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CONCEPTUAL DESIGN OF PRODUCT-SERVICE SYSTEMS DRIVEN BY PERFORMANCE

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ABSTRACT
A product-service systems (PSS) is a combination of product and service to create value for both customers and manufacturers. The paper proposes a new performance-oriented design framework for PSS development contrasted to function-oriented design in traditional product development. The framework includes three domains: requirement domain, performance domain, and concept domain. The concept characteristics can be determined based on the mapping between each two adjacent domains, which are implemented by a modified quality function deployment (QFD) tool. The PSS concept is established by using a variant configuration model based on generic bill of materials (GBOM). The proposed approach is applied in a real-world case of horizontal directional drilling machine.

Keywords: conceptual design, product-service systems, design process, generic bill of materials

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1 INTRODUCTION

With the increasing needs of sustainable production and consumption, the emphasis of customer requirements (CRs) shifts from purchasing just a physical product to a result or a function which is provided by product combining with corresponding services jointly (Liu et al., 2012; Meier et al., 2010; Sakao and Lindahl, 2012). The holistic offering of product and service, namely product service systems (PSS) which is an important concept in sustainable development, can be deemed as a competitive strategy to deal with diverse CRs for manufactures in global markets (Sun et al., 2011; Tukker and Tischner, 2006). The added services increase the dematerialization and differentiation of the offering and provide additional selling points. Furthermore, the offering can provide values for customers, improve product core competences, bring new market potentials and high profit margins, and reduce life cycle cost of a product and environmental loads (Baines, 2007; Garetti et al., 2012; Geum and Park, 2011). PSS was applied in multiple industries, e.g. public bicycle system (Lee et al., 2012), printing industry (Visintin, 2012), and manufacturing (includes household appliances, automobile, construction machine) (Geum and Park, 2011; Sakao et al., 2009; Williams, 2006).

Recently, engineering disciplines (e.g. service engineering (SE) (Sakao and Shimomura, 2007) and integrated product service engineering (Lindahl et al., 2007)) were developed and some design methods or tools were adopted (e.g. modularization design (Geum and Park, 2011), function-activity based design process and support systems (Kim et al., 2011)) for developing PSS. The conceptual design of a PSS aims to ensure customers enjoy the product's performance, i.e. make functions available throughout the whole lifecycle. Performance comprises two aspects: function and its quality, where quality expresses the function level and its availability in a time dimension (Xie, 2004). The performance can also be regarded as the carrier of the delivered values from the manufacturers to the customers. The identification and description of CRs are focused on performance in the conceptual design of PSS, which is named as Performance requirements (PRs) in the study.

Traditionally, there are two different general methods, i.e. Function-Behavior-Structure (FBS) based design (Gero and Kannengiesser, 2002) and Axiomatic design (Suh, 1990), for supporting product conceptual design. One important idea in the two methods is design domain which is a decomposing strategy for a complex design problem. Based on the domain, a PSS design framework is proposed, which includes three design domains: requirement domain, performance domain, and concept domain. The mapping between each two adjacent domains determines the following domain's specifications based on the fore domain's specifications. Traditional quality function deployment (QFD) can only realize the single objective's mapping process. PSS design includes the objectives of product and service. In order to implement the mapping process, an improved QFD tool is proposed to translate PRs into performance characteristics (PCs) and sub-system/component characteristics of product and strategies of service (i.e. design requirements). In order to manage product variants, a data model, namely generic Bill of Materials (GBOM), has been developed which describes the generic product structure (Hegge and Wortmann, 1991). In this paper, a GBOM-form model is developed to handle the PSS variants and to represent the generic structure of PSS. A rule-based configuration design is used to generate feasible PSS concepts. The proposed approach is used for conceptual design of a horizontal directional drilling (HDD) machine with its maintenance.

The paper is organized as follows. The next section develops a conceptual design framework for PSS. In the third section, a case study of HDD machine with its maintenance is presented to illustrate the proposed method. Conclusions are then presented in the final section.

2 CONCEPTUAL DESIGN FRAMEWORK FOR PSS

2.1 The framework of three domains

Conceptual design plays an important role in a PSS development, which can determine the overall "picture" of the ongoing PSS. Then, a design framework is proposed for addressing the PSS conceptual design, which begins with PRs and ends with an optimal PSS concept in Fig.1. According to Axiomatic design theory (Suh, 1990), the framework is divided into three domains: requirement domain, performance domain and concept domain. The first domain mainly expresses the performance requirements of customers, which is the design objective. The next one expresses the performance characteristics of a PSS, which is the technical requirement of the design. The last one expresses the PSS' concept, which is the design result. The three domains are described in detail as follows:

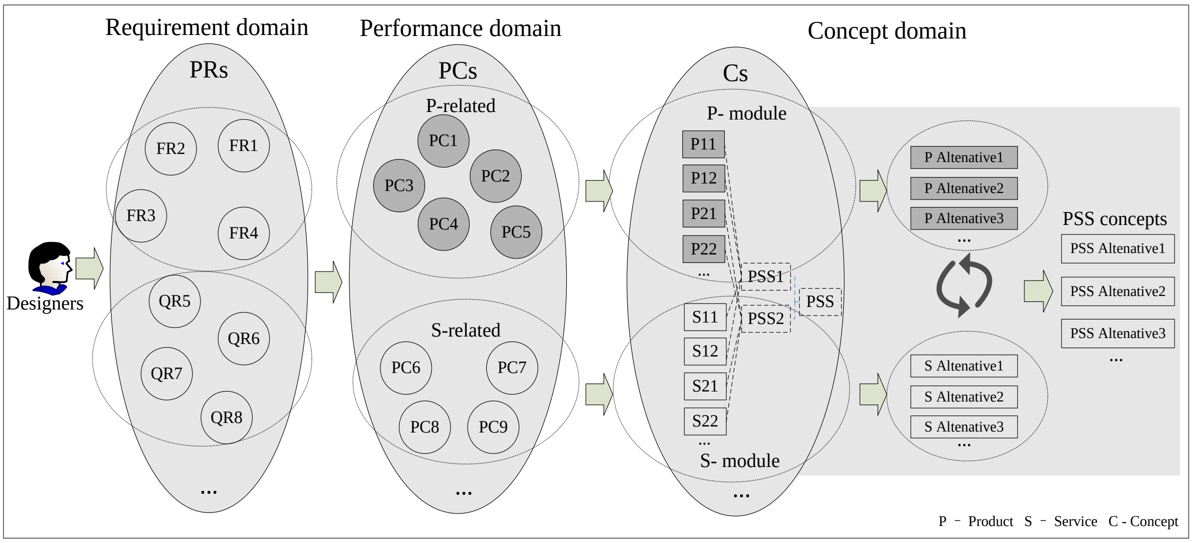


Fig.1 The concept design framework of PSS

Requirement domain: the domain is described from the perspective of performance requirements of the customers, including function requirements (FRs) and quality requirements (QRs) as shown in the requirement domain of Fig.1. In a PSS development, the PRs are focus on the use or result of a product but not on the product itself. For example, the customers pay attention to the using reliability but not only the product reliability. Generally, PRs express some key attributes of function and its quality. For example, for power supplying requirement of a HDD machine, the PRs includes three items: 50-KW power, high reliability and stabilization.

Performance domain: product and services provide partial function and quality, respectively. With a systematic design way, PCs derived from PRs can be subdivided into product-related and service-related as shown in Fig.1. For example, the index of security is divided into product security and service ensuring level for the security. Considering the ambiguous and uncertainty, some PCs cannot easily adopt quantitative expression and then use qualitative description (e.g. security level is divided into high, moderate, low). PCs express the PSS from technical perspective.

Concept domain: includes two modules, i.e. product module and service module (as shown in P-module and S-module in Fig.1), which comprise the final PSS solution. Different from the traditional product module or service module, some additional information will be added in. For example, failure sets of product module or risk information of these failure sets, which can be used to determine proper maintenance activities for a product. All these additional information helps the designers make the possible product sub-solution and service sub-solution. In the process, the correlations between these two parts should be considered. When determining product or service alternatives, the corresponding correlations can make proper actions in order to match with each other.

2.2 The improved QFD tool

With identifying and understanding the PRs, a modified QFD tool is used to effectively ensure the PRs are fully and accurately translated into appropriate design requirements. Having obtained the design requirements, the feasible PSS concepts are developed by using configuration design and then an optimal one is selected through a holistic analysis by the designers. In the requirement domain, PRs are described as a set $\{PR_k\}, PR_k = (pr_1, pr_2, \cdots, pr_k)$, where k is the total number of requirements. Performance domain contains a set of performance characteristics $\{PC_h\}, PC_h = (pc_h, pc_h, \cdots, pc_h)$, where h is the total number of performance characteristics. Generally, the PCs are classified into product-related and maintenance-related categories in order to facilitate the mapping process. In order to fulfill the mapping, the relationships between neighboring domains and the correlations among a domain should be identified.

2.3 Configuration model

In the concept domain, a variant configuration model of PSS using GBOM is established for aiding the designers to produce feasible concepts as shown in Fig.2. The model defines the structure, modules, and attributes of the PSS and related configuration rules. The GBOM expresses the specification of PSS variants by using items and their attribute descriptions. Furthermore, all instances of configuration results are also described in the configuration model. A GBOM includes two entity types, i.e. generic item and case item. A generic item represents specific variants of a module (e.g. a product or a component/sub-system). Each node expresses a set of variants for PSS or their sub-modules which associates with a set of attributes. A case item only represents a customized case of a PSS concept or a specific module (e.g. an engine concept or a service concept). In system level or sub-system/component level, a new concept may be directly configured if there has a proper case for a specific set of design requirements. The arranging manner does not only support the reuse of the existing design results (case items), but also support the creation of new design through configuration or component redesign. Furthermore, the form does not distinctly increase the storage burden of dataset because a case item (SP411) attached to a generic item (e.g. SPS11) is just added a reference where the case cell is still stored under the case of PSS2. The maintenance is belong to component service, and then each component item (e.g. SP111, SP411) is attached a sub-service item (e.g. SS111, SS411). This means that there is always a sub-service module for a component. The attached relation is represented by the corresponding constraint rules. The activity of service may include several sub-activities which comprise a service process. For example, activity 2 includes three sub-activities and sub-activity2 has two parallel-relation activities. With the judgment of the conditional node, one sub-activity can be selected for the process of activity 2. Through configuration, different attribute values, different combinations of modules form different PSS concepts.

In Fig.2, rectangle node is generic item created by the designers. Ellipse node is case item which expresses the fixed cases in the foregone design. Configuration rules are classified into two categories: outer rules (selection rules) and inner rules (constraint rules). The selection rules mean that an item in the configuration model is selected if the corresponding design requirements satisfy. Constraint rules can be divided into two categories: coexisting rules and exclusive rules. Coexisting rules means the objects must be existed (or not) simultaneously in a concept, and exclusive rules means the objects cannot be existed simultaneously in a concept. For example, a coexisting rule between A and B means that A (or B) must be selected when selecting B (or A). Similarly, an exclusive rule between A and B means that A (or B) must be not selected when selecting B (or A).

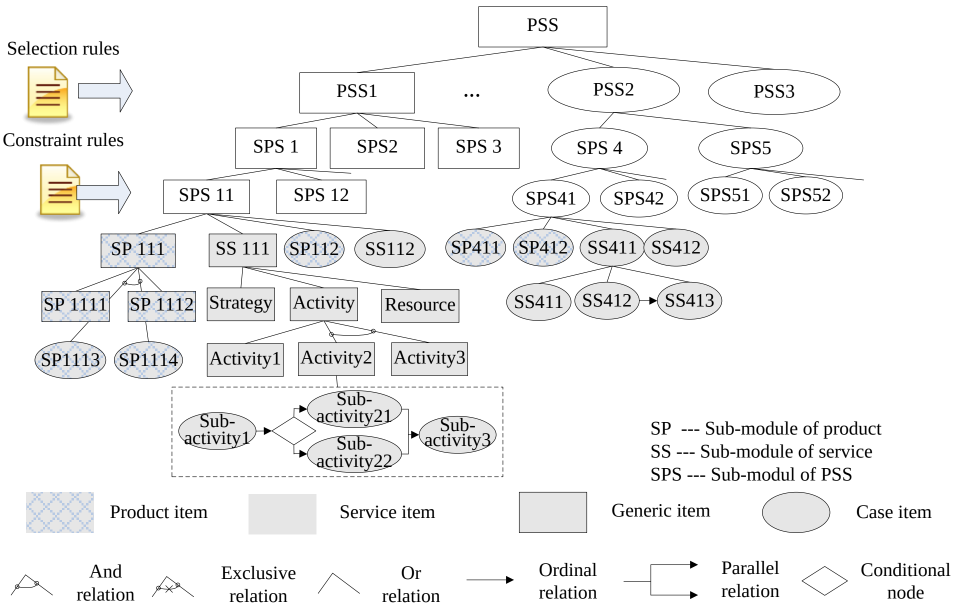


Fig.2 GBOM variant configuration model for PSS concept

3 CASE STUDY

An application of a heavy industry enterprise in China is used to illustrate the proposed method for conceptual design of PSS. The enterprise produces HDD machine, which is a trenchless equipment for the installation of pipeline and conduit. Currently, the customers pay more attention to the using but not only to the product itself. Then, the design focus is from product to product and its service (i.e. PSS). A conceptual design of a new concept of HDD machine with its maintenance is proposed for illustrating the detailed process in a systematic manner. Before a project of PSS development launched, a project team is established of which members are usually from product engineering, marketing and service department.

Fig. 3 shows the model for PSS conceptual design of a new HDD machine and its maintenance. In the requirement domain, the major PRs of the customers are identified from a market investigation: PR1 higher construction ability, PR2 higher construction reliability, PR3 higher construction efficiency, PR4 enough security, PR5 good environment protection level, PR6 comfort for driver and PR7 moderate cost. Referring to these above requirements, related P-PCs and M-PCs (Maintenance-PCs) are identified in the performance domain: P-PC1 core ability, P-PC2 component reliability, P-PC3 technology reliability, P-PC4 security protection, P-PC5 working mode, P-PC6 slurry ability, P-PC7 environment protection level, P-PC8 structure performance, P-PC9 product cost, M-PC1 reliability and security, M-PC2 maintenance technology and M-PC3 maintenance cost. In the concept domain, six key components of HDD machine are specified for product: SP1 engine system, SP2 hydraulic system, SP3 electric system, SP4 aiding system, SP5 power head and SP6 slurry system. Here, aiding system includes anchor equipment, drill tool, drill pipe loading and lubricating. Other sub-systems, e.g. vehicle body, may be important for implementing product function but has not distinct effects with PRs and then they are not considered in the QFD tool. Considering the complexity of the product, maintenance is divided into several sub-maintenance modules for each sub-system. Four alternative maintenance strategies are considered: Corrective maintenance (CM), Time-based preventive maintenance (TBM), Condition-based maintenance (CBM), and Predictive maintenance (PM). Referring to Waeyenbergh and Pintelon (2002), maintenance strategies are given briefly as following:

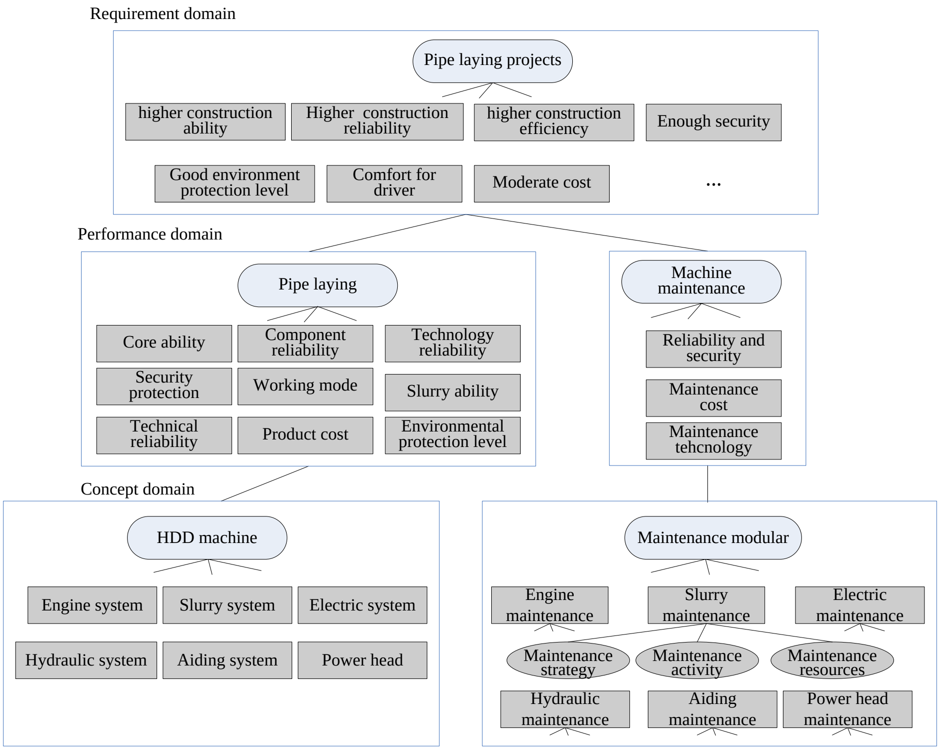


Figure 3 Models for conceptual design framework

- CM is only applied when a system or product breaks down.
- TBM is planned and applied periodically to potential failures based on component reliability characteristics. The maintenance can be divided into two classical strategies: constant-interval maintenance (constant time interval) and age-based maintenance (age is the total operating time after the previous maintenance).
- CBM is performed based on the measured data from an inspecting system.
- PM can find a possible temporal trend and predict controlling value through data analysis. And then staff can plan the retrieval activities.

Based on the historical data of HDD machine development or the typical product of competitors, project team constructs a GBOM-based variant configuration model for conceptual design of product

& maintenance (P&M) as given in Fig.4. The model is the basis of related design activities, which aiding the designers to generate feasible concepts for a specific set of PRs.

The QFD method provides the mapping mechanism of PRs and then the main characteristics of components with its maintenance (i.e. design requirements) are determined. In this study, the emphases are focused on how to use the QFD tool to support the integrated concept development of P&M. A simple scale of 0, 1, 3, 9 is proposed to rate the relationships and correlations and simple weight calculation is proposed to determine the outputs of HoQs. The QFD case is given in Fig.5. Here, MS 1-4 expresses CM, TBM, CBM and PM, respectively. The detailed outputs of QFD are given in Table 1. Based on the variant configuration model in Fig.4, several feasible concepts of P&M for the new HDD machine are generated through configuration design. Specifications of one of these feasible concepts are given as an example in Table2.

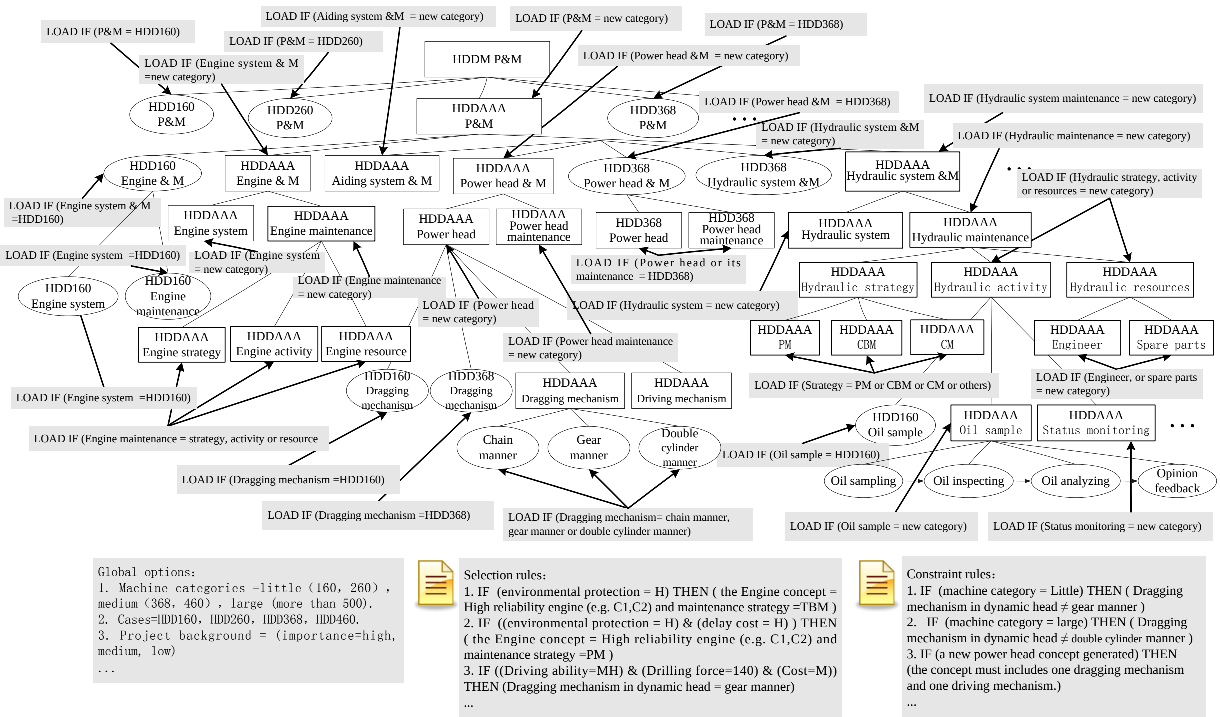
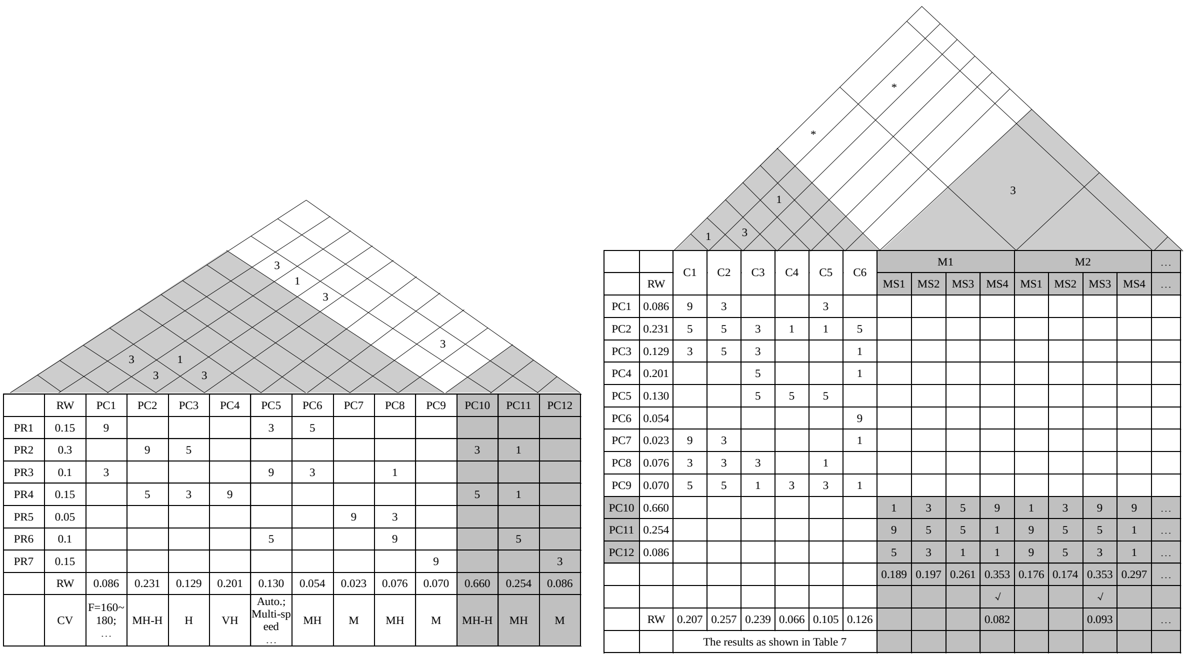


Figure 4. Variant configuration model of HDD machine with its maintenance



	RW	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12
PR1	0.15	9				3	5						
PR2	0.3		9	5							3	1	
PR3	0.1	3				9	3		1				
PR4	0.15		5	3	9						5	1	
PR5	0.05							9	3				
PR6	0.1					5			9			5	
PR7	0.15									9			3
	RW	0.086	0.231	0.129	0.201	0.130	0.054	0.023	0.076	0.070	0.660	0.254	0.086
	CV	F=160~ 180; …	MH-H	H	VH	Auto.; Multi-speed …	MH	M	MH	M	MH-H	MH	M

		C1	C2	C3	C4	C5	C6	M1				M2				…
	RW							MS1	MS2	MS3	MS4	MS1	MS2	MS3	MS4	…
PC1	0.086	9	3			3										
PC2	0.231	5	5	3	1	1	5									
PC3	0.129	3	5	3			1									
PC4	0.201			5			1									
PC5	0.130			5	5	5										
PC6	0.054						9									
PC7	0.023	9	3				1									
PC8	0.076	3	3	3		1										
PC9	0.070	5	5	1	3	3	1									
PC10	0.660							1	3	5	9	1	3	9	9	…
PC11	0.254							9	5	5	1	9	5	5	1	…
PC12	0.086							5	3	1	1	9	5	3	1	…
								0.189	0.197	0.261	0.353	0.176	0.174	0.353	0.297	…
											√			√		
	RW	0.207	0.257	0.239	0.066	0.105	0.126				0.082			0.093		…
		The results as shown in Table 7														

Figure 5 QFD cases for P&M conceptual design of a HDD machine

Table1. Design requirements of P&M concepts

Items	Characteristic values	Maintenance strategy
C1	Power-90~110KW, Rev-2400, Perf.- H, Fittings-MH	PM
C2	High reliability of element, load sensing technology, electro-hydraulic proportional controlling technology, Perf.-H or MH	CBM
C3	Voltage-36V, PLC controlling system, automatic drive ability, leakage current protection, pressure protection, remote control technology, Perf.-H	CBM
C4	Automatic load and unload of drilling pipe, automatic fastness of anchor, perf.-M	CM
C5	Double-speed drilling, perf.-MH or H	TBM/CBM
C6	parallel connection ability, instantaneous accelerating ability, perf.-MH	CBM

Table 2. Detailed specifications of one of P&M concepts

Components	Specifications of each component	Maintenance strategies	Maintenance interval
Engine system	Power-92.5KW, Rev-2400, Fittings-MH	PM	Condition-based
hydraulic system	High reliability of element, load sensing technology, electro-hydraulic proportional controlling technology	CBM	Condition-based
electric system	Voltage-36V, PLC controlling system, automatic drive ability, leakage current protection, pressure protection, remote control technology	CBM	One months
Construction aiding system	Automatic load and unload of drilling pipe, automatic fastness of anchor	CM	Three months
power head	Double-speed drilling, High-speed motor & Planetary reducer & Gear box, Chain manner	TBM	Three months
slurry system	parallel connection ability, instantaneous accelerating ability	CBM	Three months

For example, the power head adopts TBM strategy but not CBM because most potential failures can not be easily or economically monitored but be artificially identified through disassembly (e.g. abrasion). Furthermore, the maintenance activities should be implemented based on the minor cycle where all different cycles for maintenance should be integer times of minor cycle. This can facilitate the integration of maintenance activities where some activities can be fulfilled jointly. The maintenance cycle is determined based on the designers' experiences or historical data. The cycle may be adjusted in different using environments (e.g. different work hours in one week, 30 hours or 50 hours).

4 CONCLUSIONS

Conceptual design is an important step in PSS development. Started with the analysis of PSS background, the paper reviews related research works. A new conceptual design framework, which includes requirement domain, performance domain, and concept domain, is proposed to provide some clear guidelines for the designers to create a new PSS concept. A modified QFD tool is developed to support the designers to fulfill the design process. A rule-based variant configuration model is established by using GBOM for generating the feasible offerings of PSS. A case of HDD machine with its maintenance is proposed to illustrate the proposed method.

The study is an initiative work for the PSS design. How to extend the maintenance to all related services and then implement the conceptual design will be studied in the following work. Some methods will be adopted for tackle with the possible uncertainty and variety of case data. Furthermore, using life cycle data and all the information accumulated in enterprise will be considered to support new PSS design.

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