International Journal of Production Research, Volume 55, Issue 20, pp6120-6144
DOI:10.1080/00207543.2017.1325528

A Framework for Cost Evaluation in Product Service System Configuration

Jin Shen[a*], John Ahmet Erkoyuncu[b], Rajkumar Roy[b] and Bin Wu[a]
[a] *School of Business, Kanda IE Team, Shanghai Dianji University, Shanghai, China*
[b] *Through-life Engineering Services Centre, Cranfield University, Cranfield, UK*

Configuration systems are increasingly used as a means for efficient design of customized product service systems (PSS) to satisfy diverse customer needs. Cost evaluation is thereby important to assist the configuration engineers in making decisions on feasible configuration solutions. However, little research attention has been received until recently. To fill this gap, this paper contributes in developing a framework for cost evaluation in PSS configuration. A holistic view of PSS configuration, the three-dimensional PSS cost element, and a life cycle oriented cost evaluation approach are successively proposed. The framework is thereby established with a number of parts, including the preparatory stage, the evaluation stage and the configuration stage. A pump PSS is illustrated to validate the developed framework. Four feasible configuration solutions in one configuration activity are evaluated and compared. The configuration engineers are thus assisted with the decision on selecting the one with the least cost.

Keywords: product service system; configuration evaluation; cost estimation; life cycle costing; PSS configuration

1. Introduction

Driven by the increasingly global competition and more demanding customers, manufacturers are undergoing a transition from being product-centric to service-based, by bundling products and services into integrated solutions (Lindahl, Sundin et al. 2014; Song and Sakao 2016). Such offerings which deliver value-in-use so as to satisfy customer needs are commonly termed as Product Service Systems (PSS) (Baines, Lightfoot et al. 2007; Annarelli, Battistella, et al. 2016). The perceived merits of PSS for manufacturers are to lock the customer into a long-term relationship upon which raise barriers against competitors, to substantially increase the useful life of the products, and to generate higher revenues as services provide a steady income over the agreed period of time (White, Stoughton et al. 1999; Roy 2000; Aurich, Wolf et al. 2009; Rapaccini 2015; Mahut F., Daaboul J., et al. 2016). Rolls-Royce, Xerox and Canon are the commonly cited examples of the successful manufacturers that began to provide customers with different kinds of PSS (Baines, Lightfoot et al. 2007).

With the diversification of customer needs, highly personalized PSS is becoming more of a requisite than 'off the shelf ones' (Aurich, Fuchs et al. 2006; Long, Wang et al. 2013; Wurtz, Ardilio et al. 2013). Configuration systems are thus increasingly used as a means for efficient design of customized PSS (Hvam, Haug et al. 2013). Product service system configuration is a special type of design activity, with the key feature that the PSS being designed is constituted by a set of predefined PSS entities that can be bundled and connected together in certain ways. The task of PSS configuration is to find the configuration solution satisfying the individual customer needs without violating any constraint imposed on the PSS entities. No new entity types can be created and the interface of existing entity types cannot be modified (Mittal and Frayman 1989). With reference to a PSS, the PSS entities are various units that are in the form of products as well as services. The entities of the physical products are product components. Service modules or simply modules are the equivalent entities in terms of the intangible services (Aurich, Wolf et al. 2009).

Configuration problems are often weakly constrained and have several feasible configuration solutions (Junker and Mailharro 2003). It is thus essential to find the best one which maximizes the expected performance among these solutions (Pezzotta, Pirola et al. 2013). Since cost minimization is always one of the objectives that a company pursues, cost evaluation becomes important to assist the configuration engineers in making decisions on feasible candidates. However, PSS cost evaluation at the stage of configuration has received little research attention until recently, as analysed in Section 2.

In order to fill the research gap, a framework for cost evaluation in PSS configuration is proposed in this paper. Nevertheless, the difficulties of the framework development lie in several aspects. First, a PSS is a system potentially involving multiple, interconnected and interacting cost objects simultaneously (Settanni, Newnes et al. 2014). A PSS configuration solution implies a set of PSS entities that are combined in a structured manner. With reference to a PSS, the PSS entities are various units that are in the form of products as well as services. Cost analysis is thus requisite to be performed under a cost breakdown structure which is associated with the hybrid structured manner of configurable PSS. Second, the services in the PSS configuration solution are technical and life cycle oriented activities that enable or enhance products, use of the products and availability of the products (Durugbo 2014; Roy, Stark, et al. 2016). Companies face a high level of uncertainty due to the long-term nature of services (Kreye, Newnes et al. 2014). Uncertainty in the life cycle is thus noted as exacerbating the complexity of PSS cost estimation. Therefore, life cycle oriented cost analysis and uncertainty propagation are requisite to be performed in this paper. Finally, with the aim of the comparison of competing configuration solutions, knowing cost in absolute terms may not be the main aim (Settanni, Newnes et al. 2014). Relative accuracy is pursued in this paper. Much less data and information is thus needed, and the results are normally less sensitive to inaccuracy and uncertainty in the data and information.

In the end, the contribution of this paper lies in developing a framework for configuration engineers in making a comparison among the feasible PSS configuration solutions at the stage of PSS configuration. To develop this framework, a holistic view of PSS configuration is proposed to present multi-domain knowledge in PSS configuration. The three-dimensional PSS cost element is then defined to construct a cost breakdown structure linking with the PSS entity. A life cycle oriented cost evaluation approach considering uncertainty propagation is subsequently established to pursue the relative accuracy in cost evaluation.

The remainder of the paper is organized as follows. Section 2 gives an overview of related work. Section 3 describes a three-phase structured research strategy employed in this paper. Based on that strategy, a holistic view is first presented in Section 4 to present multi-domain knowledge in PSS configuration. The three-dimensional PSS cost element is then proposed in Section 5 to support cost analysis. A cost evaluation approach for PSS configuration is subsequently established based on the proposed cost element, and the framework for cost evaluation in PSS configuration is thereby presented in Section 6. To validate the proposed framework, an example of pump PSS is illustrated in Section 7. The discussion about the applicability of the framework is provided in Section 8, and the conclusions are drawn in the final section.

2. Literature Review

2.1. Related Work in Product Service System Configuration

The mass customization paradigm has been widely applied to the manufacturing industry and many achievements have been made in product configuration. However, the study on PSS configuration is not abundant. (Wang, Ming et al. 2014) proposed a modular product–service configuration method based on the structural knowledge of ontology. (Long, Wang et al. 2013; Long, Wang et al. 2016) built a multiclass support vector machine model for configuring a specific PSS that meets both functional needs and perception needs of customers. (Pezzotta, Pirola et al. 2013) proposed a Service Engineering framework that integrated a product-service design modelling tool developed at the Tokyo Metropolitan University with a discrete event simulation test-bench, which enabled the comparison of several PSS configuration solutions and the evaluation of both customer and internal performance. (Shen, Wang et al. 2012) proposed an ontology-based approach to representing service configuration knowledge and developed a service configuration system. (Dong and Su 2011) modeled a configuration system of PSS based on ontology under mass customization. (Geum, Lee et al. 2011) proposed the typological configuration solutions of product–service integrated roadmap according to the technological interface. (Shilov 2011) presented an approach based on efficient management of information services in the open information environment oriented to product-service system configuration. The approach was based on the technologies of ontology and context management. (Aurich, Wolf et al. 2009) presented a framework which comprised customer, manufacturer and product life cycle specific aspects to conduct a systematic configuration of PSS. (Becker, Beverungen et al. 2009) presented a configurative service engineering tool Adapt(X) to generate customized service processes, organizational infrastructures and IT infrastructures. (Baida, Gordijn et al. 2004) presented a service ontology to support a component-based structure of services. In their paper they used a case study from the Norwegian energy sector to describe how a component-based ontological description of services facilitates the automated configuration of a set of services.

However, all of the work above focused on the systematic configuration system, and configuration evaluation (especially cost evaluation in PSS configuration) has not been deeply studied, as Table 1 summarized.

Table 1 The summary of the related work in PSS configuration

Literature	Theoretical background	Contribution	Limitation	Link with PSS cost evaluation
(Wang, Ming et al. 2014)	Clustering method, modularization, ontology	A modular product–service configuration method	Without considering hybrid nature of PSS; lack of configuration evaluation	No
(Long, Wang et al. 2013)	Factor analysis, multiclass support vector machine model	Configuring a specific PSS that meets both functional needs and perception needs of customers	Lack of configuration evaluation	No
(Pezzotta, Pirola et al. 2013)	Service CAD methodology, Service Explorer tool, discrete event simulation	A Service Engineering framework to support the (re)engineering of a product-related service	The framework development remains at a preliminary stage. Detailed tools and methods are lacked.	Enabling the comparison of several PSS configuration solutions and the evaluation of both customer and internal performance
(Shen, Wang et al. 2012)	Ontology, rule knowledge	An approach to representing configuration knowledge and developing a configuration system	Without considering hybrid nature of PSS; lack of configuration evaluation	No
(Dong and Su 2011)	Ontology, rule	A configuration system	Lack of configuration	No

	knowledge	of PSS	evaluation	
(Geum, Lee et al. 2011)	Technological interface	The typological configuration solutions of product–service integrated roadmap	Lack of configuration evaluation	No
(Shilov 2011)	Ontology and context management.	An approach to integration of efficient management of information services in the open information environment for PSS configuration	Lack of configuration evaluation	No
(Aurich, Wolf et al. 2009)	Case study	A successful application for conducting a customer, manufacturer and product life cycle-oriented configuration of PSS	Lack of detailed tools and methods	PSS life cycle costs provide a promising starting point for the evaluation of a PSS.
(Becker, Beverungen et al. 2009)	Service Engineering	A configurative service engineering tool Adapt(X)	Without considering hybrid nature of PSS; lack of configuration evaluation	No
(Baida, Gordijn et al. 2004)	Case study, ontology	A service ontology to support a component-based structure of services	Without considering hybrid nature of PSS; lack of configuration evaluation	No

2.2. Related Work in Product Service System Costing

Since there is little extant literature focusing on PSS cost estimation at the stage of configuration, literature analysis is expanded to the research on PSS costing. (Schröder, Falk et al. 2015) developed a business model which evaluated process costs of additive manufacturing technologies. The business model and the evaluation of cost structures for additive manufacturing technologies were unique in the field of IPSS (Industrial PSS). A novel methodology for TLC was outlined by (Settanni, Newnes et al. 2014) addressing the challenges of PSS cost assessment with regard to cost object, scope and boundaries, and computations. (Settanni, Thenent et al. 2013) presented an intermediate step towards a computational structure explicitly linking cost and performance for PSS. Network formalism and principles derived from Input-Output Analysis were employed to base PSS cost estimation on a representation of a PSS as a 'system'. (Romero Rojo, Roy et al. 2012) provided a cost estimating framework for electrical, electronic and electromechanical components obsolescence within the use-oriented PSS contracts. The framework was able to estimate the non-recurring cost of obsolescence during the contracted period. It was based on the information available at the bidding stage concerning the product breakdown structure and the obsolescence management strategy deployed. (Zhang, Haapala et al. 2011) explored the utility of the IDEFO systems modelling tool as a way to support strategic sustainable business decision making in conjunction with life cycle assessment and life cycle cost analysis.

(Huang, Newnes et al. 2011) presented a new framework for estimating the cost of in-service provision for a product service system. (Kreye, Goh et al. 2009) utilized Game Theory to model the uncertainty in costs arising from conflict situations in the life cycle of PSS. Therewith, the decision making process could be modeled and made visible with its various implications.

However, the difficulties of PSS costing at the stage of configuration have not been well resolved, as Table 2 summarized. Research on the PSS cost breakdown structure, the comprehensive life cycle perspective, and the uncertainty propagation are lacked in the extant literature.

Table 2 The summary of the related work in PSS costing

Literature	Theoretical background	Contribution	Limitation	Link with PSS cost evaluation
(Schröder, Falk et al. 2015)	The time-driven activity-based costing	A business model which evaluated process costs of additive manufacturing technologies	Applicable for additive manufacturing	The evaluation of cost structures for additive manufacturing technologies
(Settanni, Newnes et al. 2014)	Through-life Costing; A review of the literature	Addressing the challenges of PSS cost assessment with regard to cost object, scope and boundaries, and computations.	Lack of concrete costing approach	PSS cost estimation
(Settanni, Thenent et al. 2013).	Input-Output Analysis	An intermediate step towards a computational structure explicitly linking cost and performance for PSS	Lack of cost breakdown structure, and the uncertainty propagation	PSS cost estimation
(Romero Rojo, Roy et al. 2012)	Product breakdown structure and the obsolescence management strategy; a review of the literature	A cost estimating framework for electrical, electronic and electromechanical components obsolescence within the use-oriented PSS contracts	Applicable for electrical, electronic and electromechanical components obsolescence within the use-oriented PSS contracts	The non-recurring cost of obsolescence during the contracted period
(Zhang, Haapala et al. 2011)	IDEFO systems modelling tool	A decision making method for PSSs using life cycle assessment and life cycle cost analysis	Lack of cost breakdown structure, and the uncertainty propagation	Life cycle cost analysis
(Huang, Newnes et al. 2011)	A review of the literature and on-site data collection	A new framework for estimating the cost of in-service provision for a PSS	Lack of costing approach	Life cycle costing; cost factors

(Kreye, Goh et al. 2009)	Game Theory	Modeling the uncertainty in costs arising from conflict situations in the life cycle of PSS.	Lack of cost structure	Uncertainty in through life costing□□□□ □□□□□ □□□□□□

3. Research Strategy

This paper is based on literature studies in the areas of product service systems, product configuration, service configuration, and life cycle cost. The authors have a wealth of research and industrial experience in these different fields, which are reflected in this paper. To validate the research, an industrial example from a pump company is included.

This section presents a three-phase structured research strategy, as illustrated in Figure 1, which is employed in the paper in order to develop the cost evaluation framework for PSS configuration.

Phase 1: Build a holistic view of PSS configuration

To link the costing activity with the configuration activity, it is important to present multi-domain knowledge in PSS configuration at first. This phase is elaborated in Section 4 by building a holistic view of PSS configuration. Axiomatic design (Suh 1990) is the theoretical basis for this part of the research.

Phase 2: Define the profiles of the PSS cost element

Based on three of the proposed domains in the holistic view, the three-dimensional cost element is then proposed. It is defined as a basic constituent that enables the conduction of PSS costing, and consumed for realizing the service activities and/or the product behaviors. It is proposed in this paper to construct a cost breakdown structure linking with the PSS entity and worked as the basis of the developed framework in this paper. Each dimension of the PSS cost element is further elaborated in Section 5. Literature analysis and Mass Customization (MC) (Jiao, Tseng et al. 2000) are the theoretical basis for this part of the research.

Phase 3: Develop the cost evaluation approach for PSS configuration

Based on the proposed PSS cost element, the cost evaluation approach for PSS configuraition is developed with the consideration of relative accurancy and uncertainty propagation. This step-by-step approach is also the core of the cost evaluation framework for PSS configuration. This phase is then presented in Section 6 based on several achievements in previous research, such as CAPTOE (Erkoyuncu, Durugbo et al. 2013), and Activity Based Costing (ABC) (Settanni, Newnes et al. 2014). CAPTOE is an acronym for commercial, affordability, performance, training, operations and engineering and acts as a reference point for identifying uncertainty sources peculiar to the service project or operations.

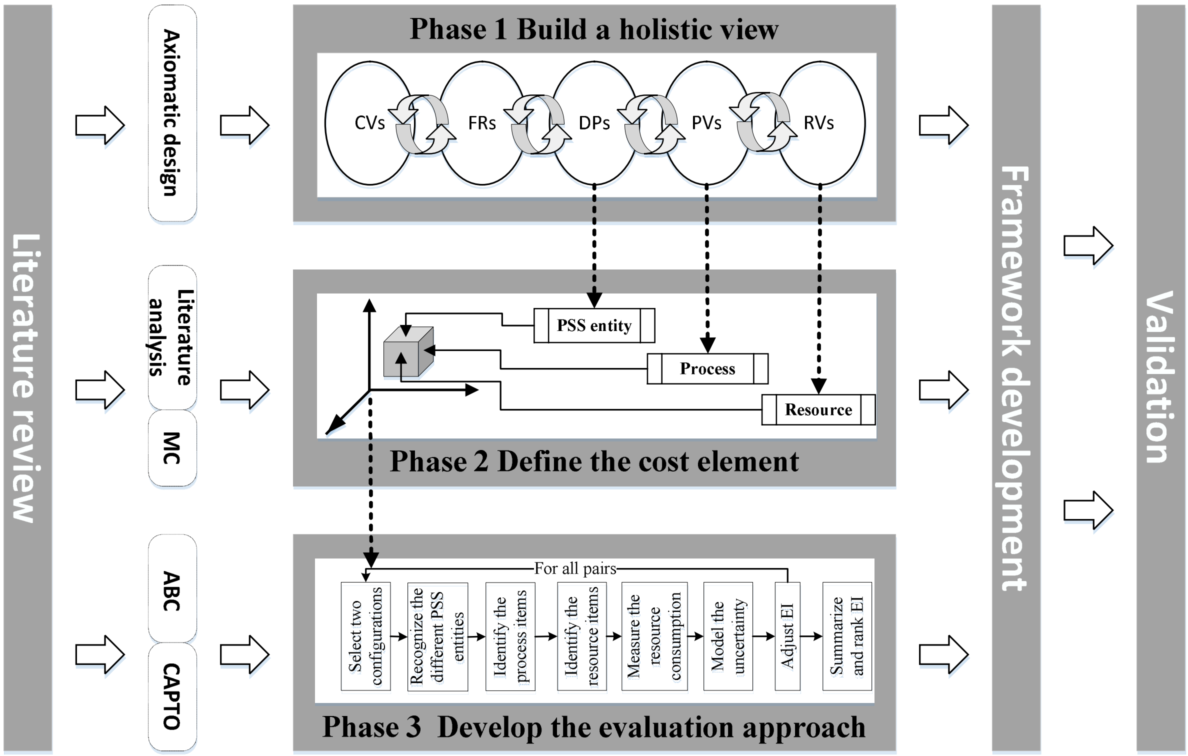

Fig. 1 Three-phase structured research strategy

4. A Holistic View of PSS Configuration

PSS configuration is to provide customers a right PSS by selecting product components and service modules from a predefined component and module library according to customer needs and other constraints (Long, Wang et al. 2013). PSS configuration essentially entails a conceptual structure and the overall logic of an organization that generates a new PSS by providing a generic umbrella of common PSS entities. Based on the theory of Axiomatic Design (Suh 1990), PSS configuration is formulated in this paper as encompassing consecutively five domains, namely the customer, function, solution, process and resource domain. Decision-making involves a series of "what-how" mappings between these domains. The rationale lies in not only modeling the configuration process of an entire class of PSS configuration solutions based on individual requirements, but also extending to process and resource planning within a coherent model. Figure 2 illustrates the holistic view of PSS configuration along the entire spectrum of PSS realization.

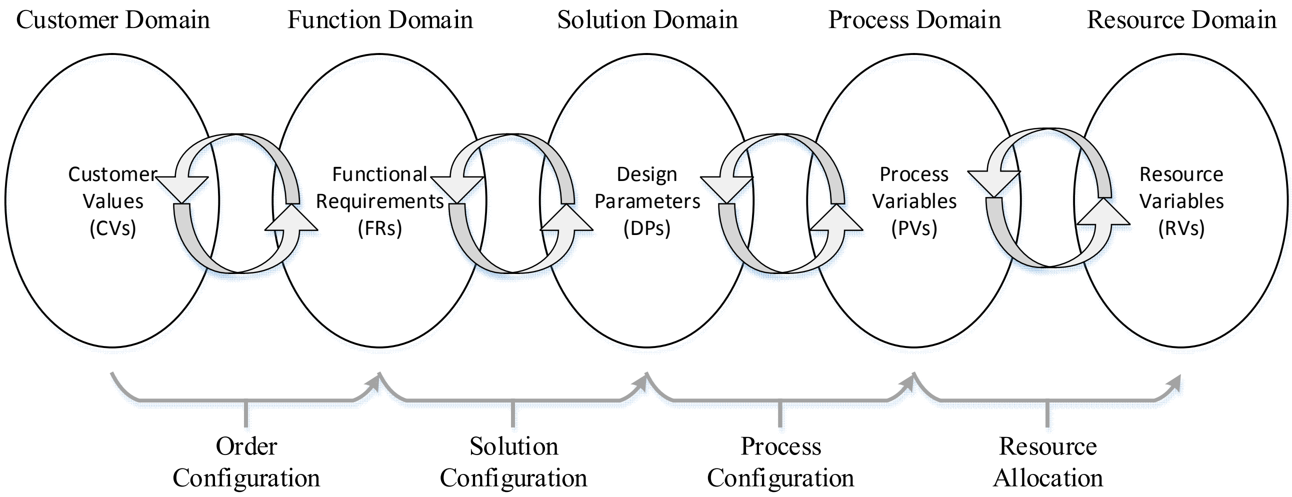

Fig. 2 A holistic view of PSS configuration

Centre to the concept of PSS is a strong focus on fulfilling increasing customer value (Xing, Wang et al. 2013). The customer domain is thus characterized by a set of customer values (CVs) representing segmentation of markets that demand for PSS and triggering downstream design mappings in a cascading manner. The main issue is to start from the unique customer value. The identified values should primarily be seen as requirements on the requested function and not as product or service-related (Sundin, Lindahl et al. 2009). Therefore, CVs are first translated into functional requirements (FRs) in the function domain. The mapping between the customer and function domain constitutes the front-end issues of order configuration. Such a design definition task is carried out within an existing portfolio, and manifests itself through those common practices like sales force automation.

In the function domain, configuration engineers take engineering concerns into account and further elaborate FRs based on available PSS technologies and capability. PSS configuration solutions are thus generated in the solution domain by mapping FRs to design parameters (DPs) based on the shared platform or family of PSS. This stage involves typical decisions regarding platform/family design and configuration reasoning. The main focus of platform-based solution configuration is the technical feasibility of DPs in terms of fulfilling the specified functionality.

The back-end issues are associated with the process and resource domains, which are characterized by process variables (PVs) and resource variables (RVs), respectively. The mapping from DPs to PVs entails the task of process configuration, which must generate process planning within existing capabilities. A process is a structured collection of interrelated purposeful actions, or operations to deliver a range of products or services (Settanni, Newnes et al. 2014). Process design is particularly important to PSS since service is inherently a series of processes. Therefore, this domain enables the implementation of PSS configuration solutions, which includes the manufacturing process of products and the production process of life cycle services. The main concern in the process domain is productionability.

The resource domain addresses the issues of resource allocation for PSS fulfillment. The main concern is to align process configuration with resource supply decisions. It is assumed that cost is generated by the consumption of the resources.Cost commitment is achieved based on the task of resource allocation. The costing activity and the configuration activity are thereby linked.

5. The Three-Dimensional PSS Cost Element

A cost object is "…any item, such as products, customers, departments, projects, activities and so on, for which costs are measured and assigned" (Settanni, Newnes et al. 2014). (Settanni, Newnes et al. 2014) also argued that PSS is a system potentially involving multiple, interconnected and interacting cost objects simultaneously. Therefore, the cost object of PSS configuration solutions is typically one or more of the following: an instance of a product platform or family; an instance of product-related service platform or family; an instance of time over which the interrelated purposeful actions of bringing forth, sustaining, or disposing of a PSS to produce a result of value to customers.

To measure this kind of cost object, the three-dimensional PSS cost element is proposed based on the multi-view PSS configuration model proposed in Section 4:

Definition 1. A PSS cost element is a basic constituent that enables the conduction of PSS costing. It is consumed for realizing the service activities and/or the product behaviors. The three-dimensional PSS cost element is specifically defined as the cost consumed by 'resource', performed by 'process' and applied to 'PSS entity'.

As illustrated in Figure 3, the cost element *CE* (*i*, *j*, *k*) is defined as the cost consumed by the resource *i,* performed by the process *j* and applied to the PSS entity *k*, where *i* can be the labor resource, *j* can be the installation process, *k* can be the printer in a Canon MDS, i.e. a kind of PSS. Furthermore, a PSS entity list defines all the relevant PSS entities comprising a PSS, a process list defines all the possible activities performed during the life cycle of a PSS, and a resource list defines all the possible resources used by the activities to implement a PSS. All the PSS cost elements of a PSS are then obtained by combining the PSS entity list, the process list and the resource list. And the final cost of a PSS can be conducted as a summation of all the PSS cost elements.

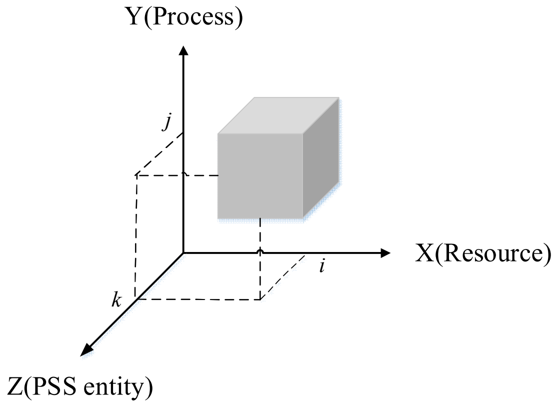

Fig. 3 A three-dimensional PSS cost element

Based on the PSS cost element, cost analysis is performed in the principle of combined Activity Based Costing (ABC) and cost breakdown structure. ABC employs resource consumption orientation with a cost attribution rationale and process metrics (Settanni, Newnes et al. 2014). Therefore, the PSS cost elements are associated first with the PSS entities; further with the processes and then with the resources. Furthermore, cost breakdown structure is a hierarchical structure that costs can be allocated to lowest level. Since configuration solution is composed of a set of entities in a structured manner, cost analysis in PSS configuration is thus decomposed into the PSS entity list. Cost categories are linked with the make-up of the PSS. Therefore, the bottom up microcosting can be employed, which has been seen as the most robust estimating model for service since all relevant cost components are identified and valued at the most detailed level (Datta and Roy 2010). The resource list and the process list are discussed respectively in the following two subsections, and the PSS entity list is presented in Section 5.3.

5.1. Resource

To obtain a thorough understanding of the subject, the authors carried out a review of the literature. Academic papers were sought on common databases such as EBSCO Business Source Complete, Emerald Insight, Scopus and

Thomson Reuters ISI. Several search combinations of keywords like ‘Product service system AND cost’, ‘Product service system AND costing’, ‘Product service system AND life cycle cost’, ‘Product service system AND whole life cost’ and ‘Product service system AND through life cost’ were applied. The abstracts of more than 267 articles that met the criterion were examined to eliminate contributions clearly beyond the scope of this paper. After quick reading these articles, 39 papers of them were left and deeply analysed.

Based on these literatures, resources for PSS implementation are identified as shown in Table 3. In the table, italic represents the different terms with similar meanings. All the terms are ranked by the literature maturity level, i.e. the number of the related references. For better understanding and classification, the authors first select the terms with high literature maturity level, then merge different terms with similar meanings into a unified resource name, subsequently cluster all the selected terms into three categories (namely human resource, material resource, immaterial resource) based on their similarity, and finally present the resource list of the PSS cost element in a tree-like structure, as illustrated in Figure 4. Cost drivers are also associated in the resource list, which are important for measuring the consumption of the resources.

Table 3 Resource identification and references in literature review

Resource	References
Labor	(Vogtländer, Brezet et al. 2001; Ye, Zhang et al. 2009; Datta and Roy 2010; Storck 2010; Kayrbekova, Markeset et al. 2011; Khataie, Bulgak et al. 2011; Kimita, Tateyama et al. 2012; Xing, Wang et al. 2013; Cheung, Marsh et al. 2015)
Human resource	*(Ben-Arieh and Qian 2003; Zhang, Haapala et al. 2011; Boehmann, Leimeister et al. 2014)*
Person	*(Baxter, Roy et al. 2009)*
Material	(Vogtländer, Brezet et al. 2001; Baxter, Roy et al. 2009; Ye, Zhang et al. 2009; Storck 2010; Kayrbekova, Markeset et al. 2011; Khataie, Bulgak et al. 2011; Xu, Elgh et al. 2012; Boehmann, Leimeister et al. 2014)
Raw material	*(Zhang, Haapala et al. 2011; Kimita, Tateyama et al. 2012)*
Administration and overheads	(Ben-Arieh and Qian 2003; Kayrbekova, Markeset et al. 2011; Khataie, Bulgak et al. 2011; Kimita, Tateyama et al. 2012; Xing, Wang et al. 2013; Cheung, Marsh et al. 2015)
Equipment	(Ben-Arieh and Qian 2003; Baxter, Roy et al. 2009; Ye, Zhang et al. 2009; Storck 2010; Zhang, Haapala et al. 2011; Kimita, Tateyama et al. 2012)
Energy	(Vogtländer, Brezet et al. 2001; Storck 2010; Zhang, Haapala et al. 2011; Kimita, Tateyama et al. 2012)
Facility	(Baxter, Roy et al. 2009; Cheung, Marsh et al. 2009; Kimita, Tateyama et al. 2012)
Infrastructure	*(Zhang, Haapala et al. 2011)*
Consumables	(Datta and Roy 2010; Cheung, Marsh et al. 2015)
Expendable	*(Kimita, Tateyama et al. 2012)*
Depreciation	(Vogtländer, Brezet et al. 2001; Kimita, Tateyama et al. 2012)
Component	(Kimita, Tateyama et al. 2012; Cheung, Marsh et al. 2015)
Layout	(Kimita, Tateyama et al. 2012)
Building space	*(Storck 2010)*
Tools	(Ye, Zhang et al. 2009; Storck 2010)
Information	(Baxter, Roy et al. 2009)
Transportation	(Kayrbekova, Markeset et al. 2011)

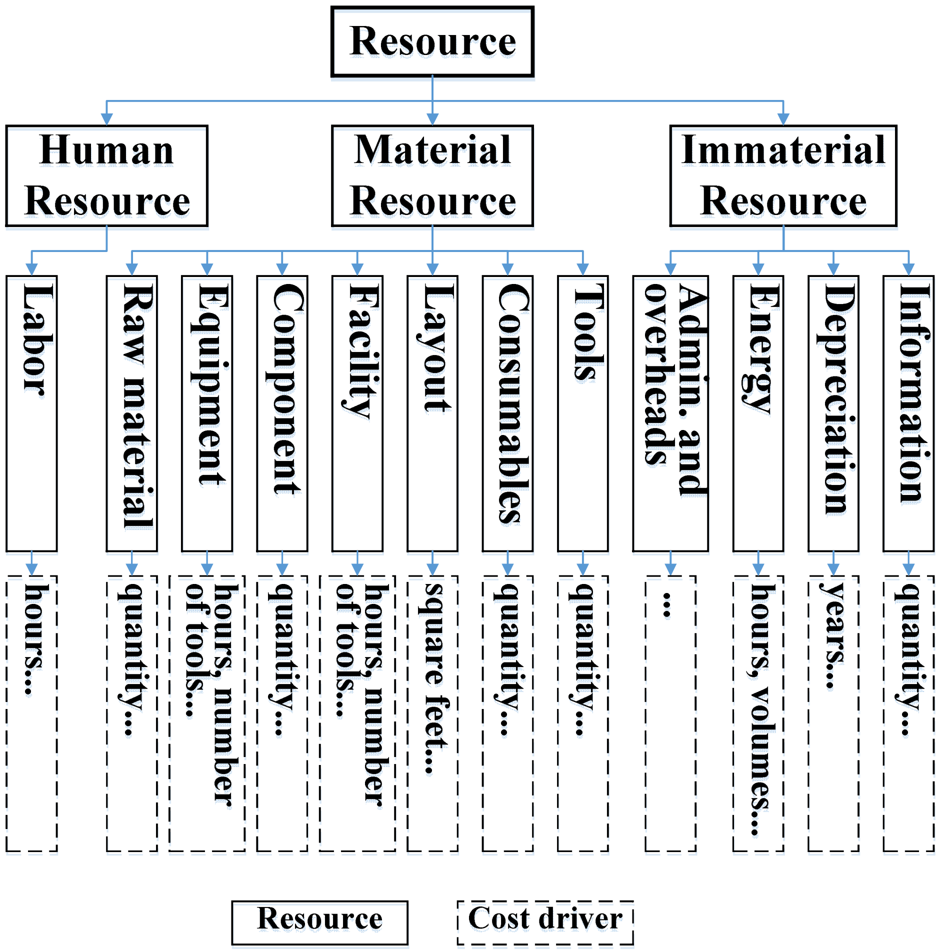

Fig. 4 The resource list of the PSS cost element

5.2. Process

Within the PSS research, a PSS configuration solution is a system combining physical products and intangible services that have been integrated and optimized from a life cycle perspective in relation to customer value (Lindahl, Sundin et al. 2014). It is thus important to trace the cost of activities performed in processes, since many processes take place in the future (e.g., planned maintenance to prevent failures, unplanned maintenance due to sudden failures, modifications due to changes in capacity needs, etc.) (Jiao and Tseng 1999). However, a bulk of work was centered on and around the product manufacturing phase and thus lacked the broader life cycle perspective (Waghmode, Sahasrabudhe et al. 2010).

In the broader life cycle perspective, resources are consumed by production, use and disposal of the core product as well as by the development and provision of the related services. Analysis of the processes of PSS implementation is also taken with the similar approach in Section 5.1. Table 4 shows the result of the literature analysis. Italic represents the different terms with similar meanings. After the selection of terms with high literature maturity level, the merging of the terms with similar meaning, the process list of the PSS cost element is presented together with the corresponding cost drivers as illustrated in Figure 5. For a better classification and representation, three distinctive sections, i.e. acquisition, operation, and end life are proposed. Based on the identification of these major processes in the PSS life cycle, the more detailed processes, activities and associated cost drivers can be formulated in the specific cases.

Table 4 Process identification and references in literature review

Process	References
Development *Design*	(Wang, Song et al. 2007; Cheung, Marsh et al. 2009; Huang, Newnes et al. 2011; Prabhakar and Sandborn 2012; Xing, Wang et al. 2013; Schuh, Pitsch et al. 2015) *(Sundin, Lindahl et al. 2009; Datta and Roy 2010; Xu, Elgh et al. 2012; Cheung, Marsh et al. 2015)*
Manufacture *Production*	(Cheung, Marsh et al. 2009; Schuh, Boos et al. 2009; Sundin 2009; Sundin, Lindahl et al. 2009; Xu, Elgh et al. 2012; Cheung, Marsh et al. 2015; Rodrigues, Erkoyuncu et al. 2015; Schuh, Pitsch et al. 2015) *(Huang, Newnes et al. 2011; Smit 2012)*
Machining *Mechanical processing*	(Xu, Elgh et al. 2012) *(Schuh, Boos et al. 2009)*
Assembly	(Schuh, Boos et al. 2009; Xu, Elgh et al. 2012; Cheung, Marsh et al. 2015; Schuh, Pitsch et al. 2015)
Testing	(Cheung, Marsh et al. 2009; Waghmode, Sahasrabudhe et al. 2010)
Delivery *Distribution* *Dispatch*	(Schuh, Boos et al. 2009; Sundin 2009; Sundin, Lindahl et al. 2009; Datta and Roy 2010) *(Cheung, Marsh et al. 2015)* *(Waghmode, Sahasrabudhe et al. 2010)*
Installation and Commissioning	(Sundin 2009; Waghmode, Sahasrabudhe et al. 2010; Erkoyuncu, Durugbo et al. 2013)
Operation	(Wang, Song et al. 2007; Kreye, Goh et al. 2009; Waghmode, Sahasrabudhe et al. 2010; Prabhakar and Sandborn 2012; Smit 2012; Xu, Elgh et al. 2012)
Utilization *Use* *Usage*	(Schuh, Boos et al. 2009; Huang, Newnes et al. 2011; Smit 2012) *(Cheung, Marsh et al. 2015)* *(Sundin 2009; Schuh, Pitsch et al. 2015)*
Support *Service* *In-service* *Sustainment*	(Cheung, Marsh et al. 2009; Huang, Newnes et al. 2011; Prabhakar and Sandborn 2012; Smit 2012) *(Xu, Elgh et al. 2012)* *(Rodrigues, Erkoyuncu et al. 2015)* *(Settanni, Newnes et al. 2014)*
Product modification	(Xu, Elgh et al. 2012)
Maintenance	(Wang, Song et al. 2007; Baxter, Roy et al. 2009; Cheung, Marsh et al. 2009; Kreye, Goh et al. 2009; Schuh, Boos et al. 2009; Sundin 2009; Datta and Roy 2010; Waghmode, Sahasrabudhe et al. 2010; Smit 2012; Xu, Elgh et al. 2012; Erkoyuncu, Durugbo et al. 2013; Durugbo 2014)
Repair	(Waghmode, Sahasrabudhe et al. 2010; Xu, Elgh et al. 2012; Erkoyuncu, Durugbo et al. 2013)
Training	(Baxter, Roy et al. 2009; Datta and Roy 2010; Smit 2012; Xu, Elgh et al. 2012; Erkoyuncu, Durugbo et al. 2013; Durugbo 2014; Rodrigues, Erkoyuncu et al. 2015)
Asset and operation management service	(Datta and Roy 2010; Xu, Elgh et al. 2012)
Supply chain management	(Datta and Roy 2010; Xu, Elgh et al. 2012)
Information service	(Rodrigues, Erkoyuncu et al. 2015)
Engineering service	(Datta and Roy 2010; Xu, Elgh et al. 2012)
Equipment management	(Xu, Elgh et al. 2012; Erkoyuncu, Durugbo et al. 2013)
Rehabilitation	(Xu, Elgh et al. 2012)

Restoration *Retrofitting* *Adaptation*	(Smit 2012) (Erkoyuncu, Durugbo et al. 2013) *(Sundin 2009; Datta and Roy 2010)*
Replacement	(Cheung, Marsh et al. 2009; Xu, Elgh et al. 2012)
Financial services	(Xu, Elgh et al. 2012; Erkoyuncu, Durugbo et al. 2013)
Spare delivery *Replenishment* *Logistics*	(Baxter, Roy et al. 2009; Cheung, Marsh et al. 2009; Xu, Elgh et al. 2012; Erkoyuncu, Durugbo et al. 2013) *(Smit 2012)* *(Rodrigues, Erkoyuncu et al. 2015)*
Upgrade	(Cheung, Marsh et al. 2009; Xing, Wang et al. 2013; Durugbo 2014)
Remedy	(Erkoyuncu, Durugbo et al. 2013)
Inspection	(Erkoyuncu, Durugbo et al. 2013)
Consulting	(Erkoyuncu, Durugbo et al. 2013)
End of life *Retirement*	(Cheung, Marsh et al. 2009; Kreye, Goh et al. 2009; Zhang and Zhang 2014; Cheung, Marsh et al. 2015) *(Huang, Newnes et al. 2011; Smit 2012)*
Disposal	(Wang, Song et al. 2007; Cheung, Marsh et al. 2009; Schuh, Boos et al. 2009; Waghmode, Sahasrabudhe et al. 2010; Prabhakar and Sandborn 2012; Xu, Elgh et al. 2012; Xing, Wang et al. 2013; Zhang and Zhang 2014; Rodrigues, Erkoyuncu et al. 2015)
Recycling	(Cheung, Marsh et al. 2009; Schuh, Boos et al. 2009; Sundin 2009; Datta and Roy 2010; Xu, Elgh et al. 2012; Zhang and Zhang 2014; Schuh, Pitsch et al. 2015)
Reuse *Remanufacturing*	(Cheung, Marsh et al. 2009; Xu, Elgh et al. 2012; Zhang and Zhang 2014; Cheung, Marsh et al. 2015) *(Sundin 2009; Datta and Roy 2010; Xu, Elgh et al. 2012; Zhang and Zhang 2014)*
Disassembly	(Cheung, Marsh et al. 2015)
Cleaning	(Cheung, Marsh et al. 2015)
Inspection	(Cheung, Marsh et al. 2015)
Component exchange, retrieval, or reprocessing	(Cheung, Marsh et al. 2015)
Assembly	(Cheung, Marsh et al. 2015)
Testing	(Cheung, Marsh et al. 2015)

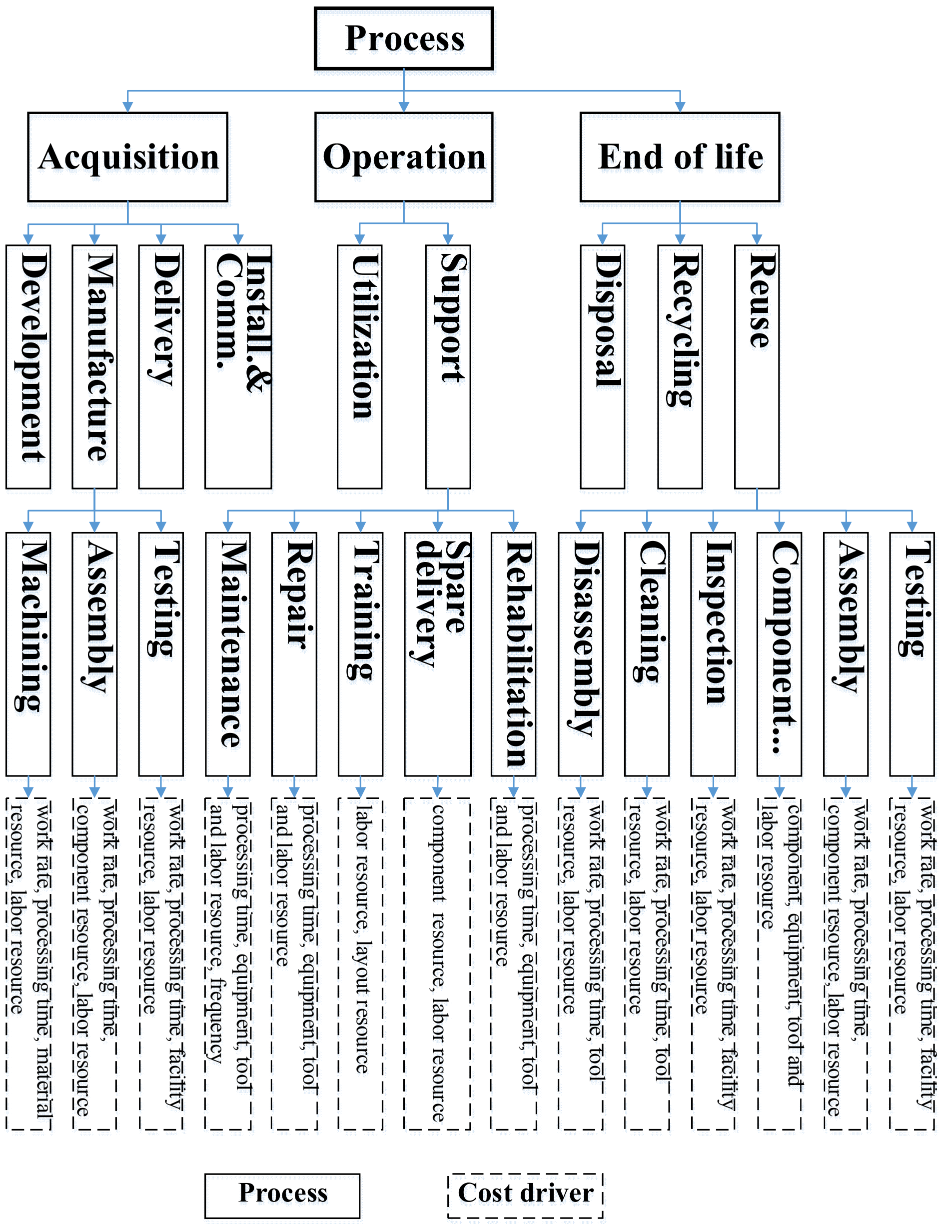

Fig. 5 The process list of the PSS cost element

5.3. *PSS entity*

PSS contains a physical product core, which is supplemented by specific non-physical services. The latter are applied throughout the whole life cycle and thus complete the PSS (Aurich, Wolf et al. 2009). Furthermore, to successfully meet increasingly diverse customer needs at reasonably low cost with high quality, theories and methodologies for mass-customized products have been applied to services, such as service family (Moon, Shu et al. 2011), service modularity (de Blok, Luijkx et al. 2010), service platform (Meyer, Jekowsky et al. 2007). These researches reinforce the claim that the component-based nature is inherent to services (Baida, Gordijn et al. 2004). Therefore, a component-based and configurable PSS is proposed in this paper and PSS entities are defined as follows:

Definition 2. A PSS entity is a constituent element, of which PSS consist. PSS entities can be either in the form of product components or service modules. The entities of the physical products are product components. Service modules or simply modules are the equivalent entities in terms of the intangible services (Aurich, Wolf et al. 2009).

The PSS entity in the form of product components can be modeled in the form of Generic Bill-of-Materials (GBOM) (Jiao, Tseng et al. 2000) based on the theory of Mass Customization. As illustrated in Figure 6, product component can be at different level of granule and ascertained with the selection of different instances of variety parameter. In addition, variety parameter is just a kind of DPs (design parameters), which results in the high variety. There are two types of relationships in the list, where a-part-of indicates a AND type relation and a-kind-of is a XOR type selection.

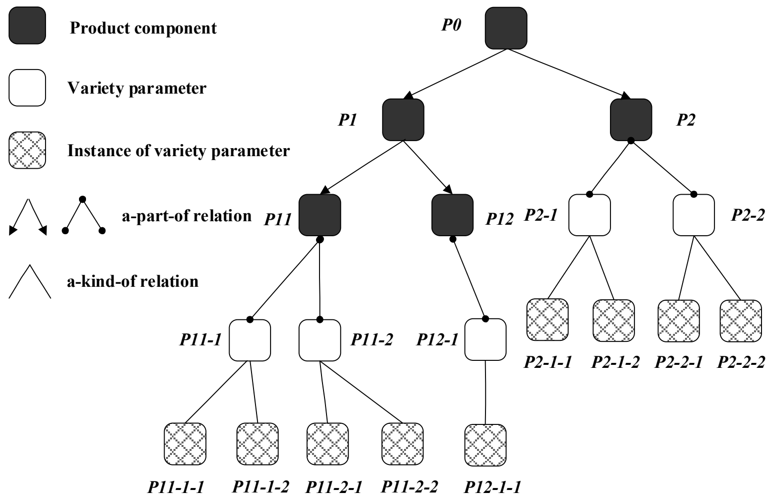

Fig. 6 Product components in PSS

The PSS entity in the form of service modules serve as building blocks to support on demand service composition, which means one service module can be composed of other modules. A service module can also be the subtype of another, i.e. two service modules form the parent–child relationship. Hence the architectural structure of service modules in PSS is imposed by composed-of (part-of) and subclass (kind-of) relations. Therefore, service modules in PSS can also be modeled in the similar form of product components in PSS, as illustrated in Figure 7, where instances of parameter are featured by DPs, and further defined with reference to PVs (process variables). In addition, there are two subtypes of service modules in PSS: Elementary component and Service Bundle (Shen, Wang et al. 2012). Elementary component is the smallest service unit that, from a commercial point of view, can be meaningfully offered to customers by a service provider. The providers may be servitised manufacturers themselves or their service suppliers. Elementary components can be classified into three types from the view of service roles: core component (the main business), supporting component (making the core service components possible) and enhancing component (improving the core service components' value by extra features). Elementary components cannot be further decomposed while service bundles are just composite services which employ and synthesize a set of core components, and possibly supporting and enhancing components through various binding rules. There is always some logic behind the decision to service modules such as they depend on each other, legislation requires it, and to make better use of existing resources.

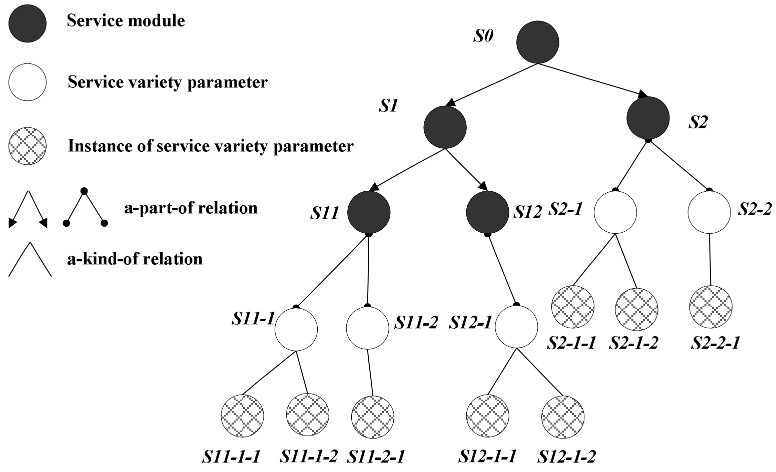

Fig. 7 Service modules in PSS

It is important that product components and service modules are interacted in the PSS life cycle to deliver value-in-use to customers, as shown in Figure 8. There interactions represent functional rule concerning how product components and service modules may or may not be bundled. For example, PSS entity P2-1-1 and S11-1-1 are under the *Require* bindings, which means S11-1-1 is a necessary occurrence if P2-1-1 exists. Therefore, the cost of the interrelated purposeful actions of bringing forth, sustaining, or disposing of a PSS is also required to be considered.

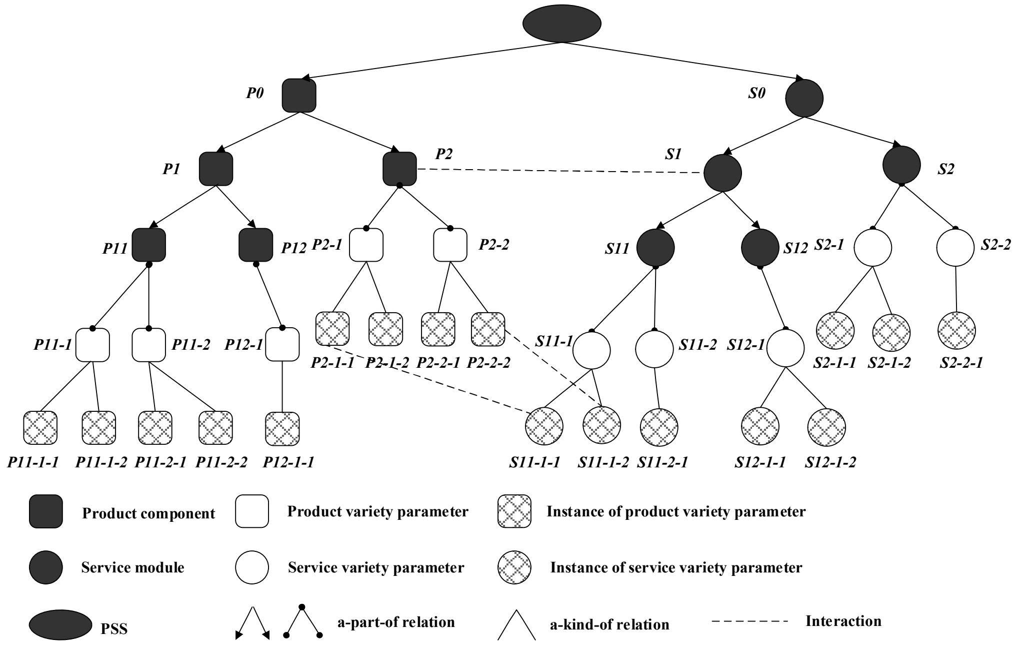

Fig. 8 The PSS entity list of the PSS cost element

6. The Cost Evaluation Approach within the Framework

With the aim of the comparison and selection of competing configuration solutions, knowing cost in absolute terms may not be the main aim, relative accuracy is sought (Settanni, Newnes et al. 2014). Therefore, in this paper, an innovative cost evaluation approach is proposed which only evaluates and compares the cost of the different PSS cost elements among the feasible configuration solutions. Much less data and information is thus needed, and the results are normally less sensitive to inaccuracy and uncertainty in the data and information.

First of all, an indicator, called PSS cost evaluation indicator (*EI*) is proposed and utilized in the evaluation approach:

Definition 3. PSS cost evaluation indicator (*EI*) can evaluate either a cost element or a configuration solution, whose cost is composed of different cost elements. The calculated *EI* does not represent the real arising cost, but supports the comparison and therewith the decision. The higher *EI* indicates the higher cost the evaluated object has.

The main principle of the proposed cost evaluation approach for PSS configuration is the evaluation and comparison of the different cost elements among the competing configuration solutions, where the cost element has been defined as the cost that is caused by the consumption of the specific resource in a specific part of a process throughout the life cycle of a specific PSS entity. The following presents the step-by-step approach of calculating *EI* and making a decision on the feasible configuration solutions, as shown in Figure 9.

Step 1: Recognize the different PSS entities

Since the approach is based on the rationale of comparison, two configuration solutions S_1, S_2 from the feasible catalogue $\{S_x, x=1\ldots n\}$ are first selected. According to the definition of the PSS cost element, cost elements are first associated with the PSS entities. To recognize the diverse cost elements in S_1, S_2, different PSS entities are identified based on the PSS entity list proposed in Section 5.3. The cost elements $CE\ (i, j, k)$ with different DPs of component k are recognized. In the process of recognition, the PSS entities are checked from the lower level to the upper level. In the end, a set of the cost elements $\{CE_x\ (i, j, k), k=1\ldots m, x=1, 2\}$ associated with different PSS entities are confirmed for further analysis.

Step 2: Identify the process items and the corresponding process drivers

For each PSS entity k recognized in Step 1, the processes j that constitute the cost element $CE_x\ (i, j, k)$ are identified and the corresponding drivers are confirmed. Based on the process list proposed in Section 5.1, the specific processes can be formulated in the specific cases. Additionally, with the rationale of comparison-based evaluation, the identification of the process items can be performed only on the different processes that are performed on the same PSS entity.

Step 3: Identify the resource items and the corresponding resource drivers

For each process j identified in Step 2, the resources i that constitute the cost element $CE_x\ (i, j, k)$ are then identified and the corresponding drivers are confirmed. Based on the resource list proposed in Section 5.2, the resources can be further specified in the specific cases. In addition, with the rationale of comparison-based evaluation, the identification of the resource items can be performed only on the different resources that are used in the same process, which leads to less data and uncertainty.

Step 4: Measure the resource consumption and establish the initial *EI*

For each cost element $CE_x\ (i, j, k)$ identified by Step 1 to Step 3, its initial *EI* is calculated based on the identified cost drivers, the quantity of resources consumed and the unit cost of the resource items. The calculation method is based on the Activity Based Costing. For S_1, S_2, the initial EI_1 and EI_2 is thus calculated by the sum of the *EI* of all $CE_1\ (i, j, k)$ and $CE_2\ (i, j, k)$, respectively.

Equation 1. $EI(S_x) = \Sigma EI[CE\ (i, j, k)] = \Sigma\ \textit{Resource cost}*\textit{resource quantity}*\textit{resource drivers}*\textit{process drivers}$

Step 5: Model the uncertainty and adjust *EI*

There are uncertainties involving unwanted events as faulty processes, uncertainties within an organization, from interaction between different partners or uncertainty in demand. These uncertainties have to be taken care of while computing cost of PSS (Datta and Roy 2010). It is more realistic to have a range of cost estimates rather than a discrete value (Curran, Raghunathan et al. 2004). Therefore, CAPTOE is utilized to model the uncertainty and add a range $\pm\Delta$ to the initial *EI*. The CAPTOE taxonomy is a classification of uncertainty sources, and acts a reference point for identifying uncertainty sources peculiar to the service project or operations. CAPTOE, an acronym for commercial, affordability, performance, training, operations and engineering areas, was derived based on an analysis of a wide range of work breakdown structures, and reflects considerations for equipment reliability, availability, maintainability and supportability for the in-service phases of manufacturing. With the limitation of the paper length, the details of CAPTOE can be referred to (Erkoyuncu, Durugbo et al. 2013). In the end, the cost comparison of completing configuration solutions S_1, S_2 can be achieved by the difference of updated EI_1 and EI_2, i.e. $(EI_1 \pm \Delta_1) - (EI_2 \pm \Delta_2)$.

Step 6: Summarize and rank all the EI_x

All the configuration solutions in the feasible catalogue $\{S_x, x=1\ldots n\}$ are selected and evaluated pairwise, repeating from Step 1 to Step 5. Based on all the pairwise cost comparison, a final ranking on *EI* of all the feasible configuration solutions is thereby achieved. From the view of the evaluation criteria of cost, the configuration engineers are recommended by the configuration solution with the lowest *EI*.

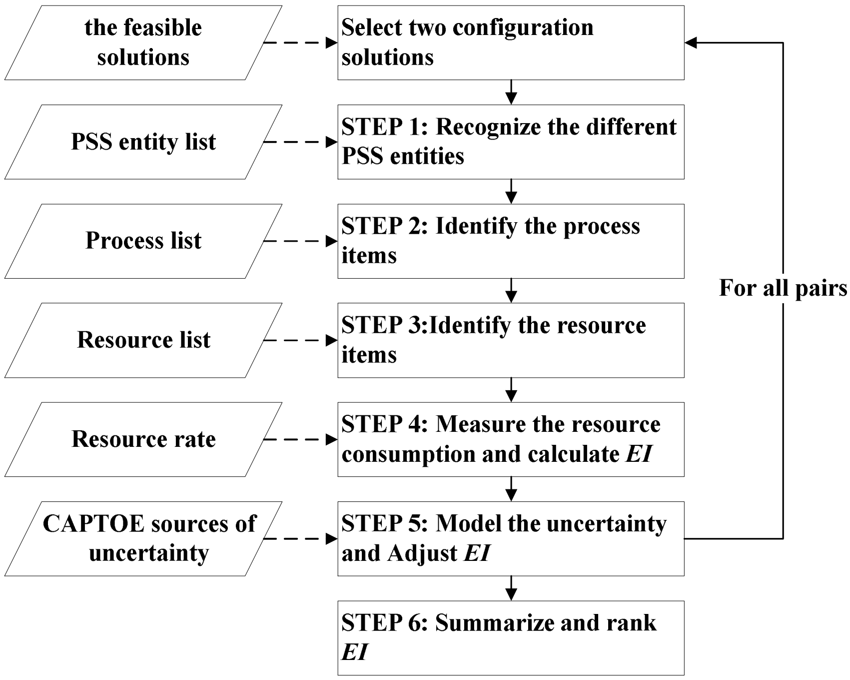

Fig. 9 The evaluation approach

Based on all the research from Section 4-6, the framework for cost evaluation in PSS configuration is finally developed, as illustrated in Figure 10, which comprises three parts, namely the preparatory stage, the evaluation stage and the configuration stage.

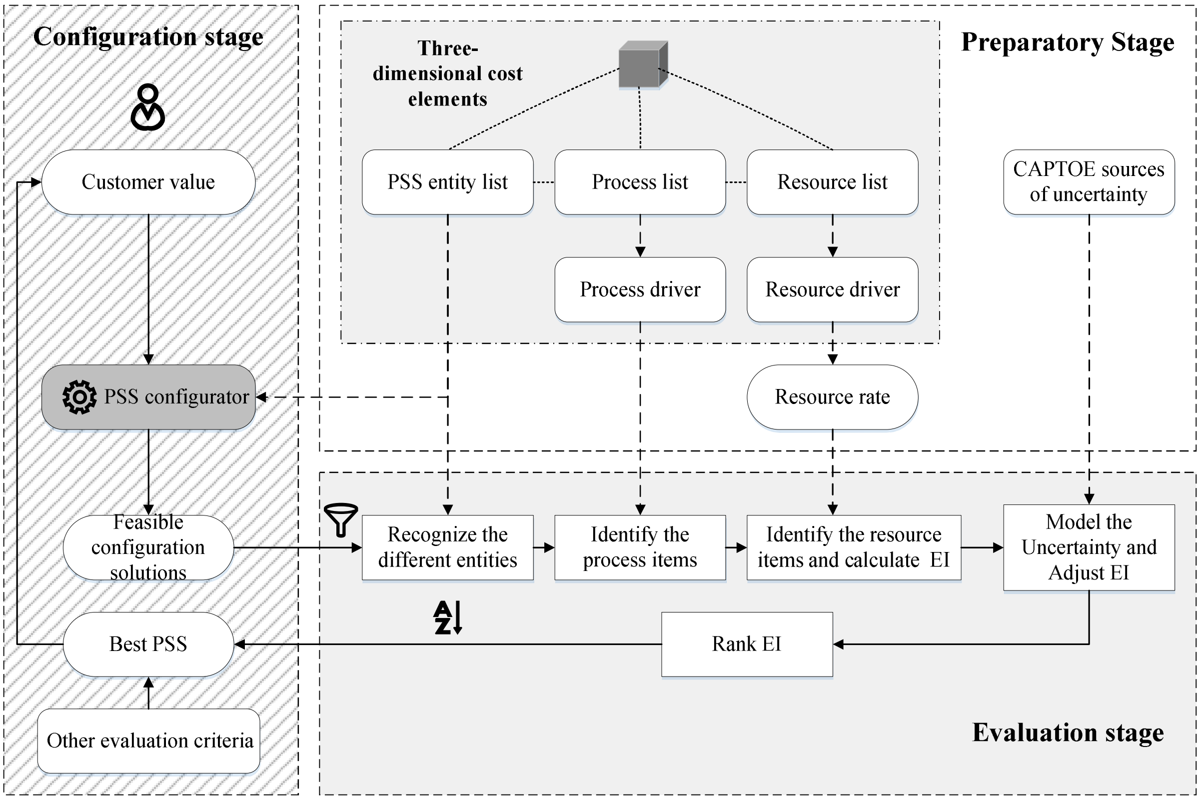

Fig. 10 The framework for cost evaluation in PSS configuration

The configuration stage is cored by a conventional configuration activity. To obtain the best PSS to fulfill the customer value, different kinds of evaluation criteria should be considered. However, cost is one of the most important criteria. To achieve the cost evaluation for the feasible PSS configuration solutions, another two stages are proposed based on the research in the former sections.

The preparatory stage of the framework is mainly composed of the three-dimensional cost element and CAPTOE sources of uncertainty. In this stage, the preparatory works are performed to support the evaluation stage. The PSS entity list, the process list, the resource list, and CAPTOE can be regarded as knowledge base to be built in advance. For different PSS, specific information and data should be identified and instantiated based on the lists proposed in this paper.

The evaluation stage is the core of the framework. It is mainly described by the key steps of the cost evaluation approach based on the work in the preparatory stage. The inputs of the evaluation stage are the set of feasible configuration solutions acquired in the configuration stage. The outputs return back to the configuration stage to achieve the best PSS among feasible configuration solutions.

7. An Illustrated Example

To demonstrate the feasibility of the proposed framework, a pump PSS is utilized as an illustrated example. The pump PSS is called PUM and provided by an anonymous company in China. PUM is used in a wide range of applications, including chemical industry, pharmaceutical industry, food industry, washing plants, fire-fighting and sprinkler systems, and so on. PUM is centered with a high-pressure pump and associated services such as installation, maintenance, for handling clean or slightly aggressive aqueous fluids. With a wide range of design variants to choose from, PUM is customized to meet customer requirements through the configuration activity. Based on the sales records, PUM configuration activities in history can be traced and one of them is selected as an example to explain how the cost evaluation framework works.

7.1. The Preparatory Stage

Following the preparatory stage of the proposed framework, the PSS entity list of the three-dimensional cost element is first established. Part of the list is illustrated in Figure 11. The process list and resource list are specified based on the lists proposed in Section 5. Details can be referred in the followings.

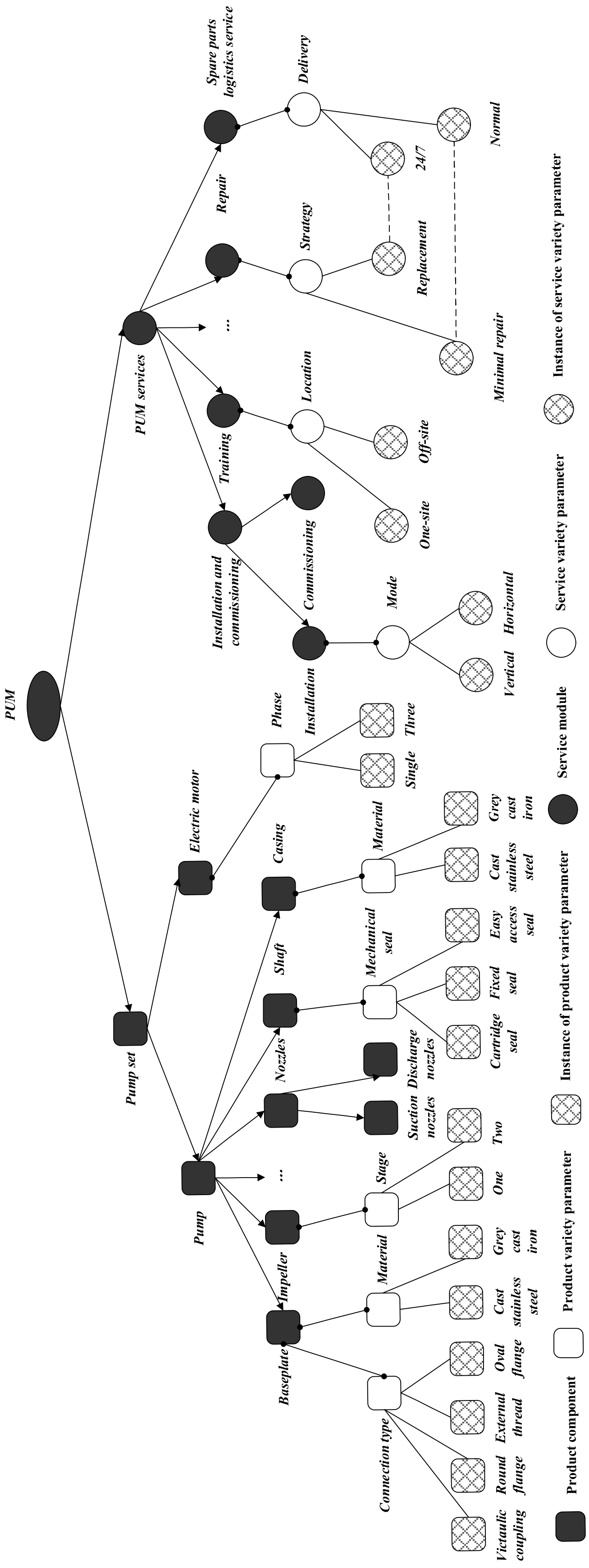

Fig. 11 The PSS entity list of PUM

7.2. The Configuration Stage

For the selected configuration activity, the configurator transforms the inputted customer value and gives out four configuration solutions that all meet the corresponding customer value at the configuration stage. The configuration solutions are four PSS instances constituted by a multitude set of selected PSS entities, together with the assignment of values to attributes of these entities, and a description of the structure of architectural relationships among the entities. As Figure 12 shown, these four configuration solutions are different mainly due to the parameter of pump casing, repair strategy and spare parts delivery. Besides, there are *Require* service binding on the parameter of repair strategy and spare parts delivery, which means if one is selected, the other one is required to be selected.

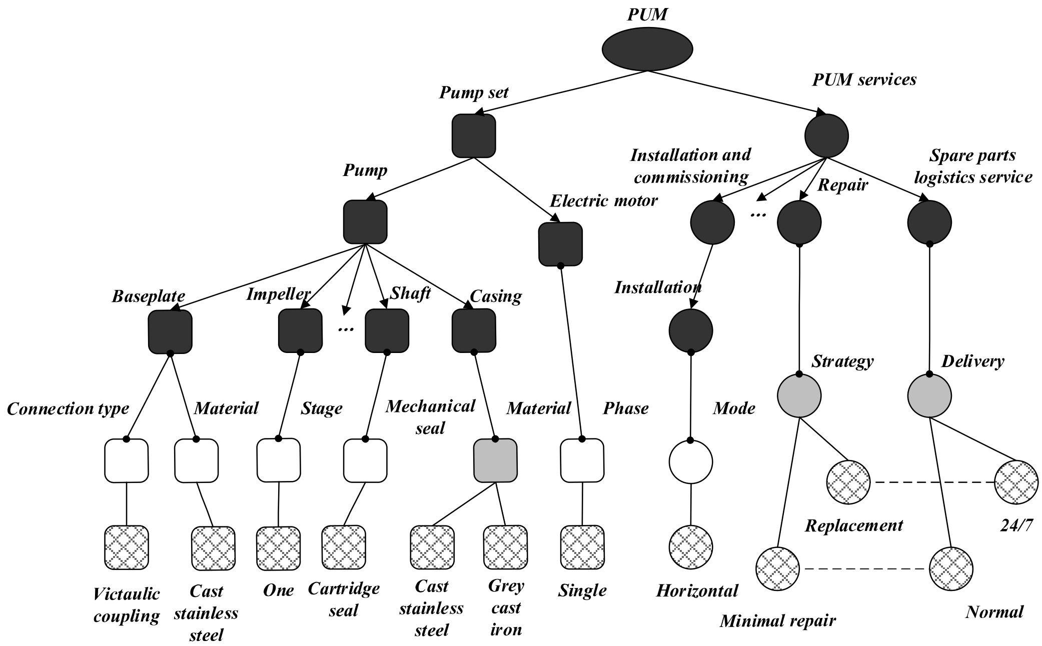

Fig. 12 Configuration solutions of one configuration activity

The configuration engineers are required to make a decision on selecting the best one from these four. Cost is regarded as one of the important evaluation criteria.

7.3. The Evaluation Stage

Step 1: Recognize the Different PSS entities

Following the evaluation approach at the evaluation stage in the proposed framework, different PSS entities among the configuration solutions being compared are first identified as listed in Table 5. To illustrate how to calculate and rank *EI* of these configuration solutions, configuration solution 1 and configuration solution 2 (x=1, 2) are selected as the examples, since they are the candidates with the most significant distinction in the feasible catalogue. The set of the cost elements for evaluation are formulated as $\{CE_x(i, j, k), k=1, 2, 3, x=1, 2\}$, where Pump casing, Repair service, and Spare parts logistics service are the entity 1, 2, 3, respectively.

Table 5 The different PSS entities among four configuration solutions

PSS entity (*k*) / **Feasible candidates**	Pump casing (*k*=1)	Repair service in 5 years (*k*=2)	Spare parts logistics service in 5 years (*k*=3)
Configuration solution 1 (S_1)	Grey cast iron	Replacement upon failure strategy	24/7 emergency service

Configuration solution 2 (S_2)	Cast stainless steel	The minimal repair upon failure strategy	Normal delivery (once a week)
Configuration solution 3 (S_3)	Cast stainless steel	Replacement upon failure strategy	24/7 emergency service
Configuration solution 4 (S_4)	Grey cast iron	The minimal repair upon failure strategy	Normal delivery (once a week)

Step 2 and 3: Identify the process items and the resource items

For each *CE*, the corresponding processes *i* and resources *j* that are further identified, as the following Table 6-8 shown.

Step 4: Measure the resource consumption and establish the initial *EI*

The initial *EI* for each *CE* is calculated based on the measurement of the resources, as the following Table 6-8 shown.

As shown in Table 6, there are three processes, two resources supporting the realization of the Pump casing. The component resource (casing) is the only distinguished item among these cost elements. Therefore, *EI* for CE_1 (*i, j,* 1) and CE_2 (*i, j,* 1) is determined and calculated based on the quantity of component resource consumed and the unit cost of the purchased casing.

Table 6 Calculation of CE_1 (*i, j,* 1) and CE_2 (*i, j,* 1)

Resources (*i*) / Processes (*j*)	Labor resource (*i*=1)		Component resource (*i*=2)	
	Time (min)	Rate (¥/min)	Quantity	Rate (¥)
	CE_1 (*i, j,* 1)			
Incoming inspection (*j*=1)	10	2	1	3500
Cleaning (*j*=2)	15	1	/	/
Assembly (*j*=3)	30	1	/	/
EI	3500			
	CE_2 (*i, j,* 1)			
Incoming inspection (*j*=1)	10	2	1	4500
Cleaning (*j*=2)	15	1	/	/
Assembly (*j*=3)	30	1	/	/
EI	4500			

As shown in Table 7, there are four processes, three resources supporting the realization of the Repair service. However, the distinction in two entities with different DPs (Replacement upon failure strategy vs. The minimal repair upon failure strategy) lies in the component resource. Therefore, *EI* for them is set by the estimation of the component consumption. Moreover, different repair strategy leads to different estimated repair time, which affects the component consumption. Estimated repair time can be calculated referring to (Waghmode, Sahasrabudhe et al. 2010) as follows:

Under replacement upon failure strategy, if *N(t)* is the total number of failures by time *t*, then the expected number of failures, *E[N(t)]*, in the interval (0, *t*) are estimated as:

$$E[N(t)] = \frac{t}{MTBF} = \frac{t}{\eta \cdot \Gamma(1+\frac{1}{\beta})}$$

where MTBF is the mean time between failure, the pump lifetime is modeled using a two parameter Weibull distribution , where η is the scale parameter, Γ is the gamma function, β is the shape parameter.

In case of minimal repair upon failure strategy, if *N(t)* is the total number of failures by time *t*, then the expected number of failures, $E'[N(t)]$, in the interval (0, t) are estimated as:

$$E^{'}[N(t)] = \int_0^t h(x)dx = \int_0^t \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} = \left(\frac{t}{\eta}\right)^{\beta}$$

Table 7 Calculation of CE_1 ($i, j,$ 2) and CE_2 ($i, j,$ 2)

Processes (*j*) \ Resources (*i*)	Labor resource (i=1)			Tool resource (i=2)	Component resource (i=3)
	Personnel	Time (min)	Rate (¥/min)	Rate (¥)	Rate (¥)
	CE_1 ($i, j,$ 2)				
Arrival (j=1)	4	60	2	2	/
Diagnosis (j=2)	4	60	2	2	/
Replacement (j=3)	4	150	2	10	800
Verification (j=4)	4	60	2	2	/
EI	800*13=10400				
	CE_2 ($i, j,$ 2)				
Arrival (j=1)	4	60	2	2	/
Diagnosis (j=2)	4	60	2	2	/
Repair (j=3)	4	150	2	10	160
Verification (j=4)	4	60	2	2	/
EI	160*15=2400				

As shown in Table 8, different processes are identified to support the realization of Spare parts logistics service with different DPs. *EI* for CE_1 ($i, j,$ 3) and CE_2 ($i, j,$ 3) is thus calculated based on the corresponding resource consumption.

Table 8 Calculation of CE_1 ($i, j,$ 3) and CE_2 ($i, j,$ 3)

Processes (*j*) \ Resources (*i*)	Labor resource (i=1)		Energy resource (i=2)		Facility resource (i=3)
	Time (min)	Rate (¥/min)	Distance (km)	Rate (¥/km)	Rate (¥)
	CE_1 ($i, j,$ 3)				
Loading (j=1)	30	1	/	/	10
Transportation to the site (j=2)	60	1	10	1	20
Emergency treatment (j=3)	90	3	10	1	20
EI	(90*3+10+20)*13=3900				
	CE_2 ($i, j,$ 3)				
Loading	30	1	/	/	10
Transportation to the site	60	1	10	1	20
EI	0				

Step 5: Model the uncertainty and adjust *EI*

Based on CAPTOE (commercial, affordability, performance, training, operation, engineering), a list of uncertainty sources are presented for experts to judge and value the uncertainty. The cost-uncertainty score (a value between 0 to 1) is then turned into three-point estimates using guidelines provided by the AACE, which specify maximum and minimum percentage ratios for cost uncertainty scoring. More details can be referred to (Erkoyuncu, Durugbo et al. 2013Erkoyuncu, Durugbo et al. 2013). The updated *EI*, i.e. EI^u, are thereby summarized in Table 9.

Table 9 Updated *EI* under uncertainty

	Cost-uncertainty score	AACE class	Range minimum (%)	Range maximum (%)	*EI*	EI^u
CE_1 (*i*, *j*, 1)	0	/	0	0	3500	3500
CE_1 (*i*, *j*, 2)	0.4	Class 2	-15	20	10400	[8840,12480]
CE_1 (*i*, *j*, 3)	0.2	Class 1	-10	15	3900	[3510, 4485]
CE_2 (*i*, *j*, 1)	0	/	0	0	4500	4500
CE_2 (*i*, *j*, 2)	0.4	Class 2	-15	20	2400	[1632,2800]
CE_2 (*i*, *j*, 3)	0.2	Class 1	-10	15	0	0

Afterwards, the cost comparison of completing configuration solutions S_1, S_2 can be achieved by the difference of updated EI_1 and EI_2,

$$EI_1^u - EI_2^u = EI^u\left[CE_1(i,j,1)\right] - EI^u\left[CE_2(i,j,1)\right] + EI^u\left[CE_1(i,j,2)\right] - EI^u\left[CE_2(i,j,2)\right] + EI^u\left[CE_1(i,j,3)\right] - EI^u\left[CE_2(i,j,3)\right]$$

= -1000 + [7208, 9680] + [3510, 4485]

= [9718, 13165]

Therefore, $EI_1^u > EI_2^u$, which indicates that S_1 has a higher cost.

Step 6: Summarize and rank all the EI_x

In the end, all the configuration solutions in the feasible catalogue {S_1, S_2, S_3, S_4} are selected and evaluated pairwise. Four candidates are required to be pairwise compared six times as Table 10 shown. Based on all the pairwise comparison result, a final ranking of all the feasible candidates is thereby achieved by point by point comparison method, as Table 11 shown. Therefore, from the view of the evaluation criteria of cost, configuration solution 4, as Figure 13 shown, is recommended to configuration engineers since it has the lowest *EI*.

Table 10 The comparison result

	S_1	S_2	S_3	S_4
S_1	=	>	<	>
S_2		=	<	>
S_3			=	>
S_4				=

Table 11 The pairwise comparison list

Configuration solutions	S_1 vs S_2	S_1 vs S_3	S_1 vs S_4	S_2 vs S_3	S_2 vs S_4	S_3 vs S_4	Accumulative point	Ranking

S_1	1	0	1				2	2
S_2	0			0	1		1	3
S_3		1		1		1	3	1
S_4			0		0	0	0	4

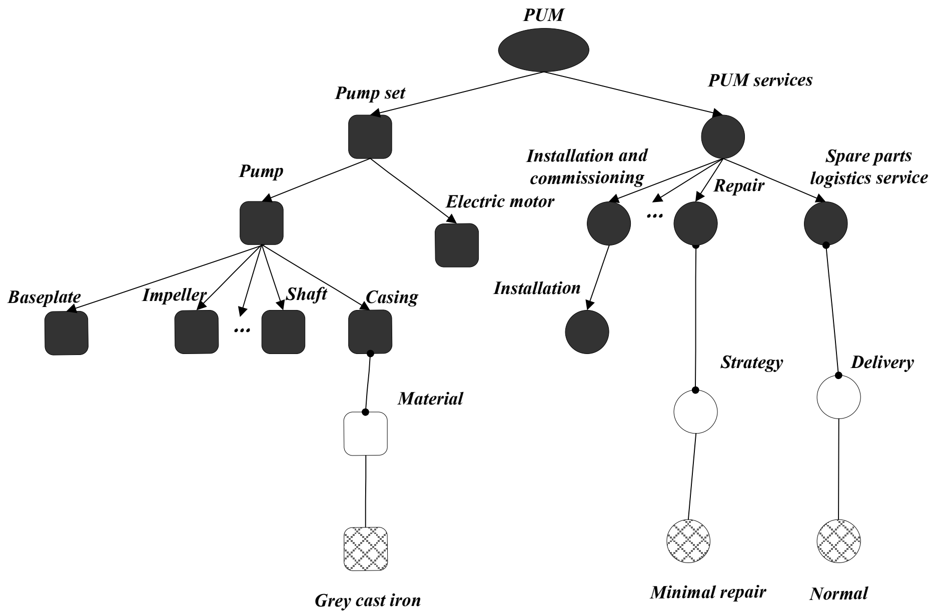

Fig. 13 PSS entities of configuration solution 4

8. Discussion

The above example demonstrates the feasibility of the proposed cost evaluation framework for PSS configuration in this paper. Following the stages and steps in the proposed framework, the best configuration solution can be selected from all the candidates. Compared with the extant cost evaluation methods such as Activity Based Costing (ABC), the advantage of this proposed framework lies in that much less data and information is required, and the uncertainty in the PSS life cycle is under consideration. If the ABC model is applied in this example, the absolute costs of each PSS candidates have to be estimated. The cost evaluation process will be more complicated.

However, it is important to note the applicability of the research. First, the cost estimation discussed in this paper is at the stage of PSS configuration, which implies that the PSS design is mature, and the availability to design information is high. To realize the configuration activity, platform design or family design is often employed. The completing PSS configuration solutions are thereby with similar structure but different options on several DPs. It leads to an acceptable number of cost elements that are required to be valued and compared, so that the analysis and calculation effort is affordable. Therefore, it is requisite that the PSS entity can be identified if using this cost evaluation framework. Second, in this framework, the uncertainty propagation is mainly dealt with CAPTOE, which is a subjective method indeed. Therefore, expert analysis is needed in our approach. Finally, the development of the PSS entity list makes products and services in a coherent model for analysis. No matter what type the PSS is (i.e. product-oriented, use-oriented, or result-oriented), the PSS entities are with similar structure that is composed of various product components and service modules, Therefore, the GBOM-based PSS entity list is thus not tied to any specific product or PSS. This enables the developed cost evaluation framework suitable to all kinds of PSS. However, it is still requisite that the processes are able to be identified when using the proposed framework.

The framework also makes it possible to estimate the cost of various PSS with different types or structures if all the cost elements of one PSS are estimated and summed up. Nevertheless, in this case, the weakness is exposed, since extensive data and analysis effort will be required when there are a large number of cost elements to be valued.

9. Conclusions

Because of the more demanding customer needs, configuration systems are increasingly used as a means for efficient design of customized product service systems. Since the configuration problems are often weakly constrained and have several feasible configuration solutions, cost evaluation is important to assist the configuration engineers in making decisions. However, the academic literature provides very little guidance on the effective approach for such problems.

A framework for cost evaluation in PSS configuration is thereby proposed in this paper to fill the research gap. A three-phase structured research strategy employed in this paper is first described. At the first phase, a holistic view is built to present multi-domain knowledge in PSS configuration. Then, the three-dimensional cost element is defined to support cost analysis. Each dimension, namely PSS entity, process, resource is further elaborated based on theory of Mass Customization and literature analysis. At the third phase, the cost evaluation approach based on the proposed cost element is presented to evaluate and rank all the feasible configuration solutions. Based on the research in the three phases, the framework for cost evaluation in PSS configuration is thereby developed with a number of parts, including the preparatory stage, the evaluation stage and the configuration stage. To validate the proposed framework, an illustrated example of a pump PSS is finally performed.

This paper offers a number of implications for academia. First, PSS configuration is formulated in this paper as encompassing consecutively five knowledge domains. The rationale lies in not only modeling the configuration process of an entire class of PSS configuration solutions based on individual requirements, but also extending to process and resource planning within a coherent model. Within this holistic view, the PSS configuration activity is linked with the costing activity. In addition, the research extends the theory of axiomatic design to the PSS domain.

Based on the PSS cost element proposed and defined in this paper, cost categories are linked with the make-up of the PSS. Cost analysis in PSS configuration is thereby in a decomposable manner, in accordance with the configuration solution that is composed of a set of entities in a structured manner. Thus, the bottom up micro-costing is utilized in PSS configuration. The PSS cost elements are associated first with the PSS entities; further with the processes and then with the resources.

Furthermore, a review of the literature on PSS costing is carried out in this paper. The resource list and the process list of the PSS cost element are thus established. All the terms are identified, unified and classified according to the literature maturity level and similarity clustering. The research develops a knowledge base for the further instantiation in the PSS specific cases. In the meanwhile, the development of the PSS entity list makes products and services in a coherent model for analysis.

With the aim of the comparison of competing configuration solutions, knowing cost in absolute terms is not the main aim of this paper. Therefore, an innovative cost evaluation approach is developed, which only evaluates and compares the cost of different PSS cost elements among the feasible candidates. Much less data and information is thus needed, and the results are normally less sensitive to inaccuracy and uncertainty in the data and information.

In the end, the contribution of this paper mostly lies in proposing PSS cost element, the PSS entity, an innovative cost evaluation approach, and developing a framework that helps configuration engineers in making decisions on the feasible PSS configuration solutions. The framework also makes it possible to estimate the cost of various PSS options with different types or structures. All of the work in previous research focused on the systematic PSS configuration system, and configuration evaluation (especially cost evaluation) has not been deeply studied. The research in this paper fills the gap to some extent.

Besides the academic contribution, the developed framework is also useful for configuration engineers in industry to perform PSS configuration. It first can be the management guide for the engineers to organize the configuration task. The framework presented is in general so that it can be applied to all kinds of PSS. Then, the proposed process and resource lists at the preparatory stage can be utilized as a knowledge base for the further instantiation in the PSS specific cases. Finally, the evaluation approach itself can be used as a tool to achieve the evaluation result, which can be performed as an essential supplement for an existing PSS configurator.

The future work will focus on the development of a software system which follows this framework. Besides, uncertainty and risk management in PSS costing is still challenging since PSS typically has a long term focus. The authors are taking simulation technology into account to reduce the challenges in uncertainty management.

Acknowledgement

This research is supported by the National Natural Science Foundation of China (Grant No. 71401099), Humanities and Social Sciences Research Youth Foundation Project of Ministry of Education of China (Grant No. 13YJC630129), Innovation Program of Shanghai Municipal Education Commission, China (No. 15ZS079), and Academic Discipline Project of Shanghai Dianji University (No. 16YSXK02). It is also supported by the Engineering and Physical Sciences Research Council (EPSRC) Centre for Innovative Manufacturing – Through-life Engineering Services (Grant No. EP/1033246/1). The core members of the Centre include Ministry of Defence, BAE Systems, Bombardier Transportation and Rolls Royce and Babcock International. Besides, the authors are most grateful to the editor and the anonymous reviewers for their constructive comments which helped improve the presentation of the paper considerably.

Reference

Annarelli, A, Battistella, C, et al. (2016). "Product service system: A conceptual framework from a systematic review." Journal of Cleaner Production 139:1011-1032.

Aurich, J. C., C. Fuchs, et al. (2006). "Life cycle oriented design of technical Product-Service Systems." Journal of Cleaner Production 14(17): 1480-1494.

Aurich, J. C., N. Wolf, et al. (2009). "Configuration of product-service systems." Journal of Manufacturing Technology Management 20(5): 591-605.

Baida, Z., J. Gordijn, et al. (2004). Energy services: A case study in real-world service configuration. 16th Intenational Conference on Advanced Information Systems Engineering. A. Persson and J. Stirna. Riga, LATVIA, Springer-Verlag Berlin: 36-50.

Baida, Z., J. Gordijn, et al. (2004). Energy services: A case study in real-world service configuration. Advanced Information Systems Engineering, Proceedings. A. Persson and J. Stirna. 3084: 36-50.

Baines, T. S., H. W. Lightfoot, et al. (2007). "State-of-the-art in product-service systems." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 221(10): 1543-1552.

Baxter, D., R. Roy, et al. (2009). "A knowledge management framework to support product-service systems design." International Journal of Computer Integrated Manufacturing 22(12): 1173-1188.

Becker, J., D. Beverungen, et al. (2009). Configurative service engineering - A rule-based configuration approach for versatile service processes in corrective maintenance. Proceedings of the 42nd Annual Hawaii International Conference on System Sciences, HICSS, Waikoloa, HI, United states, Inst. of Elec. and Elec. Eng. Computer Society.

Ben-Arieh, D. and L. Qian (2003). "Activity-based cost management for design and development stage." International Journal of Production Economics 83(2): 169-183.
Boehmann, T., J. M. Leimeister, et al. (2014). "Service Systems Engineering A Field for Future Information Systems Research." Business & Information Systems Engineering 6(2): 73-79.
Cheung, W. M., R. Marsh, et al. (2015). "Towards cleaner production: A roadmap for predicting product end-of-life costs at early design concept." Journal of Cleaner Production 87(C): 431-441.
Cheung, W. M., R. Marsh, et al. (2009). "Standards and inference of design information in through-life costing of innovative defence electronic products." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 223(2): 169-181.
Curran, R., S. Raghunathan, et al. (2004). "Review of aerospace engineering cost modelling: The genetic causal approach." Progress in Aerospace Sciences 40(8): 487-534.
Datta, P. P. and R. Roy (2010). "Cost modelling techniques for availability type service support contracts: A literature review and empirical study." CIRP Journal of Manufacturing Science and Technology 3(2): 142-157.
de Blok, C., K. Luijkx, et al. (2010). "Modular care and service packages for independently living elderly." International Journal of Operations & Production Management 30(1): 75-97.
Dong, M. and L. Su (2011). "Modeling a Configuration System of Product-Service System Based on Ontology Under Mass Customization." Advanced Science Letters 4(6-7): 2256-2261.
Durugbo, C. (2014). "Strategic framework for industrial product-service co-design: Findings from the microsystems industry." International Journal of Production Research 52(10): 2881-2900.
Erkoyuncu, J. A., C. Durugbo, et al. (2013). "Identifying uncertainties for industrial service delivery: A systems approach." International Journal of Production Research 51(21): 6295-6315.
Erkoyuncu, J. A., C. Durugbo, et al. (2013). "Uncertainty driven service cost estimation for decision support at the bidding stage." International Journal of Production Research 51(19): 5771-5788.
Mahut F., Daaboul J., et al. "Product-Service Systems for servitization of the automotive industry: a literature review." International Journal of Production Research Published online: 10 Nov 2016.
Geum, Y., S. Lee, et al. (2011). "Technology roadmapping for technology-based product-service integration: A case study." Journal of Engineering and Technology Management 28(3): 128-146.
Huang, X., L. Newnes, et al. (2011). An analysis of industrial practice for estimating the in-service costs of a product service system. Proceedings of the ASME Design Engineering Technical Conference.
Hvam, L., A. Haug, et al. (2013). "OBSERVED BENEFITS FROM PRODUCT CONFIGURATION SYSTEMS." International Journal of Industrial Engineering-Theory Applications and Practice 20(5-6): 329-338.
Jiao, J. and M. M. Tseng (1999). "A pragmatic approach to product costing based on standard time estimation." International Journal of Operations and Production Management 19(7): 738-755.
Jiao, J., M. M. Tseng, et al. (2000). "Generic bill-of-materials-and-operations for high-variety production management." Concurrent Engineering 8(4): 297-321.
Junker, U. and D. Mailharro (2003). "Preference programming: Advanced problem solving for configuration." Ai Edam-Artificial Intelligence for Engineering Design Analysis and Manufacturing 17(1): 13-29.
Kayrbekova, D., T. Markeset, et al. (2011). "Activity-based life cycle cost analysis as an alternative to conventional LCC in engineering design." International Journal of Systems Assurance Engineering and Management 2(3): 218-225.
Khataie, A. H., A. A. Bulgak, et al. (2011). "Activity-Based Costing and Management applied in a hybrid Decision Support System for order management." Decision Support Systems 52(1): 142-156.
Kimita, K., T. Tateyama, et al. (2012). Process simulation method for product-service systems design. Procedia CIRP.
Kreye, M. E., Y. M. Goh, et al. (2009). Uncertainty in Through Life Costing within the concept of Product Service

Systems: A game theoretic approach. DS 58-7: Proceedings of ICED 09, the 17th International Conference on Engineering Design.

Kreye, M. E., L. B. Newnes, et al. (2014). "Uncertainty in competitive bidding-a framework for product-service systems." Production Planning and Control 25(6): 462-477.

Lindahl, M., E. Sundin, et al. (2014). "Environmental and economic benefits of Integrated Product Service Offerings quantified with real business cases." Journal of Cleaner Production 64: 288-296.

Long, H. J., L. Y. Wang, et al. (2013). "Product service system configuration based on support vector machine considering customer perception." International Journal of Production Research 51(18): 5450-5468.

Long, H. J., L. Y. Wang, et al. (2016). " An approach to rule extraction for product service system configuration that considers customer perception." International Journal of Production Research 51(18): 1-24.

Meyer, M. H., E. Jekowsky, et al. (2007). "Applying platform design to improve the integration of patient services across the continuum of care." Managing Service Quality 17(1): 23-40.

Mittal, S. and F. Frayman (1989). "Towards a generic model of configuration tasks." Proc. Eleventh Int. Joint Conf. Artificial Intelligence: 1395-1401.

Moon, S. K., J. Shu, et al. (2011). "A module-based service model for mass customization: service family design." Iie Transactions 43(3): 153-163.

Pezzotta, G., F. Pirola, et al. (2013). A service engineering framework to design and configure Product-Service Systems. IFAC Proceedings Volumes (IFAC-PapersOnline).

Prabhakar, V. J. and P. Sandborn (2012). "A part total cost of ownership model for long life cycle electronic systems." International Journal of Computer Integrated Manufacturing 25(4-5): 384-397.

Rapaccini, M. (2015). "Pricing strategies of service offerings in manufacturing companies: a literature review and empirical investigation." Production Planning and Control.

Rodrigues, D., J. Erkoyuncu, et al. (2015). Review of the modelling approaches for availability contracts in the military context. Procedia CIRP.

Romero Rojo, F. J., R. Roy, et al. (2012). "A cost estimating framework for electronic, electrical and electromechanical (EEE) components obsolescence within the use-oriented product-service systems contracts." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 226(1): 154-166.

Roy, R. (2000). "Sustainable product-service systems." Futures 32(3-4): 289-299.

Schröder, M., B. Falk, et al. (2015). Evaluation of cost structures of additive manufacturing processes using a new business model. Procedia CIRP. 30: 311-316.

Schuh, G., W. Boos, et al. (2009). Life cycle cost-orientated service models for tool and die companies. Proceedings of the 19th CIRP Design Conference–Competitive Design, Cranfield University Press.

Schuh, G., M. Pitsch, et al. (2015). "Customer Integration to Gain Cost Efficiency Alongside Tool's Life Cycle." Procedia CIRP 29: 275-280.

Settanni, E., L. B. Newnes, et al. (2014). "A through-life costing methodology for use in product-service-systems." International Journal of Production Economics 153: 161-177.

Settanni, E., N. E. Thenent, et al. (2013). System modeling: A foundation for costing through-life availability provision. IFIP Advances in Information and Communication Technology. 409: 48-57.

Shen, J., L. Wang, et al. (2012). "Configuration of product extension services in servitisation using an ontology-based approach." International Journal of Production Research 50(22): 6469-6488.

Shilov, N. (2011). Product-service system configuration in SOA-based environment. Lecture Notes in Business Information Processing. 97 LNBIP: 184-195.

Smit, M. C. (2012). "A North Atlantic treaty organisation framework for life cycle costing." International Journal of

Computer Integrated Manufacturing 25(4-5): 444-456.
Song, W., Sakao, T., (2016) "A customization-oriented framework for design of sustainable product/service system." Journal of Cleaner Production 140:1672-1685.
Storck, J. (2010). "Exploring improvement trajectories with dynamic process cost modelling: A case from the steel industry." International Journal of Production Research 48(12): 3493-3511.
Suh, N. P. (1990). The principles of design. New York, Oxford University Press.
Sundin, E. (2009). Life-cycle perspectives of product/service-systems: Practical design experiences. Introduction to Product/Service-System Design: 51-70.
Sundin, E., M. Lindahl, et al. (2009). "Achieving mass customisation through Servicification." International Journal of Internet Manufacturing and Services 2(1): 56-75.
Vogtländer, J. G., H. C. Brezet, et al. (2001). "A single LCA-based indicator for sustainability and the Eco-costs - Value ratio (EVR) model for economic allocation: A new LCA-based calculation model to determine the sustainability of products and services." International Journal of Life Cycle Assessment 6(3): 157-166.
Waghmode, L., A. Sahasrabudhe, et al. (2010). "Life cycle cost modeling of pumps using an activity based costing methodology." Journal of Mechanical Design, Transactions of the ASME 132(12).
Wang, L., B. Song, et al. (2007). A product family based life cycle cost model for part variety and change analysis. Proceedings of ICED 2007, the 16th International Conference on Engineering Design.
Wang, P. P., X. G. Ming, et al. (2014). "Research on industrial product-service configuration driven by value demands based on ontology modeling." Computers in Industry 65(2): 247-257.
White, A. L., M. Stoughton, et al. (1999). Servicizing: The quiet transition to extended product responsibility, U.S. Environmental Protection Agency, Office of Solid Waste: 97.
Wurtz, G., A. Ardilio, et al. (2013). Towards mass individualization: Life-cycle oriented configuration of time-variable product-service systems. 2013 Proceedings of PICMET 2013: Technology Management in the IT-Driven Services.
Xing, K., H. F. Wang, et al. (2013). "A sustainability-oriented multi-dimensional value assessment model for product-service development." International Journal of Production Research 51(19): 5908-5933.
Xu, Y., F. Elgh, et al. (2012). "Cost engineering for manufacturing: Current and future research." International Journal of Computer Integrated Manufacturing 25(4-5): 300-314.
Ye, J., B. Zhang, et al. (2009). "Cost estimates to guide manufacturing of composite waved beam." Materials & Design 30(3): 452-458.
Zhang, H., K. R. Haapala, et al. (2011). Environmental impact and cost assessment of product service systems using IDEFO modeling. Transactions of the North American Manufacturing Research Institution of SME.
Zhang, Y. and L. Zhang (2014). "Organizing complex engineering operations throughout the lifecycle A service-centred view and case studies." Journal of Service Management 25(5): 580-602.