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A function availability-based integrated product-service network model for high-end manufacturing equipment

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ABSTRACT

Nowadays, product-service system (PSS) has become a popular topic that devotes to implement the integration of products and services to meet function demands. However, in the usage phase, the integration of high-end manufacturing equipment (HEME) and maintenance-repair-overhaul (MRO) services is still insufficient to ensure the long-term continuous availability for function implementation (named as function availability). Thus, in view of function information in function availability, this paper develops a function availability-based integrated product-service network model (IPSN) from the perspective of complex network. This model merges the obtained function action units, structure module units as well as service execution activities and reveals their implement-maintain-ensure mapping mechanism based on the modeling processes of function network, structure network, service network and interdependent network of networks. In this model, functions are regarded as the goals serviced, structures are deemed as the objects serviced and services are the corresponding execution processes. With this model, the function availability could be better ensured with the delivery of the linked more critical integrated services. In order to illustrate the detailed modeling process, a case for feeding function of numerical control honing machine 2MK2263 × 200 is studied. From the evaluation and comparison results, it could be seen that this model not only realizes the integration of products and services to ensure the concerned functions, but also provides a vital foundation for the identification of critical nodes and the effective service configuration for availability.

1. Introduction

During the product life cycle, product usage phase holds longer time duration, when compared with other phases such as product design, manufacturing, recycle and remanufacturing. Especially, for high-end manufacturing equipment (HEME), represented by high-end computerized numerical control (CNC) machine tool, it might take a long period of 20–30 years (Roy, Stark, Tracht, Takata, & Mori, 2016). In order to ensure the availability of equipment during product usage phase, the maintenance services are normally provided. However, for traditional manufacturing industries, the maintenance processes are mainly conducted in-house by customs or offered from passive and inactive aftermarket services by Original Equipment Manufacturers (OEMs) or service providers owing to the selling of products. This manner has failed to ensure the continuous function availability for HEME in an optimal way. The reasons are as follows:

(1) For customers or end users, with the long life span and increasing complexity of HEME, they suffer from the lack of equipment knowledge and spare parts, which leads to the limited abilities to ensure availability. Furthermore, the organized in-house maintenance processes waste amounts of resources and funds to keep equipment availability at an appropriate level.
(2) For OEMs or service providers, although they have the ability to ensure the long-term availability, the absence of effective proactive service mechanisms that integrate services with products or functions leads to the inadequate service supplies. This inadequacy makes them drain huge profits during long period's product usage phase.

Thus, in order to deal with current maintenance dilemma, it is necessary to develop a feasible proactive integrated maintenance-repair-overhaul (MRO) service manner for HEME (Zhu, Gao, Li, & Tang, 2012) from the view of OEMs or service providers. Inspired by product-service

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system (PSS) on the integration of products and services as well as the selling of product functionality (Van Ostaeyen, Van Horenbeek, Pintelon, & Duflou, 2013), the availability-based (Settanni, Thenent, Newnes, Parry, & Goh, 2017) MRO services are discussed in recent years. This service manner urges the integration of products and MRO services, and shifts the maintenance processes to OEMs or service providers by selling functions or services. It emphasizes the duty of OEMs or service providers on ensuring the function availability, not the in-house maintenance teams (Chang, Zhou, & Lu, 2017), which alleviates current maintenance troubles. In addition, the HEME could also keep high availability and productivity with minimum maintenance cost.

In the context of availability-based MRO services, the modeling processes that reveal the integration and mapping relationships among functions, structures and services are still unexplored. It is noted that if the functions suffer from failure, the OEMs or service providers have to pay high penalty for the huge losses caused in the availability-based services. In this case, the ensured functions would be the essential demands. These demands are associated with the structure entities and the entities are the carriers to plan various proactive services for corresponding demands. So, in order to avoid function failure and ensure the continuous availability, it is necessary to further study on the integration and mapping problems among ensured functions, maintained structures and executed services in a clear and quantified manner. On basis of this quantified integration relationship, the appropriate critical services could ensure the corresponding critical functions by maintaining the corresponding critical structures' conditions.

Meanwhile, the emerging technologies and methods are also urging the integration. The prognostics and health management (PHM) technology, a widely researched proactive service manner, could effectively obtain the operating condition of concerned components or parts and predict the remaining life of equipment before failures take place. Once the integration and mapping relationships are achieved, these information would have the comprehensive application situations to implement the function monitoring and fulfill the health management. In addition, the emerging cyber-physical system (CPS) and big data analytics technologies (Lee, Ardakani, Yang, & Bagheri, 2015; O Donovan, Leahy, Bruton, & O Sullivan, 2015; Zhang, Ren, Liu, Sakao, & Huisingh, 2017), combined with the cloud service platform (Mourtzis, Vlachou, Milas, & Xanthopoulos, 2016; Zhang, Liu, Jiang, & Chen, 2015), are all prompting the integration and interaction from demand information and offering information. Thus, the integration and mapping that link function demands, structure conditions and service supplies are of great importance in current research.

Learning from above issues and motivations, this paper focuses on the networked modeling processes to realize the integration of products and MRO services, and thereby to relate and ensure the function availability of HEME. To do so, a function availability-based integrated product-service network model (IPSN) is built. In view of function demands, this model integrates and discusses the function units, structure modules, service activities as well as their interactive mapping mechanisms from the built function network, structure network, service network and network of networks. On basis of these networks, their quantified relationships could be presented clearly. This finding not only establishes a foundation for future availability-based function sales or service sales for HEME, but also informs future developments of PHM, cloud service platform and other related technologies as well as methods.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literatures. Section 3 describes the integrated product-service model firstly. Then, the IPSN is built in Section 4 from four aspects, namely function network, structure network, service network and network of networks. Section 5 takes feeding function of CNC honing machine 2MK2263 × 200 as a case to reveal their integration and mapping process. Finally, the discussion and conclusion are offered in Sections 6 and 7.

2. Literature review

Considering about the characteristics of integration of products and services in PSS, this section firstly presents the research of PSS and its inspiration on availability-based MRO service manner. Afterwards, based on this effective service manner, the research about the relationships among functions, structures and services are also reviewed.

2.1. Product-service system

PSS is a wide-researched service strategy that could effectively implement the bundle of intangible services with tangible products. As defined by Tukker and Tischner (2006), PSS is "*a mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer needs*". It focuses on the "servitization" of products. Compared with traditional product sales, PSS makes use of the sales of integrated services to obtain high value-added. In the research of PSS, Geum and Park (2011) provided a visual product-service blueprint method to design the sustainable product-service integration. Meier et al. (2010) built up a dynamic IPS^2 network model considering the dynamic behavior of IPS^2 during the lifecycle, thus to discuss the relationships among stakeholders in PSS. Geng, Chu, Xue, and Zhang (2010) proposed an integrated three-domain PSS conceptual design framework including customer domain, functional domain and product-service domain based on quality function deployment (QFD), through which the importance measures of product and service specification were achieved to satisfy the customer requirement. Wang, Ming, Wu, Zheng, and Xu (2014) introduced an ontology-based modular product-service configuration method where the product-service ontology knowledge was obtained from the modular system of product-service and the analysis of customer demands. Aiming at solving current design problems, Wu et al. (2017) proposed a similarity measurement framework based on the context-based activity model to measure the indexed and quantified PSS design cases. Similarly, PSS was also studied under closely related themes such as function sales (Sundin, & Bras, 2005), performance (based) contract (Hypko, Tilebein, & Gleich, 2010), function (service) economy, service contract and availability contract. For example, Van Ostaeyen, et al. (2013) revealed that PSS involved an orientation toward selling product functionality instead of selling products so that they proposed a Functional Hierarchy Modeling (FHM) to fulfill a refined typology for PSS.

2.2. Availability-based MRO service

Although the research of PSS has become a popular subject for several years, its applications are just in a 'nascent' phase (Schenkl, Roesch, & Moertl, 2014). However, it has provided a novel route for high-end manufacturing industry to support the integration of MRO services under PSS (Roy, Erkoyuncu, & Shaw, 2013). Zhu, et al. (2012) proposed a web-based product-service system to integrate product development with MRO services in the aerospace industry. In its integration, PSS was regarded as a decision support tool to implement the mapping relationships among customer domain, function domain and product-service domain. Wibowo, Tjahjono, and Tomiyama (2017) were also aware of the great significance in the offering of product-service system for MRO service providers. In order to avoid the weaknesses such as higher cost and longer turnaround time from traditional maintenance based on intuitions and experiences, they proposed an enhanced availability-based contract design method through the simulation modeling. This model not only considered customer's requirements, but also analyzed the shop floor's operational availability. Settanni et al. (2017) analyzed the great role of availability-based contracts in challenging the incumbent business model and provided a conceptual model to explore how the delivery of availability could be realized as an advanced service in industrial sectors. Learning from above research, we could make a conclusion that availability-based