages have been developed to represent different types of product information. For example, EXPRESS is a widely used modeling language for product data and has been formalized in ISO 10303 [27], which is also known as the standard for the exchange of product (STEP) model [28]. In addition, the unified modeling language (UML) is widely used as a de facto standard modeling language in software development [29]. According to ISO 14258 [30], semantic interoperability can be achieved through approaches such as unification and federation. Unification aims at proposing a metamodel used to map certain knowledge concepts through semantic associations. Federation aims at creating mappings between knowledge models dynamically based on the use of ontologies and semantic web standards. In the context of unification, Yoshioka et al. propose a knowledge intensive engineering framework (KIEF) to integrate multiple engineering models [31]. KIEF includes an ontology-based reasoning system, known as a pluggable metamodel mechanism, to integrate and maintain relationships among engineering models. Krause and Kaufmann propose a metamodeling method for the coexistence and integration of EXPRESS with UML [32]. As for federation, Li et al. develop an ontological modeling schema to extract and reuse design knowledge [33]. Design knowledge is derived from the 3D CAD models and then represented by the function-behavior-structure ontology. Barbau et al. propose OntoSTEP to consolidate product information created using various languages in different lifecycle stages [34]. The model enables the translation of STEP schema and its instances into ontology web language (OWL), which represents rich and complex knowledge on the semantic web.

2.3. Research Gaps and Opportunities

The integrity of design information is critical for achieving the expected benefits of PSS. For example, product characteristics should be aligned with services so as to integrate both components synergistically, such as maintainability and serviceability [9, 10]. In addition, offering products and services requires the alignment of manufacturer organizations, i.e., organization design, since selling and delivering PSS require companies to develop human resource for services that are different from one for products [11, 12]. Furthermore, designing partner networks is crucial to compensate the lack of internal competencies and resources for PSS [13, 14]. However, existing methods and tools focused on particular elements that are described with domain specific knowledge, terminologies, and representations, some of which describe design information using natural language, depending on the purpose and characteristics of the design activities. Therefore, few studies have been investigated for integrating the design information. Although the specialization of design tools could prove useful for experts, it hinders companies from ensuring the integrity of design information in different design elements. This issue can be addressed by concepts and methods for interoperability given their potential to integrate PSS design information.

3. Ontological Descriptions for PSS Design

3.1. Overview

This study applies the concept of interoperability to PSS design to integrate design information across different elements. As per the foregoing, interoperability can be achieved through federation, which aims at creating mappings between knowledge models dynamically based on the use of ontologies. Therefore, in this study, an ontological approach is adopted to achieve semantic interoperability. Ontology engineering is one of the methodologies used for describing knowledge systematically on the basis of concept definitions. From a knowledge viewpoint, "ontology is defined as a theory (system) of concepts/vocabulary used as the building blocks of an information processing system" [35]. This study develops ontological descriptions for PSS design. To do so, it first conducts a literature review, synthesizing existing studies on PSS design. Second, it develops the ontology on the basis of axiomatic design perspectives. Axiomatic design is a methodology focused on how to use fundamental principles during the mapping process among domains of the design world [36]. The principles help identify elements and their respective domains: customer needs (CNs), functional requirements (FRs), design parameters (DPs), and process variables (PVs) (see **Fig. 2**). For example, in a steam engine, CNs correspond to needs for the engine, such as engine torque. FRs include "push the piston by using steam," while DPs include "injection of steam" [36]. PVs correspond to manufacturing processes of the engine.

During the design process, CNs in the customer domain are converted into FRs in the functional domain. FRs are a minimum set of independent requirements that characterize the functional needs of a design solution. FRs are embodied in DPs in the physical domain. DPs then determine PVs in the process domain to produce and/or control DPs. PVs act as constraints since the creation of new processes and selection of new PVs are not restriction free. Therefore, DPs must be chosen such that they are consistent with the constraints of PVs.

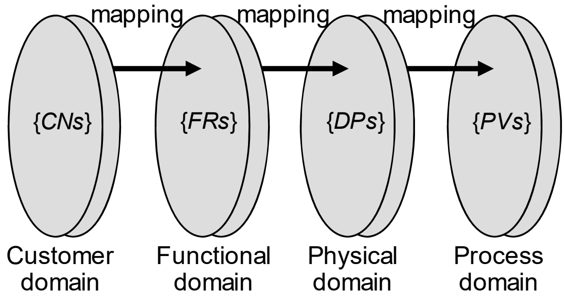

Fig. 2. Four domains of design world [36].

3.2. Conceptual Model for PSS Design

One of the most important decisions in PSS design is to elucidate two types of mechanisms: value creation and capture [14, 37]. Value creation is a mechanism that generates value for specific receivers and value capture represents profits earned through value creation. Value creation can be described from the viewpoint of a dyadic relationship between a provider and receiver. Designing a value creation mechanism can be described as a mapping process among domains in axiomatic design. PSS aims to achieve desirable changes in receiver's states [38, 39]. Therefore, CNs in the customer domain correspond to receiver's states related to those in a product life cycle as well as receiver's activities [40].

These receiver states are converted into FRs in the functional domain. In PSS design, this conversion depends on value propositions. PSS value propositions (VPs) can be categorized into four types: asset-centric, recovery provision, availability maximization, and outcome-based VPs [41, 42]. Asset-centric VPs focus on the sale of tangible and intangible asset through transactions, and therefore, have limited influence on a customer's product use. By contrast, recovery provision VPs concentrate on offering a guarantee against the loss of product quality attributes and include after-sales services. Availability maximization VPs are based on maximizing the potential use of products. For example, throughout a product's lifecycle, or for a given contract duration, providers are responsible for the operability of products. Finally, in outcome-based VPs, providers ensure the provision of agreed-upon levels of functionality and/or results to customers, which includes facilitating customers' effective use of products and supporting their achievement of goals related to product use. In the functional domain, functions are developed to realize the value propositions.

In the physical domain, resources that perform these functions are identified as DPs. The resources differ from those required to sell a product [10, 43]. For example, a dedicated service sales force should be recruited and trained to acquire new competencies to access key decision makers in client organizations and to communicate service value [10]. Facilities that are physically close to a customer's operations are key in on-going product and service improvements because this affords companies a faster response time [44]. Moreover, product and process data collected using digital technologies are essential to improve service operations [45, 46] and product design [47], maintain continuous contact with customers [48], and identify new business opportunities [49].

Finally, in the process domain, PVs are determined to produce and/or control resources in the physical domain. In PSS design, PVs include manufacturer organizations and partner networks. At the organizational level, several studies have concluded that manufacturing companies must consider organizational restructuring to prepare and sustain requisite resources for services [11, 12]. For example, service-oriented measurements and reward systems are crucial in encouraging and sustaining changes in employee behavior toward services [43]. To implement such service-oriented culture, much research has emphasized the importance of operating service organizations as a separate business unit or profit center with profit-and-loss responsibility [12]; the objective is to define adequate organizational distinctiveness between product and service businesses. Commitment and leadership of the top management are also crucial in determining additional investments needed to prepare required resources such as service employees and facilities [50]. In partner networks, PSS value propositions require manufacturers to take responsibility for risks and costs in a product's lifecycle. Since it is difficult for a single company to shoulder these responsibilities, manufacturers must collaborate with new suppliers capable of compensating the lack of internal competencies and resources [13, 43]. When a supplier is already independently offering a service, it is necessary to leverage and communicate the incentives and long-term benefits associated with becoming a partner to avoid supplier competition [50]. Importantly, the collaboration should be aligned with supplier goals, competencies, and growth directions [51]. In PSS design, resources in the physical domain must be chosen such that they are consistent with constraints facing a manufacturer's organization or a partner network.

Value capture also comprises mechanisms that differ from those used in product sales. Many PSS adopt value-based pricing commensurate with the value created for customers, instead of cost-based pricing estimated as cost plus the desired profit margin [52]. In value-based pricing, customers pay for a product's functions rather than purchasing them. Sales activities must include documenting and communicating the value of an offering to customers, thus enabling their acceptance of a price [10]. The types of offerings also influence revenue. Customized offerings, for example, impede a product's transferability across markets [53]. In this case, the definition of target customer segments is crucial to ensure a critical mass of service sales is profitable [50].

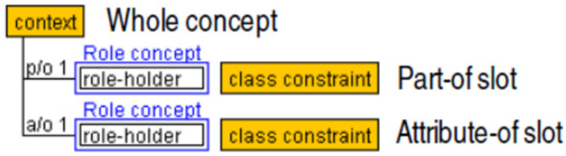

Fig. 3. Representation of nodes and links in Hozo.

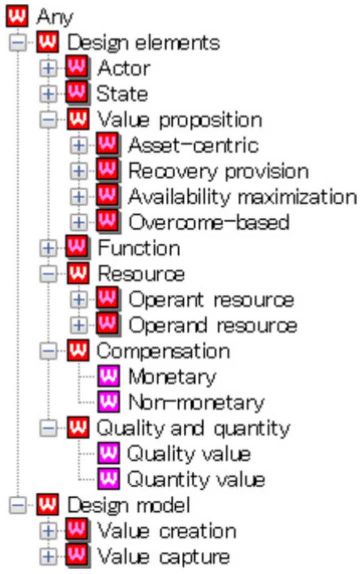

Fig. 4. Hierarchy of concepts related to PSS design.

3.3. Ontological Descriptions for PSS Design

Ontological descriptions of the conceptual model introduced in the previous section comprise design elements and design models. Design elements describe elements in each domain, and design models highlight the value creation and value capture mechanisms. This study uses the ontology development environment Hozo [54], wherein each node represents a whole concept and contains slots denoting part-of or attribute-of relations (see **Fig. 3**). Hozo helps describe role concepts, and a role depends on the contents of each whole concept. For example, a teacher's role is limited to the context of a school. Thus, every slot plays a role within a whole concept that implies a context. In the context, a class of instances that can play a role is defined by a class constraint and is termed a role-holder [55]. In this way, the role concept distinguishes between concepts within different contexts.

The proposed ontological description consists of two types of concepts: concepts related to design elements to be shared by designers in a PSS design process and those related to value creation and value capture. **Fig. 4** illustrates the hierarchy of concepts developed in this study. The concepts in this domain are mainly divided into two classes: design elements and design models. Design elements appear in the representation of design models, and design models are represented by the use of design elements. The sub-classes of the design elements are actor, state, value proposition, function, resource, compen-

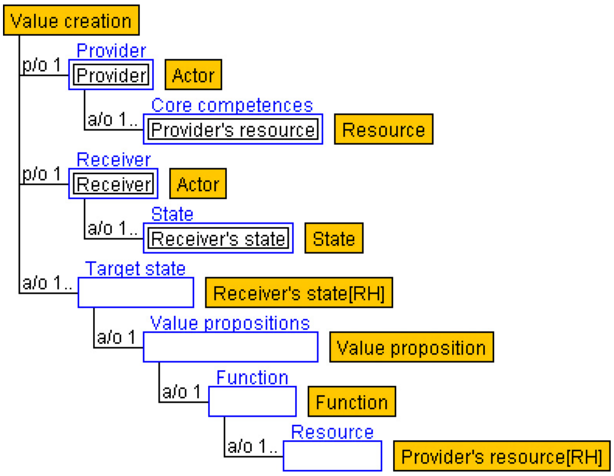

Fig. 5. Description of value creation.

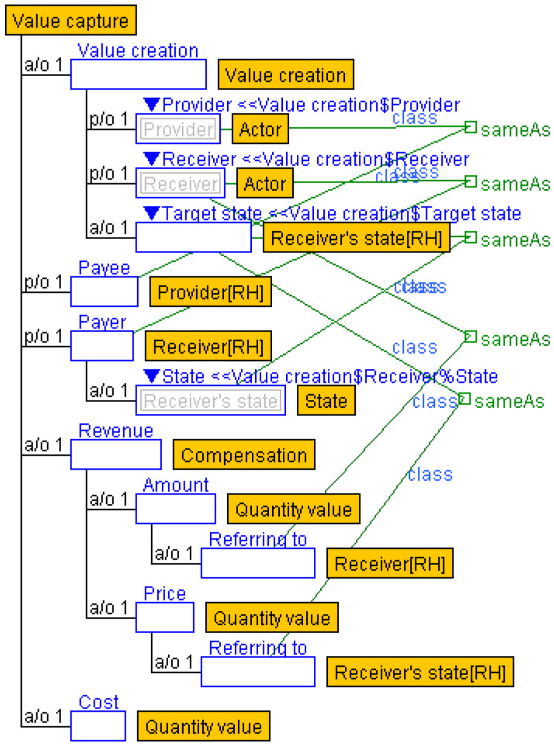

Fig. 6. Description of value capture.

sation, quality, and quantity. An actor is an agent that interacts in certain PSS contexts. A state belongs to such an agent and changes depending on the PSS context. Value propositions are a conceptualization of the types of changes observed in a state. Function implies the effect or performance of interactions including resources used to realize changes in the state of an actor. Compensation is offered in exchange for the realization of value propositions in such interactions. The realization of value proposition is conceptualized as value creation and the successive exchange values are defined as value capture, both of which are sub-classes of a design model.

Figure 5 shows the value creation structure. The provider and receiver are played by an actor as part concepts. In this context, the provider has certain attributes of core competencies played by a resource, and a receiver has some state (role) playing state (basic concept) defined in the design elements. The role-holder of the former is termed a provider's resource and the latter is the receiver's state. Value creation also has an attribute of a target state played by the receiver's state. Furthermore, the target state has an attribute of "value proposition" (role) played by "value proposition" (basic concept) defined in the design elements. Value proposition also has an attribute of function, which has a resource attribute.

Figure 6 illustrates the structure of value capture. It consists of a payee played by a provider and a payer played by a receiver. In addition, the structure is based on three attributes: value creation, revenue, and cost. The class constraints of the payee and payer are identical. This is also the case for the state associated with the payer and the target state in value creation. The attribute of revenue is earned in exchange for value creation, and therefore, is played by compensation. On the other hand, cost is merely played by quantity value defined as subclass of quality and quantity in design elements, in common with amount and price associated to revenue. Because amount and price depend on the receiver and its state, amount and price have "referring to" attributes played by the receiver and its state.

4. Application

4.1. Data Collection

This application aimed to verify the effectiveness of the proposed ontology for the integration of design information between different elements. As case examples of PSS design, we utilized data on a PSS design lecture delivered to 14 students who usually worked in companies. The lecture was divided into three sessions. In the first session, the students learned the definition of PSS as well as related cases and benefits for companies, customers, and environment. The second session included group work. The students were divided into three groups, and each group had to achieve the following tasks.

- Determine a core product for PSS design.
- Identify target customers and possible issues they may face during the product lifecycle.
- Design value propositions and offerings.
- Determine required resources and capabilities.
- Develop an ecosystem.

The duration of each session is two hours, and then the group work continued for a week. In the final session, each group presented their PSS design. About 15 min was allotted for each presentation and related discussions. In this application, instance models of the proposed ontology were developed based on the data on the PSS design solutions presented in the final session. Especially, the

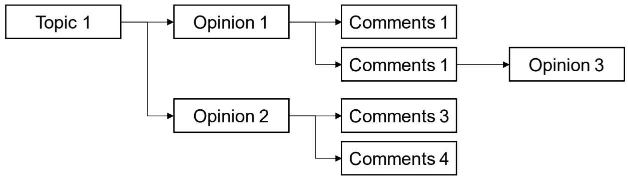

Fig. 7. Discussion paths of opinions and comments in GMSS (modified from [56]).

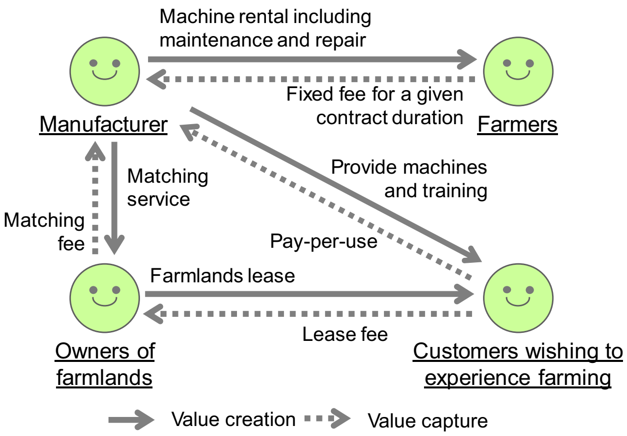

Fig. 8. Overview of PSS for agricultural machinery.

data was collected from materials of the final presentation and records of an online system. A communication support system, called Group Memory Support System (GMSS), was used for distributed groups [56]. In GMSS, users can write their opinions and comments on others' opinions. This enables the visualization of a discussion structure with opinions and comments paths (**Fig. 7**). This application utilized data of the opinions and comments in GMSS for developing instances of the design elements, while paths of the opinions and comments were utilized for the interpretation of the relationship among the elements. Furthermore, the data was supplemented with video records of the three sessions.

4.2. Data Analysis

To describe the instance models of the proposed ontology, first, opinions and comments were obtained from the online system and then, divided into single utterances. Then, each utterance was described as an instance of the design elements. Finally, the instances of the design model were developed on the basis of the relationship between the instances of the design elements. The relationship was interpreted from the discussion paths of the opinions and comments structured in GMSS. This application analyzed data from the two groups' PSS design: one focused on agricultural machinery and the other on telework systems.

4.3. Results

Figure 8 presents an overview of the PSS design results for Group A. Group A designed a use-oriented PSS on agricultural machinery for existing users, that is, farmers. In this PSS, the manufacturer leases agricultural machines as well as offers maintenance and repair services, thus making such machinery more accessible. The customers pay a fixed fee for a given contract duration.

Group A also designed a result-oriented PSS for customers who wished to experience farming. Here, customers are offered a service that allows them to match with owners of farmlands available for leasing. They are also given access to a pay-per-use service for agricultural machines and requisite training for farming.

As for design elements, farmers, customers who wish to experience farming, and farmland owners were identified as instances of receivers in the actor class. All receivers are associated with the states they desire to change. Farmers desire state changes in, for example, shortage of successors, productivity of farming, and maintenance cost of agricultural machines. The states of customers who wish to experience farming include experience of farming, shortage of knowledge, and initial and maintenance cost of agricultural machines. Farmland owners offer farmland to customers wishing to experience farming, and thus, were also determined as an instance of a provider in the actor class. Within these states, target states were determined to develop functions that can realize the desirable changes. For farmers' state of maintenance cost, an availability maximization VP was determined, and accordingly, the "provide preventive maintenance" function was developed. As for farmers' state of productivity of farming, an asset-centric VP was identified, and thus, the "knowledge on farming" function was developed. Next, requisite resources were determined to perform these functions. For example, for the "provide preventive maintenance" function, requisite resources include data on predicting failures and facilities and human resources for maintenance. Knowledge on farming was identified as a resource necessary for the "provide education" function. Finally, these resources were allocated to providers who were capable of providing them. For example, resources such as data on predicting failures, facilities and human resources for maintenance, and knowledge on farming were allocated to manufacturers given their existing access to these resources through the development and maintenance of agricultural machinery.

For customers wishing to experience farming, an asset-centric VP was determined, and accordingly, "lease farmland" was designed a requisite function and farmland as a resource. The resource was allocated to farmland owners who had farmland available for leasing.

To examine value capture, the lifecycle costs of agricultural machines were estimated, and accordingly, the price of value creation that realized the state change in the maintenance cost of agricultural machines was determined.

As shown in **Fig. 9**, Group B designed a PSS for telework systems that allows users to work from home while continuously communicating with colleagues, customers, or a central office using information technologies. In this PSS, the system provider offers a use-oriented PSS

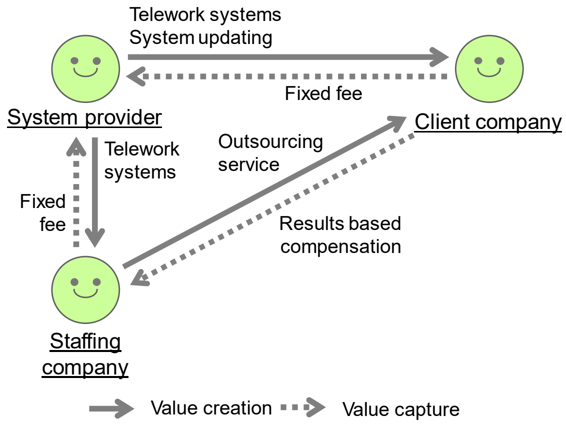

Fig. 9. Overview of PSS for telework system.

of telework systems that provides hardware and software necessary for teleworking. Customers pay a fixed fee to use the telework systems. In addition, Group B designed a result-oriented PSS that allows customers to outsource their jobs to a staffing company through the telework systems. The staffing company receives compensation from the customers as per the outsourcing results.

In the context of design elements, the system provider, customers, and the staffing company were identified as an instance of a receiver in the actor class. The states that customers desire to change include the initial costs of telework systems, the maintenance costs of telework systems, and the shortage of human resources. The system provider and staffing company were determined as an instance of a provider in the actor class. For the state of maintenance costs for the telework system, availability maximization was determined, and then, the "system updates" function was designed. Next, knowledge on systems and human resources for system updating were highlighted as requisite resources for the function. These resources were allocated to the owners of the system provider.

In terms of value capture, the price of value creation that realized state change in the maintenance costs of telework systems and the initial costs of telework systems was determined as a monthly fixed fee that offered the requisite software and hardware for telework systems. For the state of shortage of human resources, the price was determined on the basis of, for example, compensation and commission fee to dispatch workers.

4.4. Demonstration of Instance Models

Figure 10 shows a list of the instance models which are instantiated on the basis of the proposed ontology. These instance models indicate utterances collected and analyzed in the data analysis mentioned above. We obtained seven models of value creation and one model of value capture. **Fig. 11** shows an instance entitled "value creation manufacturer ⇒ farmers," for example, which means realization of farmers' state change by a manufacturer. The provider and receiver slots are filled by instances of manufacturer and farmers respectively. Two target state slots are filled by instances originally possessed by the farmers. The manufacturer has three core competences corresponding to resources that appear in the target state slots. The target state entitled "maintenance cost of agricultural machines" has a value propositions slot filled by an instance of availability maximization, and it has a function slot filled by instance of providing preventive maintenance. The resources possessed by the function are the same as core competences possessed by the manufacturer. In the same way, the other target state is described and specifies the resources used in the function that correspond to the manufacturer's core competences.

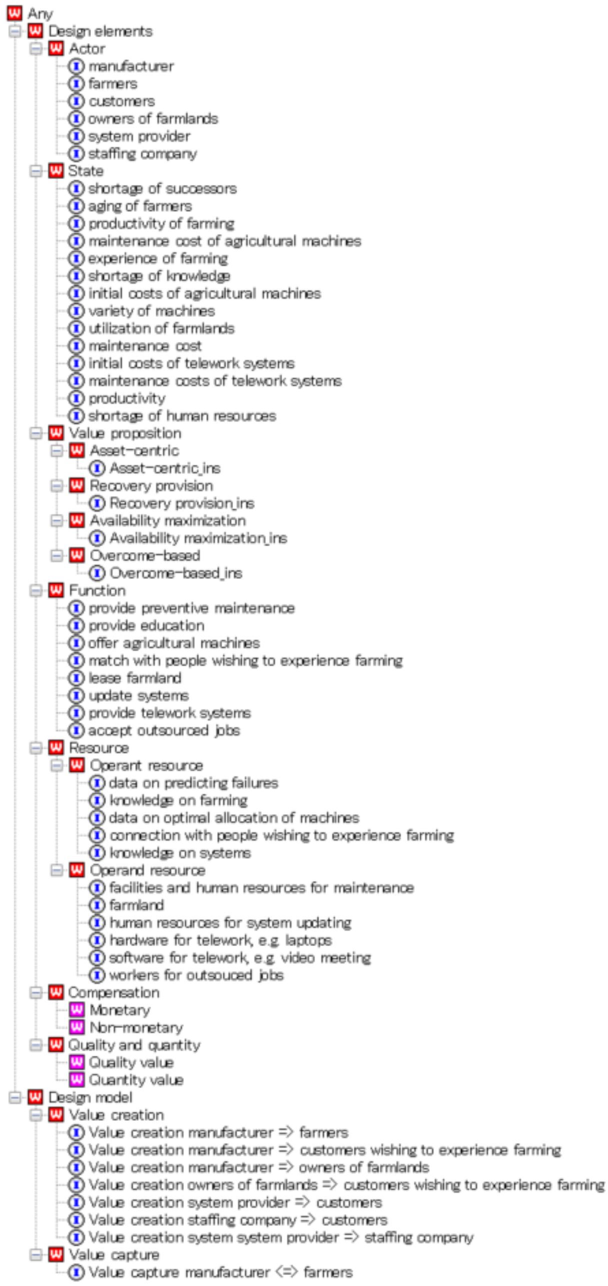

Fig. 10. Lists of instance models.

Fig. 11. Instance of a value creation.

5. Discussion

5.1. Effectiveness of the Proposed Ontology

As reviewed in Section 2.1, design information of each element was fragmented in different methods and tools, thereby difficult to ensure the integrity of these elements. The major theoretical contribution of this research lies in synthesizing PSS design elements based on the literature review, and then defining the relationships between these elements by the ontological descriptions. Through the application to a lecture on PSS design, the proposed ontology was found to be effective for the integration of design information between different elements. For example, in the case of PSS for agricultural machinery, resources "data on predicting failures" and "facilities and human resources for maintenance" were designed from the viewpoint of the optimality for realizing change in farmers' state "maintenance cost of agricultural machines." In the proposed ontology, these resources are constrained by core competences of the provider, i.e., the manufacturer. This enables to integrate design information on resources required to the state change and provider's competences to produce and control these resources.

Furthermore, the proposed ontology could be useful for integrating design information between value creation and value capture. For example, in value capture of PSS for telework systems, the price of value creation that realized the state change of "maintenance costs of telework systems" and "initial costs of telework systems" were determined as a monthly fixed fee. However, there was little discussion on enabling customers to accept the price. As mentioned in Section 3.2, ensuring customer's acceptance of a price is crucial for selling PSS [29]. For addressing this problem, in the proposed ontology, the price is determined with reference to the target state of the receiver. This could be useful for determining a price that maintains internal profits as well as its acceptance from the receiver.

Furthermore, since an ontological approach is used for describing knowledge systematically on the basis of concept definitions, the proposed ontology is expected to support sharing knowledge on the design solution among different stakeholders involved in the PSS, such as customers and service suppliers. This knowledge sharing is crucial for effective and efficient PSS operation [43].

5.2. Possible Improvements

Limitations in the effectiveness and efficiency of the proposed ontology were noted in the application. The instance models were manually described by the authors instead of the students, since this instantiation requires an understating of the proposed ontology. Furthermore, the ontological descriptions support the integration of design information, although the judgment of its integrity depends on experts' knowledge, such as acceptance of a price from customers. To resolve this problem, further research is needed to develop a computer-aided tool for the instantiation and judgment. In addition, the ontology in this study focuses on a dyadic relationship between a provider and a receiver. It is necessary for future works to extend the ontology to describe more complex relationships such as tripartite ones.

6. Conclusion

This paper developed ontological descriptions for PSS design, aiming at integrating design information from different design elements. Through application to a lecture on PSS design, the ontology was found to be effective for integrating information on design elements that include process variables that produce and/or control requisite resources for PSS. Furthermore, the proposed ontology could be useful for integrating design information between value creation and capture. Future research includes the development of a computer-aided tool and extension of the ontology to describe more complex relationships.

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