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Review

A comprehensive description of the Product-Service Systems' cost estimation process: An integrative review

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ABSTRACT

The transition from the traditional product-centric approach to the offering of integrated product service solutions, such as Product-Service Systems (PSS), has represented a major managerial challenge for companies. A major contributor to such challenge has been the inability of the Cost Estimation Process to deal with the novelty and complexity of PSS solutions, where in particular, cost under-estimation has triggered inadequate contract decisions such as under-pricing. To this end, the academic literature has extensively investigated how the PSS context has modified the cost estimation process and how it has exacerbated cost unpredictability. However, research contributions are limited to specific elements within the estimation process, where a picture of the whole process has not been yet investigated. This paper presents a comprehensive description of the whole PSS Cost Estimation Process derived from an Integrative Review that summarizes and subsumes current empirical/theoretical advancements and methodological approaches in literature. This study evidences how the PSS Cost Estimation Process differs from traditional cost estimation frameworks such as Life Cycle Costing (LCC) at various degrees, and how it is related to other interdependent processes such as PSS Engineering and PSS Contract Design. Moreover, this work suggests that cost unpredictability represents an inherent property of the PSS context, and discusses how identified properties at the process-level help to better investigate cost uncertainty. Finally, this paper evidences research gaps that inform future research, and provides a set of recommendations that call for the development of new bespoke cost estimation frameworks for the PSS context.

1. Introduction

In a wide variety of industrial sectors (e.g., manufacturing, defence, aerospace) there is an increasing demand for service contracts based on equipment performance (i.e. outcome-based contracts) rather than on the activities involved in the service of an equipment (e.g., maintenance, repairs) (Sandborn et al., 2017; Batista et al., 2017). With the growing awareness toward fulfilling customer needs while minimizing environmental impacts, Original Equipment Manufacturers (OEMs) have increasingly felt the need to provide outcome-based contracts via Product-Service Systems (PSS) (Batista et al., 2017; Mont, 2002; Baines et al., 2007). A PSS is defined as an integrated system of interconnected products and services that provides an agreed-upon functionality for customers (Cavalieri and Pezzotta, 2012) while achieving lower environmental impacts than traditional business models (Mont, 2002). A good example is the Rolls Royce's "Power by the hour" program whose contract's pricing mechanism is based on the number of hours an aircraft engine is in the air instead of the traditional approach where the customer buys the equipment and is charged by the throughput of support services that sustain the engine's operation (Smith, 2013).

For OEMs, the transition into the PSS scheme has proven to be a highly difficult endeavour (Olivia and Kallenberg, 2003), with an estimated success rate of 21% (Baveja et al., 2004), where even some studies claim that result-oriented PSS is not yet feasible in practice (Grubic and Jennions, 2018). A significant amount of the OEMs' lack of success has been attributed to inadequate contract decisions (e.g., pricing) tied to the cost under-estimation and performance over-promises of their offerings (Rapaccini, 2015). This issue has been directly associated with the novelty and intrinsic complexity of PSS behaviour (Kreye et al., 2017; Estrada et al., 2017), rationalized in PSS literature as a lack of "cost consciousness" which describes the inability of the cost estimation process to capture the causal mechanisms between the PSS operation

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and its associated cost (Settanni et al., 2013). Such statement has been further evidenced by Settanni et al., (2014), which found that traditional cost estimation approaches (e.g., Through Life Cycle Costing, Life Cycle Costing) do not provide the suitable methodological foundations to capture the intrinsic dynamics of a PSS - calling for the development of a new cost estimation paradigm.

In the spirit of such development, the academic literature has focused extensively on understanding how the PSS context has modified the cost estimation process and how such context has exacerbated cost unpredictability. Several empirical and theoretical research works have significantly contributed to the advancement of the field by addressing specific issues within the cost estimation process, commonly analysed under the optics of uncertainty theory: e.g., the identification of relevant uncertainties sources (Erkoyuncu et al. (2013a) and Erkoyuncu et al. (2011a)); the identification of relevant cost techniques and cost drivers (Schuh et al. (2016) and Shen et al., (2017)); the incorporation of uncertainty measurement into the estimation process (Erkoyuncu et al., 2011a and Erkoyuncu et al., (2013b)); the study of behavioural factors related to decision making under cost uncertainty (Kreye et al. (2017)); the proposal of a cost estimation framework within a particular application, (Datta and Roy (2009)); among many others. Despite these advancements, research contributions have limited their scope to specific steps or elements within the cost estimation process. In consequence, the knowledge base of the research field is scattered, and the whole PSS Cost Estimation Process has not been yet analysed and described comprehensively in literature. This exhaustive description is proposed to be relevant for the development of the research field as it extends current understanding by taking into account the properties endemic to the process-level (e.g. timeliness of data availability, evolution of the estimate's uncertainty). Such properties derive from the consideration of the interactions among the constituent elements of the PSS Cost Estimation Process (e.g., interdependence of intermediate outputs, feedback loops), and their interactions with exogenous processes (e.g., interoperability and information flows) – considerations that result from a comprehensive analysis.

This paper addresses this gap by conducting an integrative review of academic literature, which enables a comprehensive portrayal of the PSS Cost Estimation Process and leads to the development of an overarching narrative through a process of literature search and evaluation, data reduction and display, data comparison, conclusion drawing, and presentation (Whittemore and Knafl, 2005). An integrative review is not aggregative in the sense of "adding research works together", but interpretative in broadening understanding of a particular phenomenon. Based on such research methodology, this paper aims at providing a comprehensive description of the PSS Cost Estimation Process evidencing current advancements and methodological approaches in PSS Cost Estimation literature. This comprehensive description is denoted as the structured and complete representation of the process' main steps, its compounding elements (i.e., inputs, outputs, mechanisms, and controls/constraints), the internal interactions among elements (e.g., interdependence of intermediate outputs, feedback loops), and the cost estimation relationship with exogenous processes (e.g., interoperability and information flows). This paper contributes to literature in three different levels: 1) It integrates the current knowledge base in a synthetic representation of the cost estimation process; 2) It extends current understanding on how the PSS context has modified the cost estimation process and exacerbated cost unpredictability by incorporating into the current narrative the identified properties endemic to the process-level; and 3) It supports the future development of new PSS Cost Estimation frameworks by providing a clear depiction of current advancements, methodological approaches, and research gaps.

The remainder of the paper is structured as follows: In Section 2, the background of the research is presented. This section further evidences and describes the main research gaps, and highlights the key theoretical aspects underpinning the research work. This is followed by the description of the integrative review research methodology in Section 3. Section 4 presents the results of the research, describing the PSS Cost Estimation Process comprehensively. Section 5 summarizes the main findings of the research and discusses their main implications. Finally, Section 6 concludes the paper by pointing out the implications and theoretical contributions of the paper and related issues for future research.

2. Research background

2.1. Product-Service Systems (PSS)

In the wake of fierce competition at many levels, OEMs have increasingly matured their support services offerings in order to improve their products' performance, functionality, and environmental impact via a PSS (Mont, 2002; Baines et al., 2007). These support services are delivered under different contract mechanisms and vary in nature, e.g., spares provision, maintenance, training, supply and support chain management, integrated logistics support, asset management, equipment health monitoring, and reliability trend analysis (Erkoyuncu et al., 2011a). A PSS is a system that interconnects products and support services to provide an agreed-upon functionality to customers (Cavalieri and Pezzotta, 2012). Depending on the level of such integration, three PSS types are commonly identified in literature, namely product-oriented, use-oriented, and result-oriented PSS (Mont, 2002; Baines et al., 2007; Van Ostaeyen et al., 2013). While the first type of PSS relies on the traditional product-centric approach, both the use-oriented and the result oriented PSS rely on an outcome-based perspective where the OEM no longer sells pure products, but delivers product functionality (Van Ostaeyen et al., 2013).

From the product-centric approach, the ownership of the product is transferred to the customer and support services are offered through a separate contract, where OEMs are commonly paid according to the throughput of service transactions (Erkoyuncu et al., 2009), e.g., pay-per replacement/repair agreement (Sandborn et al., 2017). More recently, an increasing number of customers have expressed an interest in service contracts based on equipment outcomes (i.e. outcome-based contract) (Sandborn et al., 2017) rather than on the activities involved in the service of such equipment (Batista et al., 2017). Because of this trend, the use-oriented and result-oriented PSS business models have emerged as promising avenues for improving manufacturing competitiveness by complying with customer's consumption patterns and environmental regulations. While both use-oriented and result-oriented PSS have an outcome-based approach, the former focuses on the availability/use of the equipment, while the latter focuses on delivering specific results/capabilities. (Mont, 2002; Van Ostaeyen et al., 2013; Tukker and Tischner, 2006). An example of the use-oriented PSS type is found in the military context where Contract for Availability (CfA) is commonly used as an outcome-based contract agreement (Datta and Roy, 2009). In a CfA, the OEM seeks to sustain the PSS at an agreed level of readiness, over an extended period of time (Rodrigues et al., 2015). A CfA is offered at a fixed price, with defined performance metrics (e.g., mean time to repair MTTR) and incentive mechanisms (e.g., award gains beyond target costs, penalties for performance shortcomings) (Erkoyuncu et al., 2009). A good example of a result-oriented PSS is the previously described Rolls Royce "Power by the Hour" programme.

In both the use-oriented and result-oriented PSS, the OEM retains the ownership of the product. Moreover, the payments and performance requirements in outcome-based contracts are introduced at the top-most aggregate level of the PSS, where the OEM has maximum freedom to define the amount of support services' throughput and the delivery strategy required to sustain the agreed-upon performance metrics. The immediate and most evident advantages of this dynamic are those of cost reduction and performance improvement driven by incentive mechanisms such as the pay for effectiveness and penalization for performance shortcomings (Sandborn et al., 2017). Moreover, the long-term relationship between the OEM and the customer under the

PSS scheme generates lock-in situations that enable steady cash flows for the OEM, increased customer demand, and access to equipment related operational data (Kreye et al., 2017; Roy and Erkoyuncu, 2011). On the customer side, the PSS provides better risk management, guarantees technological innovation, reduces servicing costs, and makes related costs highly predictable when the payment mechanism is fixed (Roy and Erkoyuncu, 2011).

The outcome-based approach of PSS modifies the ownership structure along the product lifecycle. Indeed, the typical responsibilities for products are extended into the 'in-service' phase through the additional responsibility for services (Mont, 2002), which transfer several costs and risks from the customer to the OEM. As a result, the allocation of such operational costs and risks reduces the OEM's profit, who is no longer able to increase revenue through services throughput, but through efficiency provision (Mont, 2002; Baines et al., 2007). From the OEM's standpoint, products are now conceptualized as capital assets rather than consumables, where the OEM's profit mechanism is now driven by the optimization of product utilization instead of the maximization of product consumption - a principle that explains why PSS is observed to be more environmentally sustainable than traditional business models. This profit mechanism helps to understand why cost estimation plays a fundamental role in securing the economic growth and success of the PSS (Xu et al., 2012; Garetti et al., 2012; Meier et al., 2010; Kambanou and Lindahl, 2016) as an effective pricing of the PSS agreed-upon performance depends directly on an accurate estimation of its associated cost, and thus the OEM's profit is highly sensitive to cost estimation uncertainty.

2.2. PSS cost estimation

The transition into the PSS scheme has proven to be a highly difficult endeavour (Olivia and Kallenberg, 2003; Kreye et al., 2017). Recent studies have shown a lack of "cost consciousness", which expresses the inability to represent the causal mechanisms of a system's behaviour using cost metrics (Settanni et al., 2013), leading companies to under-estimate the cost of their offerings and overpromising performance. Because of this, OEMs often fail to make suitable contract decisions (e.g., pricing). The novelty and intrinsic complexity of PSS behaviour may be at the basis of this lack of "cost consciousness" (Kreye et al., 2017; Estrada et al., 2017). As extensively identified and described in literature, different elements, endemic to the PSS context, contribute to the unpredictability of PSS's costs (Ng et al., 2009); namely, change in the ownership structure, integration of products and support services, heterogeneity of components, variability in service quality, dynamism of performance, customer incorporation, co-creation of value, unclear boundaries between organization activities, left-shift at the point of time costing is carried out (i.e., at design or bidding stage), contractual incentive mechanisms, redistribution of responsibilities across the supply network, bidding context, and long-term nature of contracts (Erkoyuncu et al. 2011a; Kambanou and Lindahl, 2016; Shen et al., 2017). All these PSS's intrinsic elements have been identified to contribute at a different degree to the unavailability of useful data, immaturity of design solutions, and/or to the incapability to model the dynamism of PSS behaviour (Erkoyuncu et al., 2011a) – a widely accepted narrative that describes why the cost estimation process under the PSS realms is perceived to differ from traditional costing (Kambanou and Lindahl, 2016).

In PSS literature, the unpredictability of PSS costs has been often studied under the optics of uncertainty theory (Erkoyuncu et al., (2009) and Erkoyuncu et al. (2011a)). Uncertainty termed as the indefiniteness of the outcome(s) of a given situation (Erkoyuncu et al., 2011a), is noted as exacerbating the complexity of the PSS cost estimation process (Shen et al., 2017; Datta and Roy, 2009; Erkoyuncu et al., 2013a). In a recent study that aimed at identifying at what extent the traditional approach for cost estimation was appropriate for the PSS context, Settanni et al., (2014) found that the traditional Through-Life Costing (TLC) approach does not provide the methodological foundations to estimate the cost of a PSS correctly. In particular, the study underlined the inability of the traditional cost estimation approach to deal with a "system", particularly a knowledge-intensive socio-technical system (Meier et al., 2010), calling for the development of a new paradigm for PSS cost estimation. In alignment with such findings, several authors have pushed the discussion towards an ontological consensus of the PSS nature by explicitly stating the need for a "systems-thinking" approach (Settanni et al., (2013), Estrada et al., (2017), and Goh et al., (2015)); or by conceptualizing the PSS as a complex system identifying its main features, which can be summarised as i) dynamic and non-linear behaviour of PSS operation, ii) simultaneous interaction between multiple interconnected cost objects, iii) cost as an emergent attribute of the PSS operation, and iv) emergence of convoluted patterns of coordination/cooperation/integration between OEM's and customer's activities (Batista et al., 2017; Erkoyuncu et al., 2011a; Kreye et al., 2009, 2017; Settanni et al., 2014).

3. Research methodology

To address the "PSS cost estimate unpredictability" and the "lack of cost consciousness" problems, this research work provides a comprehensive description of the PSS Cost Estimation Process evidencing current advancements and methodological approaches in literature, and deepening the understanding of the PSS Cost Estimation Process as a whole.

Henceforth, the study addresses the following research questions in the context of current PSS methodological approaches for cost estimation:

RQ1. What are the main elements that constitute the PSS Cost Estimation Process?

RQ2. How do the constituent elements interact among each other and with exogenous processes?

RQ3. What are the process-level properties that arise from these interactions?

While the problem of cost unpredictability is found across the whole PSS typology, it is clearly exacerbated in the use-oriented and result-oriented PSS types by their strictly higher levels of complexity. Therefore, without loss of generality, the research describes the PSS Cost Estimation Process from the PSS outcome-based perspective. The research strategy used to address the mentioned research questions is presented in Fig. 1 and is based on the integrative review methodology updated by Whittemore and Knafl (2005). An integrative review is a method compounded by a sequence of steps (i.e. Literature search and evaluation, data reduction and display, data comparison, conclusion drawing, and Presentation) that summarizes empirical and/or theoretical literature for a comprehensive understanding of a particular phenomenon with a wide range of purposes: to define concepts, to review theory, to review evidence, and to analyse methodological issues of a particular topic (Broome, 1993). The multiplicity of purposes in an integrative review results in an exhaustive portrayal of a complex phenomenon, yet explicit and systematic methods for data retrieval and analysis are needed to protect against bias and improve the accuracy of conclusions (Whittemore and Knafl, 2005). Therefore, in order to ensure methodological rigorousness across the research strategy, a systematic approach was applied across all steps with a continuous interaction among all researchers to protect against bias.

Literature Search and Evaluation: A systematic literature search, based on scientific publications, has been carried out to understand the current academic knowledge regarding cost estimation in the realms of PSS. The chosen sources of information were Web of Science, ProQuest, Scopus, Web of Knowledge, Science Direct, EBSCO, and Google Scholar - to cover the relevant disciplines (i.e. engineering, business economics, management science, and environmental sciences) which embrace the

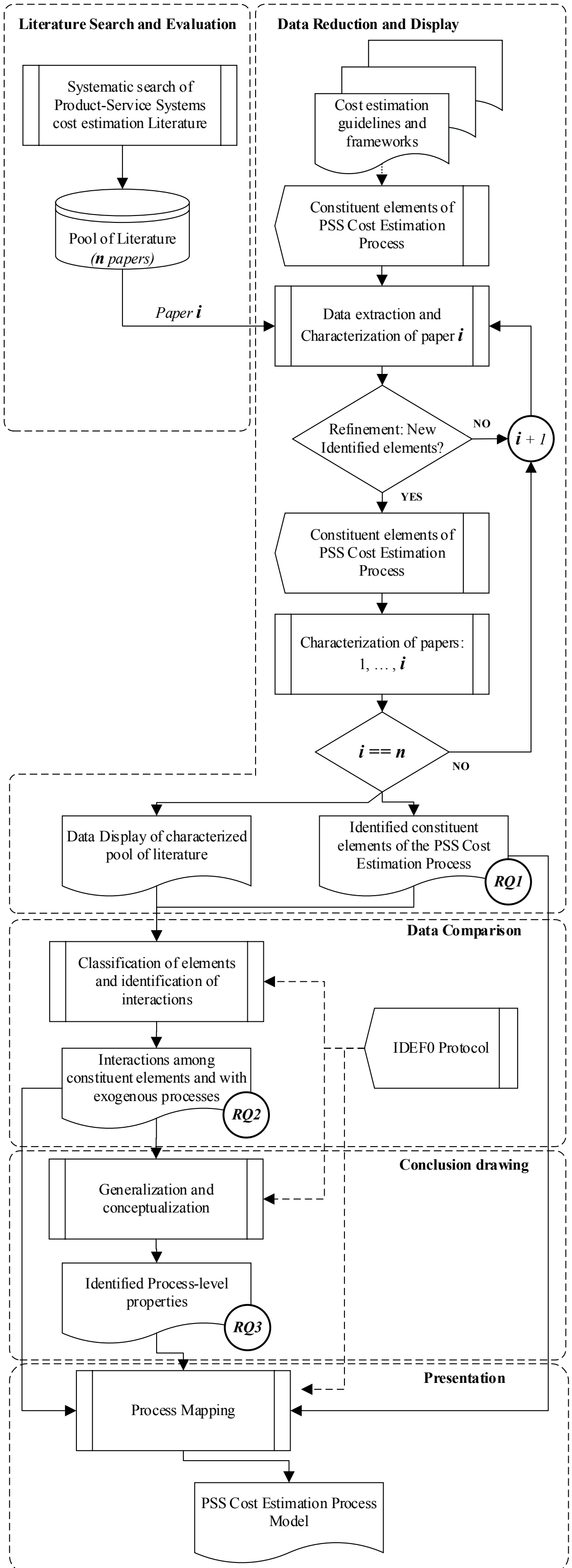

Fig. 1. Research methodology.

core academic fields related to the subject of interest (Oliveira et al., 2015). The search was limited to English language literature, and covered journals, conference papers, and book chapters without limitations on the year of publication. A first subset of literature was defined by the use of following strings: "Product-Service Systems", "servitization", "availability based contracts", and "performance-based contracts". As a result, 728 research works were identified. The next step of the selection process consisted of a refined search, with the use of following keywords: "Cost*" (to include all derivational and inflectional suffixes, e.g. -ing: costing), "Cost-Engineering", and "Cost estimation". This step resulted in a sample of 59 research works, which represented the scientific knowledge regarding PSS cost estimation, in terms of either theoretical contributions or developed cost applications. Once such sample was defined, all papers were read as an evaluation step to determine whether they complied with the intended purpose of the review and whether they were consciously focused on the PSS field. After such evaluation step, the final set of literature resulted in a pool of 39 papers (refer to Appendix 1). The final set of literature included both theoretical and empirical works that covered several disciplines and industries: Defence and Aerospace, Manufacturing, Electronics, Maritime Shipping, Rail Industry, Steel Industry, among others. It was compounded by journal papers (i.e. 28%), book chapters (i.e. 13%), and conference papers (i.e. 59%), where all research works were found to be published from 2008 - which evidences the novelty of PSS cost estimation as a topic.

Data Reduction and display: The objective of this phase was to extract data and characterize all research works to simplify, abstract and organize the previously identified pool of literature into a manageable framework that assembles all characterized research works around variables of interest (Whittemore and Knafl, 2005). Data that were extracted from the pool of literature included sample characteristics (e.g. year of publication, industry of application (if empirical)), identified constituent elements of the PSS Cost Estimation Process and related terms regarding proposed relationships of the constituent elements with other variables. The identified constituent elements served as variables for the characterization of all research works, e.g. for the identified element "estimate assessment technique", research works were characterized as "sensitivity analysis" or/and "uncertainty analysis" depending on the applied technique for that particular case. A data matrix was developed to display all research works characterized by every identified constituent element. To ensure methodological rigorousness at this phase, the data extraction and characterization steps were outlined by an iterative refinement process of the identified constituent elements. Such iterative refinement process was proposed by Settanni et al., (2014) as a research strategy in the synthesis and further analysis of an extended body of PSS literature. Moreover, the cost estimation guides/frameworks and recommended practices from the "U.S. Government Accountability Office" i.e. GAO (2009), the "U.S. Department of Energy" i.e. DoE (2011), and the "Association for the Advancement of Cost Engineering" i.e. AACEI (2011), were used as a reference point for an initial identification of relevant constituent elements of the cost estimation process. Additionally, these frameworks were utilized continuously for the standardization of terminology and concepts across the heterogeneous strands of identified literature.

Data comparison: The objective of this phase was to discern the underlying relationships among the variables of previously developed data display through a process of examination and comparison (Whittemore and Knafl, 2005). All identified constituent elements were first classified as either inputs, mechanisms, constraints, or outputs depending on their relationship with the estimation process. Once all identified constituent elements were classified, all research works from the previously defined data matrix display were examined and compared for the identification of interactions (e.g. interdependence of intermediate outputs, feedback loops). To ensure methodological rigorousness, the IDEF0 Methodology was utilized for the constituent elements classification process and the identification of interactions.

IDEF0 is a comprehensive methodology designed to model the decisions, actions, and activities of a system that includes a flexible graphical modelling language (syntax and semantics) (Wright Laboratory, 1981). It is useful in establishing the scope of an analysis outlined by its inputs, outputs, constraints and mechanisms, where activity sequencing can be embedded in the model (KBS, 2011). Furthermore, IDEF0 has been previously utilized in the literature for PSS modelling (Zhang et al., (2011) and Settanni et al., (2013)).

Conclusion drawing: The objective of this phase was to subsume identified interactions into patterns subject to generalization (Whittemore and Knafl, 2005), which moves the interpretative effort from the description of the particular (i.e. interactions among constituent elements) to a conceptualization at a higher level of abstraction (i.e. endemic properties at the process-level). The identification of patterns subject to generalization was carried out through an iterative process of verification where each of the research works within the pool of literature were reviewed to verify that the refined conceptualization (i.e. set of patterns) was congruent.

Presentation: The results of the integrative review are reported as a PSS Cost Estimation Process IDEF0 Model with its associated overarching narrative that presents the description of all the main steps of the estimation process. Such narrative depicts the findings for all three-research questions (i.e. compounding elements, compounding elements' interactions, and process-level properties) in one single argumentative line.

4. Research findings: the PSS cost estimation process

The PSS Cost Estimation Process can be expressed as a structured set of interrelated activities outlined by certain operation conditions over a time interval (Settanni et al., 2014), aimed at generating a cost estimate, i.e., a prediction of the cost of a work activity or output (Stewar et al., 1995). The cost estimate is a compilation of many lower-level cost objects (GAO, 2009), that supports decision-making across several exogenous processes and provides relevant information to a wide variety of stakeholders (Kreye et al., 2009). The PSS cost estimation method has been classified in literature as a "Management tool" or as a "Management System" (Kreye et al., 2009), depending on the usage level of its cost estimate. In the first case, the estimate is known as a "should-cost" (Settanni et al., 2014) and it is a one-time use estimate (e.g. for budgeting). In the second case, the estimate's use extends to the continuous operation during the PSS management (Kreye et al., 2009), and is commonly referred to as a "strategic estimate".

The PSS Cost estimation is a data-driven process (GAO, 2009) that directly depends on several input data, or is constrained by intermediate outputs of its analysis. Different types of data are collected (e.g., technical, cost, schedule), pre-processed (e.g., cleansing, normalization, instance selection, transformation) and analysed (e.g., exploratory, correlation, causation) (DoE, 2011) (GAO, 2009) across the whole cost estimation process in an iterative fashion between activities. These data flows describe how exogenous processes (i.e., PSS Engineering process, PSS Contract Design process) interact with the cost estimation process. The PSS Engineering process typically provides data related to the PSS Configuration and the Service Delivery Model. In turn, the PSS Contract Design process typically provides data relevant to the contract type (i.e., outcome-based), contract mechanism (e.g., Contract for Availability, Performance Based Logistics), contract conditions (e.g., contractual duration, pricing mechanisms, performance metrics), ownership policy (e.g., distribution of costs and risks), and accountability policy (e.g., rewards and/or penalty schemes). Other relevant input data sources are: account records, data collection input forms, cost reports, historical databases, interviews, program briefs, technical databases, contracts or contractor estimates, cost proposals, cost studies, focus groups, research papers, surveys, vendor quotes, expert opinion, benchmarking, cost estimation team judgement (DoE, 2011) (GAO, 2009).

The PSS Cost Estimation Process, identified from the synthesis, integration, and analysis of the relevant pool of literature, is depicted in Fig. 2. This model is presented as an IDEF0 diagram for the emphasis on relevant inputs, outputs, controls, and mechanisms. Furthermore, it describes the generic estimation's logic, i.e., some authors' methodologies may not comprise all steps displayed in the model, nevertheless the logic behind all proposals was found to be subject to generalization. Fig. 2 presents at the top-right corner a basic IDEF0 diagram, where an input arrow enters from the left side of an activity, describing the transformation of such input into an output depicted by an exit arrow. Such activity is constrained or controlled by the elements represented by the arrows flowing into the top of the box. Finally, the arrows flowing into the bottom side of the diagram are the enablers/mechanisms required to carry out the activity (KBS, 2011). The diagram presents the interconnection with other exogenous processes, namely PSS Engineering and PSS Contract Design, expressed as the flow of information and knowledge between such exogenous processes and various steps across the cost estimation process. Moreover, the process model is visualized as an iterative sequence composed of five main constituent activities, whose purposes are briefly described as follows:

1. Definition of Cost Estimation Viewpoint: to guide and bind decision making across the estimation process towards a defined objective.
2. Characterization of the cost estimate: to define the attributes of the estimate and to outline the baseline conditions on which it is built.
3. Conceptualization of PSS: to identify significant technical and operational parameters and their mathematical relationship with the cost estimate.
4. Computation and assessment of the estimate: to measure the cost estimate impacts of a given set of parameters' values.
5. Adjustment and Definition of the estimate baseline: to define the cost estimate baseline and to make the relevant adjustments for the compliance of its purpose.

Throughout the following subsections, all the elements and dynamics respective to each of these constituent activities are described in detail.

4.1. Definition of Cost Estimation Viewpoint

This first step represents the top-most aggregate level of the cost estimation process. It introduces a high-level control (i.e., estimate's purpose, scope) that guides decision making across the estimation process, e.g., to define the required estimation accuracy. The cost estimate's purpose describes the estimate's intended use (DoE, 2011) and its association with exogenous processes (e.g., define the cost estimate baseline to discriminate among potential pricing mechanisms for contract design). Not an end itself, the cost estimate was observed to support decision making across two main exogenous processes, namely the PSS Engineering process and the PSS Contract Design process. The former encompasses all activities in order to systematically develop the PSS Configuration and the Service Delivery Model (Pezzotta et al., 2014), while the latter incorporates all activities in order to define the contract terms and parameters (e.g., contract duration, payment mechanism) (Sandborn et al., 2017). Following Table 1 presents all identified cost estimate's purposes in literature, classified by their association with exogenous processes and their identified usage level.

These identified purposes resonate with Kambanou and Lindahl (2016) and Kreye et al., (2009) findings where cost estimation is described as a highly interconnected process that addresses a broad set of questions and provides information to a variety of stakeholders.

The estimate's purpose in addition to the customer's request further define the cost estimation scope (DoE, 2011). As observed in Fig. 2, the customer's request is presented as a main input of the estimation process and it results from the customer and requirement analysis, which is methodologically embedded in the PSS Engineering process. Such request is commonly specified by the customer's objectives (e.g., optimization of production), needs (e.g., expected level of plant

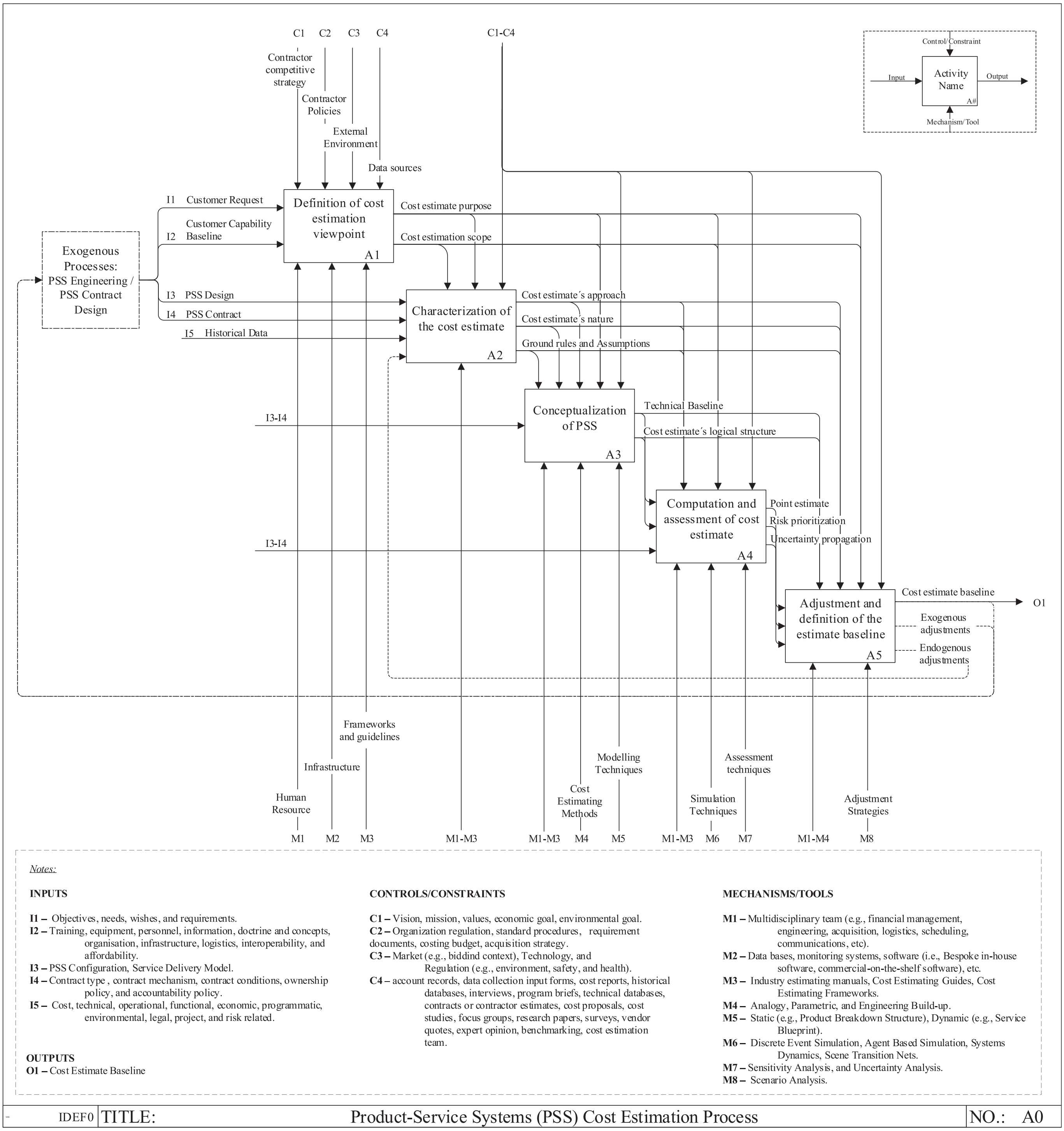

Fig. 2. Product-service system cost estimation process.

availability), wishes (e.g., reduction of breakdown time), and requirements (e.g., preventive maintenance) (Pezzotta et al., 2014). Moreover, it has been stated in the military context that the "customer capability baseline" must be taken into account for the definition of the cost estimation scope, as it provides understanding about the PSS operation in relation with contract expectations. The customer capability baseline comes from the PSS Contract Design process, and it describes the current development of customer's training, equipment, personnel, information, doctrine, infrastructure, logistics, interoperability, and affordability (i.e., budgeting, willingness to pay) (Rodrigues et al., 2015). This resonates with the need for the consideration of the link between the customer's affordability and the OEM's profitability (Xu et al., 2012), and the understanding of the co-capability that results from the integration, coordination and cooperation between the customer and the OEM (Batista et al., 2017).

The cost estimation scope discriminates whether certain cost objects are incorporated into the estimation process. A PSS cost object is any instance (e.g., product, activity, time) for which costs are assigned and measured (Settanni et al., 2014), it is a basic constituent that enables the conduction of the PSS cost estimation process (Shen et al., 2017). A shared criterion for the definition of the cost estimation scope was identified across PSS literature. Authors were found to select the cost

Table 1
PSS cost estimation purposes.

Exogenous Process	Usage Level	Purpose	Reference
PSS Engineering		PSS Configuration Design	
	Should cost	Selection of optimal configuration (variety-induced scheme)	(Schuh et al., 2017); (Mannweiler et al., 2010); (Shen et al., 2017)
		Definition of configuration	(Garetti et al., 2012); (Wrasse et al., 2015)
		Feasibility analysis of configuration solutions	(Shen et al., 2017); (Marchi et al., 2016); (Kimita et al., 2012)
		Assessment of product's platform design	Prabhakar & Sandborn (2012)
		Definition of PSS portfolio variety	(Schuh et al., 2016)
		Support for functional portfolio analysis	(Kimita et al., 2008)
		Assessment of investment requirements (budgeting)	(Schröder et al., 2015)
		Validation of configuration at the piloting stage	(Wrasse et al., 2015)
		Assessment of company's value creation architecture	(Azevedo and Sholiha, 2015)
		Service Delivery Model Design	
	Should cost	Definition of PSS service functional structure	(Kimita et al., 2012); (Kimita et al., 2008)
		Definition of PSS maintenance strategy	(Lingegard et al., 2015); (Pezzotta et al. 2013)
		Definition of PSS procurement strategy	(Marchi et al., 2016); (Wrasse et al., 2015)
		Definition of obsolescence management strategy	(Rojo et al., 2012)
	Strategic cost	Environmental assessment	(Zhang et al., 2011); (Estrada et al., 2017)
		Support the planning and scheduling of service support activities (e.g., maintenance)	(Carlander et al., 2016) ; (Seiringer and Bauer, 2016); (Lanza et al., 2011)
		Support of part and components management activities	(Prabhakar and Sandborn, 2012)
		Performance and Functionality Assessment	(Estrada et al., 2017); (Settanni et al., 2013)
PSS Contract Design	Should cost	Definition of contract mechanism	(Erkoyuncu et al., 2013a)
		Pricing at the bidding stage	(Kreye et al., 2017); (Estrada and Romero, 2016a); (Erkoyuncu et al., 2013b); (Kreye et al., 2012); (Mu et al., 2012); (Lanza et al., 2011)
		Definition of risk-sharing agreements	(Lingegard et al., 2015); (Erkoyuncu et al., 2011a)
		Definition of incentive mechanisms	(Erkoyuncu et al., 2011a)
		Definition of warranty expenses	(Lanza et al., 2011)
		Definition of support services policies (i.e., maintenance policy: product replacement or revamping)	(Marchi et al., 2016)
		Evaluation of acquisition choices for the customer	(Bonetti et al., 2016)
	Strategic cost	Analysis of stakeholder's requirements compliance	(Estrada et al., 2017)

objects that belong to the lifecycle stages relevant to the estimate's purpose. As the transition into the PSS scheme modifies the ownership structure along the product lifecycle (Mont, 2002), authors widely accept the narrative that such transition requires the OEM to broaden its costing spectrum to include other lifecycle stages.

Despite this shared lifecycle approach, literature presents a lack of consistency regarding the definition of the cost estimation scope. Three main factors were found to be related to such inconsistency: 1) Methodological discrepancy, 2) Lack of consensus about PSS lifecycle stages, and 3) Vagueness of cost estimation standpoint description. The methodological discrepancy is evidenced by the conceptual definition of the cost estimation process, as authors rely on different cost estimation frameworks i.e., Life Cycle Costing (LCC) (Shen et al. (2017) and Garetti et al. (2012)); Whole Life Cycle Costing (WLCC) (Erkoyuncu et al. (2009) and Datta and Roy (2009)); Whole Life Costing (WLC) (Kreye et al. (2009)); Through-life Costing (TLC) (Settanni et al. (2014) and Prabhakar and Sandborn (2012)); Total Cost of Ownership (TCO) (Bonetti et al. (2016)). This discrepancy is not limited to a difference in terminology, but extends onto a methodological difference in the selection of cost objects. A clear example is the "Total Cost of Ownership" approach, which focuses on the cost objects relevant to the product acquisition, use, and maintenance stages (Ellram, 1993) but ignores costs from the design and disposal phases. See Kreye et al. (2009) to observe the difference between WLC and TLC.

On top of such methodological discrepancy, it was found that a clear definition of the lifecycle stages is not yet consistent across PSS literature, where authors define and use various approaches for the identification of such stages. For example, both Datta and Roy (2009) and Garetti et al. (2012) consider the stages of operation, maintenance and disposal, but the former incorporates the installation stage while the latter considers product realization. The inconsistency in scope definition is made worse by the fact that authors do not state clearly their costing standpoint (i.e., from provider or customer perspective) (Kambanou and Lindahl, 2016). As an example, take previous Garetti et al. (2012) stages and compare them with Mannweiler et al. (2010), in which the PSS lifecycle comprises the investment, the utilization and the disinvestment phases – stages relevant to the customer standpoint. The most systematic approach for the definition of lifecycle stages was found to be developed by the United Kingdom Ministry of Defence (MoD). It identifies six main lifecycle phases: Concept, Assessment, Demonstration, Manufacture, In-service and Disposal (CADMIN) (Erkoyuncu et al., 2009). It was devised to define the categorization of the contract life cycle stages correctly for the industry to sustain a system at an agreed level of readiness and over a certain period of time (Rodrigues et al., 2015).

As observed in Fig. 2, the definition of both the estimate's purpose and scope is driven/constrained by economic and environmental forces (e.g. contractor's economic goal, contractor's environmental goal, environmental regulations). Despite the inherit sustainability perspective in the PSS context, literature has paid little attention to the development of an integrated approach that combines economic and environmental analyses - just a couple of proposals considering environmental goals were identified, see Estrada et al. (2017) and Zhang et al. (2011).

4.2. Characterization of the cost estimate

In this second step, the cost estimate is characterized by the definition of: (1) the baseline conditions (i.e. ground rules and assumptions), (2) the estimate's approach (i.e. top-down, bottom-up), and (3) the estimate's nature (i.e. deterministic, stochastic). This characterization depends on the purpose and the scope defined at the previous step, and it is mainly driven by the quality of available data, a concept typically described by an array of context-dependent attributes (e.g., reliability, availability, vagueness, structure, variability, completeness, relevance, representativeness, usability) (Roy and Erkoyuncu, 2011). The PSS context exacerbates data-related issues as it brings several challenges that undermine its quality: 1) data from all lifecycle stages has not traditionally been collected, 2) PSS represents an integrated approach, where independent data from products and services may be irrelevant, and 3) data needed for design optimization may be available late in the life cycle when costs of redesign and optimization are substantial; see (Kambanou and Lindahl, 2016).

As estimates are typically based on limited data (DoE, 2011; GAO, 2009), and as the cost estimation process is initially weakly constrained; a necessary set of baseline conditions (i.e. ground rules and assumptions) are defined at this stage. The ground rules represent the agreed estimating standards that provide guidance and reduce conflicts of communication, e.g., industrial engineering principles. On the other hand, assumptions represent the set of judgements about several conditions postulated as true in the absence of positive proof (GAO, 2009). For example, it has been identified that traditional costing approaches (e.g. LCC, TLC) pose the assumption that the responsibilities between the OEM and the customer regarding the product acquisition and ownership are clear-cut and therefore so are the cost objects of concern (Settanni et al., 2014) – an assumption that does not hold valid for the PSS context as OEMs and customers achieve joint capability through integration (Batista et al., 2017) making their boundaries more fluid (Ng et al., 2011).

In line with Roy and Erkoyuncu (2011) findings, another element that is mainly influenced by data quality is the cost estimation approach. It describes the stand from which the cost estimation process identifies relevant cost objects for the architecture of the estimate, and it can be either a top-down or a bottom-up approach (Datta and Roy, 2009). The top-down approach is found when less data is available and it is based on past projects/contracts outcomes, in which future costs projections are carried out by means of mathematical relationships derived from the similarities and differences with former projects. The bottom-up approach is based on a highly intensive data collection of individual costs, which are determined using mathematical relationships derived from relevant cost objects attribute(s). As it is observed in Fig. 2, the cost-estimation process presents several feedback loops that express the iterative nature of the process. As more data and knowledge become available from subsequent activities or exogenous processes, the approach of the estimation moves gradually from a top-down to a bottom-up approach, improving the accuracy of the cost estimate.

The estimate's accuracy dynamic is described in PSS literature from the optics of uncertainty theory, where accuracy increases as the cost associated aleatory and epistemic uncertainty are gradually reduced. While aleatory uncertainty arises from the inherent random nature of the PSS behaviour, epistemic uncertainty arises from the limits of the human knowledge and understanding (Xu et al., 2012; Estrada and Romero, 2016a). The rationale of this mechanism is described by the timeliness of data availability (Erkoyuncu et al., 2011a): as time passes, more data becomes available and causal understanding progresses (see section 4.5, Fig. 5). The measurement of cost uncertainty is strictly related to the definition of the estimate's nature (i.e. deterministic, stochastic) at this stage. When authors define the nature of the estimate as 'deterministic', cost is considered to have the exact same value upon measurements – thus uncertainty cannot be quantified. On the other hand, a 'stochastic' estimate recognizes the cost as a random variable, which takes on a range of different potential values (Casella and Berger, 2002). Despite the importance of uncertainty measurement in the PSS context, only 43% of authors in the analysed literature acknowledge the stochastic nature of cost and thus quantify its associated uncertainty. From this perspective, the measurement of aleatory uncertainty is incorporated into the estimation process via the "statistical variance" of the estimate, which refers to the random error that arises from the unattainable degree of detail required to calculate the total cost precisely (Garvey, 2015)(see section 4.3, Fig. 4). By the other hand, it has been argued that epistemic uncertainty is more difficult to measure (Xu et al., 2012), where contributions in literature are limited to "handling" such type of uncertainty, e.g. fuzzy set theory, neural networks, possibility theory, and evidence theory – techniques mentioned in Erkoyuncu et al. (2011a) but that lay outside the identified pool of literature consciously focused on PSS cost estimation. Therefore, as the measurement of epistemic uncertainty still remains open-ended in literature, the concept of the "statistical bias" of an estimate is proposed for such a purpose. The "statistical bias" refers to the systematic error of the estimate that arises from the incorporation of erroneous assumptions, and it is a concept brought from the Statistical Learning field, which encompasses the set of approaches for estimating a predictive function based on data (Hastie et al., 2009).

As described before, both aleatory and epistemic uncertainty are intrinsically related to the accuracy of the estimate, which quantifies the degree to which the estimate conforms to the real cost value (AACEI, 2011); see Section 4.3, and Fig. 4. In PSS literature, accuracy was found to be discretized into both relative and absolute accuracy when considering its relationship with the estimate's purpose. In some cases, relative accuracy is sough when the purpose of the cost estimation process is that of PSS Configuration Design, particularly under the configuration variants scheme – where a predefined library of product components and service modules is assumed (Long et al., 2013). A clear example is observed in Mannweiler et al. (2010) which proposes a LCC indicator that supports the comparison between competing PSS configuration solutions. It has been shown that under a relative accuracy scheme, the cost estimation process requires fewer data and its estimate is less sensitive to inaccuracy and imprecision (Shen et al., 2017).

4.3. Conceptualization of the PSS

At this stage, an abstract representation of the PSS is developed to understand and model the mathematical relationships between the cost estimate and relevant technical and operational parameters. This conceptual representation is expressed as both the "Technical baseline" of the PSS solution and as the "Cost estimation logical structure". The definition of the technical baseline depends on data from exogenous processes (i.e., PSS Engineering, PSS Contract Design) and provides a detailed description of the PSS technical and operational parameters that bind the estimate (GAO, 2009), e.g., PSS purpose, configuration, Work Breakdown Structure (WBS), detailed technical and performance characteristics, legacy systems, development and production, system test and evaluation, safety plans, training plans, disposal and environmental effect, operational concept, personnel and technological requirements, logistic support details, procurement strategy, service delivery model, and changes from previous technical baseline (DoE, 2011).

In the analysed PSS literature, some of the studies do not disclose whether a conceptual model is developed for the representation of the technical baseline. When disclosed, in 60% of the cases the technical baseline is expressed as a static model, which does not consider the evolution of PSS behaviour over time, e.g., typically as a Product-Breakdown Structure (Rojo et al. (2012), Mannweiler et al. (2010), and Lanza et al., (2011)); or as a Hierarchical Feature Tree (Schuh et al., (2017) and Shen et al. (2017)). In the rest 40% of the cases, the technical baseline is presented as a dynamic model, which describes the architecture and properties of physical entities in relation with the process domain of the PSS over a time period, e.g., as a Service Blueprint (Kimita et al. (2008) and Pezzotta et al. (2013)); as an IDEF0 diagram (Settanni et al. (2013) and Zhang et al., (2011)); or as a Causal Diagram (Estrada et al. (2017)). The dynamic model focuses on the operation of the PSS to gain understanding of its behaviour. As the PSS context poses the need of causal understanding preceding the estimation of costs (Settanni et al., 2013), the dynamic conceptualization of the PSS at this stage represents one of the main differences with traditional cost estimation approaches (e.g. LCC), which do not model the system delivering the service (Settanni et al., 2014).

The definition of the technical baseline enables the understanding at a qualitative level of the interaction between cost objects and the cost estimate, thus supporting the construction of the cost estimation logical structure. The cost estimation logical structure is composed by the set of predictive equations (i.e., Cost Estimation Relationships – CERs) that link all cost objects with relevant technical baseline parameters (i.e., cost drivers) - it represents the basis upon which the cost is estimated. Some authors express this logical structure as a set of independent equations (Bonetti et al., 2016; Marchi et al., 2016), but typically authors adopt the Cost Breakdown Structure technique (CBS) that further considers hierarchy and interconnection among CERs (Estrada et al., (2017) and Erkoyuncu et al., (2013b)).

Authors use different cost methods to establish such mathematical relationships (i.e., CERs), expressing the cost as a response variable that depends on the value(s) of certain cost driver(s) (GAO, 2009). Different cost drivers, relevant to the PSS context, have been identified in literature; see Schuh et al. (2016) and Shen et al., (2017). It was found that the classification of cost methods depends mainly on two factors, namely, the cost estimation approach (i.e., top-down, or bottom-up) and the CERs validation techniques (i.e., Statistical Analysis, Engineering Principles, and Expert Opinion). Following Fig. 3 depicts the identified classification based on such criteria.

Parametric cost methods look for statistical relationships between historical costs and program, physical, and performance parameters. They are based on the assumption that factors that affected cost in the past will continue to affect it in the future (GAO, 2009). Identified examples of such classification are regression models (e.g., Seiringer & Bauer. (2016)) distribution fitting (e.g., Carlander et al., (2016)). Analogy-based methods use former costs from a similar or legacy system and incorporate adjustments that account for differences between the requirements of the existing and new systems. It is based on the assumption that historical costs are good predictors of future costs (GAO, 2009). There were no examples found in literature that presented an application, this cost method was found to be described only at the theoretical level; see Datta and Roy (2009). Finally, from the bottom-up approach, the Engineering Build-up methods incorporate a mix of statistical analysis, expert opinion and engineering principles for the construction of CERs which all together build the overall cost estimate by summing detailed estimates done at the lowest level of detail. Examples of such classification are Activity Based Costing – time oriented (e.g., Schröder et al. (2015) and Marchi et al. (2016)); Activity Based Costing – resource-oriented (e.g., Bonetti et al. 2016); or a combination of both

	Cost Estimation Approach: Top-Down	Cost Estimation Approach: Bottom-up
CER Definition Technique: Statistical Analysis	Parametric methods	Engineering Build-up methods
CER Definition Technique: Subject Matter Expert	Analogy based methods	
CER Definition Technique: Engineering Principles		

Fig. 3. PSS cost methods.

resource and time oriented (e.g., Kimita et al., (2008) and Kimita et al., (2012)). In PSS literature, the classifications of cost methods are not yet consistent, and authors tend to incorporate the cost estimation approach as a well-defined cost method. For example, Datta and Roy (2009) have grouped techniques into top-down, bottom-up, mixed approaches, target costing, and analogy-based cost methods. We claim that it is preferable not to incorporate the estimation approach into the classification as a cost method since both concepts are at a different level of generality. As mentioned before, the estimation process moves from a top-down to a bottom-up approach as more data becomes available, enabling the use of Engineering Build up methods.

From the interplay between the use of engineering principles and statistical analysis as CERs validation techniques, an inference-prediction trade-off arises. The use of engineering principles provides causal understanding, but its predictive power is limited by human cognition and knowledge. On the other hand, statistical analysis could suffice as a predictive model but sacrifices causal explanation (Goh et al., 2015). The cost unpredictability implications of this trade-off are highly relevant, especially when the PSS Cost Estimation Process aims at supporting activities related to the improvement of the PSS Design. Moreover, the consideration of the logical structure in relation with the "statistical variance" and the "statistical bias" brings further understanding regarding cost unpredictability as these two statistical quantities are used in tandem to decompose the expected generalization error of a prediction (James et al., 2015). As the formal mathematical decomposition of such error lies outside the scope of this paper, a qualitative description of the involved quantities is provided in Fig. 4.

From Fig. 4 the logical structure "g" is observed as the set of predictive equations that take a set of inputs "X" and generates a cost prediction "$\widehat{Y}$" (cost observed as a random variable). The logical structure "g" represents the estimate of "f", a fixed but unknown objective truth that describes the real relationship between the set of considered data inputs X and the real cost Y. As observed in Fig. 4, the accuracy of the cost estimate is strictly related to: (1) the estimate's variance (i.e.$\mathit{Var}\,[g(x)]$) originated from its random nature, (2) the estimate's bias (i.e.$\mathit{Bias}\,[g(x)]$) introduced by wrong assumptions or cost structures misspecifications (e.g., oversimplifications), (3) the cost baseline definition (see section 4.5), and to (4) the variance of the error term (i.e.$\mathit{Var}\,(\varepsilon)$). This last quantity, sometimes referred to as the irreducible error, describes the fact that no matter how well the "Objective Truth f" is estimated, the accuracy of the cost prediction "$\widehat{Y}$" is upper bounded as the "Objective Truth" depends on unmeasurable data (i.e. it is limited by the considered data inputs X) (James et al., 2015). It is important to realize that the Objective Truth depends on the considered conditions on which the logical structure is built; as more considerations are specified into the structure, more systematic-information regarding the cost is encompassed. Thus, the qualification of "irreducible error" does not hold true if more relevant data is considered or in the case where the PSS is modified and/or does not perform continuously under the same conditions.

4.4. Computation and assessment of cost estimate

At this stage, the cost estimate is computed and analysed in order to (1) quantify the cost impacts of a given set of parameters' values, to (2) measure the aleatory uncertainty around the estimate and to (3) identify its associated risks. The cost estimate is obtained by computing each of the CERs within the cost logical structure. When the cost estimate's nature is considered as deterministic, cost drivers' values are input into the CER equation, which results in a cost value from a precise object in the logical structure. After each cost object has been computed, all objects' costs are added together (bounded by the hierarchical definition of the structure) to arrive at a final point estimate. As previously described, some authors consider the cost estimate as a random variable for the incorporation of aleatory uncertainty measurement into the estimation

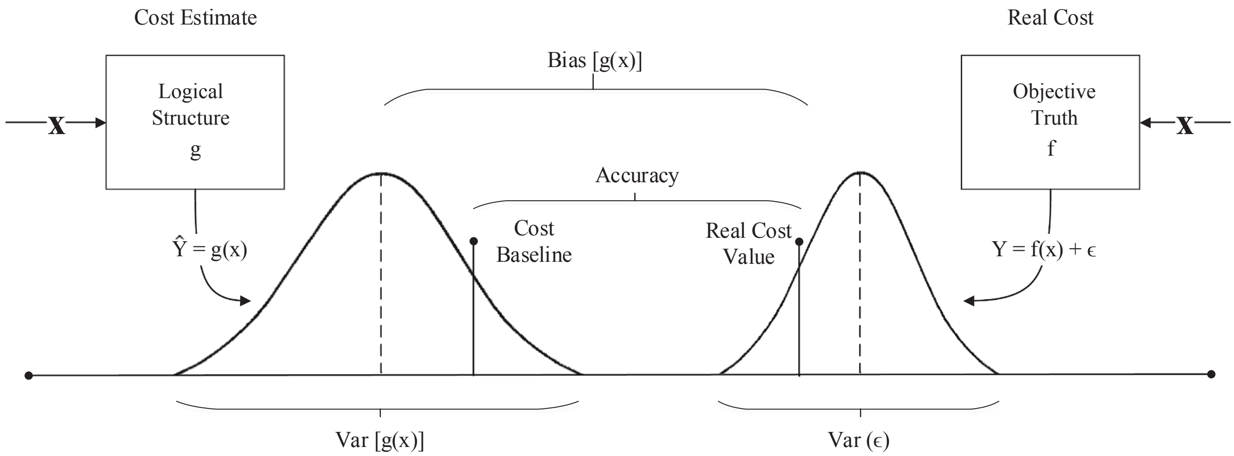

Fig. 4. Bias-Variance decomposition: *Given a set of inputs X, both the Cost Estimate and the Real Cost present different distributions (i.e. they can take on different ranges of values). The accuracy of the cost prediction depends on factors related to the estimation process (i.e. the bias and variability induced by the utilized CERs, and the definition of the cost baseline), and on the intrinsic variability of the Real Cost.*

process. For this case, the computation of the point estimate is developed exactly as in the deterministic case, but the cost driver's value is generated through a randomization process – where the cost driver may take on a set of potential values, each with a certain probability (Garvey, 2015).

Authors compute the cost estimate as a random variable, typically with the use of numerical techniques, concretely simulation techniques such as Monte Carlo Simulation (Carlander et al., (2016), Erkoyuncu et al. (2013b), and Rojo et al. (2012)); Discrete Event Simulation (Estrada et al. (2017) and Pezzotta et al. (2013)); Agent-Based Simulation (Wrasse et al., (2015) and Erkoyuncu et al., 2011a); or Scene Transition Nets Simulation (Kimita et al., (2012)). It is important to mention that the measurement of aleatory uncertainty is not limited to numerical techniques; for example, Estrada and Romero, (2016a) propose an analytical approach. Regarding the incorporation of aleatory uncertainty measurement into the cost estimation process, the use of simulation techniques is strongly supported as the cost estimation logical structure may contain CERs too complex for strict analytical study (Garvey, 2015). Authors have argued about the intrinsic complexity of the PSS behaviour, proposing different properties looking for an ontological consensus about the PSS nature. In that sense, authors state that certain simulation techniques (i.e., Agent-Based, Discrete Event, Scene Transition Nets) are able to capture dynamic results through time and space (Datta and Roy, 2009) thus enable to reproduce the evolution of a system (Erkoyuncu et al., 2011a). Moreover, authors incorporate logical statements regarding the operation of the PSS to understand, typically, the dynamics related to failure, obsolescence, demand, processing time, energy and material consumption. Furthermore, some authors take advantage of the simulation environment to compute the cost by embedding the cost logical structure into the simulation model (e.g., Pezzotta et al. (2013)), while some other authors carry out the cost computation separately by inputting the simulated data into the estimation logical structure (e.g., Estrada and Romero, (2016a)). It is important to notice that the incorporation of simulation techniques that enable the analysis of the system in evolution represents one of the main differences between the PSS Cost Estimation Process and traditional costing (e.g. LCC) - as argued in literature, cost estimation in the PSS context requires causal understanding of the system's dynamic behaviour (Settanni et al., 2013).

After the cost is computed, the estimate is assessed to gain understanding regarding its uncertainty propagation and associated risks. While uncertainty refers to the indefiniteness of an outcome (Erkoyuncu et al., 2011a) – where aleatory uncertainty is typically expressed as a set of potential outcomes – risk refers to the degree of negative exposure measured by the loss that might arise depending on whether a given event may or may not happen (Erkoyuncu et al., 2009). It was found that the risk and uncertainty of the cost estimate are commonly assessed with the use of Sensitivity Analysis and Uncertainty Analysis respectively. The former examines the cost effects of changing one cost driver at a time while holding all variables constant, in order to identify the cost objects that represent the most risk (i.e., risk prioritization) (GAO, 2009). An example is found in Estrada et al., (2017) in which the cost estimate's impact of the non-compliance risk of customer requirements is analysed.

Furthermore, Uncertainty Analysis quantifies the cumulative cost impacts of uncertainties associated with a set of cost drivers (Garvey, 2015) to measure the aleatory uncertainty around the cost estimate (i.e., uncertainty propagation). The aleatory uncertainty propagation is represented by the set of different values that results from the repeated computation of the point estimate. Depending on the estimate's purpose, authors present the cost estimate and the aleatory uncertainty around it as a probability density function (e.g., Kimita et al., (2012)); as a cumulative distribution function (e.g., Estrada et al., (2017) and Carlander et al., (2016)); or as a three-point estimate (i.e., minimum, expected, maximum) (e.g., Rojo et al. (2012) and Shen et al., (2017)). The main difference between Sensitivity Analysis and Uncertainty Analysis is that the former isolates the effects of one variable at a time, while the latter examines the aggregated effects of a set of variables changing all at once (GAO, 2009). Moreover, while Sensitivity Analysis can be applied for both a deterministic and a stochastic estimate, Uncertainty Analysis is limited to the latter case.

4.5. Adjustment and Definition of the estimate baseline

At this final step of the cost estimation process, several endogenous and/or exogenous adjustments take place, where the former refers to changes within the cost estimation process; while the latter refers to changes on exogenous processes (see Fig. 2). The endogenous type of adjustments represents the modifications of the cost assumptions, and are carried out to reduce the uncertainty around the cost estimate. Commonly these adjustments follow an uncertainty management process that aims at improving understanding (see Erkoyuncu et al. (2011a)), e.g., by conducting trade studies to further examine design or service support solutions (Erkoyuncu et al., 2009) and thus to progressively add lower levels of detail into the cost estimate logical structure. On the other hand, the exogenous type of adjustments represents the modifications on the technical baseline parameters' values (or the incorporation of new parameters) derived from exogenous processes (e.g. PSS configuration parameters), and are carried out to reduce costs, risks, uncertainty and/or to improve metrics related to the intended use

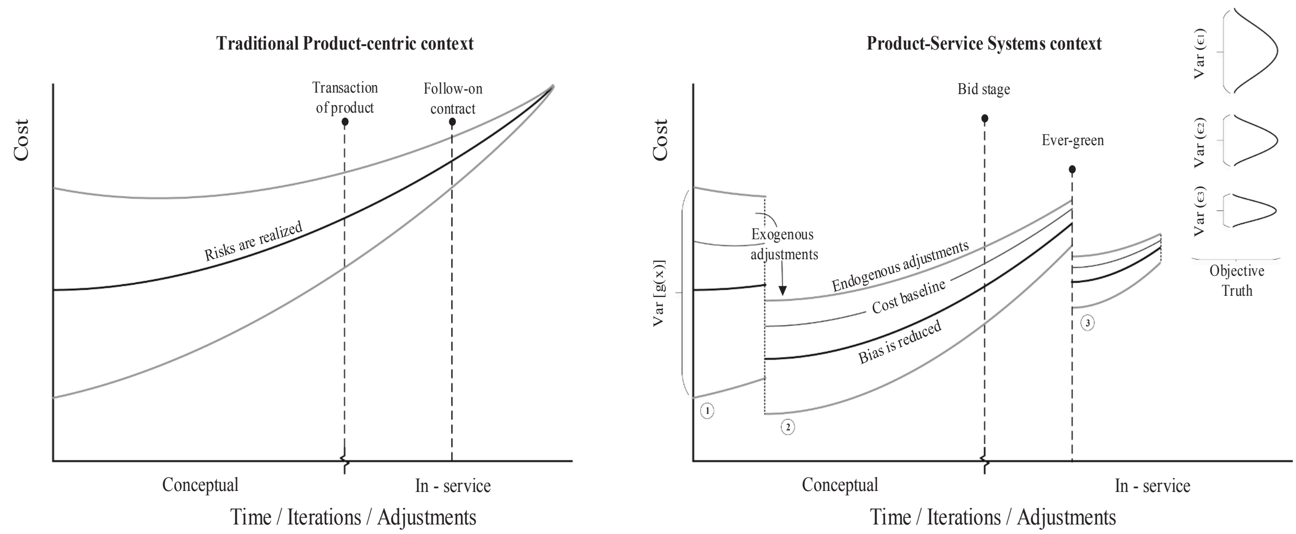

Fig. 5. Cost Estimate's Uncertainty evolution in PSS vs. Traditional product-centric context: In both the Traditional Product-centric and in the PSS context, the cost estimate uncertainty is gradually reduced as time passes - more data/understanding enable the development of more detailed cost structures (i.e., endogenous adjustments). In the PSS context, depending on the objective of the estimate, it could be the case that the PSS Design and/or Contract are changed (i.e. exogenous adjustments), or while 'In-service', contractual conditions could be re-baselined (ever-green) - both situations bring a disruption in the estimate's uncertainty evolution, and as conditions are changed the "True Cost" is itself changed.

of the estimate. These adjustments are carried out under a systematic procedure, commonly with the use of Scenario Analysis – where the input parameters that come from exogenous processes are adjusted and evaluated through retrospective interpretation. An example is found in Erkoyuncu et al. (2011a) which proposes a scenario analysis of different risk-sharing schemes to reduce the cost impacts of a Target Price Performance Incentive (TPPI) mechanism in the definition of the contract ownership policy in a military system-of-systems project. Another example is found in Pezzotta et al. (2013), which evaluates, through scenario analysis, two maintenance strategies for the design of the delivery model in a truck repair shop. The retrospective interpretation that the scenario analysis brings at the interplay between cost estimation and exogenous processes enables the integration of PSS Engineering and PSS Contract Design, where concurrent design and evaluation permits the exploration into a wider solution space (i.e., there are more potential solutions when both the PSS and the contract are simultaneously designed). Nevertheless, in alignment with Sandborn et al. (2017) findings, in current practice such processes are evaluated separately, each using the others' parameters as fixed inputs or constraints, with virtually no iteration despite their interdependency and interoperability.

The endogenous and exogenous adjustments at this stage describe the iterative nature of the estimation process, which is characterized by its data availability timeliness: as time progresses, the uncertainty of the estimate decreases since more data and understanding of the PSS behaviour is attained. This evolution of uncertainty can be described by the reduction of both the statistical variance and bias as greater detail is progressively added to the estimation logical structure (i.e., endogenous adjustments), and as the conceptual representation of the PSS (e.g., configuration design, contract mechanism) is changed (i.e., exogenous adjustments) throughout the cost estimation process. While endogenous adjustments reduce the variance and bias in a gradual manner through iterations, the exogenous adjustments disrupt the evolution of uncertainty, as the system under analysis is itself changed. To illustrate these concepts, consider a hypothetical OEM that produces numerical control machines and provides after-sales services to the aerospace industry. The OEM is interested in defining the right level of technical assistance, repairs, and maintenance (i.e., support services' throughput) and the appropriate PSS configuration and delivery strategy to sustain the machine's operation at a given level of performance within a competitive cost. As more understanding is attained through the iterative design of the PSS, the definition of the contract, and the estimation of the associated costs; the OEM better specifies the related cost structures (endogenous adjustments) and thus gradually reduces the set of potential values the estimate can take on (i.e., variance reduction), and computes an estimate that progressively converges to the true cost (i.e., bias reduction). Moreover, the evolution of the cost estimate is disrupted (exogenous adjustments) as the OEM investigates the effects of (a) redesigning the PSS (e.g., from a service delivery model based on a corrective maintenance strategy to one based on a preventive/predictive strategy), and the effects of (b) redesigning the PSS Contract (e.g., from a mechanisms based on the machine's availability to one based on the machine's level of production).

Fig. 5 presents graphically this iterative property characterized by the cost estimate's uncertainty evolution, and contrasts it with its behaviour in the traditional product-centric context (see the "Cone Curve" in GAO (2009)) to further evidence the PSS scheme implications on cost estimation.

The PSS scheme brings a left-shift at the point of time cost is estimated (Erkoyuncu et al., 2009). In the traditional approach, support services are provided through a separated follow-on contract, in which the cost estimate is based on in-service data and on real cost values that replace some estimates – depicted as a "cone curve" (GAO, 2009). As the PSS scheme entails the use of an outcome-based contract, data from the in-service stage is not available, making the cost estimate more uncertain at the point of use (e.g., bid-stage). Moreover, for the should-cost scenario (i.e., one-time estimate), this issue is exacerbated by the fact that the measurement of the estimate's bias inherently requires the existence of a true cost value (James et al., 2015) - in contrast with the case in which the estimation process is considered as a "Management System" where the estimate extends to the continuous operation of the PSS (Kreye et al., 2009) and the availability of true cost values bring the opportunity for continuous improvement. The negative impacts of the level of uncertainty at the point of use of the estimate have been partially addressed by the use of "ever-green" renewal agreements, in which contractual terms and conditions are re-baselined (e.g., change in the penalization scheme) at shorter intervals - commonly five years (Erkoyuncu et al., 2009).

Finally, after adjustments are performed, this step of the estimation process defines the cost estimate baseline, which boils down the stochastic cost estimate (when considered as a random variable) of the previous step into a constant numerical value. This process requires the definition of the estimate's confidence level that is used to upper bound the estimate's range of potential outcomes. Such an upper limit represents the cost estimate baseline, whose probability of not being exceeded is equal to the specified confidence level. In current practice, such confidence level relies on Subject Matter Experts judgement or recommended cost estimation practices, e.g. The U.S. Department of Energy (DoE) Cost Estimation Guide recommends a 70–90% range of confidence level (2011). Despite the fact that the cost estimation is based on operational and technical considerations (e.g., equipment wear-out, processing times) (Goh et al., 2010; Kreye et al., 2012), research has evidenced that subject matter experts' definition of the cost estimate baseline is significantly linked with behavioural factors related to decision making under uncertainty (Kreye et al., 2017). In such empirical research, Kreye state that the PSS cost estimate baseline depends significantly on the bidding context (i.e., competitive, single bid), where results showed that the defined certainty level under a competitive bidding scenario was lower than the one of the single bid scenario – a practice described by the authors as irrational decision making. As observed in Fig. 4, the accuracy of the cost estimation process is directly linked with the definition of the estimate baseline, where a subjective definition of the baseline, may negatively impact exogenous processes, thus the intended use of the estimate, e.g., in the case of cost-based pricing, OEMs were frequently found to under-price their offerings (Rapaccini, 2015).

5. Discussion

Many research works in the field have significantly advanced the understanding of the PSS nature and its implications on cost estimation. However, these research contributions have limited their scope to specific elements within the cost estimation process, where the investigation of the 'big picture' was missing from literature. To this end, we set out to piece a story together through an integrative review of academic literature, that enabled to provide a comprehensive portrayal of the PSS Cost Estimation Process, placing relevant articles across the estimation process, highlighting what is unique about PSS, and identifying gaps in current methodological approaches. We proposed an integrative review as a valid method as its interpretative approach is well suited for the identification of methodological approaches in a field whose knowledge base is scattered across literature (Whittemore and Knafl, 2005). Moreover, to guarantee the validity of the findings, we defined a research strategy (see Fig. 1) based on a systematic approach to ensure methodological rigorousness while sustaining a continuous interaction among researchers to protect against individual bias. Table 2 presents the summary of the main findings in relation to the stated research questions and highlights potential areas for future research.

At the aggregate level, a consolidated approach for cost estimation is not yet found in literature where the lack of methodological foundations grounded on a specific underlying understanding of the PSS context evidences the immaturity of the field. Indeed, we observed that several authors tend to oversimplify the problem of cost estimation, for example by analysing the PSS as a static entity or by deriving deterministic cost estimates, while others have put great effort in opening the discussion to understand how the PSS context requires special considerations. In particular, this latter stream of literature has proposed a "systems-thinking" approach in order to capture how different elements of the PSS operation influences the cost estimate. This discrepancy evidences how the lack of consensus regarding what constitutes a PSS and how its properties affect the estimation of cost, limits the advancement of the field.

Indeed, the findings in this work reveal the need for a cost estimation paradigm tailored to the PSS context, where we propose that new Cost Estimation Frameworks need to consider the process-level properties identified in this work (see Table 2). At its current state in the analysed literature, the PSS Cost Estimation process presents several parallels with the estimation structure of frameworks such as LCC, TLC, WLCC, and TCO. This is not surprising as authors agree on the importance of the life-cycle perspective and rely on such cost estimation frameworks for the definition of the cost scope, life-cycle stages, and/or use the underlying logic for cost estimation. However, these similarities are indeed superficial and remain at the structural level: as evidenced in this work, several authors have proposed methodological approaches that address issues particular to the PSS context. That is, while the sequence of the cost estimation steps may strike the reader with a clear resemblance to other estimation frameworks, the fundamental difference resides in how the proposed approaches within each step guide the intellectual process of identifying relevant concepts and choosing adequate techniques and tools to derive reliable cost estimates useful for the PSS context. Indeed, throughout this paper we have highlighted several of such aspects: for example, authors have argued that at the first step of the process (a) the costing scope should not assume clear-cut system boundaries between the OEM and the customer (Ng et al. (2011), Settanni et al., (2014); Batista et al., (2017)); that at the conceptualization step (b) the PSS service delivery process should be explicitly modelled (Kimita et al., (2008), Zhang et al., (2011), Pezzotta et al. (2013), Settanni et al., (2013), Estrada et al., (2017)); that at the estimate computation step (c) the space/time evolution of the PSS's behaviour should be incorporated (Erkoyuncu et al. (2011a); Estrada et al., 2017; Kimita et al., 2012; Pezzotta et al., 2013; Wrasse et al., 2015); and as found in this work that across the whole process (d) the need for a concurrent development with the PSS Engineering and PSS Contract Design processes, and (e) the intrinsic unpredictability of PSS cost should be acknowledged.

In light of the findings of this research, we believe that the latter point deserves to be emphasized and discussed, given the implications of the PSS cost unpredictability problem and its effect on the companies' lack of transition into the PSS scheme, introduced at the beginning of this paper. We believe that understanding why the PSS cost is indeed intrinsically unpredictable, can provide with some insights for academia and current practice to go about this relevant issue. From the identified properties at the process-level in this research (see Table 2), we can observe that the convoluted dynamics in the evolution of the estimate's uncertainty across the cost process shed some light on the question: *why is the PSS cost highly unpredictable?* Indeed, if we consider both the timeliness of data availability and the iterative nature of the process, the uncertainty of the estimate can be seen to decrease as more data and understanding of the PSS behaviour is attained. However, we have seen as well that modifications at the design or contract level of the PSS disrupt the evolution of uncertainty, making the real cost that is being estimated a moving target. Moreover, the high interdependency with the PSS Engineering and PSS Contract Design processes makes the improvement of the estimate's accuracy an ever more complex task that demands an increasing amount of data, time and cognitive effort. Indeed, resonating Grubic and Jennions, (2018), OEMs should proceed with caution when considering the delivery of value under outcome-based contracts.

It is important to note that since this work represents a review of the current state of the field, the overall description of the PSS Cost Estimation Process is limited by current approaches in the field. While we do not foresee a change in the overall structure of the process, as the underlying logic in the identified sequence of steps was subject to generalisation, we expect that new contributions addressing identified gaps in methodological advancement (see Table 2) uncover new interactions and process-level properties (or change pre existing ones) for a better understanding and management of cost uncertainty. For instance, consider the gap 'integrating economic and environmental analysis methods' (see Table 2). In itself, this was a surprising gap as the PSS field was first originated from an environmental perspective. However, the branch of cost estimation presents a lack of environmental approach that is reflected in the presented PSS Cost Estimation Process since it only appears at the 'controls/constraints' of the process. We envision that

Table 2
Summary of main research findings, identified gaps and future research.

PSS Cost Estimation Process' Steps	Definition of Cost Estimation Viewpoint	Characterization of the cost estimate	Conceptualization of PSS	Computation and assessment of the estimate	Adjustment and Definition of the estimate baseline
RQ1 - What are the main elements that constitute the PSS Cost Estimation Process (i.e. inputs, mechanisms, constraints, and outputs)?	*Constraints:* Contractor competitive strategy, Contractor Policies, External Environment, Data Sources. *Mechanisms*: Human resource, Infrastructure, Frameworks and guidelines.				
	Inputs: • Customer Request. • Customer Capability Baseline. *Outputs:* • Cost estimate purpose. • Cost estimation scope.	*Inputs:* • PSS Design. • PSS Contract. • Historical Data. *Outputs:* • Cost estimate's approach (i.e. top-down, bottom-up). • Cost estimate's nature (i.e. deterministic, stochastic). • Ground rules and assumptions.	*Inputs:* • PSS Design. • PSS Contract. *Mechanisms:* • Cost methods (i.e. Analogy, Parametric, and Engineering build-up). • Modelling techniques (i.e. Static, Dynamic). *Outputs:* • Technical baseline. • Cost estimate's logical structure.	*Inputs:* • PSS Design • PSS Contract *Mechanisms:* • Simulation techniques (i.e. Discrete event, Agent-based, Systems Dynamics, Scene transition nets). • Assessment techniques (i.e. Sensitivity Analysis, Uncertainty Analysis). *Outputs:* • Point estimate. • Risk prioritization. • Uncertainty propagation.	*Mechanisms:* • Adjustment strategies (i.e. Scenario Analysis). *Outputs:* • Cost estimate baseline. • Exogenous adjustments. • Endogenous adjustments.
RQ2 - How the constituent elements interact among each other (i.e. interdependence of intermediate outputs, feedback loops) and with exogenous processes (i.e. interoperability and information flows)?	*Interdependence:* • The estimate's purpose in addition to the customer's request and capability baseline further define the cost estimation scope. *Interoperability:* • Not an end itself, the cost estimate supports decision making across the PSS Engineering process (i.e. PSS Configuration and Service Delivery Model Design) and the PSS Contract Design process (e.g. definition of contract and incentive mechanisms). *Information flow:* • The customer's request and capability baseline derive from the PSS Engineering and PSS Contract Design processes respectively.	*Interdependence:* • The characterization of the estimate depends on the purpose and scope of the estimation process, and it is mainly driven by the quality of available data. *Feedback loop:* • As more data and knowledge is available/generated from subsequent activities or exogenous processes, assumptions are modified and the approach of the estimation moves gradually from a top-down to a bottom-up approach.	*Interdependence:* • The definition of the technical baseline supports the construction of the cost estimation logical structure by providing a qualitative description of the interaction between the cost objects and the cost estimate. • The selection of cost methods depends mainly on the cost estimation approach and the CERs validation techniques (i.e., Statistical Analysis, Engineering Principles, and Expert Opinion). *Feedback loop:* • As more data and knowledge is available/generated from exogenous processes, the technical baseline parameters' values are modified, or new parameters are incorporated. • As more data and knowledge is available/generated from subsequent activities and/or exogenous processes, lower levels of detail are progressively added to the cost estimate logical structure.	*Interdependence:* • When the nature of the estimate is stochastic, its computation is normally developed through simulation techniques. • While risk prioritization can be carried out for both a deterministic and a stochastic estimate, the analysis of Uncertainty propagation is limited to the latter case.	*Interdependence:* • The estimate baseline depends on the defined confidence level. *Feedback loop:* • Endogenous and/or exogenous adjustments take place, where the former refers to changes within the cost estimation process, while the latter refers to changes on exogenous processes.
		Interoperability/Information flow: • The PSS Engineering process provides data related to the PSS Configuration and the Service Delivery Model. In turn, the PSS Contract design process provides data related to the contract (i.e. type, mechanism, conditions, ownership policy, and accountability policy).			

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Table 2 (*continued*)

PSS Cost Estimation Process' Steps	Definition of Cost Estimation Viewpoint	Characterization of the cost estimate	Conceptualization of PSS	Computation and assessment of the estimate	Adjustment and Definition of the estimate baseline
RQ3 - What are the process-level properties that arise from these interactions?	*Timeliness of data availability:* • As time passes more data becomes available and causal understating progress across the PSS Cost Estimation Process. *Iterative nature:* • The PSS Cost Estimation Process is described as an iterative process since its resulting estimate is computed repeatedly - a property that arises from the feedback loops triggered by the endogenous and exogenous adjustments. *Estimate's intrinsic unpredictability:* • The accuracy of the Cost Estimation Process increases by the timeliness of data availability and its iterative nature. Nonetheless, it is upper bounded by the irreducible error term of its associated "Objective Truth" as the latter depends on unmeasurable data. *Estimate's Uncertainty Evolution:* • The uncertainty of the Cost Estimation Process decreases by the timeliness of data availability and its iterative nature. Such evolution can be described by the reduction of the statistical variance and the statistical bias - while endogenous adjustments gradually reduce the variance and bias through iterations, the exogenous adjustments disrupt the evolution of uncertainty. *Inference-Prediction trade-off:* • From the interplay between the use of engineering principles and statistical analysis in the construction of the cost estimate, an inference-prediction trade-off arises. The use of engineering principles provides causal understanding but its predictive power is limited by human cognition and knowledge. On the other hand, statistical analysis could suffice for a predictive model but sacrifices causal explanation. *Co-capability:* • The retrospective interpretation that exogenous adjustments bring at the interplay between the PSS Cost Estimation and exogenous processes, enables concurrent exploration into a wider solution space. • To develop new cost estimation frameworks that consider the process-level properties of PSS cost estimation, and the impact of the methodological approach onto cost uncertainty and its evolution through time. • To develop cost recommended practices for the PSS context. • To develop ontologies for the description of PSS that differentiate it from the traditional approach of a product-centric or pure-service systems.				
Gaps in methodological advancement and Areas of Future Research	• To further investigate the implications of the ontological definition, the lifecycle approach and the standpoint on costing scope (e.g., to consider (a) potential changes of customer requirements, (b) obsolescence mitigation/ upgrading strategies, (c) product lifecycle across contracts) - as there is a lack of consistency regarding the definition of the cost estimation scope characterized by a 1) Methodological discrepancy, 2) Lack of consensus about PSS lifecycle stages, and 3) Vagueness of cost estimation standpoint description.	• To investigate how the characterization of the estimate (as deterministic or stochastic) impacts on cost under-estimation - as this characterization is not consistent across literature. • To investigate techniques for the measurement of epistemic uncertainty - as its measurement remains open-ended in literature.	• To investigate how the ontological definition of a PSS impacts on its conceptualization - as a modelling consensus is not found yet in literature. • To investigate and develop modelling techniques that represent the evolution of the PSS behaviour over time - as the development of a dynamic model for the representation of the PSS Technical baseline is not broadly considered in literature yet. • To integrate economic and environmental analysis methods - as little attention has been pay in literature to potential cost - environmental trade-offs, and how these often competing forces shape the PSS cost estimation process. • To investigate new Engineering Build-up cost methods, and cost drivers that account for the PSS endemic properties (e.g.	• To investigate both analytical and numerical techniques for the quantification of uncertainty propagation and risk prioritization - as little attention has been paid in literature. • To investigate numerical techniques (e.g., simulation) that enable the computation and analysis of the time/spatial evolution of the PSS behaviour and its associated cost - as the PSS behaviour is often analysed from a static perspective. • To investigate the cost unpredictability effects on the OEM's Profit mechanism (e.g., how sensible is the profit to cost uncertainty under different contract mechanisms/PSS configurations?) - as no attention has been paid in literature to this issue.	• To develop uncertainty management strategies that acknowledge the cost unpredictability property of PSS and thus focus on mitigating the negative impact of cost under-estimation - as current approaches aim at just reducing uncertainty propagation. • To investigate techniques that quantify the Contract Design and PSS Engineering effects on risk and uncertainty propagation - as in current practice the cost estimation process and exogenous processes are still evaluated separately. • To develop techniques for a systematic definition of the cost estimate baseline - as in current practice the definition of the cost estimate baseline relies on Subject Matter Experts judgement or on recommended cost estimation practices.

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Table 2 (*continued*)

PSS Cost Estimation Process' Steps	Definition of Cost Estimation Viewpoint	Characterization of the cost estimate	Conceptualization of PSS	Computation and assessment of the estimate	Adjustment and Definition of the estimate baseline
			dynamism, complexity, emergence) - as current cost methods rely on traditional approaches. • To investigate systematic CERs validation techniques - as validation often relies on Subject Matter Experts. • To investigate the implications of the cost methods Inference-Prediction trade-off on PSS Design and PSS Contract Design- as in current practice the cost estimation process and exogenous processes are evaluated separately.		• To further investigate the systematic uncertainty management process that guides adjustments in the PSS cost estimation process - as no attention has been paid to this issue. • To develop scenario analysis strategies relevant for the PSS context- as little attention has been paid to this issue.

new contributions focusing on the environmental dimension of PSS and its associated cost in tandem will evidence the trade-offs between economic and environmental goals, which we believe will add an extra layer of complexity into the current description of the interaction between cost estimation and the PSS Engineering and Contract Design processes. Another important limitation derives from how the general approach towards the reduction of uncertainty in literature shapes the PSS Cost Estimation Process. Based on this current approach the underlying logic of the process aims at progressively improve the accuracy of the estimate. However, by acknowledging the intrinsic unpredictability of the cost estimate, new contributions could focus on the development of strategies that mitigate the negative impact of the exposure to uncertainty instead of reducing it, changing the identified interactions within the cost process. Take for example the case in which cost estimation is used for the correct pricing of the PSS offer. While current approaches invest an increasing effort on improving the prediction accuracy of the estimation process through uncertainty management strategies, we suggest that parallel to such efforts, research and practice could focus on the assessment of pricing mechanisms at the contractual level in accordance to the expected loss/penalization that results from the exposure to cost under-estimation and performance shortcomings.

6. Conclusions

An increasing number of customers interested in outcome-based contracts has been continuously reported in literature, where Original Equipment Manufacturers have increasingly felt the need to provide PSS solutions to remain competitive. The transition into the PSS scheme has proven to be a highly difficult endeavour where a significant part of this lack of success has been attributed to inadequate contract decisions outlined by under-estimation of costs and performance overpromises (Rapaccini, 2015). This issue has been directly associated with the novelty and intrinsic complexity of PSS behaviour (Kreye et al., 2017; Estrada et al., 2017; Settanni et al., 2013), where traditional cost estimation methods do not have the appropriate methodological foundations to capture the causal mechanisms between the PSS operation and its associated cost (Settanni et al., 2014) - calling for the development of a new cost estimation paradigm for the PSS scheme. The academic literature dealing with the theoretical dimension of PSS cost estimation has focused extensively on understanding how the PSS context has modified several elements of the cost estimation process, nevertheless, a comprehensive and integrated depiction of the whole PSS cost estimation process, had not been yet analysed and portrayed in PSS literature. This paper addressed this gap by proposing an exhaustive description of the PSS cost estimation process through an integrative review which extends current PSS literature in three different levels: 1) It integrates the current knowledge base in a synthetic representation of the cost estimation process; 2) It extends current understanding on how the PSS context has modified the cost estimation process and exacerbated cost unpredictability; and 3) It supports the future development of new PSS Cost Estimation frameworks by providing a clear depiction of current advancements, methodological approaches, and research gaps.

Moreover, based on the findings of the research work, the paper: 1) Underlines the need for a concurrent development of the cost estimation process with the PSS Engineering and PSS Contract Design exogenous processes; 2) Calls for a shift of perspective from the development of strategies that look for the elimination of uncertainty into the development of strategies that acknowledge its intrinsic nature and mitigate the negative impact of the exposure to it; 3) Resonates the need for an ontological consensus of the PSS observed as a complex system; and 4) Calls for the development of cost estimation frameworks that consider the previously stated points. The research study is limited to an identified pool of literature consciously focuses on the PSS scheme. Further research work needs to be carried out in order to 1) Expand the scope of the analysis to gain insights from similar fields of study (e.g., Through-life Engineering Services, Functional Products, Integrated Product Service Offerings) as the findings of this review are limited to the current literature approach towards cost estimation; to 2) Identify in a detailed fashion the precise elements that interact between the PSS Cost Estimation Process and exogenous process; to 3) Develop frameworks that consolidates the PSS Cost Estimation process acknowledging its ontological implications and the findings of this study; and to 4) Develop strategies for a better management of uncertainty throughout the evolution of the estimation process.

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Appendix 1

Author	Year	Title	Type of Contribution	Application
(Kreye et al., 2017)	2017	Uncertainty perception in bidding for Product-Service Systems under competition	Theoretical, Empirical	NA
(Estrada et al., 2017)	2017	A Cost-Engineering Method for Product-Service Systems Based on Stochastic Process Modelling: Bergamo's Bike-Sharing PSS	Theoretical, Methodological, Empirical	Bike-sharing system
(Schuh et al., 2017)	2017	Evaluation of Variety-induced Costs in Product-Service Systems (PSS)	Theoretical, Methodological, Empirical	Machinery Industry
(Shen et al., 2017)	2017	A framework for cost evaluation in product service system configuration	Theoretical, Methodological, Empirical	High-Pressure pumps
(Bonetti et al., 2016)	2016	Total Cost of Ownership for Product-Service System: application of a prototypal model to aluminium melting furnaces	Theoretical, Methodological, Empirical	Aluminum Melting Furnaces
(Carlander et al., 2016)	2016	Integration of cost-risk assessment of denial of service within an intelligent maintenance system	Theoretical, Methodological, Empirical	Rail Industry
((Estrada & Romero, 2016b))	2016	A System Quality Attributes Ontology for Product-Service Systems Functional Measurement Based on a Holistic Approach	Theoretical	NA
(Estrada and Romero, 2016a)	2016	Towards a Cost Engineering Method for Product-Service Systems Based on a System Cost Uncertainty Analysis	Theoretical, Methodological	NA
(Kambanou and Lindahl, 2016)	2016	A Literature Review of Life Cycle Costing in the Product-Service System Context	Theoretical	NA
(Marchi et al., 2016)	2016	Product-Service System for sustainable EAF transformers: real operation conditions and maintenance impacts on the life-cycle cost	Theoretical, Methodological, Empirical	Steel Industry
(Seiringer and Bauer, 2016)	2016	Improving PSS Costing Based on Customer Integration	Theoretical, Methodological, Empirical	Repair service of a medical manufacturer
(Schuh et al., 2016)	2016	Characterization and empirical analysis of variety-induced costs in integrated product-service systems (PSS)	Theoretical, Empirical	NA
(Azevedo and Sholiha, 2015)	2015	Innovative costing system framework in industrial product-service system environment	Theoretical, Methodological	NA
(Lingegard et al., 2015)	2015	Life-cycle cost strategies for harbours - a case study	Theoretical, Empirical	Maritime shipping
(Schröder et al., 2015)	2015	Evaluation of Cost Structures of Additive Manufacturing Processes Using a New Business Model	Theoretical, Methodological, Empirical	Additive Manufacturing
(Wrasse et al., 2015)	2015	Simulation of Product-Service-Systems Piloting with Agent-Based Models (outlined revision).	Theoretical, Methodological, Empirical	Solar home systems
(Goh et al., 2015)	2015	Addressing Uncertainty in Estimating the Cost for a Product-Service System Delivering Availability: Epistemology and Ontology	Theoretical	NA
(Settanni et al., 2014)	2014	A through-life costing methodology for use in product-service-systems	Theoretical, Methodological	NA
(Erkoyuncu et al., 2013a)	2013	Identifying uncertainties for industrial service delivery: a systems approach	Theoretical, Empirical	Aerospace Industry
(Pezzotta et al. 2013)	2013	A Service Engineering Framework to Design and Configure Product-Service Systems	Theoretical, Methodological, Empirical	Repair workshop of truck company
(Settanni et al., 2013)	2013	System Modelling: A Foundation for Costing Through-Life Availability Provision	Theoretical, Methodological	Aerospace Industry
(Erkoyuncu et al., 2013b)	2013	Uncertainty driven service cost estimation for decision support at the bidding stage	Methodological, Empirical	Aircraft carrier, naval system
(Garetti et al., 2012)	2012	Life Cycle Simulation for the design of Product-Service Systems	Theoretical	NA
(Kimita et al., 2012)	2012	Process Simulation Method for Product-Service Systems Design	Theoretical, Methodological, Empirical	Elevator operating service
(Mu et al., 2012)	2012	Machining Process Level Cost Estimation in Cutting-Tool IPSS	Methodological	Machining Process
(Prabhakar and Sandborn, 2012)	2012	A part total cost of ownership model for long life cycle electronic systems	Theoretical, Methodological, Empirical	Electronic Systems

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Author	Year	Title	Type of Contribution	Application
(Rojo et al., 2012)	2012	A cost estimating framework for electronic, electrical and electromechanical (EEE) components obsolescence within the use-oriented product-service systems contracts	Theoretical, Methodological, Empirical	Defence and Aerospace
(Xu et al., 2012)	2012	Cost Engineering for manufacturing: Current and future research	Theoretical	Manufacturing Sector
(Erkoyuncu et al., 2011a)	2011	Service Uncertainty and Cost for Product Service Systems	Theoretical, Methodological, Empirical	Militar Naval Systems
Erkoyuncu et al., 2011a	2011	Understanding service uncertainties in industrial product-service system cost estimation	Theoretical	NA
(Lanza et al., 2011)	2011	Simulation of Life Cycle Costs of a Product Service System	Methodological, Empirical	Machine Tool Manufacturer
(Roy and Erkoyuncu, 2011)	2011	Service Cost Estimation Challenges in Industrial Product-Service Systems	Theoretical, Methodological	NA
(Zhang et al., 2011)	2011	Environmental impact and cost assessment of product service systems using IDEFO modelling	Theoretical, Methodological	A copy center
(Huang et al., 2011)	2011	An analysis of industrial practice for estimating the in-service costs of a product service system	Theoretical, Methodological, Empirical	Machine Manufacturer and Service Provider
(Mannweiler et al., 2010)	2010	Lifecycle Cost oriented Evaluation and Selection of Product-Service Systems Variants	Methodological, Empirical	Winegrowers cultivators
(Datta and Roy, 2009)	2009	Cost Modelling Techniques for Availability Type Service Support Contracts: a Literature Review and Empirical Study	Theoretical	Mechanical and Electrical equipment for defence industry
(Erkoyuncu et al., 2009)	2009	Uncertainty challenges in service cost estimation for product - service systems in the aerospace and defence industries	Theoretical	Aerospace and Defence Industry
(Kreye et al., 2009)	2009	Uncertainty in Trough life costing within the concept of Product-Service Systems: A Game Theoretic Approach	Theoretical	NA
(Kimita et al., 2008)	2008	Cost evaluation method for service design based on activity-based costing	Theoretical, Methodological, Empirical	IT System

References

AACEI, 2011. Recommended Practices No. 17R-97:Cost Estimate Classification System, and No. 18R-97: Cost Estimate Classification System - as Applied in Engineering, Procurement and Construction for the Process Industries. Association for the Advancement of Cost Engineering International.

Azevedo, A., Sholiha, M., 2015. Innovative costing system framework in industrial product-service system environment. In: Proceedings of the Industrial Engineering and Service Science. Procedia CIRP, pp. 224–230.

Baines, T., Braganza, A., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I., Wilson, H., 2007. State-of-the-art in product-service systems. J. Eng. Manuf. 1543–1551.

Batista, L., Davis-poynter, S., Ng, I., Maull, R., 2017. Servitization through outcome-based contract – a systems perspective from the defence industry. Int. J. Prod. Econ. 192, 133–143. https://doi.org/10.1016/j.ijpe.2016.12.005.

Baveja, S., Gilbert, J., Ledingham, D., 2004. From products to services: why it's not so simple. Harv. Manag. Update 9 (4), 3–5.

Bonetti, S., Perona, M., Saccani, N., 2016. Total Cost of Ownership for Product-Service System: Application of a Prototypal Model to Aluminum Melting Furnaces. Product-Service Systems across Life Cycle. Procedia CIRP, Bergamo, Italy, pp. 166–177. In: https://doi.org/10.1016/j.procir.2016.03.069.

Broome, M., 1993. Integrative literature reviews for the development of concepts. Concept Dev. Nurs. 231–250.

Carlander, L., Kirkwood, L., Shehab, E., Baguley, P., Durazo-Cardenas, I., 2016. Integration of Cost-Risk Assessment of Denial of Service within an Intelligent Maintenance System. Product-Service Systems across Life Cycle. Procedia CIRP, pp. 66–71. https://doi.org/10.1016/j.procir.2016.03.229.

Casella, G., Berger, R., 2002. Statistical Inference, 2 ed. Thomson Learning.

Cavalieri, S., Pezzotta, G., 2012. Product–service systems engineering: state of the art and research challenges. Comput. Ind. 63 (4), 278–288. https://doi.org/10.1016/j.compind.2012.02.006.

Datta, P., Roy, R., 2009. Cost Modelling Techniques for Availability Type Service Support Contracts: a Literature Review and Empirical Study. 1st CIRP Industrial Product-Service Systems. Procedia CIRP, p. 216.

DoE, 2011. U.S. Department of Energy Cost Estimation Guide, G 413. DOE, pp. 3–21.

Ellram, E., 1993. Total cost of ownership: elements and implementation. J. Supply Chain Manag. 29 (3), 2–11. https://doi.org/10.1111/j.1745-493X.1993.tb00013.x.

Erkoyuncu, J., Roy, R., Datta, P., Wardle, P., Murphy, F., 2011a. Service uncertainty and cost for product service systems. In: Ng, I., et al. (Eds.), Complex Engineering Service Systems. Springer-Verlag, pp. 129–147.

Erkoyuncu, J., Roy, R., Shebab, E., Cheruvu, K., 2011a. Understanding service uncertainties in industrial product-service system cost estimation. Int. J. Adv. Manuf. Technol. 52 (9–12), 1223–1238. https://doi.org/10.1007/s00170-010-2767-3.

Erkoyuncu, J., Roy, R., Shehab, E., Wardle, P., 2009. Uncertainty Challenges in Service Cost Estimation for Product-Service Systems in the Aerospace and Defence Industries. The 1st CIRP Industrial Product-Service Systems. Cranfield University, Procedia CIRP, p. 200.

Erkoyuncu, J., Durugbo, C., Roy, R., 2013a. Identifying uncertainties for industrial service delivery: a systems approach. Int. J. Prod. Res. 6295–6315. https://doi.org/10.1080/00207543.2013.794316.

Erkoyuncu, J., Durugbo, C., Shehab, E., Roy, R., Parker, R., Gath, A., Howell, D., 2013b. Uncertainty driven service cost estimation for decision support at the bidding stage. Int. J. Prod. Res. 5771–5788. https://doi.org/10.1080/00207543.2013.794318.

Estrada, A., Romero, D., Pinto, R., Pezzotta, G., Lagorio, A., Rondini, A., 2017. A cost-engineering method for product-service systems based on stochastic process modelling: Bergamo's bike-sharing PSS. In: The 9th CIRP IPSS Conference: Circular Perspectives on Product-Service Systems. Procedia CIRP, Copenhagen, pp. 417–422. In: https://doi.org/10.1016/j.procir.2017.03.066.

Estrada, A., Romero, D., 2016a. Towards a Cost Engineering Method for Product-Service Systems Based on a System Cost Uncertainty Analysis. Industrial Product-Service Systems - PSS across Life Cycle, vol. 47. Procedia CIRP, Bergamo, Italy, pp. 84–89.

Estrada, A., Romero, D., 2016b. A System Quality Attributes Ontology for Product-Service Systems Functional Measurement Based on a Holistc Approach. Industrial Product-Service Systems - PSS across Life Cycle, vol. 47. Procedia CIRP, Bergamo, Italy, pp. 78–83.

GAO, 2009. GAO Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs (GAO-09-3SP, ed. United States Government Accountability Office.

Garetti, M., Rosa, P., Terzi, S., 2012. Life cycle simulation for the design of product-service systems. Comput. Ind. 63 (4), 361–369. https://doi.org/10.1016/j.compind.2012.02.007.

Garvey, P., 2015. Probability Methods for Cost Uncertainty Analysis: A Systems Engineering Perspective, second ed. Chapman and Hall.

Grubic, T., Jennions, I., 2018. Do outcome-based contracts exist? The investigation of power-by-the-hour and similar result-oriented cases. Int. J. Prod. Econ. 206, 209–219.

Goh, Y., Newnes, L., Mileham, A., Mcmahon, C., Saravi, M., 2010. Uncertainty in through-life costing–-review and perspectives. IEEE Trans. Eng. Manag. 57 (4), 689–701. https://doi.org/10.1109/TEM.2010.2040745.

Goh, Y., Newnes, L., Settanni, E., Thenent, N., Parry, G., 2015. Addressing uncertainity in estimating cost for a PSS delivering availability: epistemology and ontology. Ontol. Model. Phys. Asset Integr. Manag. 199–219. https://doi.org/10.1007/978-3-319-15326-1_7.

Hastie, T., Tibshirani, R., Friedman, J., 2009. The Elements of Statistical Learning. Springer Series in Statistics.

Huang, X.X., Newnes, L.B., Parry, G.C., 2011. The adaptation of product cost estimation techniques to estimate the cost of service. Int. J. Comput. Integr. Manuf. 25 (4–5) https://doi.org/10.1080/0951192x.2011.596281.

James, G., Witten, D., Hastie, T., Tibshirani, R., 2015. An Introduction to Statistical Learning. Springer New York Heidelberg Dordrecht London. https://doi.org/10.1007/978-1-4614-7138-7.

Kambanou, M., Lindahl, M., 2016. A literature review of life cycle costing in the product-service system context. In: The 8th CIRP IPSS Conference: Product-Service Systems across Life Cycle, vol. 47. Procedia CIRP, Bergamo, Italy, pp. 186–191. In: https://doi.org/10.1016/j.procir.2016.03.054.

KBS, 2011. IDEF0. Retrieved from Kowledge Based Systems, Inc. http://www.idef.com.

Kimita, K., Hara, T., Shimomura, Y., Arai, T., 2008. Cost evaluation method for service design based on activity based costing. Manufacturing systems and technologies for the new frontier. In: The 41st CIRP Conference on Manufacturing Systems, pp. 477–480.

Kimita, K., Tateyama, T., Shimomura, Y., 2012. Process Simulation Method for Product-Service Systems Design, vol. 3. Procedia CIRP, pp. 489–494.

Kreye, M., Goh, Y., Newnes, L., 2009. Uncertainty in through life costing within the concept of product service systems: a game theoretic approach. Int. Conf. Eng. Des. 57–68.

Kreye, M., Goh, Y., Newnes, L., Goodwin, P., 2012. Approaches to displaying information to assist decisions under uncertainty. Omega 40 (6), 682–692. https://doi.org/10.1016/j.omega.2011.05.010.

Kreye, M., Goh, Y., Newnes, L., 2017. Uncertainty perception in bidding for Product-Service Systems under competition. J. Purch. Supply Manag. 24 (1), 31–40. https://doi.org/10.1016/j.pursup.2017.10.003.

Lanza, G., Behmann, B., Werner, P., Vöhringer, S., 2011. Simulation of life cycle costs of a product service system. Functional thinking for value creation. In: Proceedings of the 3rd CIRP International Conference on Industrial Product Service Systems, pp. 159–164. https://doi.org/10.1007/978-3-642-19689-8.

Lingegard, S., Lindahl, M., Syberg, A., 2015. Life-cycle cost strategies for harbors – a case study. In: 7th Industrial Product-Service Systems Conference - PSS, Industry Transformation for Sustainability and Business. Procedia CIRP, pp. 317–322.

Long, H., Wang, L., Shen, J., Wu, M., Jiang, Z., 2013. Product service system configuration based on support vector machine considering customer perception. Int. J. Prod. Res. 51 (18), 5450–5468.

Mannweiler, C., Siener, M., Aurich, J., 2010. Lifecycle Cost Oriented Evaluation and Selection of Product-Service System Variants. Procedia CIRP.

Marchi, B., Zanoni, S., Mazzoldi, L., Reboldi, R., 2016. Product-Service System for Sustainable EAF Transformers: Real Operation Conditions and Maintenance Impacts on the Life-Cycle Cost. Industrial Product-Service Systems - PSS across Life Cycle, vol. 47. Procedia CIRP, Bergamo, Italy, pp. 72–77.

Meier, H., Roy, R., Seliger, G., 2010. Industrial product-service systems - IPS2. CIRP Ann. - Manuf. Technol. 59 (2), 607–627. https://doi.org/10.1016/j.cirp.2010.05.004.

Mont, O., 2002. Clarifying the concept of product–service system. J. Clean. Prod. 10, 237–245. https://doi.org/10.1016/S0959-6526(01)00039-7.

Mu, H., Jiang, P., Zhu, Q., 2012. Machining process level cost estimation in cutting-tool IPSS. Appl. Mech. Mater. 101 – 102, 759–762. 10.4028/www.scientific.net/AMM.101-102.759.

Ng, I., Williams, J., Neely, A., 2009. Outcome-based Contracting: Changing the Boundaries of B2B Customer Relationships: an Executive Briefing. Advanced Institute of Management Research. (Advanced Institute of Management (AIM) Research Executive Briefing Series, London, UK.

Ng, I., Parry, G., Wild, P., McFarlane, D., Tasker, P., 2011. Complex Engineering Service Systems: Concepts and Research. Springer, Berlin.

Oliveira, M., Mendes, G., Rozenfeld, H., 2015. Bibliometric analysis of the product-service system research field. In: 7th Industrial Product-Service Systems Conference - PSS, Industry Transformation for Sustainability and Business. Procedia CIRP 30, pp. 114–119.

Olivia, R., Kallenberg, R., 2003. Managing the transition from product to services. Int. J. Serv. Ind. Manag. 14 (2), 160–172. https://doi.org/10.1108/09564230310474138.

Pezzotta, G., Pirola, F., Akasaka, F., Cavalieri, S., Shimomura, Y., Gaiardelli, P., 2013. A service engineering framework to design and configure product-service systems. 11th IFAC Workshop on Intelligent Manufacturing Systems 46 (7), 263–268. https://doi.org/10.3182/20130522-3-BR-4036.00079.

Pezzotta, G., Pinto, R., Pirola, F., Ouertani, M., 2014. Balancing product-service provider's performance and customer's value: the SErvice Engineering Methodology (SEEM). Product Services Systems and Value Creation. In: Proceedings of the 6th CIRP Conference on Industrial Product-Service Systems, pp. 50–55. https://doi.org/10.1016/j.procir.2014.01.008.

Prabhakar, V., Sandborn, P., 2012. A part total cost of ownership model for long life cycle electronic systems. Int. J. Comput. Integr. Manuf. 25 (4 - 5), 384–397. https://doi.org/10.1080/0951192X.2010.531293.

Rapaccini, M., 2015. Pricing strategies of service offerings in manufacturing companies: a literature review and empirical investigation. Prod. Plan. Control 26 (14–15), 1247–1263.

Rodrigues, D., Erkoyuncu, J., Starr, A., Wilding, S., Dibble, A., Laity, M., 2015. Review of the modelling approaches for Availability Contracts in the military context. In: Proceedings of the 7th CIRP Conference on Industrial Product-Service Systems: Industry Transformation for Sustainability and Business. Procedia CIRP, pp. 451–456. In: https://doi.org/10.1016/j.procir.2015.02.132.

Rojo, F., Roy, R., Shehab, E., Cheruvu, K., Mason, P., 2012. A cost estimating framework for electronic, electrical and electromechanical (EEE) components obsolescence within the use-oriented product-service systems contracts. J. Eng. Manuf. 226 (1), 154–166. https://doi.org/10.1177/0954405411406774.

Roy, R., Erkoyuncu, J., 2011. Service cost estimation challenges in industrial product-service systems. In: Herrmann, C. (Ed.), Functional Thinking for Value Creation. Springer, Berlin, Heidelberg, pp. 1–10. https://doi.org/10.1007/978-3-642-19689-8_1.

Sandborn, P., Kashani-Pour, A., Goudarzi, N., Lei, X., 2017. Outcome-based contracts - towards concurrently designing products and contracts. In: The 5th International Conference on Through-Life Engineering Services (TESConf 2016), vol. 59. Procedia CIRP, pp. 8–13. https://doi.org/10.1016/j.procir.2016.09.017.

Schröder, M., Falk, B., Schmitt, R., 2015. Evaluation of Cost Structures of Additive Manufacturing Processes Using a New Business Model. PSS, industry transformation for sustainability and business, pp. 311–316. https://doi.org/10.1016/j.procir.2015.02.144. Procedia CIRP.

Schuh, G., Riesener, M., Koch, J., Breunig, S., Kuntz, J., 2016. Characterization and empirical analysis of variety-induced costs in integrated product-service systems (PSS). In: IEEE International Conference on Industrial Engineering and Engineering Management, pp. 572–576. https://doi.org/10.1109/IEEM.2016.7797940.

Schuh, G., Riesener, M., Breunig, S., Koch, J., Kuntz, J., 2017. Evaluation of variety-induced costs in product-service systems (PSS). In: The 24th CIRP Conference on Life Cycle Engineering. Procedia CIRP, pp. 673–678. https://doi.org/10.1016/j.procir.2016.11.239.

Seiringer, W., Bauer, W., 2016. Improving PSS costing based on customer integration. Product-Service Systems across Life Cycle 47, 36–41. https://doi.org/10.1016/j.procir.2016.03.081.

Settanni, E., Thenent, N., Newnes, L., 2013. System modeling: a foundation for costing through-life availability provision. IFIP Adv. Inf. Commun. Technol. 48–57.

Settanni, E., Newnes, L., Thenent, N., Parry, G., Goh, Y., 2014. A through-life costing methodology for use in product-service-systems. Int. J. Prod. Econ. 166–177. https://doi.org/10.1016/j.ijpe.2014.02.016.

Shen, J., Erkoyuncu, J., Roy, R., Wu, B., 2017. A framework for cost evaluation in product service system configuration. Int. J. Prod. Res. 6120–6144. https://doi.org/10.1080/00207543.2017.1325528.

Smith, J., 2013. Power-by-the-hour: the Role of Technology in Reshaping Business Strategy at Rolls-Royce. Technology Analysis and Strategic Management, pp. 987–1007.

Stewar, R., Wyskida, R., Johannes, J., 1995. Cost Estimator's Reference Manual, second ed. Wiley Interscience.

Tukker, A., Tischner, U., 2006. Product-services as a research field: past, present and future. Reflections from a decade of research. J. Clean. Prod. 14 (17), 1552–1556. https://doi.org/10.1016/j.jclepro.2006.01.022.

Van Ostaeyen, J., Van Horenbeek, A., Pintelon, L., Duflou, J., 2013. A refined typology of product-service systems based on functional hierarchy modeling. J. Clean. Prod. 51, 261–276. https://doi.org/10.1016/j.jclepro.2013.01.036.

Whittemore, R., Knafl, K., 2005. The integrative review: updated methodology. J. Adv. Nurs. 52 (5), 546–553.

Wrasse, K., Hayka, H., Stark, R., 2015. Simulation of Product-Service Systems Piloting with Agent-Based Models. Procedia CIRP, pp. 108–113.

Wright Laboratory, 1981. ICAM Architecture Part II-Volume IV - Function Modeling Manual (IDEF0). Wright-Patterson Air Force Base, Ohio.

Xu, Y., Elgh, F., Erkoyuncu, J., Bankole, O., Goh, Y., Cheung, W., Baguley, P., Wang, Q., Arundachawat, P., Shehab, E., Newnes, L., Roy, R., 2012. Cost Engineering for manufacturing: current and future research. Int. J. Comput. Integr. Manuf. 25 (4–5), 300–314. https://doi.org/10.1080/0951192x.2010.542183.

Zhang, H., Haapala, K., Vanlue, M., Funk, K., 2011. Environmental impact and cost assessment of product service systems using IDEFO modeling. Trans. North Am. Manuf. Res. Inst. SME 39, 172–181.