

An Agent-based Approach to Quantify the Uncertainty in Product-Service System Contract Decisions: A Case Study in the Machine Tool Industry

Abstract

Product-service system (PSS) business models appraise the relationship between different stakeholders and focus on a partnership based on profit. Existing literature discusses servitization and the associated cost-benefit analysis (CBA) models mostly from the perspective of original equipment manufacturers. Additionally, CBA is typically conducted using top-down approaches and standard activity-based costing, with limited available data and without considering uncertainty. As a result, inadequate and under-priced contract decisions may be made. To address the problem, this paper extends the current literature by proposing a novel framework for quantifying uncertainty in cost and benefit estimates of PSS contracts. The framework offers a bottom-up costing approach using the agent-based simulation technique. The framework comprises a stochastic CBA model for PSS. It is developed by considering through-life cost and benefit of products and services with aggregate uncertainty in terms of service costs, service lead-times, and their occurrences. The framework has been tested successfully on a real-world case study with a bespoke service provider in the machine tool industry. The model is applied to include spare-parts and availability-based servitization contracts. The simulation results are validated by real-world measurements and expert knowledge. The results involve a comprehensive stochastic analyses of a through-life CBA under probabilistic uncertainty and provide the opportunity to quantify the uncertainty in PSS contract decisions. Moreover, the results highlight that servitization is more beneficial for bespoke service providers in long-term contracts, and for relatively new or retrofitted products. Further research works are required to apply the model on capability-based contracts.

Keywords: Product-service systems (PSS), Servitization, Cost-benefit analysis, PSS cost estimation, Agent-based modeling, Uncertainty quantification

1. Introduction

Over the past decades, there has been an increasing awareness within many manufacturing firms to change their business strategies toward value-creation chains that maximise profitability and keep their customers loyal. Product-service integrated models are, therefore examined by extending service offerings throughout the product lifecycle (Vandermerwe and Rada, 1988; Mont, 2002; Baines et al., 2007). Industries are always under pressure from the market to maintain competitiveness and increase their profit as well as their customers' satisfaction (Sacconi, Visintin and Rapaccini, 2014). In Product-Service Systems (PSS), to retain competitiveness, optimal design of a product, and flexibility and wholeness of services are crucial. Moreover, the lifetime ownership of products and service data play a key role in the estimation of through-life cost and benefits (Settanni et al., 2014).

Despite the formation of PSS in the late '90s, PSS has not yet been properly understood and adopted by many industries, especially by service-oriented sectors. Moreover, the use of advanced computational models and simulation techniques to design PSS service decisions are limited and relatively new. Several challenges regarding the PSS implementation are identified in the literature. These challenges are categorised into three domains of business strategy, business transition and business design (Baines, H. Lightfoot, et al., 2009). Since

2009, the majority of literature addressed the business strategy and transition challenges to find a reliable transformation framework and methodologies for adopting PSS solutions (Baines et al., 2020). Although the business design challenge has been discussed previously in the literature, the studies that focus on quantitative approaches are sparse. For instance, Baines et al. (2009; 2010) argued that service-focused operations incline to invest in information technologies to enhance customers' satisfaction when decreasing the operation cost. Erkoyuncu et al. (2009, 2014; 2013) discussed the business challenges from the uncertainty in estimating long term contracts in the defence and aerospace industry perspective. Although several studies have highlighted the importance of uncertainty analysis in PSS, the challenge for the industry is to quantify the uncertainty to inform their decisions with respect to affordability and profitability of the service contracts (Erkoyuncu et al., 2009; Erkoyuncu, Durugbo and Roy, 2013; Durugbo and Erkoyuncu, 2016; Visnjic, Neely and Jovanovic, 2018; Rodríguez et al., 2020).

Considering the existing literature and theories behind PSS and uncertainty analysis in cost and benefit estimation, this paper extends the current literature by proposing a framework for quantifying uncertainty in cost/benefit analysis of PSS contracts. In this study, the following research question is considered: "How can an agent-based technique be developed to quantify the uncertainty in the cost/benefit estimates of PSS contracts in order to measure the overall profitability?". This research question is addressed by developing a generic, yet a novel agent-based modelling approach to estimate CBA and to quantify uncertainty in PSS contract decisions; this model provides the opportunity for the decision-makers to assess the profitability of different PSS contracts effectively. The agent-based technique captures the aggregate uncertainty and dynamism of interactions between cost and benefit drivers and provides a stochastic cost-benefit analysis (CBA) through the length of the PSS contract.

In this paper, the dynamic complexity and aggregate uncertainty of PSS arise from the interactive aleatory uncertainty due to the probabilistic variability in service costs and benefits, service lead-times, and occurrence of maintenance and repair interventions over a PSS contract. Considering such stochastic uncertainty in the cost estimation process enhances the accuracy and confidence level in PSS contract design decisions and tackles the under-pricing challenge. Moreover, the presented CBA model and the agent-based simulation extend the current literature to accommodate service development and to support service focused operations under servitization. The model validity and functionality are illustrated through a detailed servitization case study from a bespoke service provider for two types of PSS contract, namely inclusive spare part (product-oriented) and availability-based (use-oriented). In this paper, these contracts are referred to as PSS-1 and PSS-2, respectively. The bespoke service provider in this study offers a comprehensive, specialist and tailored service for machine tools. Moreover, the cost and benefit drivers are presented for PSS-1 and PSS-2, using expert knowledge from the case study organization. The proposed CBA simulation model evaluates the through-life cost and benefit of PSS for the bespoke service provider. Furthermore, the key findings and limitations of the proposed simulation model are discussed.

This research work contributes to the literature by proposing a framework using the agent-based simulation technique for quantifying the uncertainty in cost and benefit estimates of PSS contracts. The context for this is CBA for PSS, which is innovative due to the range and scale of the experienced uncertainties by (i) considering through-life cost and benefit of service and a product from creation until the end of the servitization contract, (ii) adopting a bottom-up costing approach for CBA and provision of comprehensive stochastic analytical results of a through-life CBA under probabilistic uncertainty and (iii) quantifying uncertainty in PSS contract decisions using the ABM and Probability Distribution Function (pdf) techniques. Therefore, the main contributions of this work can be summarised as follows:

- A novel PSS through-life CBA simulation model is developed using a bottom-up ABM approach by

conceptualising the PSS as a complex system using a UML state machine diagram.

- Aleatory uncertainty is quantified in terms of service cost and benefits, service lead-times and occurrence of maintenance and repair interventions for PSS contract decisions.
- The optimal PSS solution for a beneficial contractual agreement from a service provider perspective is analysed in the presence of an aggregated aleatory uncertainty for several service contract scenarios.

This paper is structured as follows: Section 2. discusses the literature review on servitization, the simulation approach for PSS service design and CBA and uncertainty analysis in cost estimation for PSS contract decisions. The research methodology adopted by the authors to carry out this work is detailed in Section 3. A framework comprising the PSS through-life cost-benefit model and ABM simulation is developed in Section 4. A case study in the machine tool industry is conducted in Section 5. to test the validity of the framework. Moreover, the simulation results are verified and validated with the actual data derived from the case study. Summary of critical discussion on the developed model and the simulation outcomes are presented in Section 6. Finally, Section 7 highlights the conclusions and potential future research work.

2. Literature Review

2.1. *Product-Service Systems & servitization*

The movement of industries towards a product-service integrated market strategy was initially introduced by Vandermerwe and Rada in (1988) as “servitization of business”. They proposed that servitization could evolve from ‘product or service’ to ‘product plus service’ to finally ‘product plus service plus support plus knowledge plus self-service’(Vandermerwe and Rada, 1988). Business models and market strategies are mostly demand-driven. Therefore, manufacturers and service providers are required to provide products and services based on their customers’ specification. However, it is crucial for both manufacturers and service providers, as well as their customers, to have a value-added business agreement. In this regard, product-based and service-based strategies exist for businesses who provide more product than service (i.e. product-oriented) and more service than a product (i.e. service-oriented) respectively. Both are referred to as product-service combinations known as Product-Service System (PSS or PS system), which was introduced by Goedkoop et al. in (1999). Tukker, A. in (2004) raised the question of ‘what are the measures to determine the PSS value?’ He proposed a PSS taxonomy with eight different business models within the main three PSS categories, namely product-oriented, use-oriented and result-oriented (Tukker, 2004). Baines et al. (2009) took a different angle in classifying the PSS solutions and proposed a theoretical framework that categorises operation strategies and presents effective PSS solutions for each category (Baines, H. W. Lightfoot, et al., 2009). Later, Baines et al. (2010) found that reduction in operating cost (i.e. operation and maintenance) is the key driver for customers to adopt contractual agreements under PSS (Baines et al., 2010). Bankole et al. (2009) took this further by introducing affordability in Industrial Product-Service System (IPS2) offerings when considering the whole lifecycle cost of a project rather than the product and service lifecycle cost (Bankole et al., 2009).

In more recent servitization literature, there has been a growing interest in the result-oriented PSS and outcome-based contracts. For instance, Batista et al. (2017) presented a system perspective of outcome-based (i.e. result-oriented, which in this paper is referred to as PSS-3) contracts within the defence industry. Bustinza et al. (2017) provided a framework for service implementation and transformation in manufacturing with a focus on digital technologies and outcome-based contracts. Additionally, Visnjic et al. (2018) presented an outcome delivery path for industries to overcome the risks of penalties in the case of failure to meet customers’ requirement, while

relying on third parties and suppliers. Their proposed approach supports industries to keep the balance between ‘the increase in value’ and ‘uncertainty’ associated with service market strategy. Recently, Sjödin et al. (2020) argued that the effectiveness of the business model heavily relies on value proposition definition, value provision design, and value-in-use delivery.

PSS design for bespoke service providers is crucial to enhance integrity, innovation and value creation for their service proposition and meeting customers’ needs more effectively. Such service-oriented companies have a clear understanding of service and support requirements. However, they still require having a holistic understanding of products’ specifications in order to design a profitable integrated product-service solution. Lack of comprehensive knowledge about products creates uncertainty for service providers when integrating a product to their service in the servitization journey. Moreover, it is more challenging for them and their customers to be adaptive to the culture of the new PSS environment with new intellectual property set-ups, remote health monitoring, and long-term service offerings. In the machine tool industry, in particular, it has been challenging for both original manufactures and bespoke service providers to shift toward servitization. This was mainly due to the inherent complexities and diversity of machine tools, and their long lifespan. These increase the uncertainty around preventive and condition-based maintenance strategies, and therefore in value-creation in the sector (Greenough and Grubic, 2011). Moreover, Kamp and Diaz (2017) discussed other challenges around real-time remote diagnostic of machine tools and building trust in data-exchange in a servitization environment in collaboration with customers. Furthermore, commercial visibility and value creation, costing and financial feasibility, managing customers’ involvement in servitization process, and meeting customers’ demands for flexibility have to be taken into account (Zine et al., 2016).

2.2. *Uncertainty analysis & quantification in PSS*

Servitization and moving towards PSS business models create a variety of uncertainties around contract decisions and profitability of PSS contracts. Therefore, risk and uncertainty assessments are crucial to examine the value creation of such contracts. Ziaee Bigdeli et al. (2018) argued that evaluating the actual risks and uncertainties for servitization is a challenging task, and that further research is required. They presented a case study within the UK road transport industry using a payment card exercise to estimate risk perception. Their study enhances the understanding of managers’ risk perception and servitization implications. Benedettini et al. (2015) conducted an empirical study to examine the impact of service provision on bankruptcy risks, by attempting to answer the following research question “why do servitized firms fail?”. Their study found that the presence of a service provision business leads to a more significant number of bankruptcy risks, due to the greater internal risks within supplying firms. Erkoyuncu et al. (2013) proposed six main categories of uncertainty in the PSS environment, namely commercial, affordability, training, performance, operation, and engineering. Later, they presented a framework to manage the influence of uncertainty on cost estimation at the bidding stage. In this regard, plan, identify, prioritise, classify, and manage cost uncertainties were presented as the key steps within their framework (Erkoyuncu et al., 2014). Moreover, a qualitative multi-case logic methodology is adopted by Durugbo and Erkoyuncu (2016) to assess the evolution of industrial service uncertainties and corresponding mitigating methods. They found the aftermarket-oriented organisation, audit-oriented governance, relationship-oriented intelligence and lifecycle-oriented contracts as the crucial factors to mitigate uncertainty. Furthermore, Visnjic et al. (2018) argued that within a PSS contract, risks could be associated with both internal, and partners’ activities. Accordingly, Hou and Neely (2018) categorised the risk factors in servitization as: complexity, dynamism, dependency, lack of capability, and alignment in PSS contracts. They argued that the complexity mainly arises from interrelationship and involvement of several

stakeholders, and diversity and uncertainty in customers' demands. Moreover, dynamism refers to the time-dependency of PSS contracts, in the 'long-term availability' and 'capability-based' types, in which dynamism can lead to commercial and operational risks.

Simulation and computational models have been widely adopted by the manufacturing and service sectors to conduct data analysis, performance evaluation, configuration optimization, and economic performance assessments for PSS. Bianchi et al. (2009) considered PSS as a deviation from existing businesses and proposed a qualitative system dynamics approach to evaluate the influence of PSS proposition under a set of assumptions. Phumbua and Tjahjono (2010, 2011) presented a simulation model for an OEM to examine the feasibility of availability-based contracting using the agent-based modelling (ABM) technique (Phumbua and Tjahjono, 2010, 2011). They highlighted the importance of simulation techniques to capture the PSS dynamic behaviour to model product and service system designs under servitization. In their research work, PSS dynamic behaviour mainly arises from the sub-system levels such as asset failure, customer characteristics, supplies, asset performance measures (Phumbua and Tjahjono, 2012). Mainenbacher et al. (2014) discussed the applicability of ABM for PSS development (Mainenbacher et al., 2014). They determined ABM as an effective collection of autonomous decision-making entities, which create adaptive strategies to develop uncertain behaviour of the assembly. However, their model used deterministic PSS performance indicators to capture such combined uncertainty for PSS.

The literature also identified several gaps regarding the LCC implementation for products and services in servitization that are not addressed properly: commonalities between different types of PSS solutions, inconsistency in LCC terminologies, and significance of end-of-life cost in LCC (Kambanou and Lindahl, 2016). In this regard, a framework for LCC evaluation of PSS configuration is developed by Shen et al. (2017) providing a holistic view of PSS configuration, the three-dimensional PSS cost element, and a lifecycle oriented cost evaluation. The proposed cost evaluation indicators for each PSS solution estimate the total activity-based costing (ABC) considering uncertainty propagation. Moreover, the ABC approach has been deployed to create the PSS configuration and select the best PSS solution from the manufacturer perspective (Shen et al., 2017). Pagoropoulos et al. (2017) extend the economic evaluation of service strategies by presenting a cost-benefit analysis as a factor in the formulation of PSS strategies. They examined both manufacturer and customer perspectives using the shipping sector as a case study (Pagoropoulos et al., 2017). A recent research work by Rodríguez, et al. (2020) presents a comprehensive description of the PSS cost estimation process through an integrative review. Their work argued that cost uncertainty denotes an inherent property of the PSS and still need to be investigated. Their work concluded that there is still an essential need for the development of cost estimation model for PSS contract design which considers the intrinsic unpredictability of its nature and acknowledge uncertainty rather than eliminate it (Rodríguez et al., 2020).

As mentioned earlier, PSS exhibit dynamic behaviour due to the delivery of several service solutions over the length of the contract. PSS also present stochastic behaviour as a result of the inseparability of services and variability of support interventions and customer demands. Furthermore, PSS contracts are characterised by different types of uncertainty which are mainly caused by the dynamism, dependency, stochastic nature of the customers' demand, service requirements, and product utilization and operations (Erkoyuncu *et al.*, 2019). In such a highly dynamic and uncertain environment, an appropriate and effective approach to quantify uncertainty is required. Moreover, in order to better estimate the profitability of PSS contracts, there is a need to consider the interlink between through-life cost/benefit events over the contract length. Stochastic cost estimates and bottom-up simulation techniques are, therefore, more adequate and effective to overcome such complexities (Estrada et al., 2017; Farsi et al., 2019). Compared to the other dynamic simulation techniques such as discrete-event and system dynamics, ABM is a fairly new approach in PSS literature and provides innovative

opportunities to resolve companies' complex problems. The bottom-up approach and the modular state structure of ABM support PSS development in a more flexible, interactive, and effective way (Maisenbacher et al., 2014; Wrasse, Hayka and Stark, 2015; van der Veen, Kisjes and Nikolic, 2017). However, one of the main criticisms to such bottom-up approaches has always been the data-intensive and complexity of cost calculations.

3. Research methodology

This research work builds on the literature in servitization, PSS business models, CBA, uncertainty analysis and through-life cost in PSS. Moreover, it is established based on expert knowledge and industrial experience in the field of servitization and machine tool technologies. The research methodology is illustrated in Figure 1.

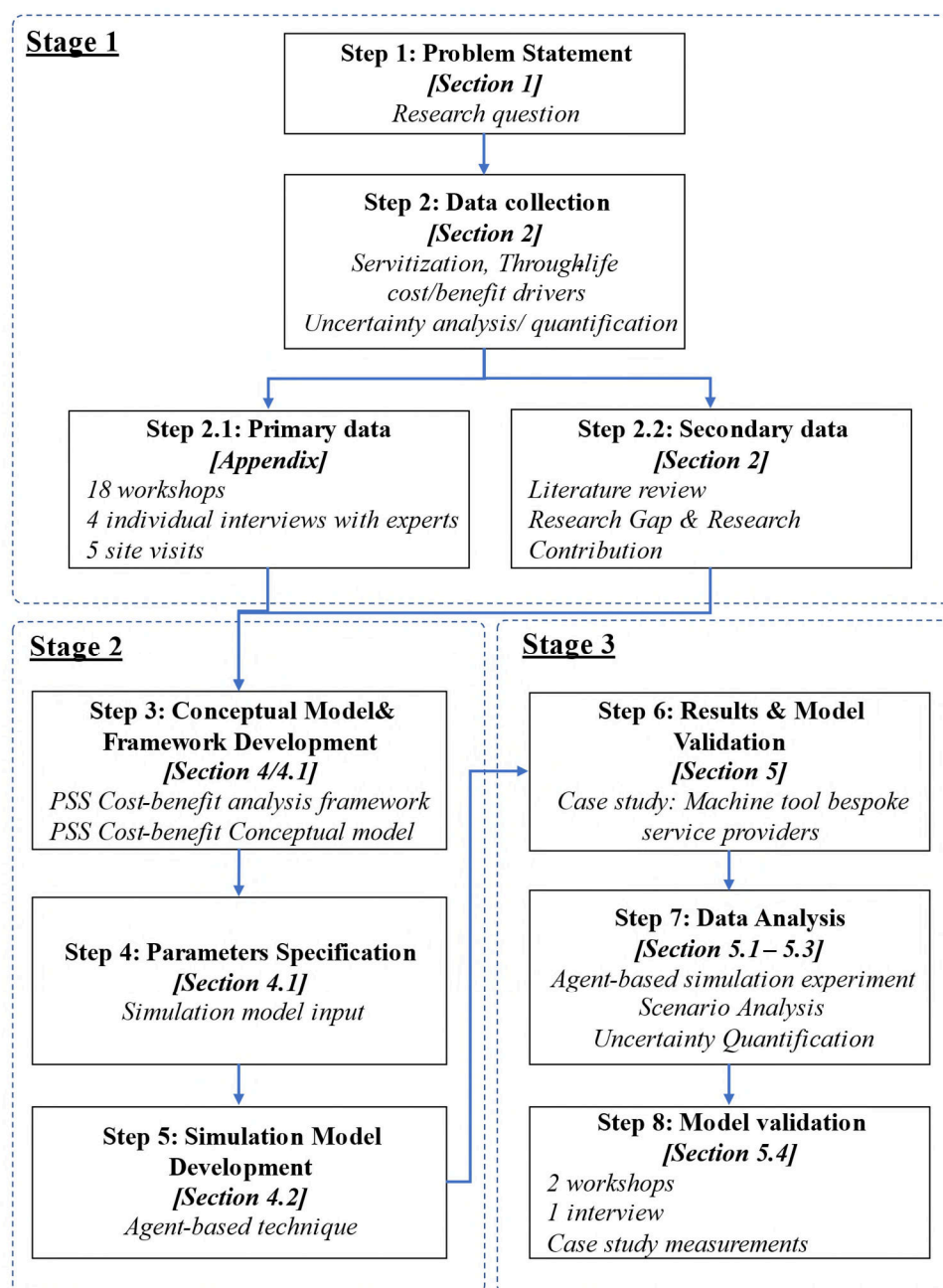


Figure 1: The Research Methodology

The research methodology was inspired by the soft systems methodology, and utilised several data collection methods, including the use of workshops, site visits and semi-structured interviews. The methodology consists of three main stages; Stage 1 itself has two steps i.e. step 1 which is outlining problem statement, and step 2 that is collecting data. Stage 2 embraces Steps 3, 4 and 5 to develop the proposed framework, and the conceptual model for PSS CBA; it is at this stage that we developed the agent-based simulation model for PSS contractual decision using the AnyLogic software. Stage 3 concentrates on the case study in step 6, and the simulation results are presented in step 7; finally, the model is validated in step 8.

Stage 1: Based on the existing literature and the theories behind servitization, uncertainty analysis and cost estimation, the research question and contributions are identified, as presented in Section 1 (step 1). Moreover, the thorough literature review (i.e. secondary data collection) is conducted and presented in Section 2 (step 2.2). The study has also collected primary data from a bespoke service provider by having 18 workshops, 4 interviews and 5 site visits, as detailed in the Appendix (step 2.1).

Stage 2: The proposed framework for quantifying the uncertainty in cost and benefit estimates of PSS contracts is illustrated as an IDEF0 diagram (step 3), and the PSS cost-benefit conceptual model (step 3) are developed and presented in Section 4.1. Moreover, the detailed, PSS cost and benefit drivers are identified and specified from a service provider' perspective (step 4). Finally, the proposed UML state machine diagram of the cost-benefit model for servitization is presented in Section 4.2 (step 5).

Stage 3: To validate the proposed framework, an industrial case study from the machine tool industry is considered (step 6), and several simulation experiments for CBA, scenario analysis, and uncertainty quantification are conducted and presented in Sections 5.1 – 5.3 (step 7). A two-phased strategy is implemented to validate the developed PSS cost-benefit model and the simulation for the design of the PSS contract decision (step 8). Phase 1 focuses on verifying the cost and benefit drivers of PSS for a bespoke service provider. This phase relies on primary and secondary data collection to identify the key cost and benefit drivers through the service and product lifecycle and over the length of the servitization contractual agreement. Afterwards, the developed conceptual model is validated based on a workshop with the industrial experts; the outcomes are presented in Section 4. Phase 2 focuses on validating the dynamic simulation model for the design of the PSS contract decision. This phase is conducted according to the outcomes of Phase 1. Subsequently, the developed simulation model is verified within the workshop with the industrial experts and validated for the three main scenarios within the machine tool industry case study, and the 96 different sub-scenarios by performing parameter variation experiments. The outcomes are presented in Sections 4 and 5.

4. Model Development for PSS Cost-Benefit Analysis

Following the research methodology, at stage 1, a comprehensive literature review was implemented to identify the research gaps and potential contributions as presented earlier. Primary data has been collected by carrying out 18 workshops and 4 individual interviews with industry experts and 5 site visits (see Appendix for details). Completing the stage 1, led to the development of the framework for CBA model in PSS (Figure 2), a generic PSS cost-benefit conceptual model for service providers (Figure 3), and the PSS cost and benefit drivers (Table 1), as detailed in this Section. Figure 2 presents the framework for cost-benefit analysis model development processes for PSS as an IDEF0 diagram to show the relevant inputs, outputs, controls, and mechanisms.

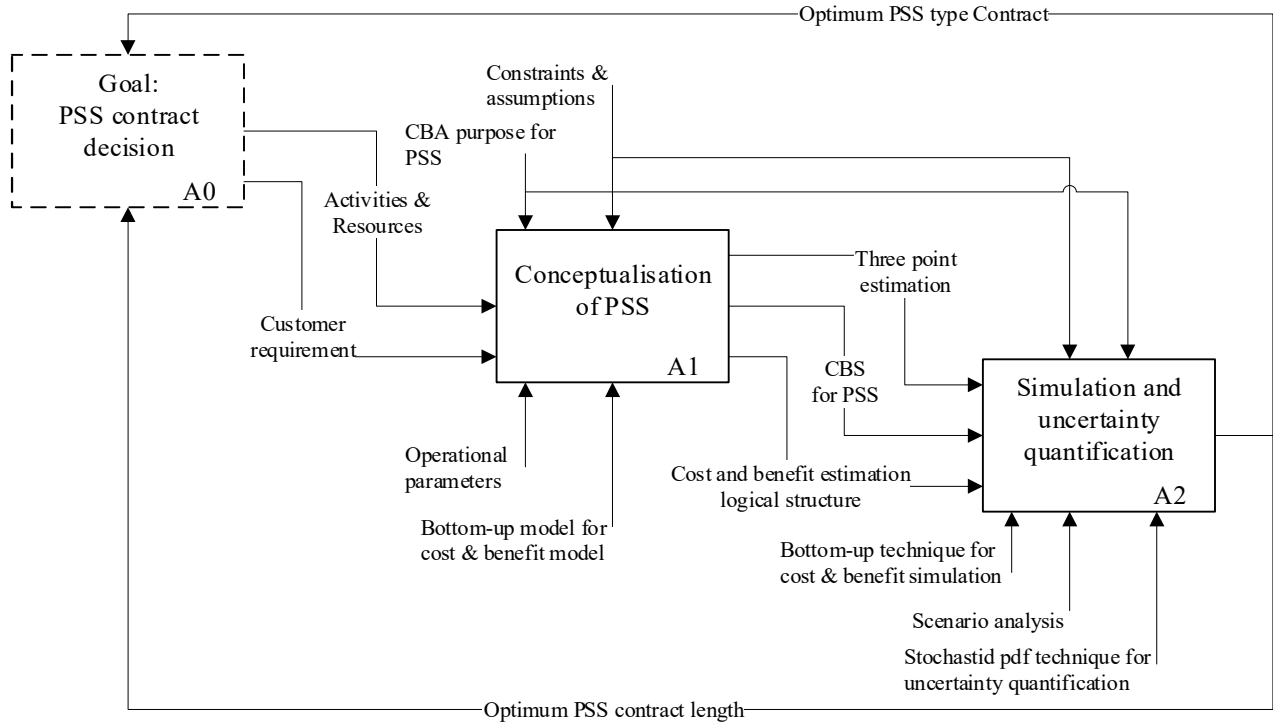


Figure 2: A framework for cost-benefit analysis model development processes for PSS

The first main action box is ‘Conceptualisation of PSS’. This action is to develop the logical structure of cost and benefit events (or activities) and their mathematical relationship for the cost estimation. The action’s inputs are ‘customer requirement’ and ‘activities and resources’. The requirements can be in terms of the type of the product, service and support and training within the PSS contract. *Activities* are a set of tasks that can be applied to products during its lifecycle (e.g. acquire, manufacturing, maintenance). *Resources* are a set of human resources, equipment and information to complete the activity (e.g. maintainer, consumables) (TREATY, 2003). The action ‘A1’ is controlled by a set of ‘assumptions and constraints’ (e.g. level of product’s availability) and the ‘CBA purpose for PSS’ (e.g. decrease in product’s breakdowns, preventive maintenance) (Gokula Vijaykumar et al., 2013). The action uses operational parameters (e.g. human resources, service and support activities) and a bottom-up approach to develop a cost-benefit model for PSS. The initial action leads to the action of ‘Simulation and uncertainty quantification’. At this stage, the cost and benefit estimation of PSS type contract is simulated, optimised and analysed. The inputs for the action ‘A2’ are the three-point estimation for the unit cost of each activity and resource discussed earlier. Moreover, the logical structure of cost and benefit events and the mathematical estimation models for cost and benefit are the inputs for the second action. The goal is to quantify the uncertainty around the CBA using a bottom-up simulation technique. Moreover, scenario analysis of different operational parameters and stochastic pdf for uncertainty quantification are the other mechanisms. The outputs are the optimum PSS contract type and optimum PSS contract length. In this paper, for ‘A1’, the conceptual model of CBA in servitization is first developed to define the through-life CBS for PSS. The model is developed considering real-world scenarios. Moreover, for ‘A2’, a simulation model of servitization is presented for different PSS solutions using a bottom-up ABM technique. The PSS CBA model is presented and discussed in detail in Section 3.1. This is followed by the ABM simulation model in Section 3.2. In Section 4, the mechanisms for ‘A2’ are presented, and the outcomes are calculated based on the case study. The presented framework and the methodologies aim to support decision-makers in PSS type contracts to find the most profitable servitization agreement with the presence of uncertainty.

4.1. Framework Action A1: PSS Cost-Benefit Conceptual Model

As mentioned earlier, the traditional through-life CBA methods do not provide an adequate and accurate approach to estimate the cost of PSS type's contracts. This is mainly due to neglecting of the PSS inherent complexity which can arise from the dynamic, interactivity and nonlinearity of PSS operations and cost and benefit objects. To address the PSS complexity and the aggregate uncertainty, this work presents a conceptual design of a bottom-up approach for servitization process at steady-state as illustrated in Figure 3.

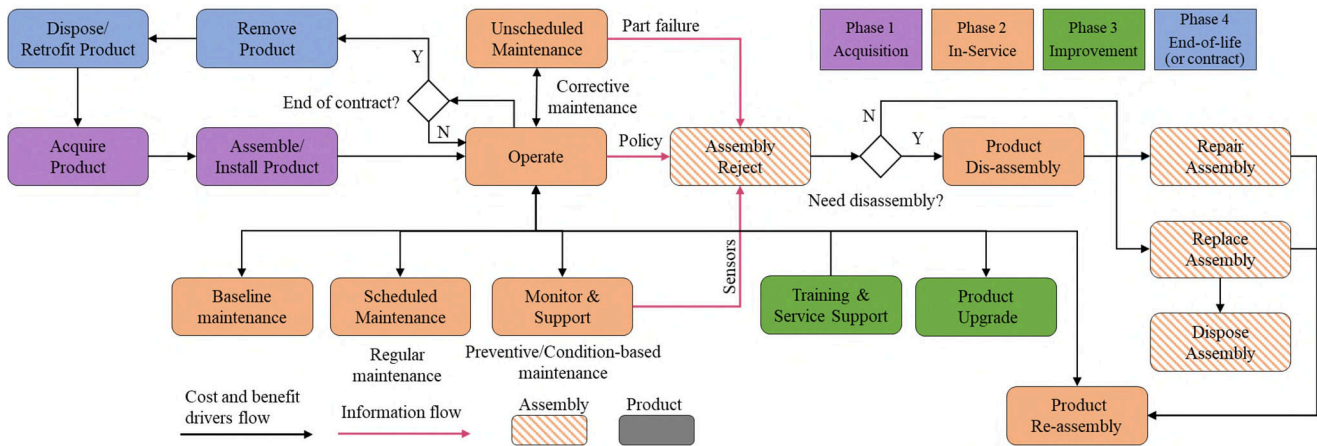


Figure 3: A generic PSS cost-benefit conceptual model for service providers

Four main phases are considered through the service and product lifecycle over the length of the servitization contract to assess the cost and benefit drivers of product and service focussed. The initial phase is 'acquisition' which includes the cost and benefit drivers of procurement in a servitization agreement. There are two states in this phase for acquiring, assembling and installing the product in order to make it available for operation. Phase 2 is 'In-service' and includes operation, maintenance and repair intervention states to ensure the availability of a product in service. A separate 'Improvement' phase has been added to the conceptual model as it is a key cost and benefit driver to find the optimal design and flexible service solutions such as training, support and upgrade states. The cost and benefit drivers in these states are crucial for service and result oriented solution when productivity, quality and precision are as important as functionality, performance and availability. The final phase refers to the product end-of-life or the end-of-the servitization contractual agreement, when the product is removed and disposed (e.g. retrofit, recycle, and reuse). A detailed, PSS cost and benefit drivers are identified and summarised in Table 1. Additional cost and benefit drivers for service-oriented and result-oriented PSS are also highlighted for the four servitisation phases separately.

Phase	Unit Cost drivers	Unit Benefit drivers
Phase 1	<i>Product-oriented (PSS 1)</i>	
	Product purchase (or OEM product) Product legal fee Product disassembly Product transport to the provider site Product transport to the customer site Product assembly Product specification Product installation (OEM may install) Product installation testing Product integration	Selling product to a customer Revenue from product assembly & install

	<i>Additional drivers for use-oriented (PSS 2)</i>	
		Renting product to a customer Leasing product to a customer
	<i>Additional drivers for result-oriented (PSS 3)</i>	
	Final product/component may be provided by the bespoke service provider	Revenue from selling product/component to a customer
Phase 2	<i>PSS 1</i>	
	Product spare parts (contract agreement) Product spare parts Storage Operator labour	Basic maintenance Regular maintenance Corrective maintenance Consultancy Revenue from spare parts (upkeep agreement) 24/7 support (or standby)
	<i>Additional drivers for PSS 2</i>	
	Penalty paid to a customer due to Asset downtime Consumables, and Sensors <ul style="list-style-type: none"> Sensors Purchase & installation Sensors' data analytics (IT infrastructure) Condition monitoring equipment Spare parts disposal after replacement	Condition-based maintenance Incentives for additional product availability spare part (update agreement)
	<i>Additional drivers for PSS 3</i>	
	Penalty paid to a customer due to lack of Product/component quality	Incentives for additional component quality Reliability centred maintenance Autonomous Maintenance
Phase 3	<i>PSS 1</i>	
	Customer operator training	Return on customer operator training
	<i>Additional drivers for PSS 2</i>	
	Invest in new technology for upgrade parts Invest in new technology for an upgrade product	Return on investment for product part upgrade Return on investment for product upgrade
	<i>Additional drivers for PSS 3</i>	
	Invest in new skills/technology for IT and data analytics upgrades	Return on investment for IT and data analytics upgrade
Phase 4	<i>PSS 1</i>	
	No cost – ownership retains with customer	No benefit – ownership retains with a customer
	<i>Additional drivers for PSS 2</i>	
	Product uninstallation Product disassembly Product transport – remove from the customer site Product disposal – retrofit /scrapping	Resale product to other customers without retrofit Resale product to other customers after retrofit Re-lease product Lease contract extension Sale to current consumer
	<i>No Additional drivers for PSS 3</i>	

Table 1: PSS Cost and Benefit drivers from a bespoke service provider perspective

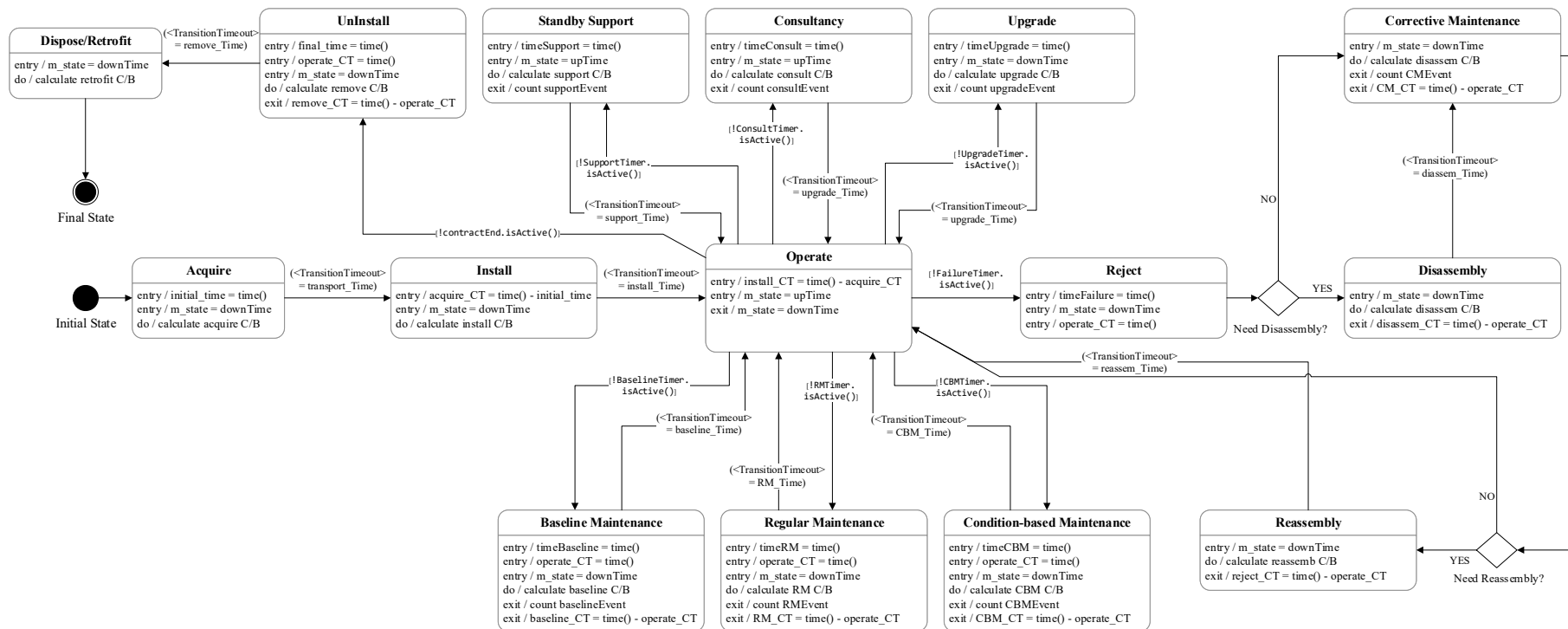
4.2. Framework Action A2: PSS Cost-Benefit Simulation Model

A dynamic object-oriented approach is implemented to simulate the proposed PSS cost-benefit conceptual model from the bespoke provider perspective (see Figure 3). In this study, the ABM approach has been selected to create the servitization model. The top-level (or macro-level) agent is called `Main()` class. The `Main` class contains several `Transition()` classes. Based on their trigger type, transitions can be categorised into `Timeout (<TransitionTimeout>)`, `Rate (<TransitionRate>)`, `Condition (<TransitionCondition>)` and `Message (<TransitionMessage>)` classes. All these classes are inherited from the base class `Transition`. In this study, the

ABM of servitization is presented using the UML State Machine diagram, as shown in Figure 4. The state machine diagram is used as an effective UML type diagram to represent the condition of the PSS cost-benefit model at different phases over time. Different ‘states’ of the presented PSS cost-benefit simulation model are detailed in this section. Each state represents one of the cost events throughout the service and product lifecycle, and over the length of the servitization contractual agreement. The ABC approach for through-life CBA for PSS, the variables and parameters were used to estimate the costs and benefits, as shown in Table 2.

Variables		Variables	
B_p	Purchase Boolean value	C_{Opr}, π_{Opr}	Cost and benefit of operating
p	Purchase price	c_{Spr}	Cost of spare parts
c_L	Legal fee	c_{Opr}	Operator labour cost
c_{D1}	Disassembly cost at provider’s site	c_{Sen}	Sensor related cost
c_{T1}	Transport cost to provider’s site	c_{mnt}	Cost of repair and maintenance
c_{T2}	Transport cost to customer’s site	c_p	Penalty due to lack of availability
C_{Acq}, π_{Acq}	Cost (C) and benefit (π) of acquire	π_{inc}	Incentives due to additional availability
CT_{Acq}	Acquire cycle-time	C_{Imp}, π_{Imp}	Cost and benefit of improvement
B_s	Selling Boolean value	c_{Opr}^u	Operator new training
B_r	Renting Boolean value	c_{tech}^u	Investment on new technology
d	Deposit value	C_{Rmv}	Cost of removal
r	Monthly rent	B_R	Removal Boolean value
C_{Ins}, π_{Ins}	Cost and benefit of install and assembly	c_{unl}	Uninstallation cost
c_{Int}	Integration cost	c_{D2}	Disassembly cost at customer’s site
c_A	Assembly cost	c_{T3}	Transport cost from customer’s site
c_S	Specification cost	CT_{Rmv}	Removal cycle-time
c_{Ins}	Installation cost	c_r	Cost of retrofit
c_{Tes}	Testing the installation cost	π_r	Product residual value
CT_{Ins}	Install and assembly cycle-time	$\theta(t)$	Depreciation rate

Table 2: Notations



Consider a service supply chain composed of a bespoke service provider that provides PSS solutions to the customers. In Phase 1, the product may be already purchased from the OEM by the customer ($B_p = 0$) or the provider can acquire both product and service for the customer ($B_p = 1$), where B_p is the purchase Boolean value. The UML diagram starts from the ‘Initial State’ point. The first state to simulate the through-life CBA is ‘Acquire State’, where the cost and benefit (C/B) of acquire can be calculated as:

$$C_{Acq} = B_p \cdot (p + c_L + c_{D1} + c_{T1} + c_{T2}) \cdot CT_{Acq}, \quad (1)$$

where CT_{Acq} is the acquire cycle-time. The service provider benefit π_{Acq} can be calculated as:

$$\pi_{Acq} = B_s \cdot \sum_{i=1} C_{Acq}^i \times (1 + R_{Acq}^i) + B_r \cdot (d + 12 \times r), \quad (2)$$

where C_{Acq}^i is the i th acquire cost element and R_{Acq}^i is the i th acquire rate of return. For PSS-1, in the case of selling the product to the customer, $B_s = 1$ and $B_r = 0$, where B_s and B_r are the selling and renting Boolean values, respectively. For PSS-2, in the case of renting or leasing the product to the customer, $B_s = 0$ and $B_r = 1$; d and r are the value of the deposit and monthly rent respectively. After the ‘Acquire State’, there exists a Timeout trigger which has the syntax of $\langle \text{expression} \rangle$, where $\langle \text{expression} \rangle$ is the number of time units that is going to the ‘Install State’. The install cost C_{Ins} can be calculated as:

$$C_{Ins} = (c_A + c_S + c_{Ins} + c_{Tes} + c_{Int}) \cdot CT_{Ins}, \quad (3)$$

where CT_{Ins} is the install cycle-time. The service provider benefit π_{Ins} can be calculated as:

$$\pi_{Ins} = \sum_{i=1} C_{Ins}^i \times (1 + R_{Ins}^i), \quad (4)$$

where C_{Ins}^i is the i th install cost element and R_{Ins}^i is the i -th install rate of return. Hitherto, the cost and benefit of Phase 1 have been calculated. At Phase 2, the product is in-service at the ‘Operate State’. The operating cost C_{Opr} from the service provider perspective can be calculated as:

$$C_{Opr} = c_{Spr} + c_{Opr} + c_{Sen} + c_{mnt} + c_p. \quad (5)$$

Cost of spare part storage and disposal can be included in the spare part for upkeep agreement, c_{Spr} . Moreover, the operator’s labour cost, c_{Opr} , can include labour transport cost. In PSS-2, additional cost elements for sensors related to condition monitoring maintenance c_{Sen} and the penalty charge c_p - due to the lack of agreed availability of the product - are considered. Cost of sensors includes the price of the purchase, installation, and labour cost for data analytics and condition-monitoring equipment cost. The latter two can be calculated on a monthly basis. Cost of several repair and maintenance interventions c_{mnt} , comprises of the labour and consumable costs for the provider. The unit penalty cost c_p can be estimated based on any 1% lack of agreed availability on average during the contract or on a regular (i.e. daily, monthly, yearly) basis. The operate benefits π_{Opr} can be calculated as:

$$\pi_{Opr} = \sum_{i=1} C_{Opr}^i \times (1 + R_{Opr}^i) + \sum_{j=1} c_{mnt}^j \times CT_{mnt}^j \times (1 + R_{mnt}^j) + \pi_{inc}, \quad (6)$$

where C_{Opr}^i is the i -th operate cost element (except for c_{mnt}) and R_{Opr}^i is the i -th operate rate of return (except for c_{mnt}). For PSS-1, the provider may charge the customer for several services, j , such as baseline maintenance (BM), at ‘Baseline Maintenance State’, regular maintenance (RM), at ‘Regular Maintenance State’, corrective maintenance (CM), at ‘Reject State’, consultancy, at ‘Consultancy State’, and 24/7 standby support, at ‘Standby Support State’. If any failure occurs to the product at the ‘Reject State’, for corrective maintenance part, disassembly and reassembly may be required at ‘Disassembly State’ and ‘Reassembly State’, respectively. The associated costs and benefits should be therefore included in c_{mnt} . For PSS-2, the benefit from any condition-based maintenance (CBM), at ‘condition-based Maintenance State’, and incentives for extra product availability π_{inc} are included. For each of the maintenance and support events, c_{mnt}^j , the corresponding Condition Transition triggers based on the frequency of the event. The machine state is going back to the Operate State after the Timeout Transition triggers with the specified time for the event. In parallel to Phase 2. in Phase 3. costs and benefits can be attributed to any upgrades in the supply chain such

as operator new training, c_{opr}^u , investment in new technology, c_{tech}^u for the product and its disassemblies, and investment in new IT and data analytics technologies to improve the reliability-centred maintenance (RCM) in PSS-3. The cost and benefits of improvements can be calculated as thus:

$$C_{Imp} = c_{opr}^u + c_{tech}^u \quad (7)$$

$$\pi_{Imp} = \sum_{i=1} C_{Imp}^i \times (1 + R_{Imp}^i) \quad (8)$$

where, C_{Imp}^i is the i -th improvement cost element and R_{Imp}^i is the i -th improvement rate of return on investments. At the end of a contract at Phase 4., a Condition Transition (i.e. `!contractEnd.isActive()`) triggers, and the state moves to 'Uninstall State' for the product removal. For PSS-2, which the product owner stays with the provider, the costs and benefits of removal include uninstallation, c_{unl} , disassembly, c_{D2} , and transport, c_{T3} , to the provider site. In the case of the customer being the product owner, the service provider may charge the customer for any removal request. The removal cost C_{Rmv} can be calculated as:

$$C_{Rmv} = B_R \cdot (c_{unl} + c_{D2} + c_{T3}) \cdot CT_{Rmv} + B_R \cdot c_r, \quad (9)$$

where B_R is removal Boolean value, CT_{Rmv} is the removal cycle-time and c_r is the cost of retrofit, if applicable. The removal benefit π_{Rmv} is thus:

$$\pi_{Rmv} = B_R \cdot \sum_{i=1} C_{Rmv}^i \times (1 + R_{Rmv}^i) + B_R \cdot \pi_r, \quad (10)$$

where C_{Rmv}^i is the i -th removal cost element, R_{Rmv}^i is the i -th removal rate of return and π_r is the product's residual value which can be calculated as:

$$\pi_r = B_p \cdot p \times (1 - \theta(t)), \quad (11)$$

where, $\theta(t)$ is the depreciation rate (in years). The rate can be considered either as a constant, or an exponential value over time t . The presented CBA model provides a comprehensive through-life cost and benefit evaluation from the provider's perspective considering different processes, resources and PSS solutions.

5. Case study: Machine tool bespoke service providers

In this study, a service supply chain for machine tool products is selected as the case study to test the validity of the proposed cost-benefit PSS model for PSS-1 and PSS-2 types of contracts and the proposed framework. Machine tools have a long lifespan of up to thirty years. In PSS form contracts, after the OEM guarantee period, the bespoke service providers acquire and possibly retrofit the machines and sell, rent or lease the machine to the customers and provide service based on the PSS contract agreement. The current service providers' contract design is mainly upkeep and is inadequate to enhance customers' satisfaction. The upkeep contracts are often based on corrective maintenance and previous experience, resulting in lower quality, higher cost and longer downtime of the machine for maintenance. Designing a beneficial service contract for this is relatively complicated and challenging. As discussed in Section-2, the completion and challenges arise from the existence of several machine tool types and understanding of their monitoring and performance correctly. Machine tools can be categorised into several types based on their technology (e.g. milling, turning, grinding), the number of axes (e.g. three axis, five axis), spindle arrangement (e.g. vertical/horizontal, single/multi-spindle), kinematic configuration (e.g. serial, parallel, hybrid) and applications (e.g. material removing, material deposit, material handling). Considering the different states of the PSS model (see Figure 4), the required parameters and variables for the case study are summarised in Table 3. The uncertainty of the collected data aggregates the uncertainty in cost and benefit values, cost event cycle-times, and repair and maintenance interventions' frequencies and cycle-times were analysed. The continuous probability distributions are used for the input data within the simulation model. The simulation modelling tool, AnyLogic version 8. was selected to create the ABM of the PSS model. The dynamic behaviour of the model is captured by considering the parameter of time

(i.e. contract length) when performing the simulation experiment (Section 5.1). Different scenarios of the PSS contract are simulated and analysed by varying the length of the contract and age of the asset (Section 5.2). The uncertainty of annual CBA for different servitization agreements are quantified in the form of pdf graphs (Section 5.3.). Validation of the model is accomplished using the data from the case study in Section 5.4.

Parameter/Variable	Symbol	Value/Distribution		Unit
Purchase price	p	£ 348,000.00		One-off
Machine renting/leasing		£ 10,000.00		/month
Legal fee	c_L	£ 1,600.00		One-off
Machine disassembly at the provider site	c_D	£ 2,000.00		One-off
Machine transport-2 (provider to a customer site)	c_{T2}	£ 2,000.00		/week
Machine assembly	c_A	£ 4,000.00		/week
Machine specification	c_S	£ 4,000.00		/week
Machine installation	c_{Ins}	£ 800.00		/day
Machine testing	c_{Tes}	£ 8,000.00		/day
Machine integration	c_{Int}	£ 8,000.00		/day
Agreed spare parts	c_{Spr}	Age (y)	$c_{Spr} (£)$	/year
		1 - 5	Uniform (1000, 2000)	
		5 - 10 ⁺	Triangular (5000, 15000, 30000)	
Spare part disposal		£ 5,000.00		/year
Operator training (labour/transport)	c_{Opr}	£ 900.00		/day
Baseline maintenance (i.e. MPEOM)	BM	£ 3,750.00		/year
Regular maintenance (repair & replacement)	RM	£ 475.00		/day
Corrective maintenance (repair & replacement)	CM	£ 475.00		/day
Condition-based Maintenance	CBM	£ 475.00		/day
Consultancy		£ 1,500.00		/request
Standby support		£ 500.00		/month
Penalty per 1% lack of machine availability	c_p	£ 100.00		
Sensors purchase price		£ 20,000.00		One-off
Sensors installation		£ 2,500.00		One-off
Sensors' data analytics		£ 200.00		/month
Condition monitoring equipment		£ 200.00		/month
Incentives per 1% extra machine availability	π_{inc}	£ 100.00		
Machine's part disassemblies		£ 475.00		/day
Machine uninstallation	c_{unl}	£ 500.00		/day
Machine disassembly at customer site	c_{D2}	£ 500.00		/day
Machine Transport (customer to provider site)	c_{T3}	£ 500.00		/day
Machine retrofit	π_r	£ 50,000.00		One-off

Table 3: Input data for the case study simulation model

Other essential simulation parameters regarding the cost events, cycle-times, lead-time, and frequencies for the case study are summarised in Table 4.

Parameter/Variable	Value/Distribution		Unit
Machine transport-2 cycle-time	Triangular (1 ± 0.05)		week
Machine assembly cycle-time	Triangular (4 ± 0.05)		week
Machine specification cycle-time	Triangular (1 ± 0.05)		week
Machine installation cycle-time	Triangular (1 ± 0.05)		week
Machine testing cycle-time	Triangular (2 ± 0.05)		week
Machine integration cycle-time	Triangular (2 ± 0.05)		week
Machine's part disassemblies cycle-time	Triangular (10 ± 0.05)		day
Machine uninstallation cycle-time	Triangular (5 ± 0.05)		day
Machine disassembly at customer's cycle-time	Triangular (5 ± 0.05)		day
Baseline maintenance frequency	1		/year
Baseline maintenance lead-time	Uniform (5, 10)		day
Regular maintenance frequency	2		/year
Regular maintenance lead-time	Uniform (1, 2) + 1		day
Corrective maintenance frequency (f)	Age (year)	f	/year
	≤ 1	10	
	2-5	5	
	5-10	5	
	≥ 10	10	
Corrective maintenance lead-time (l)	Age (year)	l	day
	≤ 1	Uniform (1, 2)	
	2-5	Uniform (1, 2) + 1	
	5-10	Uniform (3, 4) + 1	
	≥ 10	Uniform (3, 4) + 1	
Condition-based Maintenance frequency	2		/year
Condition-based Maintenance lead-time	Uniform (2, 5)		day
Consultancy frequency	2		/year
Standby support frequency	12		/year
Machine's part disassemblies cycle-time	1		day
Operator training	2		day
Rate of return on purchases and Investments	20% - 30%		
Rate of return on service	90% - 110%		
Rate of depreciation	17%		Per year

Table 4: Additional input data for the case study simulation model

The simulation time unit is set as 'day', and the model generates the results for the residual value of the studied machine tool over a 30-year period for the product lifespan. The assumptions and other input parameters are based on the data in Table 3 and Table 4. The residual value of the machine tool over its lifespan is calculated from Equation 11, as illustrated in Figure 5. The rate of depreciation is assumed to be fixed with the value of 0.17 over the thirty years for the case study as presented in Table 4.

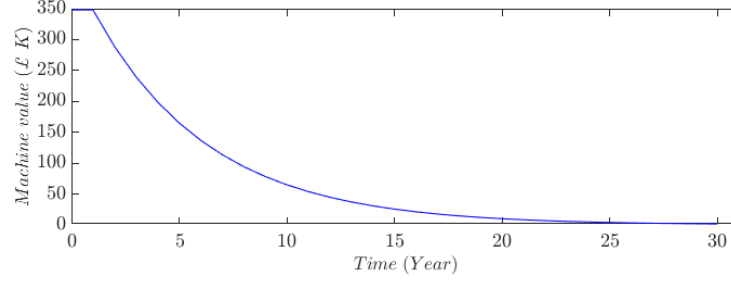


Figure 5: Machine tool's residual value over thirty years product lifespan

5.1. Results: bottom-up technique for CBA simulation

For the first set of experiments, the simulation model generates the CBA results for one year. Note that different scenarios have been considered based on the case study in this research. For the first scenario, it is assumed that the company provides service for an OEM machine at the customer site. Customer owns the machine and thus $B_p = B_s = B_r = B_R = 0$. Moreover, it is assumed that there are no improvement and upgrade activities for either the machine or its assemblies. The age of the machine at the start of the contract is considered to change from one, to five, ten and fifteen years old. The CBA results of PSS-1 for Scenario-1 is illustrated in Figure 6. Both service cost (Phase 2.) and total cost (including Phases 1– 4) are analysed.

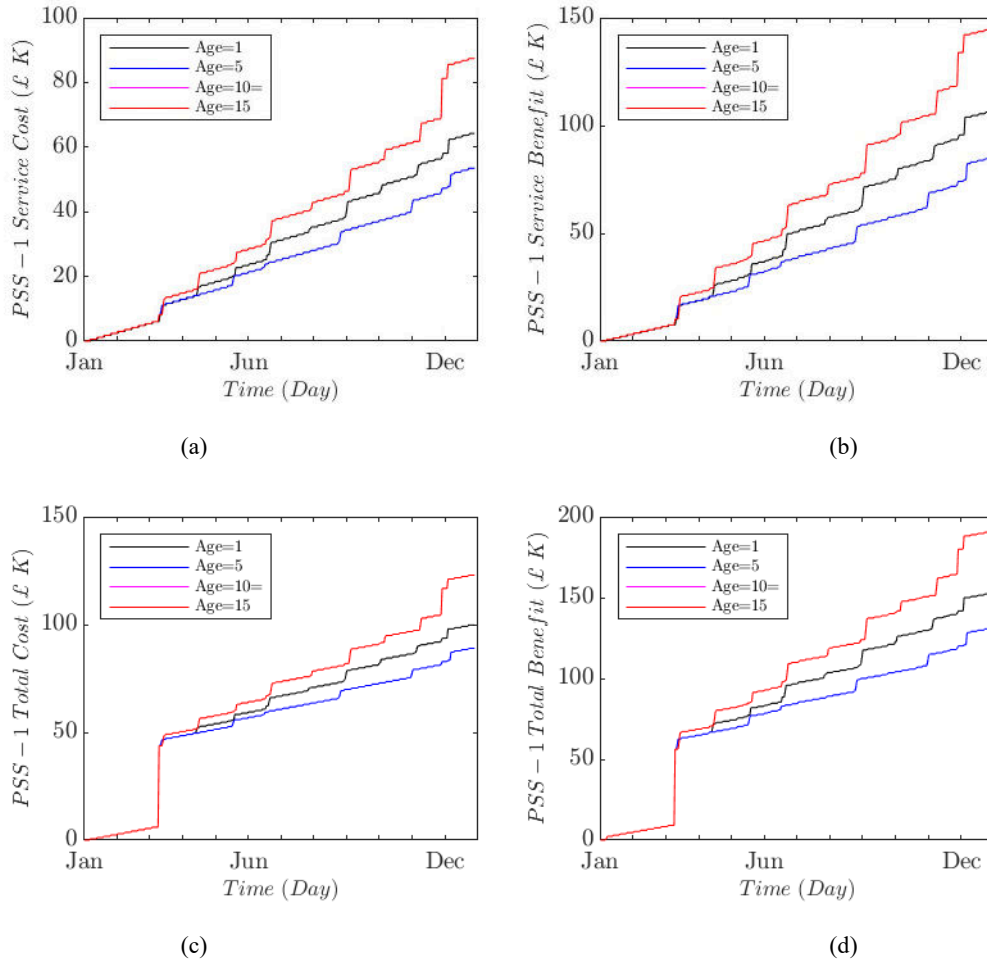


Figure 6: Scenario-1 Service (a) cost and (b) benefit and total cost (c) and benefit (d) of PSS-1 type contract over one year

In this case, for PSS-1 type contract, the total annual cost of servitization includes acquire and in-service cost of machine for the service provider. The monthly total cost is estimated to be between £7.4K and £10.2K and the monthly total benefit is between £10.9K and £15.9K from the provider's perspective. Similarly, these figures for service cost and benefit are £4.5 – 7.3K and £7.0 – 12.0K, respectively. Therefore, the total cost-benefit ratio for Scenario-1 changes between 1.47 and 1.55, and there is an average of 51% profit for the service provider. In this scenario, the variations in the cost and benefit depend on the initial purchase prices of the machine and the rate of failures, in other words, corrective maintenance. For the second scenario, the company purchases the machine and sells it to the customer. Customer owns the machine and thus $B_p = B_s = 1$ and $B_r = B_R = 0$. The CBA results of PSS-1 for Scenario-2 are illustrated in Figure 7 .

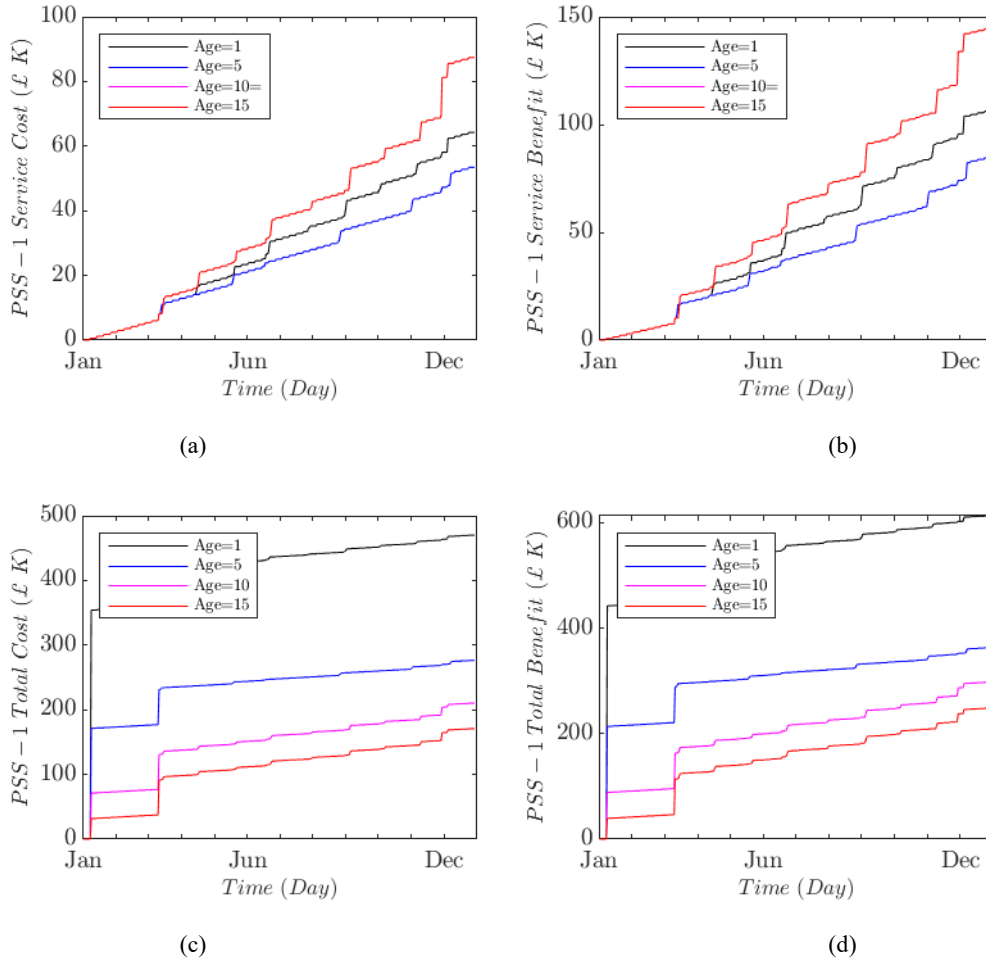


Figure 7: Scenario-2 Service (a) cost and (b) benefit and total cost (c) and benefit (d) of PSS-1 type contract over one year

For the second set of experiments, the monthly total cost is between £14.2K and £39.2K, and the monthly total benefit is between £20.7K and £51.1K. Similarly, these figures for service cost and benefit are £4.5 – 7.3K and £7.0 – 12.0K, respectively. Therefore, the cost-benefit ratio for Scenario-2 varies between 1.3 and 1.45, and there is an average profit of 38% for the service provider. By increasing the machine age, cost and benefit of ‘acquire’ decreases due to the deterioration rate. However, service cost and benefit vary based on the increase in the required number of services for the machine.

In the third scenario, it is assumed that the company purchases the machine and rents it to the customer. In this case, the provider owns the machine and thus $B_p = 1$ and $B_s = 0$. The CBA results of PSS-2 ($B_r = B_R = 1$) for Scenario-3 is illustrated in Figure 8. In this scenario, the total annual cost of servitization includes acquire, in-service and end-of-life (i.e. end of contract) costs. The monthly cost is between £32.7K and £80.8K, and the

monthly total benefit is between £41.6K and £100K. Therefore, the cost-benefit ratio for Scenario-3 differs between 1.24 and 1.27, and there is an average of 26% profit for the service provider. In these scenarios, the contract length is considered as one year only. For such a short-term contract, although the service cost-benefit ratio increases ($\sim 65\%$) for PSS-2 type, the total ratio is the lowest. Further scenario analysis is, therefore performed and presented in Section 5.2.

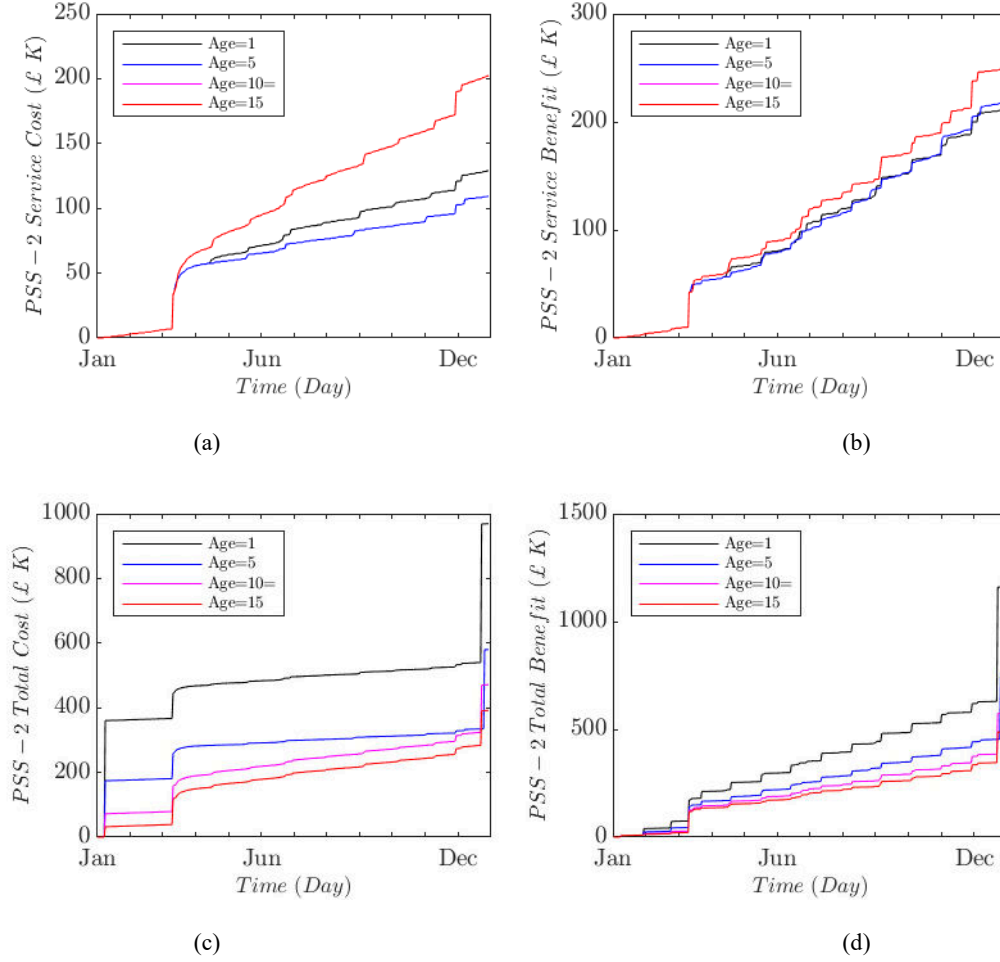


Figure 8: Scenario-3 Service (a) cost and (b) benefit and total cost (c) and benefit (d) of PSS-1 type contract over one year

5.2. Scenario Analysis

To perform the CBA estimation under uncertainty further and to analyse PSS contract decisions through speculating various possible outcomes, scenario analysis is presented in this section. For the next set of experiments, the simulation model time was set for 5, 10 and 15 years for the length of the contract. The age of the machine tool varies between 1 and 15 years old. Other model inputs were considered based on the data within Table 3 and Table 4. The three scenarios were considered separately testing 16 (i.e. 4 different contract length with 4 different machine ages) simulation experiments for each scenario. In total, 96 simulation experiments were completed, and the results are presented as a heat-map showing the service and total cost-benefit ratios for each, as illustrated in Figure 9 to Figure 11 for scenarios 1 to 3 respectively. In Scenario 1, the average ratio for the total cost and benefit increases slightly when the machine is older. However, for long-term contracts (i.e. > 10 years), this ratio decreases. The average ratio for the service cost and benefit are similar for the first and the second scenarios, since the service contracts are the same and there is no product purchase or

end-of contract cost and benefit elements. In Scenario 2, the average ratio for total cost and benefit increases slightly when the machine is older. However, this ratio is less than the ratios in the first scenario. However, for long-term servitisation contracts, the cost-benefit ratio increases by 3% in the second scenario. This figure increases by 50% in the third scenario. Considering the total cost and benefit, PSS-2 is more beneficial for the service provider compared to PSS-1 type contract.

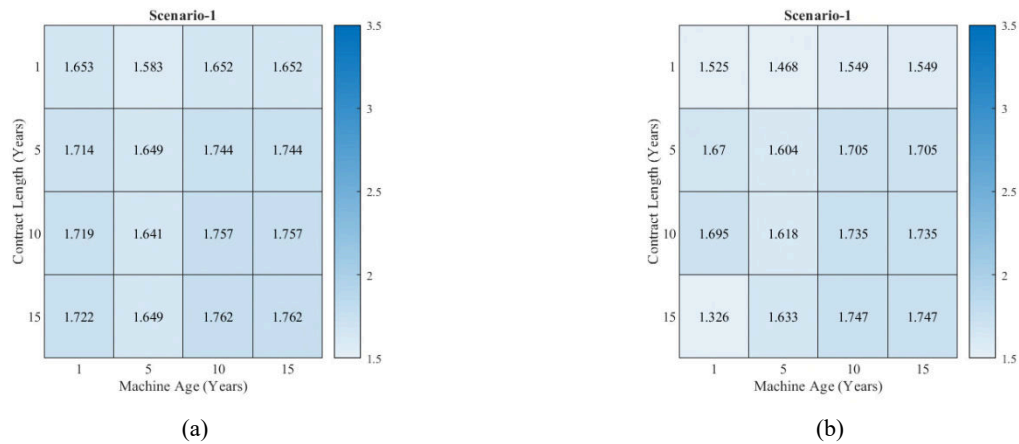


Figure 9: Scenario-1: Heat-map matrix of machine age versus contract length for (a) Service and (b) Total CBA ratio

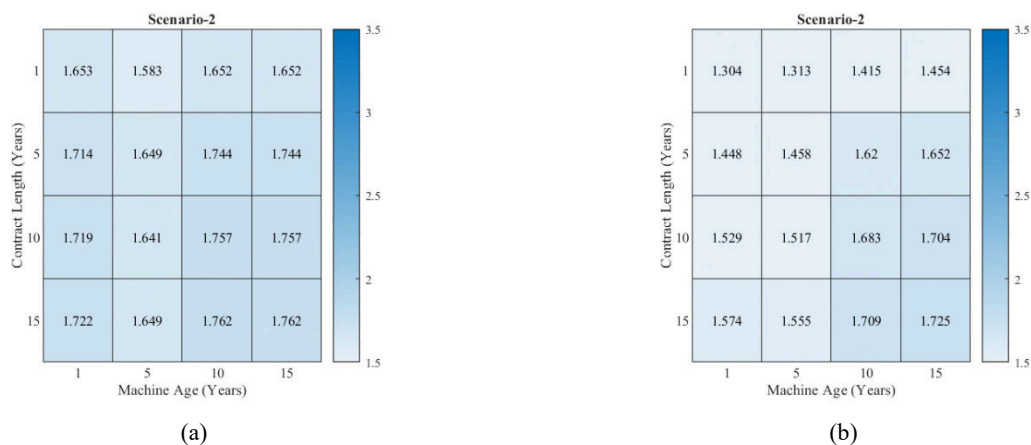


Figure 10: Scenario-2: Heat-map matrix of machine age versus contract length for (a) Service and (b) Total CBA ratio

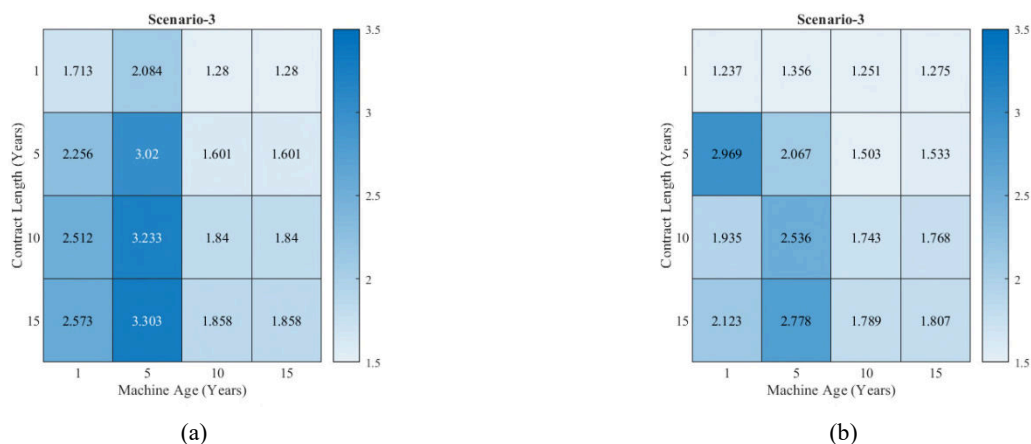


Figure 11: Scenario-3: Heat-map matrix of machine age versus contract length for (a) Service and (b) Total CBA ratio

5.3. Uncertainty Quantification

The simulation model time (i.e. the length of the contract) is set to 15 years and the model generates the CBA results considering the model parameters' distributions and their variations. The probability distribution of the model parameters are based on Table 3 and Table 4. To quantify the uncertainty in the annual cost and benefit of the contract, the random number generation in the agent-based simulation model is used. The uncertainty is quantified using stochastic data analysis. The histogram graphs have been developed to calculate the Probability Density Function (pdf) for the service and total cost and benefits over 15 years for a 15 year-old machine tool, as illustrated in Figure 12.

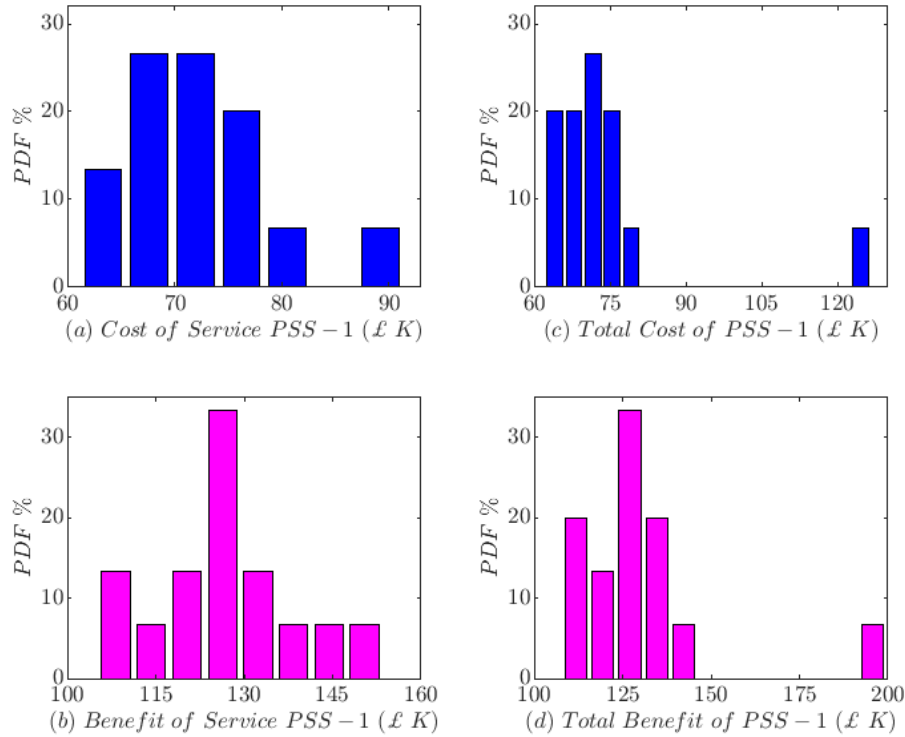


Figure 12: Scenario-1: Histogram pdf for the annual (a) cost and (b) benefit of PSS-1 from provider perspective over 15 years

The pdf has a Poisson distribution with $\lambda_c = \sim£74.2K$ and $\lambda_\pi = \sim£129.5K$ for total cost and benefit mean values respectively. Moreover, the graphs illustrate that 86.6% of the monthly PSS cost falls between £5.2 – 6.5K and similarly 86.6% the annual benefits fall between £9 – 11.54K. However, just above 1.3% of the monthly costs and benefit become over £10.42K and £16.39K respectively. Validation is therefore completed by the expert intuition from the studied company and real system measurements in terms of simulation model inputs and outputs. Similarly, for Scenario 2 and 3, the uncertainty in CBA for PSS-1 and PSS-2 type contracts are quantified as presented in Figure 13 and Figure 14, respectively. In the second scenario, the pdf has a Poisson distribution with $\lambda_c = £77.35K$ and $\lambda_\pi = £133.4K$ for cost and benefit mean values respectively. Moreover, the graphs show that 80% of the monthly PSS cost falls between £5.23 – £6.4K and 80% of the annual benefits fall between £9.15 – £11.4K. However, just above 3% of the monthly costs and benefit become over £14.3K and £20.8K respectively. In the final scenario, $\lambda_c = £128.6K$ and $\lambda_\pi = £232.3K$ for cost and benefit mean values respectively. The histogram pdfs show that 80% of the monthly PSS cost and 73% of monthly benefits fall between £7.9 – 10.8K and £17.5 – 20K respectively. Moreover, just below 1% of the monthly cost is over

£23.2K and just above 1.3% of the month benefits is over £26.95K.

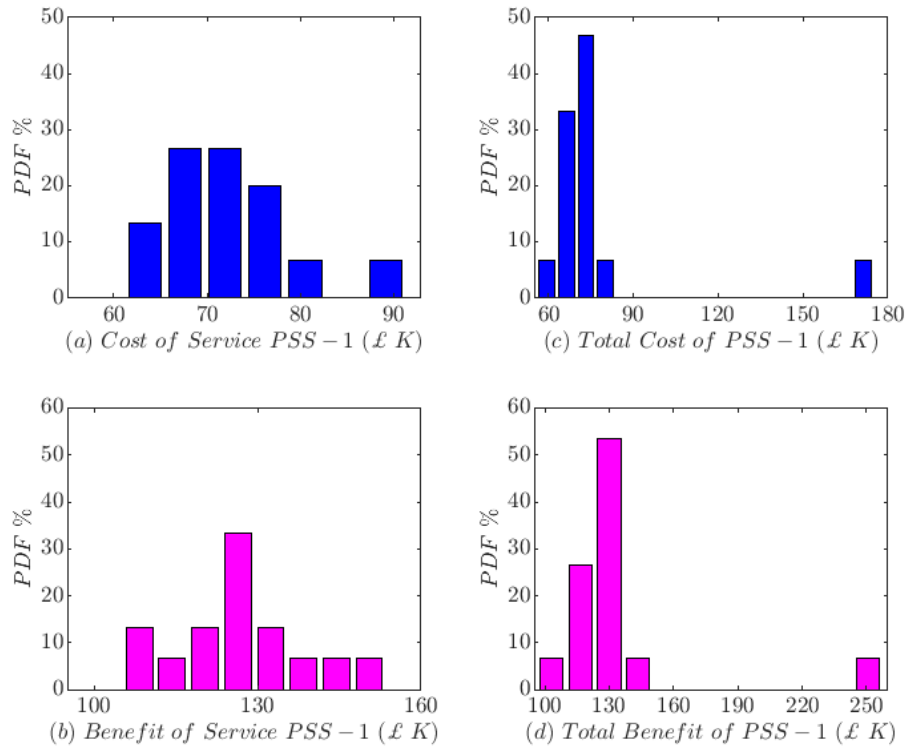


Figure 13: Scenario-2: Histogram pdf for the annual (a) cost and (b) benefit of PSS-1 from provider perspective over 15 years

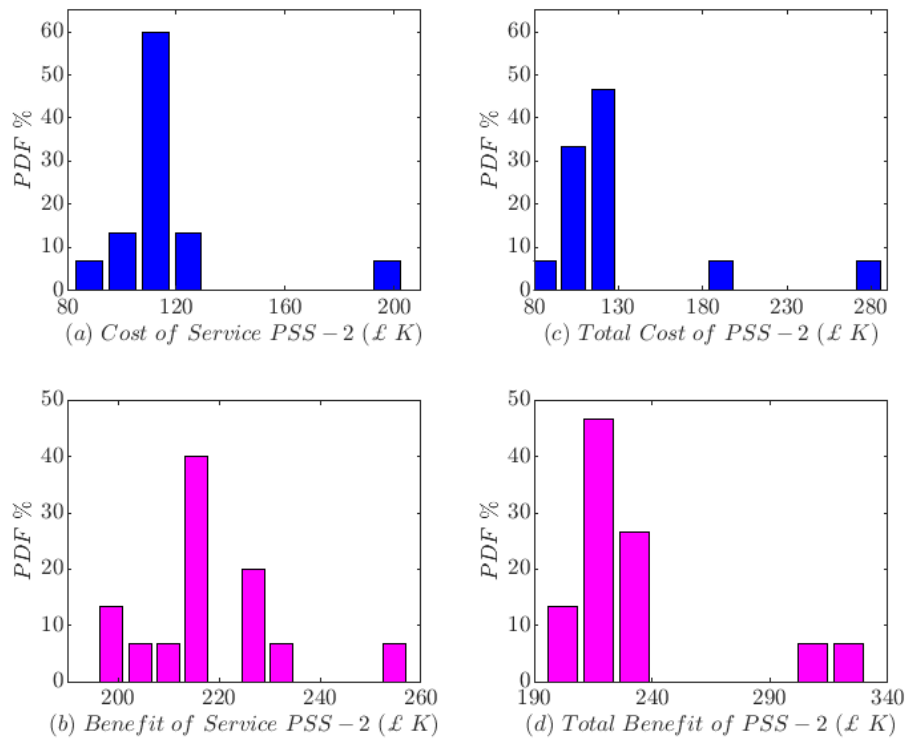


Figure 14: Scenario-3: Histogram pdf for the annual (a) cost and (b) benefit of PSS-1 from provider perspective over 15 years

5.4. Model Verification and Validation

Model verification and validation have been completed over the development of PSS cost-benefit conceptual and simulation models with a view of presenting an effective agent-based model for quantifying the uncertainty in PSS type contract decisions. Initially, to verify the presented PSS cost-benefit conceptual model and the simulation model in AnyLogic, two full-day workshops with the Research and Development Manager (with more than thirty-five years' experience) and one interview with the Commercial Director (with more than twenty years' experience) of the Company were carried out. **Workshop-1:** logical structure of the agent-based cost-benefit conceptual model (Figure 3) is verified by comparing it with the real-world case study and according to the customer requirements. In the workshop, the structure of the through-life cost and benefit events (i.e. states in the ABM), and cost and benefit drivers and unit of measures for different PSS solutions have been tested and confirmed. **Workshop-2:** the outcome from the first workshop verified the CBS for PSS at each phase of the service and product lifecycle. Specification requirements, three-point estimation and rate of returns for each cost and benefit driver, are verified based on the same real-world case study. The outcome from the second workshop has been later used to test the simulation model. The simulation model was anti-bugged before the interview to check the behaviour of the model based on different parameter selection and scenarios, as discussed in Section 5. At the **Interview** session, a structured walk-through technique was implemented to verify the simulation model. The simulation model structure (see Figure 4), different states in the ABM model and the input parameters, variables were explained to the company's experts. The outcomes from the different scenarios based on the studied case (see Figure 6-Figure 8) were thoroughly discussed in details. To provide the information about the internal behaviour of the model, a graphical dashboard and data analysis results were presented. The developed simulation model provides a dynamic display of model behaviour whilst the model is executing. This provides detailed information about the current inputs and outputs of the simulation performance. Model validation is carried out using a real-scenario approach. The simulation model has been used to predict the PSS contract cost, and the results have been compared with the case study. Three distinct aspects were considered: model assumptions, input parameters and distributions, and output values. The simulation model considered three different servitization scenarios, and it generates the CBA outcomes for PSS-1 (inclusive spare part) and PSS-2 (availability-based) with the presence of uncertainty. Since the studied company has not yet implemented and practised PSS-2 servitisation type contract, the output values are tested for PSS-1 type contract. According to the historical data from the company, the base service cost for scenario-1 can be approximated with a flat monthly rate of £4.0K. The uncertainty quantification results for this scenario presents that 86.6% of the monthly PSS cost falls between £5.2 – 6.5K (Figure 12a). The outcome indicates that an approximate 33.11% deviation should be considered between the base cost and the contract service cost to prevent an under-pricing contract decision (Figure 15). This occurrence can be triggered by eliminating the uncertainty in cost estimation in PSS contractual agreements.

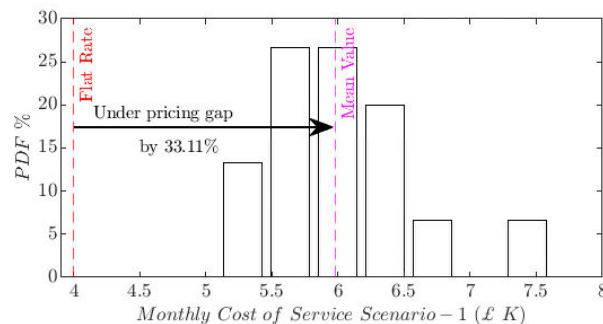


Figure 15: Histogram pdf for the annual cost of PSS-1 in Scenario-1 over 15 years versus the case study flat rate value

6. Discussion

Most of the existing PSS frameworks and models for cost and benefit estimation follow top-down approaches, or standard activity-based costing without considering uncertainty (Baxter et al., 2009; Bianchi et al., 2009; Geum et al., 2011). These methods are found beneficial in PSS contract decisions when limited data about products and services are available, and the cost/benefit estimates are based on past projects and similar service contracts. When more data is available, a bottom-up approach can be used to provide a more accurate estimation. Despite their accuracy, such methods are data-intensive and require relatively detailed and complicated calculations. Regardless of the estimation approach, assessing uncertainty in PSS is informed by the preparation of estimates for cost and benefit elements (i.e. deterministic, stochastic) (Erkoyuncu et al., 2011). Deterministic uncertainty in the form of sensitivity analysis is a popular approach where variability in service costs and benefits are constant and repeated over time. In contrast, stochastic estimation with probabilistic variability enables the uncertainty quantification; this can be done by considering the cost/benefit measures as random variables that take a range of different values over time (Estrada et al., 2017).

In this paper, it is argued that PSS has several behaviours that necessitate the use of a stochastic approach for quantifying the uncertainty in PSS contract decisions. These behaviours are dynamic due to the delivery of several service solutions over the length of the contract, and stochastics due to the inseparability of services and variability of support interventions and customer demands. Moreover, PSS can be characterised by different types of uncertainty (Erkoyuncu et al., 2019). Accordingly, considering the inter-relationships between through-life cost/benefit events over the contract length benefits the uncertainty quantification in PSS decisions. Compared to the other dynamic simulation techniques, ABM offers a more flexible, interactive, and effective approach (van der Veen, Kisjes and Nikolic, 2017). Using ABM, the profitability of PSS contracts can be assessed more effectively in view of aggregate uncertainty and dynamism of interactions between cost and benefit drivers through the length of PSS contracts. In this paper, a through-life CBA conceptual model for PSS from the service providers' perspective is presented. The cost-benefit evaluation is completed by adopting the bottom-up ABM approach to evaluate the cost and benefit values of the two types of inclusive spare part and availability-based PSS solutions. The proposed CBA simulation model is designed and developed to predict and estimate the through-life cost/benefit for service providers in PSS contract types. The proposed model offers flexibility with respect to customer requirements, service interventions, and product lifespan considerations. It also enables decision-makers to efficiently assess different PSS contracts' profitability at the bidding stage and with a higher confidence level. These advantages of the model have been demonstrated in the servitization case study for spare-parts and availability-based contracts, as presented in Section 5.

This paper contributes to the literature by proposing a generic, yet novel framework using the agent-based simulation technique for quantifying the uncertainty in cost and benefit estimates of PSS contracts. The contribution of this study has three main pillars: 1) the development of through-life CBA simulation model for PSS contractual agreements from bespoke service providers' perspective using a bottom-up ABM approach, 2) uncertainty quantification in PSS contract decisions in the presence of dynamic complexity due to the aggregate uncertainty related to service cost and benefits, service lead-time and occurrence of maintenance and repair interventions, and 3) analysis of the optimal PSS solutions for a more profitable contractual agreement under an aggregated aleatory uncertainty.

This study enhances the current understanding of PSS business models for solution providers. It goes beyond the existing qualitative research by providing a thorough quantitative analysis to assess different PSS contracts' profitability under aggregate uncertainty. The findings and simulation results are in-line with the current studies (Storbacka, 2011; Raddats et al., 2019) on effective PSS business models. Integrating the CBA model with stochastic data analysis leads to the examination of CBA over short-term (i.e. <10years) and long-term

(i.e. >10years) contracts and identification of most profitable servitization agreements. The developed model is applicable to service providers in different industrial sectors, and the presented bottom-up CBA approach provides a detailed and accurate estimation of the contract. Accuracy in the proposed bottom-up approach is achieved through the process of starting at the very foundation of a service contractual agreement and working the way up through each cost and benefit on the servitisation breakdown structure for each PSS solution. Such detailed analysis can ultimately facilitate strategic decision making for the PSS solutions.

According to the case study, this paper examines three main outcomes: First, the PSS through-life CBA is studied for the case study. Second, the uncertainty of annual CBA for different servitization agreements are quantified in the form of pdf graphs using stochastic data analysis. Third, the optimal servitization solution is analysed for a more profitable PSS solution. The results show that for long-term service contracts, servitisation with PSS-2 solution are more beneficial as the profit increases by about 48% compared to PSS-1 solution in Scenario 2 for the availability-based contract (use-oriented), and 50% compare to upkeep contract in Scenario 1 for the inclusive spare part contract (product-oriented). However, for short-term service contracts upkeep is more beneficial. Moreover, for relatively new products (e.g. machine tool under age 5 years) PSS-2 contract is more beneficial with an increase of 56% in profit. However, for rather old products without retrofit PSS-1 is more profitable. Moreover, the results from the case study confirmed that excluding the uncertainty for PSS cost estimation leads to an under-pricing contract decision.

7. Concluding remarks

This paper has presented a framework for PSS cost-benefit analysis model development comprising stochastic CBA model and simulation considering aggregate uncertainty. The simulation is implemented for different PSS solutions from the service provider perspective using the bottom-up ABM technique. The state-chart machine UML diagram of servitization and the list of input for different cost and benefit drivers, through-life cost event cycle-times, frequency of events and different contractual agreement scenarios have been presented. The model considers dynamic complexity in terms of aggregate uncertainty in cost and benefit values, processing cycle-times and frequency of events such as failure and different maintenance interventions, over the contractual agreement. Considering dynamism and aggregate uncertainty in cost estimation enhance the accuracy and the level of confidence in PSS contract decisions. To test the validity of the CBA conceptual model and the dynamic simulation model, a case study in the machine tool sector was used. Based on the real-world data from the case study, different servitization scenarios were tested and validated using experts' intuition. Moreover, the optimal PSS solution and the uncertainty of the annual PSS cost and benefits were quantified. The outcomes from the simulation model provide support and detailed information regarding the efficiency and profitability of servitisation agreements from the provider's perspective.

The conceptual CBA model and the servitization simulation model can be used by decision-makers as a tool to make a more informed commercial servitization agreement. The proposed framework and the CBA model differ from the existing models; in our approach, the through-life costs and benefits of a service or a product throughout the servitization contract are considered. Moreover, the model and the framework follow a stochastic bottom-up costing approach for CBA, to quantify the aggregate uncertainty in PSS contract decisions using the ABM and pdf techniques.

The interactive bottom-up nature of the CBA model using the agent-based technique for PSS, together with the integration of probabilistic uncertainties on the model input, can enhance the flexibility and modularity of PSS design. Further to this work, the effect of the proposed framework and the CBA model on PSS flexibility, modularity and customization (Chen and Hao, 2010; Li et al., 2019; Zhang et al., 2019) can be studied in more

details. Moreover, further research should examine other scenarios that might incorporate additional uncertainties embedded into PSS contracts. For instance, short product lifespan may imply that the product lifespan is less than the PSS contract, therefore requiring other uncertainties such as product replacement to be incorporated into the model. In this regard, future research should explore how product lifespan may influence PSS contracts implementation and its effectiveness. The applicability of the framework can also be tested in wider service industries such as marine, and oil and gas. Moreover, the proposed framework can be utilised in different contexts to explore the impacts of product and service innovation capabilities in order to improve servitization. Furthermore, the dynamic simulation model can be applied and tested for capability-based and outcome-based PSS contracts (as referred to as PSS-3 in this study). Moreover, by integrating the CBA model of PSS from the customer perspective, a win-win PSS can be designed, which is beneficial and profitable to both sides of a servitization agreement. Furthermore, the simulation model can be integrated with sensitivity analysis and parameter variation techniques to provide more detailed information regarding PSS contractual agreements.

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Appendix

Primary data collection	Purpose and findings
<u>workshops</u>	
<u>with:</u>	
Service provider	<ol style="list-style-type: none"> 1. Current practice, opportunities of servitisation for Machine Tools sector 2. Servitisation needs and requirements <ul style="list-style-type: none"> o Breakdown responses o Machine tool capability testing and optimising o Machine relocations and installations o Maintenance support o Training and Retrofits 3. Possible servitisation scenarios for service provider and their customer (and partners) <ul style="list-style-type: none"> o Inclusive spare part contract & corrective maintenance o Availability-based contract, remote monitoring (using different sensor technologies) & preventive maintenance 4. Servitization conceptual model – version 01 <ul style="list-style-type: none"> o Intellectual property rights 5. Decision factors that influence the level of servitisation <ul style="list-style-type: none"> o Resource availability o Quality of service o Customer requirement (Equipment availability, maintainability, reliability, supportability) o Flexibility and adaptability of industry (service providers and customer) o Servitization maturity level (data, information, knowledge, culture) o Affordability and cash flow 6. Performance and precisions aspects of servitisation business model requirement for machine tool maintenance 7. Excel-based cost-benefit analysis tool 8. Servitization conceptual model – version 02, Servitization agent-based conceptual model – version 01 <ul style="list-style-type: none"> o Lifecycle cost breakdown structure o PSS environment interlinks, stakeholders and agents for product-oriented and use-oriented PSS o Decision-making framework of service-based business models for machine tool maintenance

	9. Completion of lifecycle cost structure based on the initial verification session with the service provider company 10. Requirements specification for the servitization agent-based model following the initial verification session with the service provider company 11. Finalizing the cost and benefit drivers for different PSS scenarios with the service provider company 12. Servitization agent-based conceptual model – version 02 based on final cost/benefit structure 13. Reviewing data analysis and cost estimation approaches, requirements 14. Reviewing servitization scenarios and what-if conditions with the service provider company 15. Confirming desirable outcome, interface (dashboard) with the service provider company 16. Finalizing agent-based conceptual model
Customer	17. Servitisation needs and requirements <ul style="list-style-type: none"> ○ Condition monitoring ○ Preventive maintenance ○ Spare parts availability ○ Upkeep, upgrade, retrofit ○ Training and knowledge 18. Servitisation challenges in implementation <ul style="list-style-type: none"> ○ Data security and data sharing ○ Commercial visibility ○ Costing and financial feasibility
<u>Interviews with:</u>	
Service provider	1. Verifying the repair and maintenance practices for a machine tool 2. Verifying the decision factors that influence the level of servitisation within the service provider and their customer 3. Verifying the lifecycle cost structure using an agent-based technique 4. Verifying the requirement specification for the servitization agent-based model
<u>Site visits</u>	
Both Service provider & Customer	1. Familiarised with the service provider company practice and operation 2. Familiarised with the case study of a Machine Tool in order to establish performance metrics 3. Familiarised with the service provider customer practice and operation 4. Familiarised with the concept of servitization and PSS conceptual models for wider audience and its implementation 5. Familiarised with the agent-based technique, simulation approach and cost-benefit analysis at its implementation

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