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A framework for cost estimation in product-service systems: A systems thinking approach

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ABSTRACT

Original Equipment Manufacturers (OEMs) are increasingly undergoing a transition into the offering of Product-Service System (PSS) solutions. This transition has proven to be a difficult challenge characterised by inadequate contract decisions due to cost under-estimations and performance overpromises. Despite the relevance of cost estimation for the OEM's transition into the PSS scheme, little research attention has been received until recently for the development of cost estimation frameworks appropriate for the PSS context. To fill this gap, this paper proposes a framework for cost estimation in the PSS context based on the "systems-thinking" approach, composed of a set of iterative modules and methodological foundations that bring into discussion several properties relevant to the PSS context. A numerical control multi-axis machine centre PSS is illustrated to evidence the capability of the framework to analyse the cost impacts on both the customer and on the OEM side and to support the design and improvement of PSS configurations and associated contract mechanisms.

Introduction

The current industrial environment is outlined by an increasing demand for service contracts based on equipment performance rather than on the activities involved in the service of such equipment [4,53]. In consequence, Original Equipment Manufacturers (OEMs) are undergoing a transition into the delivery of Product-Service Systems (PSS), defined as an integrated system of interconnected products and services that provide an agreed-upon functionality for customers [8] - where the OEM no longer sells pure products but delivers product performance [62]. For instance, PSS has attracted interest in the defence industry as a candidate for availability contracting [10,50], where the OEM receives a fixed price to sustain an agreed level of readiness [48] and is responsible for the number of service transactions required to sustain such agreed level of availability, otherwise, payments may be withheld or reduced [42,52].

For OEMs, this transition into the PSS context has proven to be a difficult challenge [43] characterised by inadequate contract decisions due to cost under-estimations and performance overpromises [47]. This issue has been rationalised in literature by the novelty and intrinsic complexity of the PSS behaviour. Moreover, it has been directly associated with the inability of the cost estimation process to capture the causal mechanisms between the PSS operation and its associated costs [59] since traditional cost estimation frameworks were found to lack the methodological foundations suitable to capture the intrinsic dynamics of a PSS [60].

Despite the relevance of cost estimation for the OEM's transition into the PSS scheme, little research attention has been received until recently for the development of cost estimation frameworks appropriate for the PSS context. [49] provide a detailed review of PSS cost estimation literature and identify gaps in current methodological approaches. In particular, [49] call for bespoke cost estimation frameworks that acknowledge the intrinsic complexity of PSS by taking into account the cost impacts of the uncertain environment of the PSS operation and the cost impacts of the design of the PSS configuration and the PSS contract. This paper addresses such a call and proposes a framework based on the systems thinking approach from systems engineering cost analysis. In particular, the framework provides (1) a series of steps with concrete and well defined intermediate outcomes and highlights (2) appropriate considerations that practitioners should not overlook while conducting cost estimations in the PSS context. Moreover, we illustrate the proposed framework with a numerical control multi-axis machine centre PSS, where the costs (for both the OEM and the customer) of a preventive

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maintenance strategy are analysed within an outcome-based contract mechanism and further compared with the current traditional product-centric OEM's corrective maintenance strategy. This illustrated example highlights how the proposed framework allows capturing the dynamic nature of the PSS operation and how it is useful to analyse the cost impacts of a given PSS conceptualisation on both the customer and on the OEM side, which ultimately supports the design and improvement of PSS configurations and associated contract mechanisms.

The remainder of the paper is structured as follows: *Research background* presents the relevant literature to further evidence and describes the main research gaps and highlights the key theoretical aspects underpinning the research work. *Proposed PSS Cost Estimation Framework* presents the proposed PSS Cost Estimation Framework followed by an application in a multi-axis machine centre PSS in *Application of Proposed Framework*. Finally, *Discussion and Conclusions* provides a discussion of the framework's applicability and concludes the paper by pointing out the main contributions and related issues for future research.

Research background

OEMs have increasingly felt the need to provide support services to improve their products' performance and functionality [11,3,40]. As a consequence, PSS has emerged as a promising avenue for improving manufacturing competitiveness by complying with customers' consumption patterns under outcome-based contracts [62] (Tukker and Tischner,) [40]. On the OEM side, the PSS solution has proven to attain cost reductions and performance improvements driven by incentive mechanisms and penalisations for performance shortcomings [53] and to have the potential to reduce environmental impacts [1,23,45]. Moreover, the long-term relationship between the OEM and the customer has been shown to generate lock-in situations that enable steady cash flows, increased customer demand, and access to customers' equipment operational data [30,52]. On the customer side, the PSS has been shown to provide better risk management solutions, reduce servicing costs, and guarantee technological innovation [52].

Despite the PSS merits, the transition into this scheme has proven to be a highly difficult endeavour [30,43,5] challenged by a persistent product centred mindset, a lack of adjustment to new incentive structures, a separation of product and service design processes, and the prevalence of product-focus information and cost structures [37]. As OEMs begin to transition towards offering PSS solutions, defining relevant performance indicators becomes a challenging task as OEMs require to change their focus from capturing a monetary value at the point of sale towards the opportunity to capture value throughout the contract lifecycle [38]. Indeed, recent studies have shown that OEMs fail to make suitable contract decisions (e.g., pricing) by commonly underestimating the cost of their offerings and overpromising performance [47].

For the transition into the PSS scheme, Cost Estimation places cost as a driving consideration in decisions that determine how the PSS is designed, produced and sustained. As the literature evidences, Cost Estimation addresses a broad set of questions that provide information to a variety of stakeholders [24,29] and supports decision making across several processes such as PSS Design and PSS Contract Design [2,27,49].

As the transition into the PSS scheme modifies the ownership structure [40], a shared approach is found in literature where authors observe the PSS as a dynamic entity that evolves through various stages, where the OEM requires to broaden its costing scope to include other lifecycle stages. Indeed, authors tend to use traditional frameworks such as Life Cycle Costing (LCC) or Total Cost of Ownership (TCO) for the definition of the cost scope, lifecycle stages, and/or use the underlying logic for cost estimation. In line with this, several empirical and theoretical research works have significantly contributed to the advancement of the field by identifying relevant cost techniques and cost drivers [34,51,56,57,61], or by developing methodologies that analyse both economic and performance outcomes (e.g., environmental impact) by bringing together well-established traditional cost frameworks (e.g., LCC, TCO) and tools for the analysis and design of system functionality [15–18,23,25,41,55,66,6,54,33,46,65,35]. However, a consolidated approach is not yet found in the literature, where current costing approaches are sector-specific, tailored by practitioners and characterised by a slow adoption in industry [26].

Importantly, it has been pointed out that the PSS context has exacerbated cost unpredictability [10,12], and that new cost estimation frameworks based on bespoke methodological foundations for the PSS context are required to derive reliable and useful cost estimates [9]. In particular, [49] call for cost estimation frameworks that account for the intrinsic complexity of PSS by (1) reproducing the dynamic behaviour of the PSS operation, by (2) simultaneously quantifying performance metrics and associated costs and the relative impact of confounding parameters, by (3) analysing the cost impacts of a given PSS conceptualisation on both the customer and on the OEM side, and by (4) supporting the design and improvement of PSS configurations and associated contract mechanisms.

To this end, some of the academic literature has explicitly described the need for a 'system' approach (e.g., Settanni et al. [59], Estrada et al. [15], Goh et al. [22], Meier et al. [39]) to capture the complexity of the PSS context. For example, Bertoni and Bertoni, propose a model-based approach to estimate the life cycle cost of a PSS solution at a concept design stage, as they state that the design and selection of components in engineering systems are typically done based on their technical feasibility, rather than relevant life cycle value and cost metrics at the system level. More generally, a system approach allows to include the 'process' domain of the PSS, which is essential to understand behaviours at the system level, e.g., dynamic and non-linear behaviour of PSS operation, coordination between OEM's and customer's activities, the interaction between multiple interconnected cost objects (Kreye et al. [4,60,11,29]. For instance, several research works have championed the use of simulation techniques (e.g., Discrete Event Simulation, Agent-Based Simulation) [20,28,44,63] to account for the uncertainties and complex interdependences between the cost and operational factors (e.g., failure, demand, processing time, energy and material consumption, contractual requirements) [13,14,36,58,64] as such relationships are too complex for rigorous analytical study [31,32,7]. Overall, cost estimation under the PSS context has been described in the literature to differ from traditional costing frameworks [24] which lack the methodological foundations suitable to capture the intrinsic dynamics of a PSS. We refer the reader to [49] for a recent detailed review of the PSS Cost Estimation Process.

Proposed PSS cost estimation framework

The framework was developed based on [49] description of the PSS cost estimation process and identified methodological gaps in current cost estimation approaches.

Logical structure and steps

The developed framework is visualised as an iterative sequence composed of four modules (see Fig. 1):

- *Cost Estimation Purpose and Scope Definition*: the objective of this step is to guide and constrain decision-making across the cost estimation process towards a defined objective. At this first stage of the framework, the PSS is understood as a channel for the delivery of functionality, where the outputs of this step are (1)

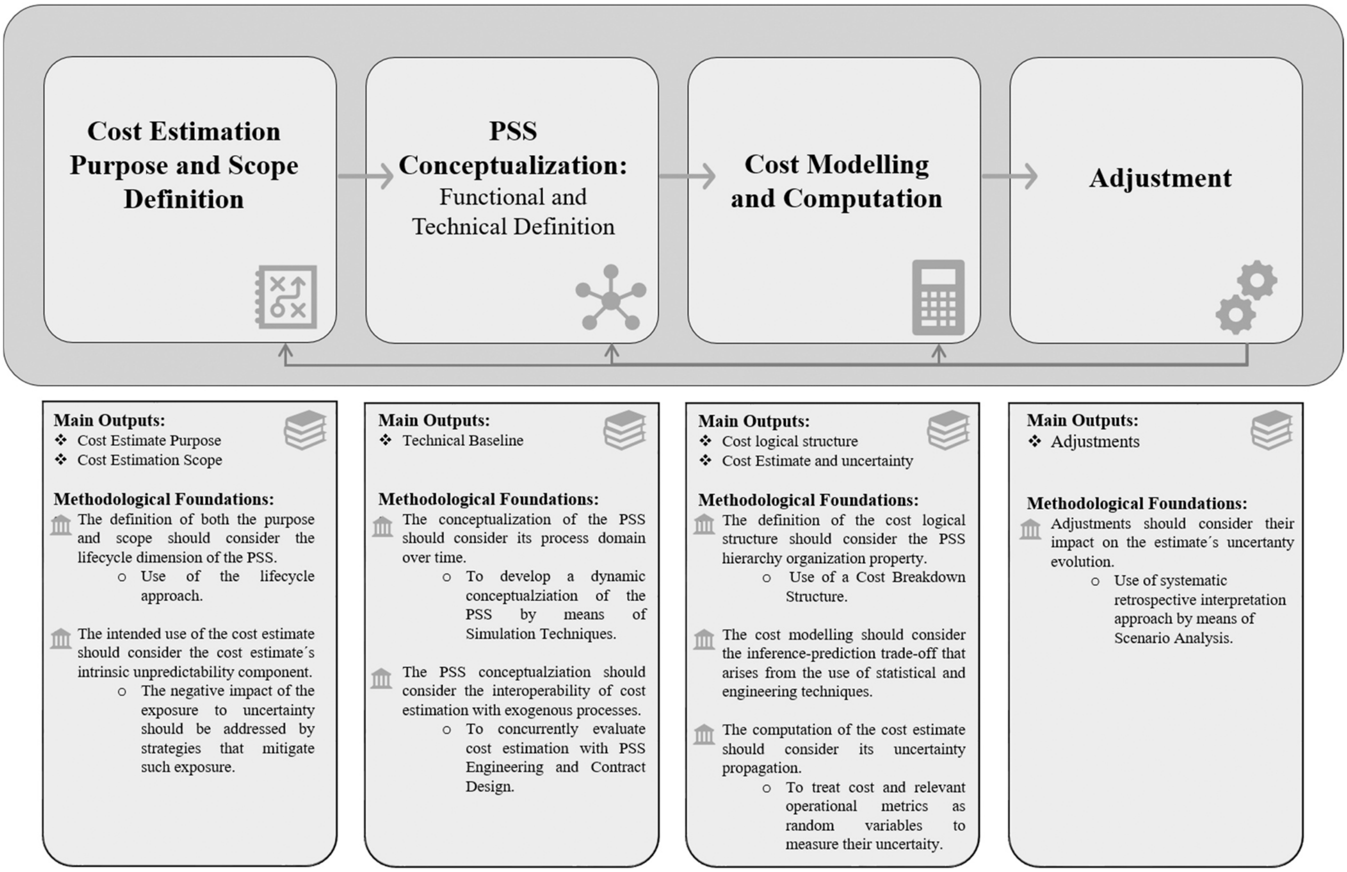

Fig. 1. Developed PSS cost estimation framework.

the definition of the intended use of the cost estimate in relation to relevant processes (e.g., the cost can be used to select the best configuration at the PSS Engineering process), and (2) the definition of the scope for cost estimation in alignment with its intended purpose. The cost estimation scope discriminates whether certain instances (e.g., products, activities, time) are incorporated into the estimation process for which costs are assigned and measured.

- *PSS Conceptualisation*: the objective of this step is to develop an abstract representation of the PSS to support the identification of relevant variables and parameters that affect the cost. At this stage, the output is an abstract representation of the functional and technical definition of the PSS, termed the "Technical Baseline". This representation supports the identification of the relevant variables and parameters that affect the cost of the PSS and bind the estimate [19].
- *Cost Modelling and Computation*: the objective of this step is to measure the cost estimate and the associated uncertainty for a given PSS conceptualisation. Once the conceptualisation of the PSS is established, the outputs at this stage are (1) the cost estimate's logical structure, i.e. the set of mathematical equations (i.e., Cost Estimation Relationships – CERs) that link all cost objects with relevant cost drivers, and (2) the actual computation of the cost estimate and its associated uncertainty.
- *Adjustment*: the objective of this step is to make relevant modifications to reduce costs, risks, and uncertainty and to improve metrics related to the purpose of the estimate. At this final stage, modifications are commonly done on the cost assumptions or the technical baseline parameters, nevertheless, adjustments on the intended use or scope of the estimate may take place.

Methodological foundations

This paper resonates with the need for a system approach, and stands on Systems Engineering advances in cost analysis which observes cost estimation as the set of scientific principles and techniques related to cost prediction and control aimed at quantifying the cost impacts of a system's functional definition, technical definition and the applied cost estimation methodologies [21]:

- System's Functional Definition – definition/identification of the system's intended purposes, customer requirements and the business/political landscapes that affect the need for the system.
- System's Technical Definition – specification of the system's configuration (i.e. the constituent elements that define the system and their respective interconnections/interactions).
- Cost Modelling – definition of cost estimation models, cost estimation methodologies, and the identification of economic factors/geopolitical policies that influence the cost of technology and labour force.

This approach expresses that the n-system configurations are defined in response to the purpose and requirements of the system, where a bespoke cost estimation model is developed for a given system configuration (see Fig. 2). This approach allows analysing a variety of design configurations in response to the purpose and contractual requirements of the system, where bespoke cost estimation models are developed iteratively for each configuration.

This system approach allows to derive several methodological foundations for each step in the framework, which express the elements endemic to the PSS context that must be taken into account when carrying out the cost estimation process:

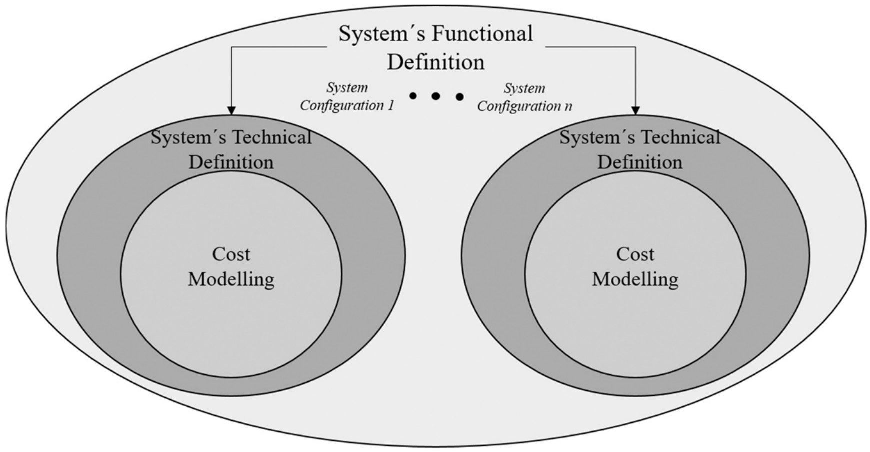

Fig. 2. The systems thinking approach for cost estimation.
Adapted from Garvey [21].

- *Cost Estimation Purpose and Scope Definition*: from the systems thinking perspective, the complexity associated with the system's operation exacerbates cost unpredictability. Indeed, the academic literature has evidenced a cost under-estimation issue in the PSS context, with negative impacts (e.g., under-pricing) at the time of use of the cost estimate (e.g., contract conditions definition). Therefore, the framework suggests that when an estimate's purpose is defined, the negative impact of the exposure to uncertainty should be considered and strategies to mitigate such exposure need to be explored. For example, if the cost estimate is used to select the pricing mechanism at the contract design, such selection should consider the negative implications that each of the potential pricing mechanisms would have in case of cost underestimation. Moreover, as the transition into the PSS scheme modifies the ownership structure along the product lifecycle, cost estimation requires broadening its spectrum to include other lifecycle stages. Thus, this framework proposes as a methodological foundation that both the definition of the purpose and scope should not overlook the lifecycle approach.
- *PSS Conceptualisation*: the systems thinking approach focuses on the description of the interconnections and interactions (i.e., the system's operation) among cost objects and their impact on the PSS cost. It has been evidenced in the literature that the PSS context requires modelling the system delivering the service over time to capture results relevant to the operation of the PSS (e.g., failure, processing time, energy and material consumption). Thus, the framework champions the use of numerical techniques, specifically simulation techniques (e.g., Agent-Based, Discrete Event) for a dynamic conceptualisation of the PSS to reproduce its operation over time. Furthermore, as the PSS conceptualisation supports the identification of the relevant variables and parameters that affect the cost variable, this framework proposes that such conceptualisation should consider the interoperability of cost estimation with the related process (e.g., PSS Configuration Design, PSS Contract Design). From a Systems Thinking perspective, concurrent design and evaluation enable the exploration into a wider solution space for all processes.
- *Cost Modelling and Computation*: from the Systems Thinking perspective, multiple cost objects are observed to be interconnected and to interact with each other organised by many levels that can be thought of as forming a hierarchical structure. This framework proposes the consideration of hierarchy and interconnection among CERs for the definition of the cost estimate's logical structure (e.g., through the definition of a Cost Breakdown Structure - CBS). Importantly, depending on the availability of data, several techniques can be used to define and validate the CERs (e.g., Statistical Analysis, Engineering Principles, and Expert Opinion). The framework highlights an important trade-off when defining CERs. On one hand, the use of engineering principles provides causal understanding, however, human knowledge and cognition restrict its prediction power. On the other hand, statistical analysis could suffice for prediction purposes but sacrifices causal explanation [22]. Finally, from the Systems Thinking approach, cost estimation depends on a computational process based on non-deterministic models where cost is observed as an uncertain quantity that is composed of a significant number of elements whose individual contributions are not able to be defined to a degree of detail sufficient to calculate the cost. This framework proposes to treat the cost estimate and relevant operational metrics as random variables – variables that can take on a range of potential values and use a probability distribution as the mathematical vehicle to measure the uncertainty around it.
- *Adjustment*: From the Systems Thinking approach, modifications in the cost estimation represent an iterative process where a cost estimate is continuously computed under evolving conditions across time until it complies with its intended purpose. When considering the iterative nature of the cost estimation process, the uncertainty of the estimate is observed to vary as more data and understanding of the PSS behaviour are attained and adjustments are carried out accordingly. While adjustments may reduce costs or improve relevant performance metrics, they may as well increase the estimate's associated uncertainty. Therefore, the developed framework proposes to consider the impact of adjustments on the evolution of the cost estimate's uncertainty. As the PSS scheme entails the use of an outcome-based contract, the potential negative impacts of the intrinsic PSS unpredictability are exacerbated at the point of use, where the estimate's uncertainty may have more significant negative impacts than its actual value (e.g., under-pricing in a single bid situation). This framework proposes a retrospective interpretation approach (e.g., Scenario Analysis) for the adjustment procedure, where the aggregated effects of a set of changing variables are examined systematically. The retrospective interpretation approach brings the opportunity for improvement through a trial-error procedure.

Application of proposed framework

An industrial case study is presented to illustrate the concepts and applicability of the proposed PSS Cost Estimation Framework. The case study is based on real data and for purposes of privacy, both companies involved, the OEM (i.e., PSS provider) and the PSS customer have been anonymized. The OEM firm is located in the province of Bergamo (Italy), and it produces numerical control machines (i.e., multi-axis machine centres, thermoforming machines, and waterjet cutting systems) utilised in a wide variety of industrial sectors (e.g., aerospace, automotive, defence, maritime, construction). Moreover, the OEM provides support services as post-acquisition interventions at the customer's site (i.e., repairs). The operational data of a multi-axis machine centre is retrieved from a customer located in Turin (Italy) which has acquired the multi-axis machine for finishing operations of different products. To evidence the applicability of the proposed framework, it is used in this illustrated example to estimate the cost of two service solutions: (1) a corrective maintenance solution underlined by a traditional product-centric contract mechanism, and (2) a preventive maintenance solution as a support service within an outcome-based contract mechanism. Further details are presented throughout the case study.

Cost estimation purpose and scope definition

The OEM is currently analysing the possibility of making the transition from its current product-centric approach to the offering of integrated product-service solutions. Currently, the OEM's revenue comes from selling numerical control machines (i.e., acquisition contracts) and from repair activities provided as separated after-sales services (i.e., follow-on support services contracts). For competitive reasons, the OEM wants to offer instead an integrated product-service solution based on a *single fixed-price contract* that incorporates both the access to the machines and the delivery of support services. In this type of contract, the customer does not longer buy the machine but its functionality. Indeed, to improve the competitiveness of the solutions, the OEM wants their contracts to guarantee a minimum level of machines' availability and/or level of production (i.e., outcome-based contracts). Since the current service component of the OEM's offer is mainly based on a *corrective maintenance* strategy (i.e., machine repairs), the OEM wants to investigate the cost of providing *preventive maintenance* services to sustain agreed-upon performance metrics in an outcome-based contract. The *purpose* of the cost estimation process for this particular case is to evaluate a preventive maintenance strategy as a support service within an outcome-based contract mechanism, and to compare its respective costs (for both the OEM and the customer) with the current corrective maintenance strategy. It is important to note that given the availability of operational data at the customer site, the *scope* of the analysis is limited to the acquisition and in-service lifecycle stages of a multi-axis machine centre for one operational year at one customer site.

PSS conceptualisation: functional and technical definition

At the customer site, the acquired multi-axis machine centre is used for the finishing operations of five different products of composite materials and light alloys. The machine is run by two operators who carry out the load and unload activities of products, the supervision of the machining process, and the set-up of the machine for every change of product type and right after a breakdown and resume of the machine. When the machine suffers a failure, the in-house maintenance team is called for an evaluation and possible repair of the machine. In case it cannot be repaired, the breakdown is labelled as critical and the OEM is called for further inspection and repair. To sustain agreed-upon performance metrics in the outcome-based contract, the OEM defines the number of preventive maintenance interventions, that is, the schedule of interventions. These interventions are scheduled in coordination with the customer in alignment with its production planning. A Service Delivery Model is developed to conceptualise the dynamism of the service solutions – a model that expresses how the OEM delivers the agreed-upon support services. The 'Business Process Model and Notation' (BPMN) is used for the specification and graphical representation of the Service Delivery Model, which is then simulated with FlexSim Discrete-Event Simulation software. The developed Service Delivery Model of the multi-axis machine centre for the preventive maintenance service solution is presented in Fig. 3.

The presented Service Delivery Model describes the new integrated product-service solution, that is, the service solution based on a preventive maintenance strategy. Notice that this strategy does not eliminate the need for corrective maintenance interventions. Indeed, corrective activities are still expected to happen in the new scenario, however, their frequency of occurrence is expected to decrease given the incorporation of preventive maintenance activities. The Service Delivery Model captures this latter fact as it presents both corrective and preventive interventions. It is important to mention, that for this particular case study, the current OEM service solution, that is the corrective maintenance solution, is captured as well by the diagram if one ignores the 'Scheduled Interventions' element - again since the diagram presents as well corrective interventions.

Cost modelling and computation

The PSS customer site runs 250 working days/year with 2 shifts/day and a net operational time of 7 h/shift. One multi-axis machine centre is acquired for the finishing operations of five different products whose processing times are treated as stochastic variables and depend on the product's type. For matters of simplicity, a non-incremental production rate and an invariant batch production sequence are assumed for all products over the whole operational year. The time to repair and the time between failures are treated as well as stochastic variables. For instance, the time to failure for an in-house failure such as the machine's void pump is distributed as exponential(1201) in days units and with a time to repair distributed as uniform(0.9, 1.1) in hours units (see Appendix 1). Moreover, it is assumed that an increase in the number of scheduled interventions per month, increases the scale distribution parameter (i.e., MTBF) of the critical failures stochastic variable by 50%.

To compare the costs between the product-centric and the PSS solution, as mentioned in the purpose of the case study, two Cost Breakdown Structures (CBS) are developed at this stage. The first one represents the traditional product-centric approach of the customer, while the second one expresses the preventive maintenance support service delivered through the integrated product services solution. The main differences between both CBSs are the allocation of costs to either the customer or to the OEM and the incorporation of the *Scheduled maintenance* cost object that expresses the preventive maintenance support service. Slight differences between both CBSs are presented in the cost drivers and cost drivers' values. For instance, the cost of the machine in the current corrective maintenance solution is 250,000 € which represents its actual selling price. Recall that in such a product-centric approach, the machine is acquired by the customer. On the other hand, in the product-service integrated solution, the customer does not longer acquires the

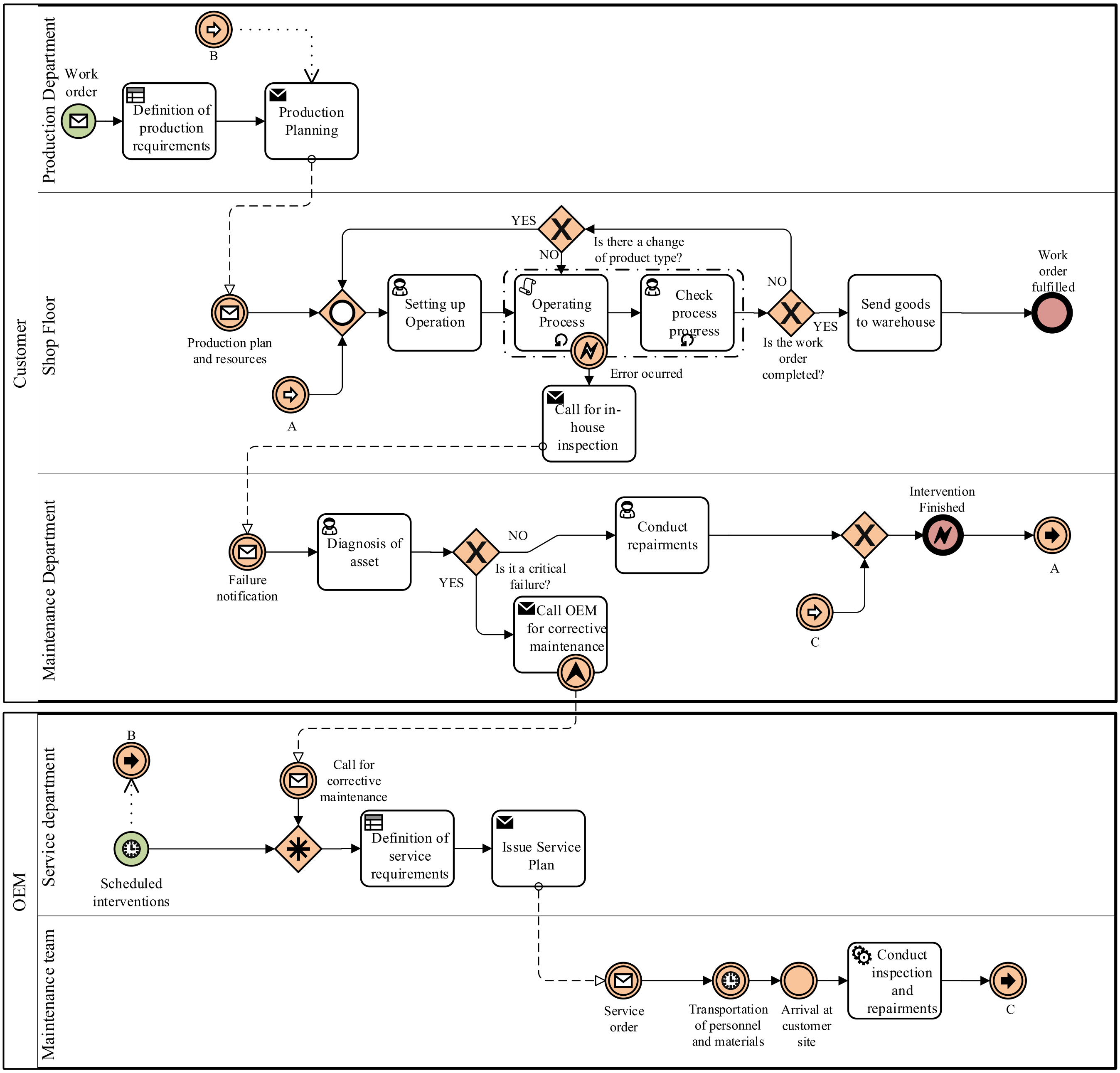

Fig. 3. Service Delivery Model of multi-axis machine centre and associated maintenance support services.

machine. Thus the cost of the machine is now allocated to the OEM and represents its final manufacturing cost of 150,000 €. Notice that in the product-service integrated solution the pricing of the whole outcome-based contract is not yet allocated to the customer in the CBS. Indeed, once the cost of providing preventive maintenance is estimated, the OEM can define a competitive price for the outcome-based contract. This will be further discussed when the cost estimation results are presented.

Figs. 4 and 5 present the developed CBSs for the product-centric and the PSS solution respectively. The definition of mathematical equations that link cost drivers and the cost objects both are based on simple engineering principles. Furthermore, both CBSs consider the dynamic property of the system under analysis as it incorporates variables whose values are retrieved from the simulation results of the system's operation. Such consideration and the inclusion of several random variables within the CBS enable the mathematical treatment of the total cost as a random variable itself which in turn allows the measurement of its uncertainty. The results of the cost computation are presented in the following step.

Adjustment

In the preventive maintenance solution, the OEM requires to define the appropriate service throughput to effectively balance the cost-service trade-off of the outcome-based solution. In this case study, such service throughput depends on the *number of scheduled interventions* and on *the Personnel in the maintenance team.* Since the current OEM corrective maintenance activities are delivered by a

Cost Element			Cost Object		Allocation of Cost		Cost driver	Value	Units
ACQUISITION COSTS			PP = *nm*pm*	Purchase Price	Customer	*nm*	Number of acquired machines	1	machines
						pm	Cost of machine	250000	€/machine
			TC = *(nm*No)Tl*Cl*	Training Costs	Customer	*nm*	Number of acquired machines	1	machines
						Tl	Time required to learn	40	h/person
						No	Number of operators per machine	1	op/machine
						Cl	Cost for training	35	€/hour*person
			SC = *nm*Sc*	Shipping Costs	Customer	*nm*	Number of acquired machines	1	machines
						Sc	Shipping cost	1000	€/machine
IN-SERVICE COSTS	OC	Operating Costs	SUC = *Ns*Ts*Cs*	Set up Costs	Customer	*Ts*	Time to setup	tria(25,30,37)	minutes/machine
						Ns	Number of setups		setups
						Cs	Setup cost	35	€/hour-setup
			EC = *FPt*Ke*Ce*	Energy Costs (electricity)	Customer	*Ce*	Cost of Energy	0.24	€/Kwh
						Ke	Energy Consumption rate	48	Kw/h
						FPt	Fully Production time		production time
			WF = *nm*no*fs*sd*	Workforce costs	Customer	*nm*	Number of acquired machines	1	machines
						no	Number of operators	2	operators/machine
						sd	Number of working shifts	2	shifts/day
						fs	Fix salary	26253	€/year*operator
	MC	Maintenance Costs	IMC = *npp*Cpp + Cm*ni*	In-house maintenance costs	Customer	*ni*	Number of Interventions		breakdowns
						npp	Personnel in maintenance team	2	people
						Cpp	Personnel cost	81	€/hour*person
						Cm	Cost of components&materials		€/spare part
			UMC = *nb*npc*(Tt + It + TTR)*Cpc + (Ctr + Cm)*	Unplanned maintenance costs	Customer	*nb*	Number of critical breakdowns		critical breakdowns
						npc	Personnel in maintenance team	1	people
						Cpc	Personnel cost	90	€/hour*person
						TTR	Time to repair		hours
						It	Inspection time	3	hours
						Tt	Logistics time to travel	N(5, 0.2)	hour
						Ctr	Overall Transportation cost	566.5	€/one-way
						Cm	Cost of components&materials		€/spare parts

Variable from Simulation   Array of data

Fig. 4. Cost breakdown structure for the product-centric approach with corrective maintenance.

single employee, for simplicity and comparison purposes the *number of scheduled interventions* is selected for the analysis of different scenarios. The objective of such analysis is to understand how the number of preventive maintenance interventions impacts the overall cost and the availability and total production of the multi-axis machine centre at the customer site. Based on the experience and historical data from the OEM (see Appendix 1), the customer can require up to 8 corrective interventions in a period of 250 days (i.e., 1 operational year), which represents 0.66 corrective interventions in a period of 1 operational month. Based on this, as a first analysis, the OEM is interested in understanding the impact of at least 1 preventive maintenance intervention per month. In line with this, four scenarios are conceptualised and computed: (1) the product-centric approach (i.e., current state), (2) the PSS-1 Intervention/month solution, (3) the PSS-2 Interventions/month solution, and (4) the PSS-3 Interventions/month solution. The following paragraphs discuss how the results of this analysis help to define subsequent intervention strategies to investigate.

Based on the Service Delivery Model, the analysis considers a hundred replications of one operational year each for every scenario and is carried out within FlexSim simulation software via a 'design of experiments' tool in the software used to define, run and analyse experiments on defined model scenarios. The results of such analysis are presented in the following Fig. 6, where the replication statistics associated with each scenario are presented as box plots and where each replication is presented as a dot in the diagram. The replication statistics associated with each box plot are further presented in Table 1.

It can be readily observed that the OEM's transition into the PSS scheme provides further performance improvements to the customer in terms of total production (i.e., pieces produced) and availability. This is a direct consequence of a reduction in the multi-axes machine centre critical breakdowns and associated negative effects. Indeed, by increasing the service throughput, the total production and machine availability at the customer site increases at the expense of higher costs for the OEM. This evidences the proposed framework's ability due to the systems approach to analyse the cost impacts of a given PSS conceptualisation on both the customer and on the OEM side, and to carry out the measurement of performance metrics and their associated cost simultaneously.

Interestingly, the transition into PSS could result in a reduction of costs for the customer (or a solution at the same cost) that brings better risk management, guaranteed technological innovation, and improved performance. To see this, consider the case of the PSS-1 scheduled intervention per month scenario. In this case, the minimum-maximum range of potential customer costs is 195,300 € - 211,800 €, while for the traditional product-centric approach is 473,200 € - 511,100 €. To be conservative, consider the PSS worst-case cost (i.e., 211,800 €), if the OEM sets a price up to 261,400 € for the PSS solution, in this case, the resulting cost for the customer will always be smaller than or equal to the best-case cost in the product-centric solution (i.e., 473.200 €), see Fig. 7.

Cost Element	Cost Object				Allcoation of Cost		Cost driver	Value	Units
ACQUISITION COSTS			PP = *nm*pm*	Purchase Price	OEM	*nm*	Number of acquired machines	1	machines
						pm	Cost of machine	150000	€/machine
			TC = *Tl*nte*dc*	Training Costs	OEM	*nte*	Number of training employees	1	employee
						dc	fixed hourly cost	15	€/hour*person
						Tl	Time required to learn	40	hours
			SC = *nm*Sc*	Shipping Costs	OEM	*nm*	Number of acquired machines	1	machines
						Sc	Shipping cost	1000	€/machine
IN-SERVICE COSTS	OC	Operating Costs	SUC = *Ns*Ts*Cs*	Set up Costs	Customer	*Ts*	Time to setup	tria(25,30,37)	minutes/machine
						Ns	Number of setups		setups
						Cs	Setup cost	35	€/hour-setup
			EC = *FPt*Ke*Ce*	Energy Costs (electricity)	Customer	*Ce*	Cost of Energy	0.24	€/Kwh
						Ke	Energy Consumption rate	48	Kw/h
						FPt	Fully Production time		production time
			WF = *nm*no*fs*sd*	Workforce Costs	Customer	*nm*	Number of acquired machines	1	machines
						no	Number of operators	2	operators/machine
						sd	Number of working shifts	2	shifts/day
						fs	Fix salary	26253	€/year*operator
	MC	Maintenance Costs	SMC = *npp*Cpp + Cm*ni*	In-house maintenance costs	Customer	*ni*	Number of Interventions		breakdowns
						npp	Personnel in maintenance team	2	people
						Cpp	Personnel cost	81	€/hour*person
						Cm	Cost of components&materials		€/spare part
			SMC = *ni*npc*(Tt + It + TTR)*Cpc + (Ctr + Cm)*	Schedulled maintenance costs	OEM	*ni*	Number of Interventions	1	interventions/month
						npc	Personnel in maintenance team	1	people
						Cpc	Personnel cost	25	€/hour*person
						TTR	Time to repair		hours
						It	Inspection time	3	hours
						Tt	Logistics time to travel	N(5, 0.2)	hour
						Ctr	Overall Transportation cost	356	€/one-way
						Cm	Cost of components&materials		€/spare parts
			UMC = *nb*npc*(Tt + It + TTR)*Cpc + (Ctr + Cm)*	Unplanned maintenance costs	OEM	*nb*	Number of critical breakdowns		critical breakdowns
						npc	Personnel in maintenance team	1	people
						Cpc	Personnel cost	25	€/hour*person
						TTR	Time to repair		hours
						It	Inspection time	3	hours
						Tt	Logistics time to travel	N(5, 0.2)	hour
						Ctr	Overall Transportation cost	566.5	€/one-way
						Cm	Cost of components&materials		€/spare parts

Variable from Simulation   Array of data

Fig. 5. Cost breakdown structure for the PSS solution with preventive maintenance support services.

In the PSS solution the OEM does not sell the machine, however, the OEM can set the fixed price of the PSS contract to be smaller than or equal to the customer's best-case cost in the product-centric solution while providing outcome-based guarantees to the customer in terms of availability or total production. This result highlights the competitive advantage that the transition into PSS represents for the OEM. Moreover, this opens up the possibility to optimise profit for the OEM: on one hand, a higher number of interventions guarantee higher levels of production and availability which can translate into higher prices for the contract, on the other hand, a higher number of interventions represent higher costs for the OEM. Follow-up analyses should aim to find the number of interventions that optimally balance this trade-off. The results show that with 1 preventive maintenance intervention per month, the OEM can guarantee production and availability levels very similar to those achieved by the 2 and 3 intervention strategies. Indeed, the results suggest that the increase in the number of interventions results in smaller increases in availability and production (i.e., diminishing marginal returns), while the associated OEM costs increase linearly in the number of interventions. Based on this, the optimal intervention level may be found below the 1 intervention per month (e.g., 1 intervention per 2 months), which warrants further analyses considering intervention strategies with lower frequencies of occurrence.

Importantly, due to the systems approach, the proposed framework allows us to see when the PSS solution is preferred over the traditional product-centric approach in terms of economic efficiency in the interaction between the OEM and the customer, i.e., the overall cost incurred by both the OEM and the customer. In the product-centric scenario, the average cost of the customer is 236, 959 € + 250,000 € = 486, 959 €, where 250,000 € represents the price of the machine. On the OEM side, recall that 150,000 € represents the manufacturing cost of the machine, however, the OEM receives revenue of 250,000 € for the machine. The overall cost in this case is thus computed as 236, 959 € + 250,000 € + 150,000 € - 250,000 € = 386,959 €. Note that when we consider the overall cost of the customer and the OEM, the monetary transactions between both of them do not contribute to the overall cost as they cancel out. Similarly, in the PSS-1 intervention per month scenario, the average cost of the customer is 202,794.9 € plus a given "fixed price" for the PSS contract (recall in this case the customer does not buy the

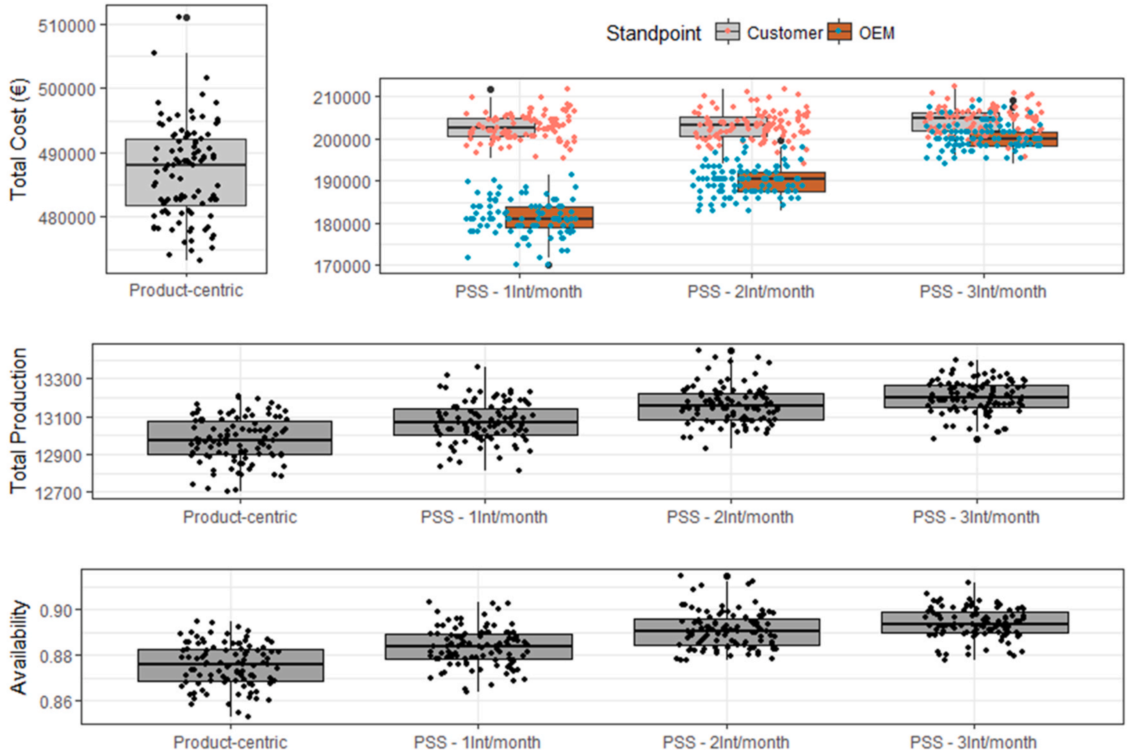

Fig. 6. Replication plots: scenario analysis results for the product-centric and PSS solutions.

Table 1
Summary statistics: scenario analysis results for the product-centric and PSS solutions.

Metric	Statistic	Standpoint	Scenario			
			Product-centric	PSS 1Int/month	PSS 2Int/month	PSS 3Int/month
Total Cost (*n* = 100)	Min	Customer	473,200.00 €	195,300.00 €	194,100.00 €	195,900.00 €
		OEM	150,000.00 €	170,300.00 €	182,900.00 €	193,900.00 €
	Max	Customer	511,100.00 €	211,800.00 €	211,600.00 €	212,300.00 €
		OEM	150,000.00 €	191,400.00 €	199,600.00 €	209,100.00 €
	Sample Mean	Customer	486,959.00 €	202,794.90 €	203,137.70 €	204,319.70 €
		OEM	150,000.00 €	181,162.10 €	189,990.10 €	200,570.30 €
	Sample Standard Deviation	Customer	7228.97 €	3153.82 €	3383.24 €	3026.53 €
		OEM	/	4224.75 €	3597.28 €	2994.70 €
	Confidence Interval (95%)	Customer	485,524.6 € ≤ μ ≤ 488,393.4 €	202,169.1 € ≤ μ ≤ 203,420.7 €	202,464.3 € ≤ μ ≤ 203,807 €	203,719.1 € ≤ μ ≤ 204,920.2 €
		OEM	/	180,323.8 € ≤ μ ≤ 182,000.4 €	189,276.3 € ≤ μ ≤ 190,703.9 €	199,976.1 € ≤ μ ≤ 201,164.5 €
Total Production (*n* = 100)	Min	Customer	12,700	12,810	12,930	12,980
	Max	Customer	13,200	13,360	13,450	13,400
	Sample Mean	Customer	12,976.66	13,071.16	13,161.54	13,200.92
	Sample Standard Deviation	Customer	118.28	105.78	99.07	85.35
	Confidence Interval (95%)	Customer	12,953.19 ≤ μ ≤ 13,000.13	13,050.17 ≤ μ ≤ 13,092.15	13,141.88 ≤ μ ≤ 13,181.2	13,183.98 ≤ μ ≤ 13,217.86
Availability (*n* = 100)	Min	Customer	0.852	0.863	0.877	0.878
	Max	Customer	0.894	0.903	0.915	0.912
	Sample Mean	Customer	0.875	0.883	0.891	0.894
	Sample Standard Deviation	Customer	0.009	0.008	0.007	0.006
	Confidence Interval (95%)	Customer	0.873 ≤ μ ≤ 0.877	0.881 ≤ μ ≤ 0.885	0.889 ≤ μ ≤ 0.892	0.892 ≤ μ ≤ 0.895

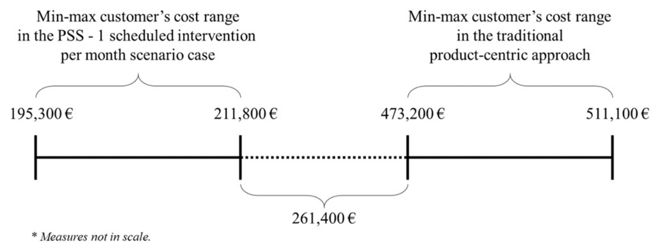

Fig. 7. Min-max customer's cost range.

machine). On the OEM side, the cost is 181,162.1 € which already includes the 150,000 € of the manufacturing cost of the machine, minus the "fixed price" paid by the customer, which represents revenue here. The overall cost in this case is computed as 202,794.9 € + 181,162.1 € = 383,957 €. The same logic applies to the other PSS scenarios.Table 2.

Notice that the PSS-1 intervention per month scenario provides the lowest overall cost among the considered PSS scenarios. Moreover, this scenario allows for reducing the overall cost in comparison to the traditional product-centric approach. This is relevant since this result shows that the PSS-1 intervention solution allows for a more efficient economic interaction between the OEM and the customer as it allocates tasks to both of them in a more appropriate way. Overall, these results evidence the proposed framework's ability due to the systems approach to better inform decision making regarding the design of PSS configurations and associated contract mechanisms.

It is important to remind the reader that given the availability of data at the customer site (i.e., one operational year), the illustrated example is limited to a comparative analysis of the cost of defined maintenance scenarios in the acquisition and in-service lifecycle stages. More elaborated analyses (e.g., profitability analysis of different scenarios) require a better understanding of the PSS context implications on both the customer and the OEM, which is acquired by an increased level of detail in both the PSS conceptualisation and the CBS. For example, the Service Delivery Model and the CBS can further include pricing mechanisms, payment schedules, and penalty schemes for a concurrent design of contract requirements and PSS design. Another example could be the inclusion of end-of-life strategies (e.g., buy-back, refurbishing, remanufacturing, upgrading, overhauling, recycling, reuse, disposal) to measure their impact on the overall life cycle cost. Overall, the framework provides a flexible approach that can incorporate increasingly higher levels of detail and complexity.

Discussion and conclusions

Original Equipment Manufacturers are increasingly undergoing a transition into the delivery of integrated product-service solutions via a Product-Service System. This transition has proven to be a difficult challenge for OEMs, characterised by inadequate contract decisions due to cost under-estimations and performance overpromises. This issue has been attributed to the novelty and intrinsic complexity of the PSS behaviour, and the inability of traditional cost estimation frameworks to capture the causal mechanisms between the PSS operation and its associated cost [49]. Indeed, it is stressed that current cost estimation approaches focus on developing methodologies that analyse both economic and performance outcomes by coupling traditional cost frameworks (e.g., LCC, TCO) and tools for the analysis and design of system functionality. However, it is argued that new cost estimation frameworks, based on bespoke methodological foundations for the PSS context are required to derive reliable and useful cost estimates.

In line with this, this paper proposes a framework for cost estimation in the PSS context based on the "systems-thinking" approach, composed of a set of iterative modules and methodological foundations. The developed framework brings into discussion several properties endemic to the PSS context characterised by the systems thinking approach at different stages of the cost estimation process. From this approach, the developed framework describes the PSS's operation as the aggregate of the interactions among multiple and interconnected elements that present nonlinear relationships, which generate complex patterns of behaviour. In alignment with such an approach, the developed framework proposes a set of methodological foundations aimed at addressing the body of knowledge on cost estimation considerations and at capturing the PSS dynamism.

The proposed methodological foundations provide direction, where authors are not restricted to a specific way of going about the problem of cost estimation, e.g., the developed framework proposes the use of simulation techniques, nonetheless, it does not establish a specific simulation technique. Indeed, the illustrated application of the framework highlights its usefulness in guiding the intellectual process of choosing the concepts and techniques relevant to the systems thinking approach. In response to the call of [49] for bespoke cost frameworks that address current methodological gaps, the illustrated case also evidenced the applicability of the proposed framework, which is outlined by its capacity to (1) analyse the cost impacts of a given PSS conceptualisation on both the customer and on the OEM side, to (2) define the required level of detail in accordance to the estimate's intended use, to (3) analyse the associated uncertainty around the estimates, to (4) support the design and improvement of PSS configurations and associated contract mechanisms, to (5) carry out the measurement of performance metrics and their associated cost simultaneously, to (6) reproduce the dynamic behaviour of the PSS operation, and to (7) analyse the relative impact of compounding parameters on cost and related performance metrics.

The developed framework is limited to the identified pool of PSS literature, therefore further research work needs to consider relevant literature from similar fields of study (e.g., Through-life engineering services) to identify and incorporate new methodological foundations into the developed framework. For the generalisation and further validation of the findings of this research work, the developed framework should be further tested across diverse industrial contexts and with a wider set of cost estimation purposes.

Table 2
Overall OEM and customer cost.

Metric	Standpoint	Scenario			
		Product-centric	**PSS 1Int/month**	**PSS 2Int/month**	**PSS 3Int/month**
Monetary Transaction	Customer	236,959.00 € 250,000.00 €	202,794.90 € *+ fixed price*	203,137.70 € *+ fixed price*	204,319.70 € *+ fixed price*
	OEM	150,000.00 € - 250,000.00 €	181,162.10 € *- fixed price*	189,990.10 € *- fixed price*	200,570.30 € *- fixed price*
Overall Cost	Customer + OEM	*386,959.00 €*	*383,957.00 €*	*393,127.80 €*	*404,890.00 €*

Note: positive values represent costs, while negative values represent revenues.

Appendix 1. Components TTF, TTR, and Costs

Critical Component	Failure Distribution (TTF - days)	Repair Distribution (TTR - hours)	Average component cost (€)
Encoder cable	exponential(0, 1554.33)	uniform(0.45,0.55)	2.0 €
Cooling unit	exponential(0, 1688)	uniform(0.9,1.1)	479.0 €
Closed loop belt	exponential(0, 4031)	uniform(0.9,1.1)	7.0 €
Electrospindle	weibull(0.0, 842.07, 1.36)	uniform(1.80,2.20)	3399.0 €
Electrovalve	exponential(0, 1003.54)	uniform(0.87,1.07)	145.0 €
Limit sensor	exponential(0, 797.57)	uniform(0.20,0.27)	14.0 €
Brake system	weibull(0.0, 2001.73, 2.25)	uniform(1.12,1.38)	26.0 €
Air group	exponential(0, 2477)	uniform(0.70,0.87)	185.0 €
Lubrification group	exponential(0, 4363)	uniform(0.45,0.55)	242.0 €
Inverter	exponential(0, 1580)	uniform(0.40,0.52)	639.0 €
Joint	exponential(0, 2175)	uniform(1.80,2.20)	135.0 €
Safety system	exponential(0, 1499)	uniform(0.45,0.55)	58.0 €
Operator panel	exponential(0, 1433)	uniform(0.15,0.18)	73.0 €
Recirculating ball guide	exponential(0, 1183.75)	uniform(0.9,1.1)	23.0 €
PC	exponential(0, 691.33)	uniform(0.42,0.53)	297.0 €
Void pump	exponential(0, 1201.8)	uniform(0.9,1.1)	607.0 €
Pressure reducer	weibull(0, 2387.93, 8.56)	uniform(1.42,1.75)	573.0 €
Servomotor	exponential(0, 2256.19)	uniform(0.90,1.10)	475.0 €

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