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A manufacturing framework for capability-based product-service systems design

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Abstract

Manufacturers aim to design product-service systems (PSS) which integrate services with products to attain sustained competitive advantage from a life cycle perspective. PSS design should be customised solutions which are aligned to integrated stakeholders' capabilities, a subject which the extant literature has not sufficiently addressed. This paper proposes a systematic framework for the PSS solution provider to address this aim and operationalizes this through software developed for PSS design which models stakeholders' individual activities and simulates their occurrences depending on their relations. The framework stresses that integrated stakeholders' capabilities define continuing ability to generate a desired operational outcome for the customers. The paper reports a PSS design case for a laser system manufacturer and then applies the framework to it. The industrial experts' views on this framework reveal that it helps to develop PSS design from a holistic systems approach which facilitates a change in the designer's mindset from a product-centric to a systems-centric. The level of trust and transparency required for this framework is argued to be absent in most industrial sectors, being one of the foremost limitations for implementation of PSS.

Keywords: Product-service system; Design; Framework; Simulation; Representation

Background

Particularly in the light of recent economic downturns, manufacturers require alternative strategies to cope with globalization and reduced profit margins, and for retaining and attracting customers. One promising approach in helping manufacturers to achieve these objectives is product-service systems (PSS). This approach facilitates manufacturers in bundling products and services together to create a sustained competitive advantage. It aims at providing more value by fostering the optimal use of resources which can be sustained for both consumption and production. Major advantages for the PSS solution provider include prolonged and strategic relationships with the customer and product/service improvements based on the improved understanding of customer needs. However, Neely's [1] findings from the analyses of a large industrial database were that designing, implementing and managing PSS is a huge challenge to the provider as there are distinct possibilities of economic downturns.

A review of current PSS literature [2] reveals that the theories and methodologies to aid the design of PSS are still in their initial stages of development, and substantial research is required to develop a practical PSS design methodology along with supporting tools. Also, from the interviews which were conducted with 15 industrial maintenance experts of large technical systems such as aerospace engines and related systems, naval ships, land vehicle systems, trains and trucks, our understanding is that, currently, PSS conceptual design in practice is *ad hoc* (fairly intuitive) and lacks a systematic approach in allowing heterogeneous (tangible and intangible characteristics) aspects to be reflected within the PSS design process. The interaction of the stakeholders in the design process and the unique characteristics of products, services, networks of players as well as the supporting infrastructure [3] which are involved in the design of PSS all demand new theories, methodologies, tools and techniques.

The aim of our research is the formal development of a PSS design framework for the PSS solution provider to create customised PSS designs aligned to integrated stakeholders' capabilities. The proposed PSS framework has a view to developing PSS designs to support long-term business solutions from a capability viewpoint whilst stressing the development of additional value to customers by fostering the optimal use of integrated stakeholders' resources. A framework has been developed to address gaps identified in the literature. The framework encompasses a systems thinking perspective, which aims to improve overall PSS design on a system level and avoid sub-optimized solution towards any single activity across the whole life cycle-including remanufacturing. Therefore, this work did not focus specifically on the remanufacturing phase. To help PSS designers' model and simulate PSS designs, a framework has been implemented in a software environment. Service CAD integrated with a life cycle simulator (ISCL) [4] has been chosen because it provides both modelling and simulation facilities. A simulation facility is used to quantitatively evaluate the performance of the PSS designs regarding the requirements. This paper is structured into seven sections detailing: the gaps identified in the literature, understanding industrial challenges in PSS development, defining the constituents of PSS design, a step-by-step illustration of the proposed framework, application of the proposed framework to an industrial laser system case study, academic and industrial experts' views on this framework, and conclusions with future directions of research. Figure 1 illustrates the structure of the paper with the research methodology description.

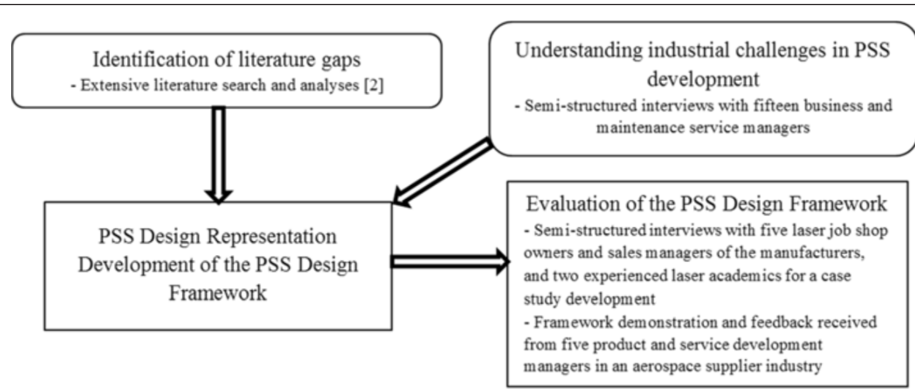

Figure 1 Structure of the paper with the research methodology description.

Related PSS design research

In this paper, four state-of-the-art methodologies which have been proposed for PSS design are reviewed: Komoto and Tomiyama [4,5] proposed a method to design and analyze business models of manufacturers by focusing on the variations of services in product life cycles (e.g. rental, sharing, maintenance and upgrade services, and pay-per-function sales). The business models are modelled using Service CAD and are quantitatively analyzed using a life cycle simulation technique [6]. Sakao and Shimomura [7] and Shimomura et al. [8,9] developed Service Explorer for service engineering to design products with a higher added value from enhanced services. Service Explorer is also a Service CAD software which employs discrete event simulation methods for the evaluation of PSS design. The scope of evaluation is different from the sequence of activities of customers in a specific service environment (e.g. restaurants) [9] to those of the activities of manufacturers and users of products during their entire life cycle [4]. Maussang et al. [10] presented a PSS design model to assist engineers in the joint development of physical products and interacting services to generate more added value. Alonso-Rasgado et al. [11] and Alonso-Rasgado and Thompson [12] proposed a total care design process to develop innovative offerings consisting of hardware and services integrated to provide complete functional performance. Compared to other methodologies in the literature, these four methodologies are detailed, demonstrated through industrial examples, published in refereed journals and widely discussed in the literature. Table 1 compares four state-of-the-art PSS design methodologies with reference to six characteristics. The chosen six characteristics are important for discussion based on which the proposed framework is developed and nurtured. Table 1 illustrates the differences between the approaches proposed in the literature and aids to identify the literature gaps.

This table shows that all of the authors define PSS in terms of increasing the value of hardware (functional entities that carry out the elementary functions of the system) by focusing on services (entities that will ensure the smooth functioning of the whole system). Some of the aforementioned methods can deal with capabilities of stakeholders as parameters of PSS models employed in their methods. However, they do not provide specific methods or guidelines for PSS design based on the measurement, control and increase of capabilities. Furthermore, a common problem in PSS definition is the usage of different terms to define constituents of PSS. Various terms such as environment, activity, provider, receiver, channel, content, receiver state parameter (RSP), agent, and relationship among RSPs, function, entity and attribute parameters can create confusion and misunderstanding with regards to defining and communicating PSS design amongst research and industrial practitioners - a simple and unified PSS definition illustrating its constituents is required. Also, a PSS design representation technique should be commonly accepted to implement and develop a computer-supported PSS design platform for the effective evaluation of PSS performance and the capture and reuse of PSS design knowledge. The next section summarizes the industrial challenges in the PSS development.

Industrial challenges in designing PSS

This section summarizes the challenges which have been observed by the experts in business and maintenance of several providers of large, technical, capital-intensive and sensored product-service systems. Specifically, these are challenges observed in

Table 1 Comparison of state-of-the-art PSS design methodologies

Characteristics of the proposed methods	**Komoto and Tomiyama** [4,5]	**Shimomura et al.** [7-9]	**Maussang et al.** [10]	**Alonso-Rasgado et al.** [11,12]
PSS definition	A set of services in the life cycle of products, whose characteristics are customized with respect to the services	Service/product engineering as a discipline seeking to increase the value of artefacts by focusing on service	PSS are composed of physical objects and service units that relate to each other	Total care products as integrated systems comprising hardware and support services
Aim	Support the design and analysis of integration of services with a product life cycle and the identification of the characteristics of products	Focuses on service engineering to design products with a higher added value from enhanced services	Assists engineers in the joint development of physical products and interacting services to generate more added value	Develop innovative offerings consisting of hardware and services integrated to provide complete functional performance
The first step	Define goal(s) and quality as specified by product users	Define the state change of the receiver	Customer expectations, needs and specifications involved in the whole life cycle	Business ambitions of the client
PSS variables	Stakeholders in a product life cycle and the activities (e.g. production, use and services)	RSP, sequential chain of agents, relationships among RSPs, function, entity and attribute parameters	External functional representation, specifications of the physical elements	Customer's business needs, business solutions, clearer view of the hardware and/or services
PSS design representation technique	A graph description based on service formulation	Business process markup language, service blueprint	Scenarios and FBD	No representation technique is mentioned
Evaluation of PSS designs	Life cycle simulation considering multi-objectives (e.g. economic and environmental)	AHP, Dematel and Petri nets (discrete event simulation)	No evaluation approach proposed	Business case validation and evaluation of alternatives

RSP, receiver state parameter; FBD, functional block diagram; AHP, analytic hierarchy process.

maintenance planning. The maintenance experts were interviewed to understand engineering services issues because maintenance service occupy nearly three quarters of acquisition and support costs as compared to other aftermarket services [13]. Semi-structured interviews were held with five companies: aerospace engines and related systems, naval ships, land vehicle systems as well as, trains and trucks. Overall, manufacturers generally lack the competence to address the challenges of PSS-type contracts. The reasons for this situation are listed below:

- Customers now have higher expectations from manufacturers.
- Product-orientated manufacturers tend to be product-centric and so do not have the mindset to develop and deliver PSS.
- There tends to be very few technical employees of manufacturers interacting with customers.
- Customer issues could take months or years to be resolved if they are to be addressed by services.
- Current PSS design methodologies tend to be *ad hoc* and tend not to start with the business case.
- The design of the product and service is not completely performed simultaneously and maintenance is mostly an afterthought; only slight modifications to the product are considered following a decision to create a PSS.
- Manufacturers tend not to perform enough modelling to fully understand maintenance activities sufficiently to undertake PSS-type contracts.
- There is a lack of high-level strategic decisions to, for example, trade-off between design, maintenance and supply network solutions for the efficiency of the overall solution.
- A common understanding of PSS-type contracts is lacking across teams.
- The framing of competitive maintenance offerings is a challenge. Most importantly, the consideration of value-added benefits to customers and a suitable operative model between stakeholders to ensure the throughput of inputs as well as reasonable profits tends to be lacking.

These challenges present obstacles to the design of PSS solutions offered by these companies. As a result of an investigation of the state-of-the-art methodologies and challenges in designing PSS in the literature, we have framed the following research questions to be answered in this paper:

- What constitutes PSS design? (This question intends to define characteristics and properties of the system).
- How can customised PSS solutions be designed to be aligned to integrated stakeholders' capabilities?

The next section discusses our definition and constituents of PSS design.

What constitutes PSS design?

PSS design aligned to integrated stakeholders' capabilities is mandatory to achieve a viable and sustained solution for an intended duration. A capability can be defined as the continuing ability to generate a desired operational outcome [14]. The definition of capability exemplifies how the joint capability of all the stakeholders could achieve the desired outcome required by the PSS customer and for the PSS provider to design economically sustainable PSS. Considering capabilities as a core element, we defined PSS design as a process to synthesize and create sustained functional behaviour through tangible products and intangible services. Sustained functional behaviour represents the degree to which a system can continuously achieve its purpose by adapting its capabilities. To represent sustained functional behaviour, an activity-based modelling approach is proposed (Figure 2). An activity could be defined as an action incorporated or influenced in the customer's system. The activity-based modelling approach is in-line with the definition of the PSS design processes provided by Komoto and Tomiyama [4], in which designers define the activity to meet a specified goal and quality, and also define environment as being the circumstance within which that activity is realized. Furthermore, Matzen [15] and Tan [16] emphasized activity systems in modelling PSS development. Tan focused on customer activity cycles whereas Matzen viewed activity systems with a broader and general view encompassing both customer and company activities. Both Matzen and Tan conceptualized PSS solutions by considering artefact-, activity- and actor-based domains with slight differences. In this work, capability is mapped through resources, competences, responsibilities undertaken and outcomes. Inputs to a particular activity are mapped through customer needs and precedence activities' outcomes. Other influential parameters on an activity are enforced through an environmental variable. In Figure 2, the coloured boxes represent modification incorporated in the existing system.

We propose in this work that a network of seven parameters, namely *activities*, *customer needs*, *environmental influences*, *resources*, *competences*, *responsibilities*, *inputs (precedence activities' outcomes) and outcomes*, are sufficient to model PSS design. We have chosen these familiar and simpler terminologies for easy acceptance within industrial practitioners. These parameters map the required information for mapping products, services, processes and interactions of all the elements involved within the system.

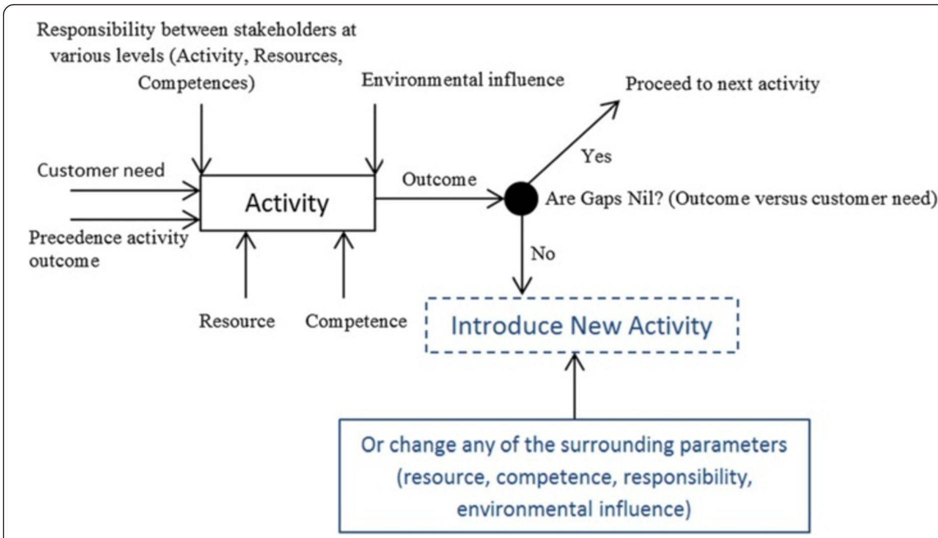

Figure 2 **Representation of PSS design constituents (coloured boxes represent modification to the existing system).**

Mapping of these parameters helps to understand the gaps within the current customer's system (PSS user) and aids the development of innovative PSS designs to satisfy customer business needs. The derivation of these parameters in PSS design is presented in the proposed framework. The framework is detailed step by step in the next section.

A capability-based PSS design framework

The proposed framework aims to support manufacturers in designing customer-adjusted PSS designs which are aligned to stakeholders' capabilities. The core principles supporting this framework to realize this aim are as follows:

- Gap analysis: Identification of value addition required in the customer's system (PSS user) by understanding their needs through assessing customer's business activities and constructing relative key performance indicators [17]. This initial step lays a foundation to develop customised solutions.
- Generation of new and/or re-designs of integrated product and service solutions along with conditions and consequences of each design. These designs take into consideration the partial substitution of product and service shares over the life cycle.
- Responsibility assignment which considers the capabilities of all the stakeholders involved at various levels: activity, object (resources), and parameter (competences). This assignment enables the derivation of innovative function-, availability- or result-oriented business models.
- Synthesis-generated solutions in each gap to improve the overall PSS design on a system level and avoid a sub-optimized solution towards any of single activity, stressing the importance of resource effectiveness.
- Standard representation of PSS designs is required for effective communication across all the stakeholders.

These core principles are structured into 10 steps in the proposed framework (Figure 3). The steps mentioned in this framework are highly inter-dependent, and feedback loops exist between every step. The following sub-sections describe each step individually and detail the course of action involved.

Step 1: understand customer needs

The first step in deriving customer needs from their complete business activities and existing systems is not taken into consideration in most of the PSS methodologies; commonly, customer needs are deemed to be the requirements of products and services. Note that the term ‘customer’ represents the PSS user throughout this framework. Figure 4 illustrates a typical product-centric life cycle. The product life cycle within the customer's business process only partly covers operation. Although the consideration of the product life cycle improves the understanding of what is required of products and services, extra value could be offered by considering the customer's goals as revealed by their business processes (Figure 4). Moreover, understanding the customer's business processes reveals the ‘need behind the need’ [18] of the customer that has to be fulfilled. Tan [16] has emphasized that PSS solutions may be conceptualized by considering the product life phase, customer activities and actor network.

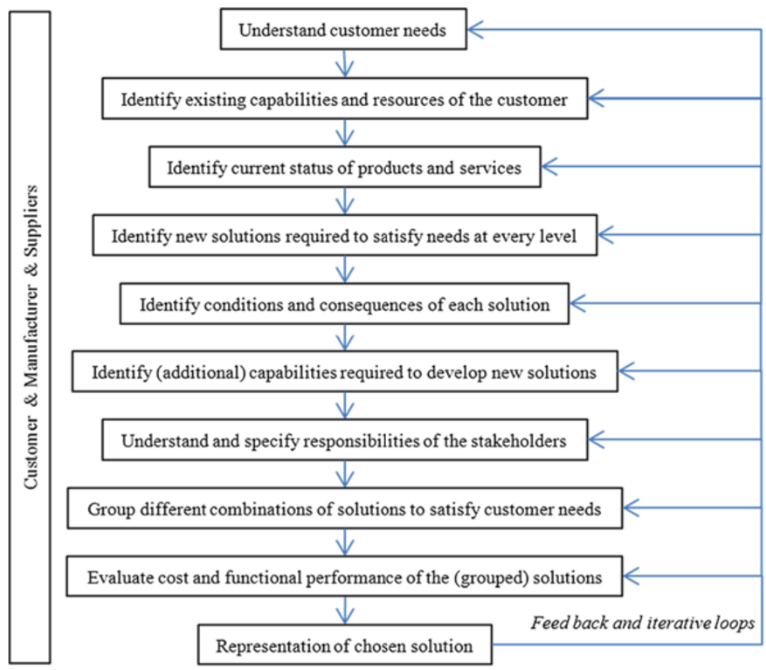

Figure 3 The proposed capability-based PSS design framework.

Figure 4 illustrates the point that it is the consideration of the capabilities that are required to use a product that presents opportunities to add value. Identifying and understanding the customer's overall needs should therefore be the foremost step in the design process. Once the overall customer needs have been identified by focusing on their business processes, the next step would be to identify the current capabilities of the customer.

Step 2: identify existing capabilities and resources of the customer

Identifying the customer's needs is followed by understanding of the customer's existing capabilities. Such an understanding helps to develop designs which are more aligned to their capabilities. A capability can be defined as the continuing ability to generate a desired operational outcome [14]. Capabilities can be realized through people, processes, tools and technology [19]. It should be noted that these elements are highly coupled and should be visualized together. Integration of these elements will be facilitated if the customer's activities are identified and the efficiency of each activity is measured. For this reason, capabilities should be mapped depicting their outcomes and the reasons for deficiency. Some of the parameters to assess each activity could be performance, time taken, reliability, responsiveness, expense and quality [20,21]. Such analyses will highlight the gaps within the customer capabilities that need to be filled by a PSS design. In the next step, in-depth analyses of existing products and services are performed to ascertain the degree to which the needs can be addressed.

Step 3: identify current status of products and services

The identification of existing products and services (whether they are on the market or just being developed) that could help to address the identified customer needs is

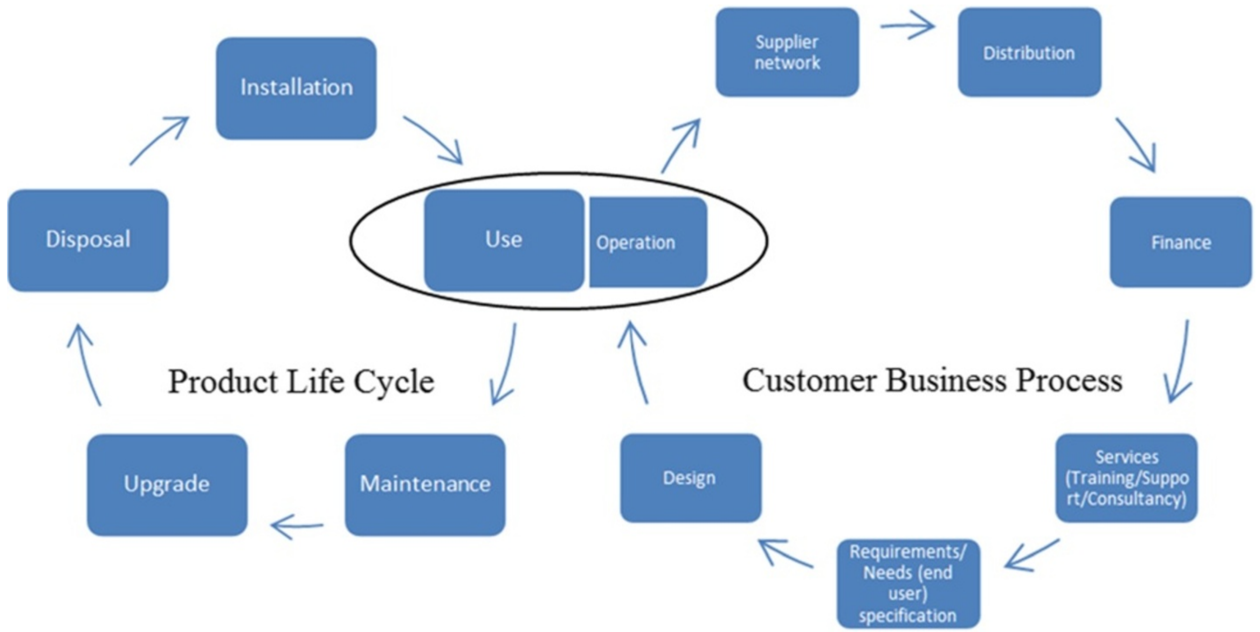

Figure 4 Integration of product life cycle in customer business process.

mandatory. The next step is to identify and highlight how these offerings could be changed or added to meet customer needs even more closely; this would involve identifying sub-systems within those products and services that need to be considered to achieve this change. This outcome could be achieved by:

- Comparing the key performance indicators for these products and services against those of the solution to meet customer needs.
- Performing root cause analyses to find out which sub-system within the products or services is responsible for failing to fully meet customer needs.

The data required for this step is available in most organizations through condition based monitoring and effective data management systems. The outcomes from these points should help to inform design as to how these offerings could be improved. It should help in the design of the right product and service mix to satisfy the needs of customers. For example, Figure 5 illustrates the capability shifts between machine capability and maintenance service. In scenario 1, the customer finds the amount of maintenance unacceptable as there is too much disturbance to business operations. Scenario 2 shows how the capability for a certain level of availability has shifted from the maintenance service to the machine: here, the machine is re-designed to require less maintenance. The next step details on approaches to develop PSS designs based on the gaps identified in the last two steps.

Step 4: identify new design required to satisfy needs at every level

The outcomes from steps 1 to 3: customer needs and capabilities and the properties of existing apposite products and services, will highlight the current gaps which could be filled by PSS designs. In particular, the capability map of the customer's processes will pinpoint the focus areas for development. Based on the conceptualization of PSS design through the network of seven parameters described in the 'What constitutes PSS design?' section, a new design should be generated for each gap by either introducing and/or modifying the current system in terms of activity, resource, competence and environmental influence. In this step, PSS designers have to identify possible designs for each gap identified. The designs should aim to eliminate or reduce the gap. For each gap, designs need to be explored at all of these levels. Design generation is a creative activity. To structure this process at the conceptual stage, we mapped resources for objects and competences for parameters and values. Table 2 illustrates sample designs

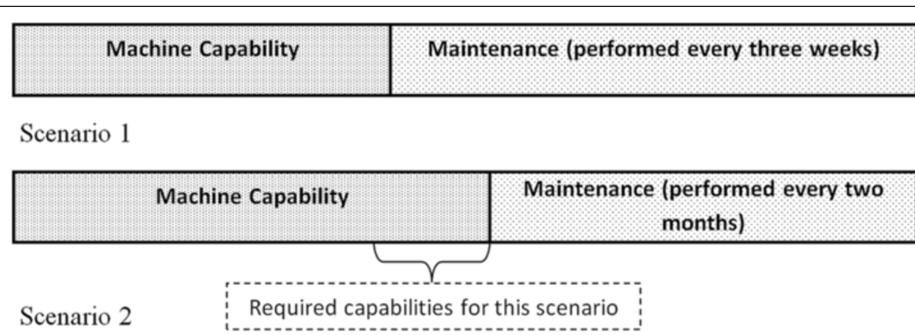

Figure 5 Scenarios 1 and 2: shifted availability division between product and service capability.

Table 2 Illustration of usefulness of mapping elements in design generation for a gap

Gap	Mapping elements	Designs
Difficulty in cutting parts with varying complexity and different shapes	Objects (resources)	1. New system with inbuilt knowledge
		2. Modify feature extraction mechanism
	Activities	1. To develop a technique to group parts
		2. New technical assistance team
	Parameters and values (competences)	1. The customer should specify the cutting parameters and respective values
	Environment	1. Availability of using off-the-shelf standard parts

generated for a gap in these elements. The subsequent sections illustrate steps in the framework to understand, evaluate, chose and represent the design.

Step 5: identify conditions and consequences of each design

In this step, the conditions and consequences of each generated design from the last step need to be identified. This is an important step in understanding the ramifications of every generated design. The conditions should detail the circumstances which are required by the particular design. The consequences express the changes which occur in the system or which could affect another system if the particular design is executed. Since the overall system impacts upon both the conditions and consequences, these could be expressed in terms of environmental factors, product and service attributes, as well as economic and socio-cultural factors. At the conceptual stage, it can be difficult to identify the conditions and consequences. For this reason, the heuristic judgement of experts can play a vital role in predicting the conditions and consequences of each design; organizing a group exercise between experts would enrich the specification of conditions and consequences. From the conditions and consequences, the additional capabilities required for each design are derived in the next step.

Step 6: identify (additional) capabilities required to develop new designs

The identified designs that have been selected (given the understanding of the customer's capabilities) will help the provider to develop their own capabilities along with those of the supply network. The commonalities and differences between the stakeholders' capabilities need to be explicitly shared and understood by the stakeholders. The following processes are involved in explicating the capabilities required:

- For each design, a detailed list of activities to be carried out to implement the design should be documented.
- The evaluation of the required resources and their efficiency in each activity and which stakeholders are best placed to offer them.
- Identification of the parameters, which can be monitored and controlled by stakeholders, within each design considering past, present and future scenarios.

Shifts in the capabilities between the stakeholders which may then require additional resources should be carefully aligned and integrated. Any difficulties the stakeholders may have in meeting increased capability demands could be compensated for with variations in resources and time constraints. In the next step, the additional capabilities required are assigned between stakeholders.

Step 7: understand and specify the responsibilities of the stakeholders

Based on the required capabilities identified from the previous step and the preferences and views of stakeholders, responsibilities have to be assigned. Responsibilities could be taken at various levels: activity, object and parameter levels. These assignments form a core part of the PSS design process. This step develops various business models based on the responsibilities undertaken by the stakeholders. This alignment of responsibilities will precisely define network relationships. Various soft elements play vital roles in such relationship development such as trust, confidence, commitment and culture. The development of an open network would be valuable as the responsibility map should ideally be visible to all in the network, since, ultimately, all of the responsibilities are the concern of all in the network. In the next step, different PSS designs and responsibilities of the stakeholders across identified gaps are merged to meet customer needs.

Step 8: group different combinations of designs to satisfy customer needs

While analyzing product life cycle activities along with the customer business process, it is important to improve PSS at an overall system level and avoid sub-optimizing any individual activity. To avoid sub-optimizing any single activity and to satisfy the identified customer needs, different combinations of designs addressing different activities could be grouped based on the responsibilities assigned. Although synthesizing different designs could produce a variety of possible designs, this could expand exponentially and, therefore, could be difficult to manage. To systematically explore this process, Taguchi's factorial method [22] could be used to synthesize the different designs generated. Taguchi's method intends to ensure sufficient performance at the design stage of products and services. It is a systematic procedure in which all controllable factors (except one) are held constant as a variable factor is altered discretely. The controllable factor is considered to influence the simulation response, and its level can be controlled by designers. The control parameters identified in each design in step 6 could be used to vary the values to generate multiple options within each design. This synthesizing process also helps in understanding the sensitivity of important variables in the performance of the proposed PSS designs. At the conceptual stage, the detailed application by the development of Taguchi's orthogonal matrices may not be required. Each synthesized design should be evaluated in detail in the next step.

Step 9: evaluation of the cost and functional performance of the (grouped) designs

Evaluation should be part of every step in the proposed framework. To emphasize this evaluation process, it is dealt with separately in the framework. The evaluation should focus on three primary dimensions: economic, social and environmental [20]. From a business perspective, the major evaluation criteria will be profit, customer satisfaction, quality of products and services, value-in-use and risk reduction [23]. Both the tangible and intangible merits and demerits should be evaluated. To evaluate and choose the generated designs for an intended period, the sequence of activities involved in the grouped design has to be specified. By varying the conditions and consequences of designs, the responsibility assignments, and the combinations of designs for each gap, a variety of designs could be evaluated. To understand variable changes at important distinct points for an intended period, discrete event simulation is recommended at this stage to identify the performance of each design. In the final step, the evaluated and chosen design should be represented clearly to ensure a common interpretation across stakeholders.

Step 10: representation of the chosen design

The final step is to represent the chosen design in a format which could be easily generated and commonly interpreted by the stakeholders involved. The primary motivation in PSS modelling is to co-produce conceptual models that can be systematically shared by stakeholders. By analyzing various elements discussed from the above steps, a common representation map through extended IDEF0 modelling has been developed (Figure 2). The representation is based on the mapping of each activity in PSS design into inputs, outcomes, resources, competences, responsibilities, environmental variables and customer needs. The sequence of activities is linked as each activity is based on the satisfaction of preceding activity's outcomes. This representation emphasizes important PSS parameters and the interactions amongst them. This representation helps to highlight the current and modified system states, and assesses the performance of each activity involved in the grouped design. This representation appears to be simple, flexible and easy to maintain. Advantages of this framework and representation are illustrated using an industrial case study in the following section.

Framework corroboration with a laser system case study and implemented in ISCL

To corroborate the proposed framework, a step-by-step application of the framework to laser systems for cutting operations which are used in manufacturing is used. A number of interviews were conducted with laser job shop owners (users of laser cutters), sales managers of manufacturers of laser cutters and also with experienced academics within this field to determine the current level of servitization within laser job shops. Table 3 provides details about the approaches used to build this laser system case study and for its evaluation. A step-by-step illustration to implement a higher level PSS is offered.

To assist PSS designers computationally, the framework has been illustrated through ISCL [4]. ISCL has been chosen over other software proposed in the literature for the following reasons:

- ISCL is well aligned with our framework especially with regard to the elements used: entities in a service environment, attributes, specifications and activities changing attribute values and realizing specifications.
- ISCL supports life cycle simulation through a quantitative and probabilistic approach, which is important for assessing PSS designs. Life cycle simulation evaluates product life cycles from an integrated view of economic profitability and environmental awareness and optimizes the life cycles [6]. In ISCL, life cycle simulation is implemented through a discrete event simulation technique applied to life cycle design, such as the selection of end-of-life options (e.g. reuse, recycle and remanufacturing), the design of product modularity considering the options, and the timing and contents of service during the contract period.

Table 3 Details about the approaches used to collect necessary data

Purpose	Roles and responsibilities	Number of interviews	Approaches	Duration
To build a laser system case study to apply the developed framework	Laser job shop owner (laser system user)	3	Semi-structured interviews - questions covered broad concerns of job shops: business needs, laser system specification, available resources, types of customers, applications, usage, current business solutions, types of services, laser system life cycle and laser cutting process parameters	Approximately 1 h each
	Laser system manufacturer	2	Semi-structured interviews - questions covered the broad topics of company background, types of laser system manufactured, types of customers, types of services, types of business solutions, supplier network and costing process	Approximately 1 h each
Evaluation of the developed laser case study along with the proposed framework	Academic researchers on laser system and processes	2	Discussion and feedback received through a PowerPoint presentation	Approximately 1 h each
Evaluation of the framework with industrial practitioners	Product development team	3	Discussion and feedback received through a PowerPoint presentation and also filled an assessment sheet to rate the proposed framework in a 5-point scale for potential usefulness, completeness, usability and clarity	Approximately 30 min to 1 h
	Business programme operation team	1		
	Technology development team	1		

- Standard process modelling and simulation approaches are not encouraged in this work because the PSS domain requires a specialized software environment defining its own terminologies and incorporating specific methods to support development. It helps to develop and integrate PSS research knowledge generation and understanding into a specific platform for wider uses and support tools evaluation.
- Although there is significant scope for improvements, from the authors' opinion, ISCL is a mature, reliable and accessible PSS software which well integrates modelling and simulation modules.
- Finally, the software is currently in the public domain and is actively supported by the developers, which is an incentive for industries to use it in practice.

Before describing the case study, the PSS modelling method employed in ISCL is briefly explained. A PSS-based business model in ISCL consists of activities, scenes and entities which are described along with their attributes (what the entity owns) and specifications (what the entity aims are) (Figure 6). Scenes represent partial states of the service environment as defined by the attribute values of entities. Activities treat scenes as the execution condition and change the value of attributes and realize specifications. As shown, these elements have several ports that are connected with lines. These lines have 11 different relations between elements instantiated during life cycle simulation. Figure 7 illustrates these links, and Table 4 shows the meanings (for details of the modelling method and grammar of the simulation codes, please refer to [24] and the user manual on the supporting website [25], respectively). Designers can create these elements on the canvas of ISCL and also move, inspect and delete these elements on the canvas.

Step 1: understanding customer needs

The laser systems under consideration in this case study are mature products as are the laser processes which are structured and mostly inbuilt to the system. The customers are laser job shop owners who procure laser systems from the original equipment manufacturer and supply semi-finished goods to the end product manufacturer. Figure 8 illustrates stakeholders' map of the laser system case study. As the laser job shops have many years of experience in this field, they are able to precisely specify their requirements of laser-cutting systems. The transaction type between the laser system manufacturer and the laser job shop customer is business-to-business. The semi-structured interviews with the laser job shops revealed the importance of the need behind the need, experiences, required state change and business ambitions of the laser

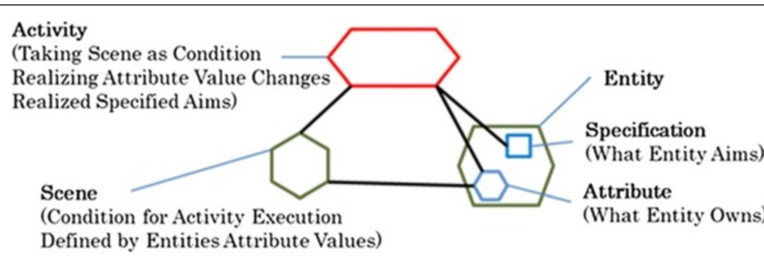

Figure 6 Elements in a business model on ISCL.

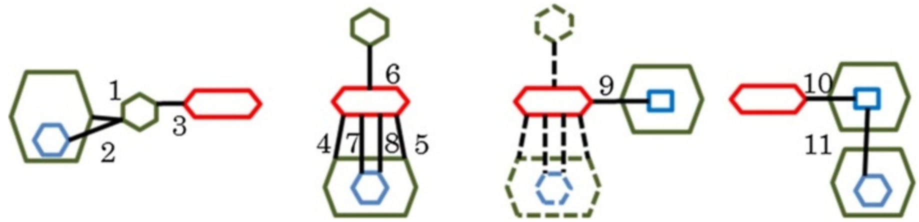

Figure 7 Relations in a business model on ISCL (please read Table 4 for link description).

job shop. We developed a PSS customer needs specifications of the laser system by using overall equipment effectiveness which is a multiplication of availability, performance and quality. The required values are mapped to be:

- Overall equipment effectiveness ($A \times P \times Q$), 50% to 60%
- Availability (Mean time between failure (MTBF) / (MTBF + Mean time to repair (MTTR)), 85% to 95%
- Performance (Working speed / Designed speed), 55% to 65%
- Quality (Good units within tolerance / Total units produced), 95% to 99%
- Laser system usage period, 5 years

At this point, ISCL supports the designer to define the specifications of the users of laser systems as well as the attributes of the laser systems, which are identified at this step. Figure 9 details the specifications and the attributes of the laser systems with examples. In Figure 9a, three entities: 'Manufacturer', 'LaserSystem' and 'User', are shown. The model includes an activity 'Use' to deliver 'Function' as a specification targeted by User. LaserSystem already includes the overall equipment effectiveness specification and the relevant attributes such as *MTBF* and *MTTR*. The value of these attributes can be individually calculated with respect to each instance of LaserSystem during the life cycle simulation. Figure 9b shows the objectives of the model, which are statistical values obtained as a result of life cycle simulation. For instance, 'AvrOEE' is the average overall equipment effectiveness of all laser systems in the market with respect to

Table 4 Definition of relations in a business model on ISCL in relation to Figure 7

Figure 7 link number	Element 1	Element 2	Meaning
1	Scene	Entity	Scene includes all instances of Entity
2	Scene	Attribute	Entity instances included in Scene are specified by the value of Attribute
3	Activity	Scene	Scene is regarded as the execution condition of Activity
4	Activity	Entity	Activity creates instances of Entity
5	Activity	Entity	Activity deletes instances of Entity
6	Activity	Scene	Activity refers to (calls) an instance of Entity specified by Scene
7	Activity	Attribute	Activity gets the value of Attribute
8	Activity	Attribute	Activity assigns the value of Attribute
9	Activity	Specification	Specification is realized as a result of execution of Activity
10	Activity	Specification	Specification is evaluated during the execution of Activity
11	Specification	Attribute	The value of Specification is related with Attribute

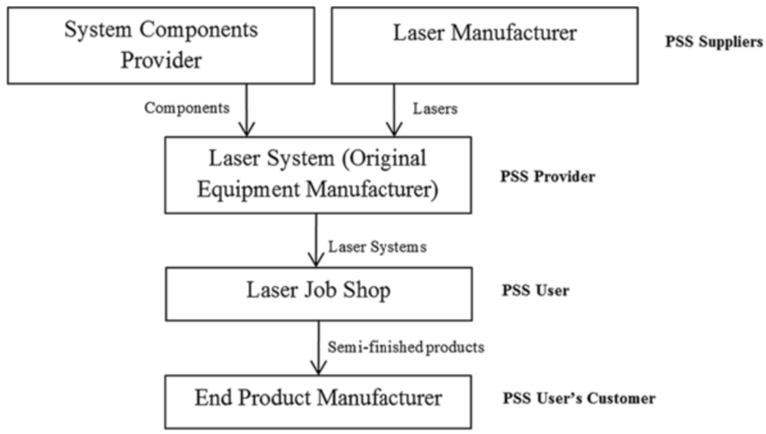

Figure 8 **Stakeholders' map of the laser system case study.**

simulation time, which is defined with the window in Figure 9c. At this moment, the dynamic behaviour of laser systems such as physical deterioration has not been defined yet. In the next step, to understand whether required needs levels are achievable through existing customer's capabilities, they are noted.

Step 2: identification of the existing capabilities and resources of the laser job shop

To understand the laser job shop's capabilities, currently performed activities are mapped with resources, outcomes and the reasons for deficiency. The important tasks which are mapped include machine calibration, CAD file preparation, identification of process parameters, material preparation, work piece (un)loading, work piece alignment, machining operation, daily and planned maintenance, repair work, and material

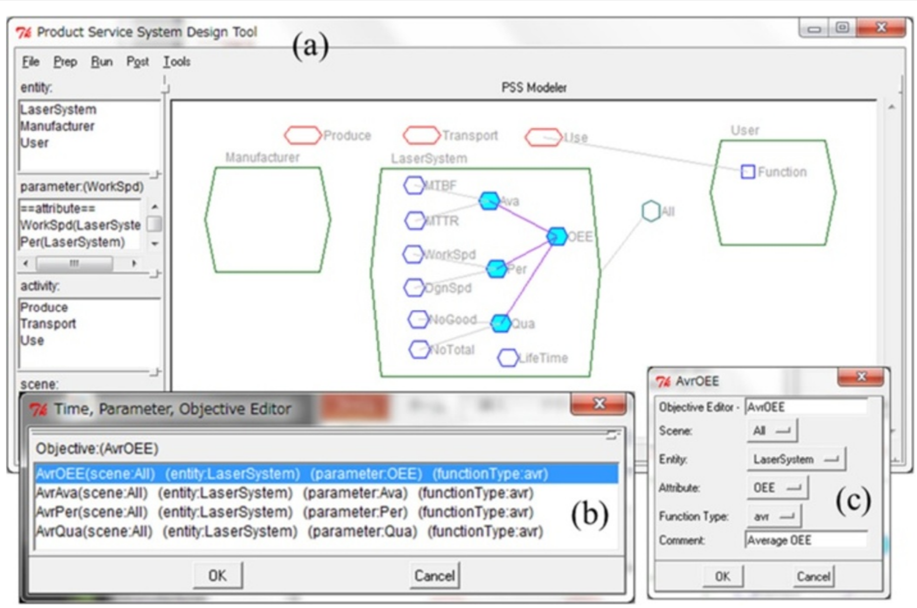

Figure 9 **Modelled attributes of laser systems and their objectives in ISCL. (a)** Entities of the model. **(b)** Objectives of the model. **(c)** Average overall equipment effectiveness.

Table 5 Mapping existing capabilities of laser job shops

Activities	Resources	Outcomes	Reasons
Machine calibration	Limited skills. One employee	Trial and error	Not having enough understanding of the machine. The system is partially protected by the manufacturer
Work piece loading/unloading	Manual process. Two unskilled employees	Time-consuming	Automated machine unavailable

and gas procurement. Some of the activities to map the laser job shop's capabilities are detailed in Table 5. The complete list of activities and the respective status of each helps us to understand the capability gaps of laser job shops. Along with these gaps, current products and services are assessed in the next step.

Step 3: identify current status of laser systems and services

A laser system is an assemblage of a laser generator unit, beam delivery system, beam manipulation system, motion system, process monitoring system and a control system (Figure 10). The key performance indicators (KPIs) for these systems are failure rate, repair time, degradation rate, redundancy and reliability. Mapping these KPIs to the sub-systems shows that beam delivery and beam manipulation systems have to be improved. Identifying root causes through discussions with the experts revealed that mirror misalignment, laser instability, variation within suppliers, operator's error and a mismatch in cooling needs could be possible problems to be addressed. Mapping the KPIs of services (frequency, number of technicians available, time consumed, spare parts and tools availability, and location) with provided services (training, planned maintenance, technical assistance and repair activity) revealed several potential improvement areas like the operator's knowledge of the machine, complexity regarding the different shapes to be machined, constraints in space requirements, the probability of making mistakes being high and escalated expense of module replacement. In this study, there was restriction to collect required industrial data. Therefore, the current scenario was simulated through data collected from the interviews. If data could have been available, ISCL supports to import these data through .CSV format. From the interviews, it was revealed that the overall equipment effectiveness at the required level is not maintained and, in particular, that performance should be improved.

At this point, ISCL supports the designer in adding other necessary elements to describe the current design. The refined model (Figure 11) includes new activities, entities and attributes so that the model can represent the current design. For instance, 'Fail(ure)Rate', 'Deg(radation)Rate' and 'Rep(air)Rate' are added as attributes of LaserSystem, which influence the degradation in terms of the availability, performance and quality. Furthermore, 'Engineer' and 'Operator' are treated as the entities of the current design. Their 'Skill' also influences the degradation and its recovery through activities 'Repair' and 'Maintenance'. By supplying codes specific to each activity, the model becomes the input of life cycle simulation. For instance, Figure 12a shows the codes specific to an activity Repair. These codes are used to automatically create links between the model elements as shown in Figure 12b, which is helpful to the designer in debugging these codes. An explanation of coding as the input to life cycle simulation is beyond the

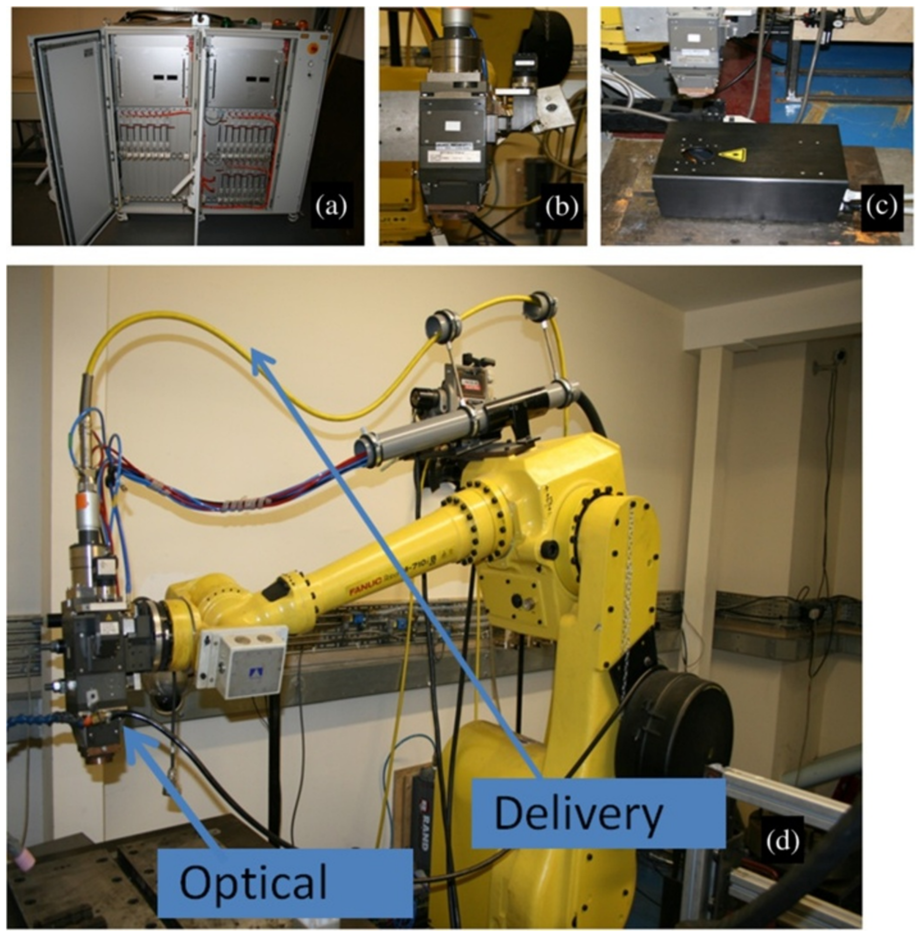

Figure 10 Laser system. (a) Laser unit (IPG YLR-8000). **(b)** Optical head. **(c)** Monitoring system. **(d)** Robot motion system.

scope of this paper. Figure 13 shows the simulation result of the current design, the average overall equipment effectiveness with respect to simulation time. At this stage, the simulation results are partly based on fictive parameter values, which should be specified in the design process. The gaps identified in these first three steps facilitate generation of PSS designs in steps as described in the following sections.

Step 4: identification of new designs required to satisfy the needs at every level

From steps 2 to 3, 10 activities have been identified for improvement. Within the 10 activities, 18 problems are observed. Through group brainstorming with the researchers, 54 designs have been generated. From the perspectives of adding and modifying activities, enriching the laser systems through support systems and focusing on specific parameters helped to generate many designs. These designs have been checked and rated by the researchers in preference with the feasibility scope. The highlighted circles in Figure 14 are some of the preferred designs. In order to add these designs in ISCL, corresponding model elements should be added to the model to represent the current design. Alternatively, corresponding model elements can be separately modelled and stored in the knowledge base of ISCL. The stored model elements are instantiated

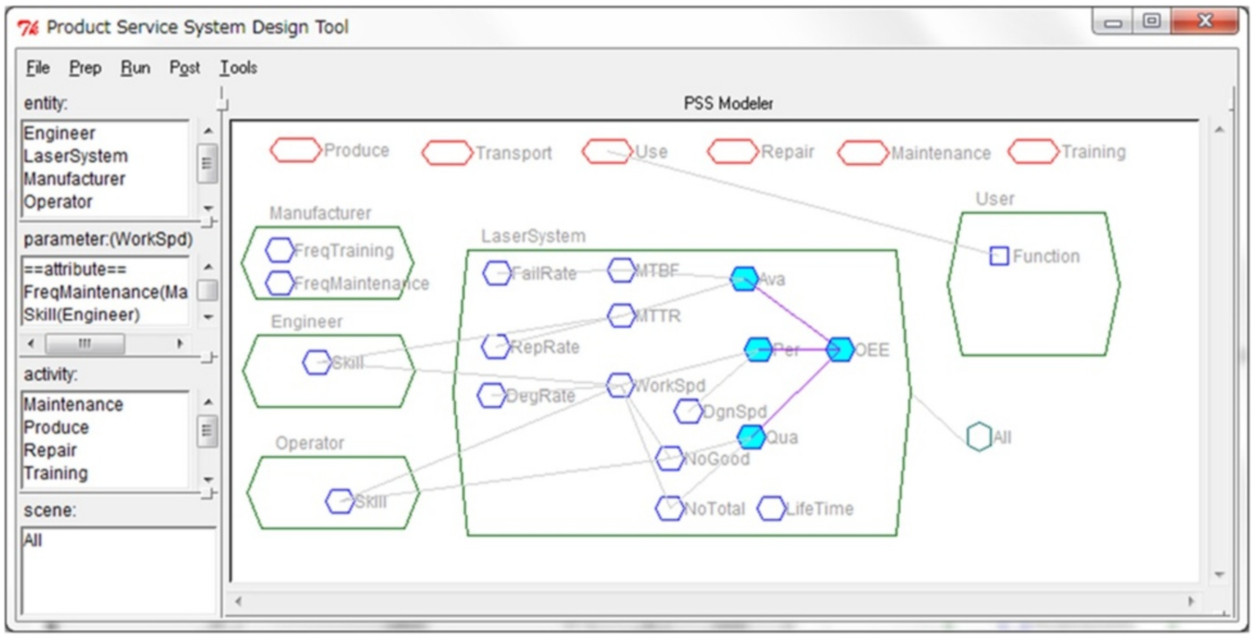

Figure 11 Modelling the current design in ISCL.

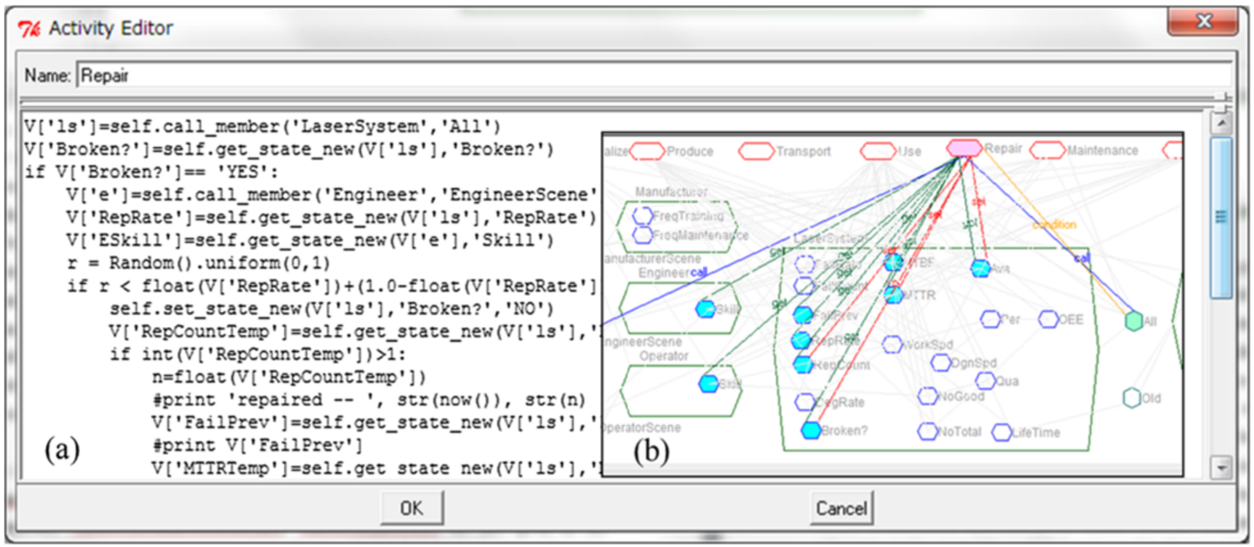

Figure 12 The detail of an activity repair in the current design. (a) Codes specific to an activity Repair. **(b)** Links between the model elements.

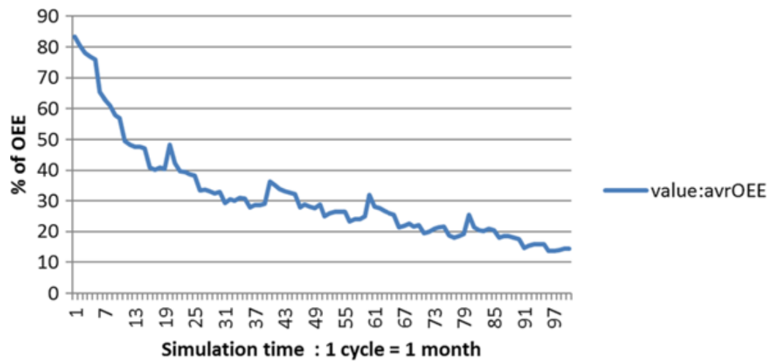

Figure 13 The simulation results of the current situation.

when necessary. Furthermore, the formalization of this step can be useful for ISCL to automatically synthesize new designs using the knowledge base. The subsequent steps help to develop and assess these designs.

Step 5: identify conditions and consequences of each design

Steps 5 and 6 are jointly discussed in the next section due to greater continuity between them.

Step 6: identify (additional) capabilities required to develop new designs

Even though preferred designs are highlighted in the previous step, the potential of every design is identified by specifying conditions and consequences. The conditions are mainly specified through the frequency and complexity of the activities, laser system usage period and patterns, required skills, parameters values, man-days required and the condition of the laser system. The consequences of each of the proposed designs are expressed in terms of the impact on availability, performance and quality to set the overall equipment effectiveness and incurred costs. The generated conditions

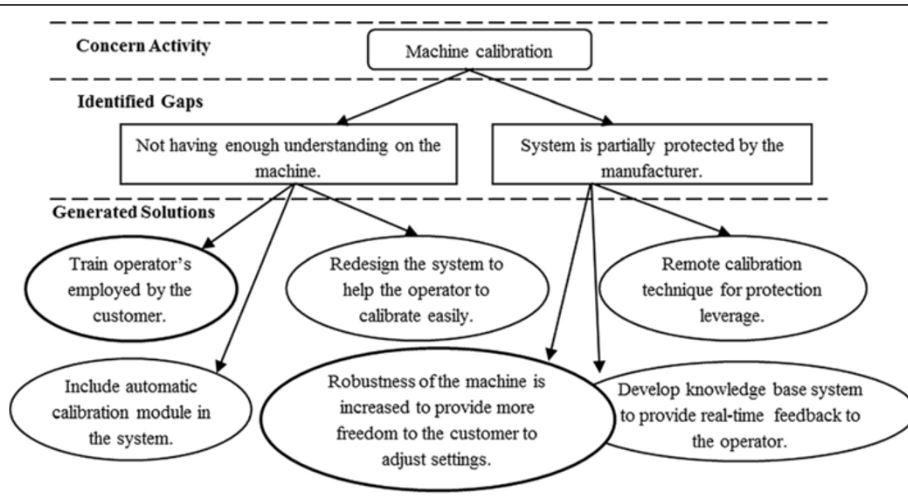

Figure 14 Representation of generated designs for two problems in the concern activity.

and consequences have been evaluated by the heuristic judgements of two experts. From the conditions and consequences, the capabilities required by each design are derived. Table 6 illustrates the conditions, consequences, capabilities, resources and control variables derived for new designs which have been generated. Conditions and consequences are inherent processes in ISCL. Support should be developed to highlight the new capabilities achieved, and the additional resources should be incorporated in the PSS laser system modelling. Developing new integrated business models between the laser job shop, the manufacturer and suppliers through the alignment of capabilities for each design will be the next step.

Step 7: understand and specify responsibilities of the stakeholders

Responsibilities have to be assigned precisely between the laser job shop, the manufacturer and suppliers (based on the identified required resources) for the capability shift to occur to satisfy the proposed design and eventually to satisfy the required level of overall equipment effectiveness. These assignments are precisely defined either at the level of activities, objects or parameters. Based on inputs of preferences and views from the laser job shops and manufacturers, various possibilities of responsibility assignment are generated. The outcome of such a PSS design process has stark impact upon business model generation. Table 7 illustrates responsibilities aligned within a new design generated. Using ISCL, such responsibilities are defined by selecting appropriate entities (such as Manufacturer) as the service provider of specific activities. This assignment results in modification of financial flow. In some cases, the expected service may not be realized in life cycle simulation, because some entities may not satisfy the conditions to provide the expected service (such as the level of Skill of Engineer). Synthesizing designs generated for 18 problems through responsibility alignment is the next step.

Step 8: group different combinations of designs to satisfy customer needs

To satisfy the required overall equipment effectiveness levels throughout the usage period, a wide variety of designs are generated by synthesizing the designs identified for each gap. The synthesis process is systematically carried out through Taguchi's factorial method. The control variables identified in each design in step 6 are used to vary values to generate multiple options within each design. Table 8 details the combinations possible across four activities. In Table 8, the four columns explain the chosen four activities (in which gaps exist in the current system) to be addressed in PSS designs. The six cells in each column explain two solutions with three improvement levels each (based on Taguchi's factorial method) to fill the gap in each activity.

Similar to step 4, the automatic synthesis of the new design by combining model elements stored in the knowledge base including these activities can be implemented in ISCL. Currently, ISCL supports the automatic synthesis process, when the conditions and consequences of added activities are defined and these activities solely influence the state of a single entity with a hierarchical structure. For instance, [4] shows a procedure implemented in ISCL to generate possible functional upgrading services combined with repair services for medical equipment systems. The next step evaluates combinations to understand the satisfaction of required overall equipment effectiveness levels.

Table 6 Outcomes from steps 5 and 6 for the derived new design

Solutions	Conditions	Consequences at each time	Capability shift	Resources	Control variables
Technical assistance to set efficient process parameters	Laser parts (new shape and size parts)	Man-days, +0.2 (24-h day); performance, +0.5%; quality, +1%; set (overall equipment effectiveness (laser system)); total cost, +£50	Efficient process parameters irrespective of varying shapes and sizes	To employ an additional three technical employees to support process query	Frequency of new shapes and sizes, technical employees, number of queries

Table 7 Responsibility assignment at various levels for new designs

Responsibilities	Laser job shop	Manufacturer	Supplier
Activities	Identifying machined part variety	Measurement of operator skills	To develop learning content
Objects (resources)	Experienced operators	Web-based support system	Control system for error identification
Parameters (competences)	Skills of operators	Frequency of training	Queries redirection

Step 9: evaluate cost and functional performance of the (grouped) designs

The primary questions to be answered in the evaluation process for the laser system case study are as follows:

- Which designs and combination of designs satisfy the required level of overall equipment effectiveness for a specific period?
- How much does each successful implemented design cost for the specific period?
- How should cost be shared between the laser job shop, manufacturer and suppliers for each design based on responsibility assignment?

Answering these questions provides predictable costs, cost transparency and maximal security that are important factors to be considered in laser business model selection. ISCL provides an exceptional environment to carry out life cycle simulation. Discrete event simulation is carried out by sequencing activities involved in the grouped designs. By varying possible conditions and consequences of designs, responsibility assignments and combination of designs for each gap, a variety of designs are evaluated. Figure 15 points out the increase in overall equipment effectiveness levels for each design identified to improve machine calibration activity. All of the identified 54 designs are evaluated, and the best designs for each gap are synthesized to achieve the aforementioned overall equipment effectiveness intervals. The final synthesized chosen design should prove to be an improvement of operator skills, module repair, as well as daily, preventative and repair maintenance by advanced and frequent training, an efficient diagnostic and prognostic system and enhanced support systems. Figure 16 shows that the overall equipment effectiveness depreciation of this combined design would satisfy the required value throughout 5 years. The cost sharing between the laser job shop,

Table 8 Combination of designs possible for four activities of focus and variable change in brackets

	Chosen four activities in which gaps exist in the current system			
	Machine calibration	**Process path/ parameters**	**Daily maintenance**	**Repair work**
Two solutions with three improvement levels each (control variable in bracket)	S1-CalibrationTraining-1 (*operator's skill level*)	S3-GroupTech-1 (*system's reliability*)	S5-OperTraining-1 (*operator's skill level*)	S7-DiagnosSys-1 (*system's reliability*)
	S1-CalibrationTraining-2	S3-GroupTech-2	S5-OperTraining-2	S7-DiagnosSys-2
	S1-CalibrationTraining-3	S3-GroupTech-3	S5-OperTraining-3	S7-DiagnosSys-3
	S2-Calibrateassist-1 (*service level*)	S4-TechAsst-1 (*service level*)	S6-SysRedesign-1 (*system's reliability*)	S8-MTTRIncres-1 (*time to repair*)
	S2-Calibrateassist-2	S4-TechAsst-2	S6-SysRedesign-2	S8-MTTRIncres-2
	S2-Calibrateassist-3	S4-TechAsst-3	S6-SysRedesign-3	S8-MTTRIncres-3

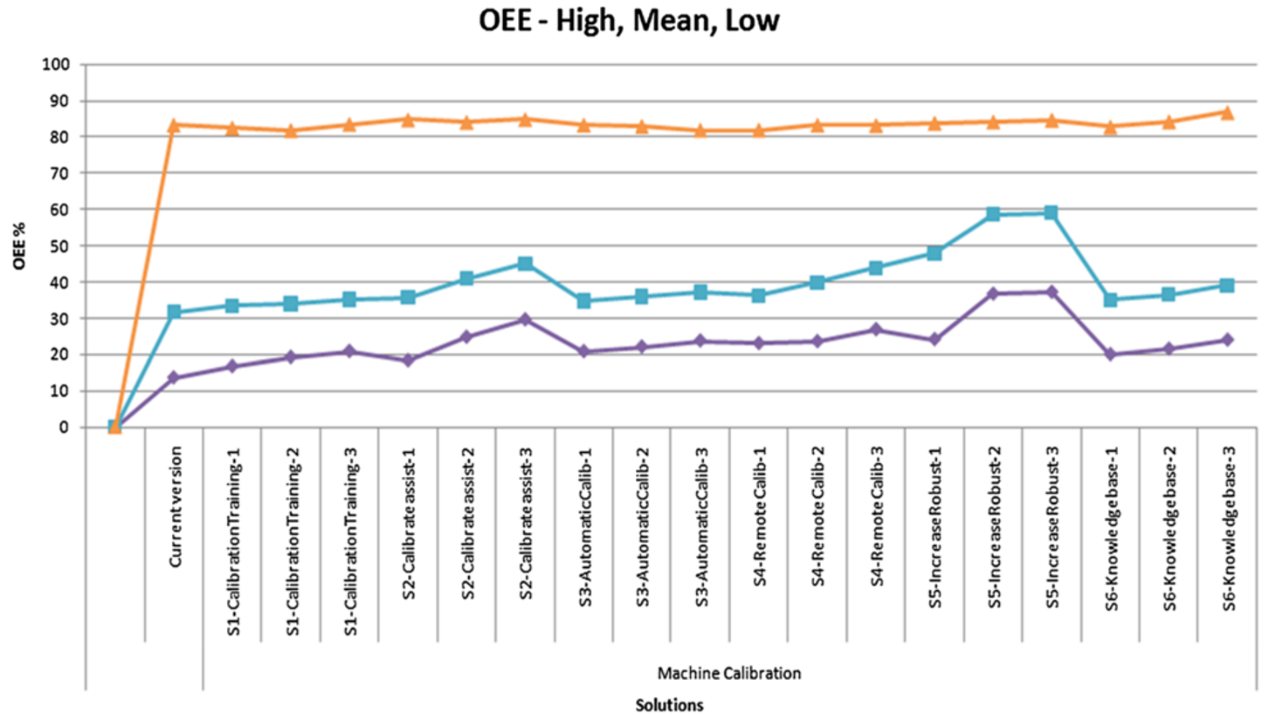

Figure 15 Overall equipment effectiveness increases due to the implementation of the new design (for three improvement levels each).

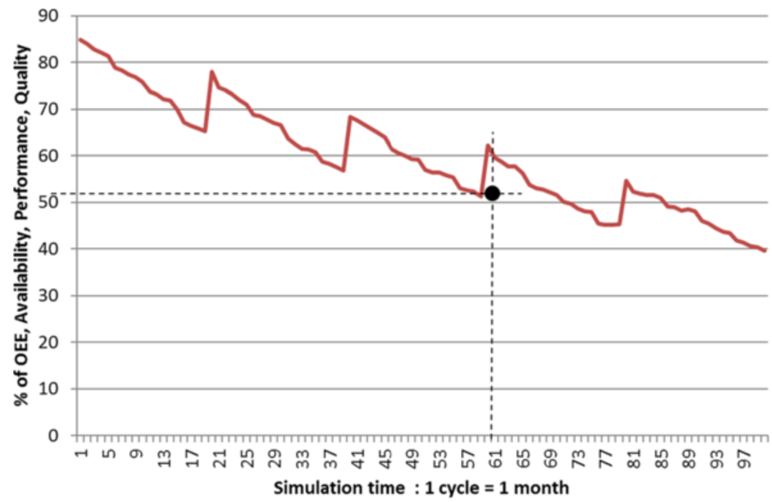

Figure 16 Overall equipment effectiveness depreciation for the proposed finalized design. The black dot represents the required level of overall equipment effectiveness to be maintained.

manufacturer and suppliers is shown in Figure 17. The representation of this chosen design is detailed in the last step.

Step 10: representation of chosen design

The chosen design is represented by an extended IDEF0 format for common interpretation amongst the stakeholders involved (Figure 18). It highlights the activities of repair, maintenance, replacement module, daily maintenance, operator training and preventive maintenance along with customer needs, environmental variables, responsibilities, resources, the current and reached states, outcomes of a particular activity and interactions amongst them. The modifications to the current system are highlighted through dotted boxes (reduced daily maintenance) and colour changes. It represents alternatives between activities (repair maintenance and module replacement) and achievable outcomes. A module should be developed in ISCL to implement the extended IDEF0

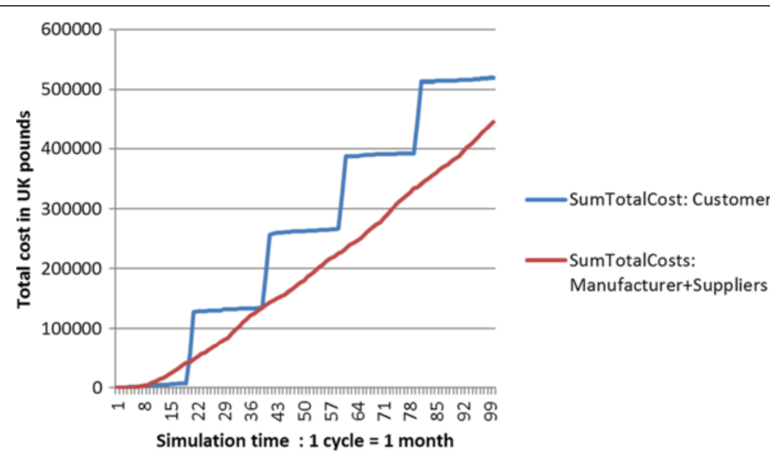

Figure 17 Cost sharing between the laser job shop, manufacturer and suppliers.

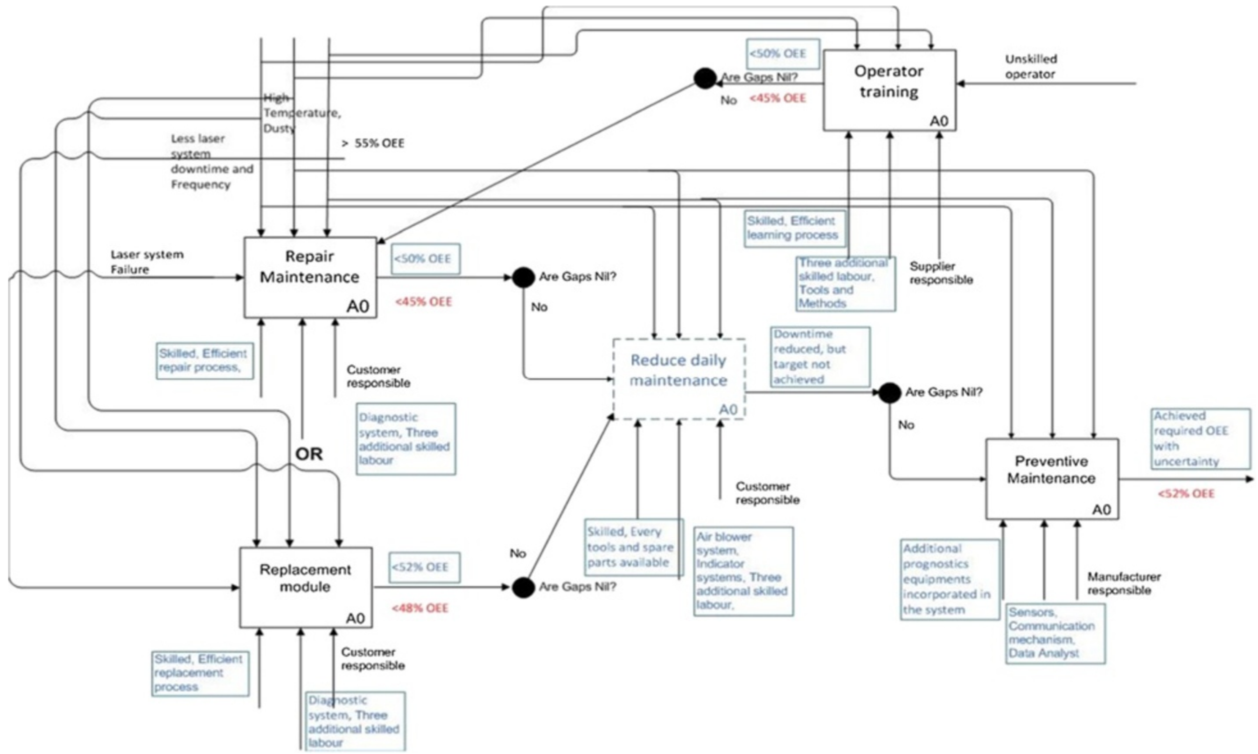

Figure 18 Extended IDEF0 model of the synthesized chosen PSS design.

representation. Also, this representation helps to frame the final contract using terms and conditions that are relevant to all of the stakeholders involved. The academic and industrial views of these steps and the results produced are detailed in the next step.

Academic and industrial views

To understand merits and limitations of the proposed framework, it has been corroborated by a step-by-step application with two laser system experienced academics and five industrial experts who are knowledgeable in PSS. The overall feedback is encouraging and potential applications of this framework have been stressed; notable benefits are that the structure and flow of the framework are clear and robust, the framework helps to develop PSS design from a holistic systems approach which facilitates a change in the designer's mindset from product-centric to systems-centric, the framework could be used as a general problem solving approach which incorporates the co-production process between relevant stakeholders, and the IDEF0 representation is perceived to be clear and informative. Potential usefulness, completeness, usability and clarity are highly graded by the experts (Figure 19). The limitations that have been expressed are that the level of trust and transparency required for this framework is absent in most industrial sectors, there exists a need to measure intangible benefits and to perform more quantitative data analysis to assess gaps, and the assessment of the skill set of industries and the development of tutorials to train employees to apply this framework along with obtaining the necessary information required for each step could all be problematic.

All of the discussed methodologies have novel steps in designing PSS. However, compared to other methodologies, the merits of the proposed framework are that its starting point is an existing system and that the customer needs are elicited as deficiencies within that system, it develops PSS designs which are aligned to the stakeholders'

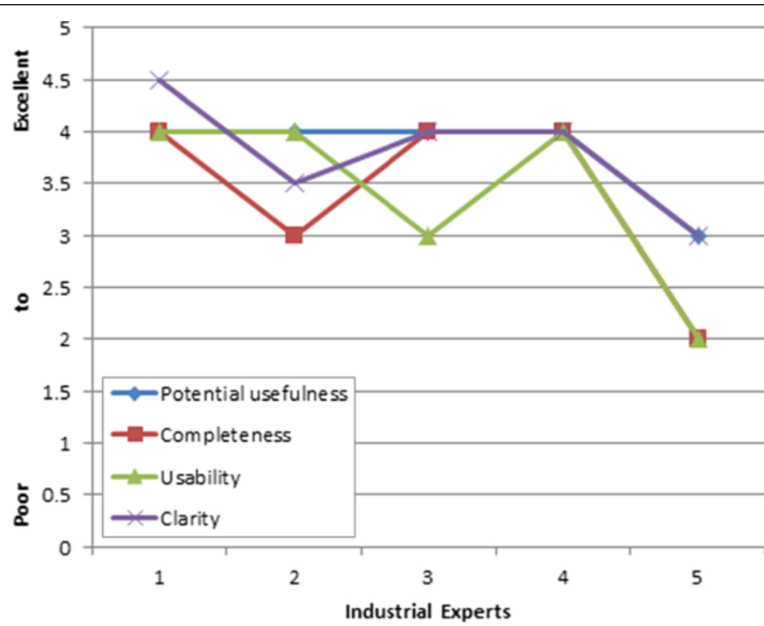

Figure 19 Five industrial experts' ratings for the proposed framework.

capabilities, and it synthesizes solutions to produce optimized designs which can encompass the whole of the customer business process. We believe that the proposed framework could be further developed by applying it to industrial case studies to develop functional and sustained PSS designs. As most of the proposed methodologies in the literature have not been formally applied to industrial case studies and demonstrated, a comparison using performance metrics is not possible. Further work in validation would involve a methodological effectiveness comparison to measure performance metrics. A list of performance metrics that could be potentially applied in this comparative exercise are tabulated in Table 9.

Discussion and conclusions

Based on identified gaps from the literature, a capability-based PSS design framework is proposed. This framework highlights the important features required in designing

Table 9 PSS design methodology performance metrics parameters

	Performance metrics parameters
Methodological applicability	Potential usefulness
	Completeness
	Usability
	Clarity
	Systematic approach
	Reliability
	Effectiveness of feedback loops
	Change in designer's perspective from product-centric to PSS-centric
	Avoidance of re-work
	Time consumed in designing and delivering PSS
Methodological outcomes	PSS design functional performance for a specified duration
	Customer satisfaction (requirements and solutions)
	Enhanced value-in-use
	Agility and responsiveness of designed PSS
	Reliability of PSS
	PSS revenue and profit generation
	Whole life cycle PSS design
	Optimization of costs and resources
	Effectiveness of integrated system and co-production
	Common interpretation of PSS
	Innovative and usable PSS designs
	Minimum number of loopholes in PSS
	Robust stakeholders network and responsibility adherence
	Sustainable PSS solutions by stakeholders' capabilities
	Quality of PSS
	Prolonged relationship with customers
	Product/service improvements
	Understanding and control of the existing and developed system
	Validity of simulation results in real time
	Diffusion of product and service integration

PSS to help meet customer goals. A capability-based approach generates a wide variety of PSS designs which are intended to produce sustained functional behaviour in the proposed system to achieve its purpose continuously and create an innovative value addition for the customer. It encourages a broader customer business perspective in designing PSS as compared to the traditional approach where the functional availability of products is considered given their deterioration during the use stage. Details of a capability map of the customer's processes help to pinpoint the focus areas for PSS development. It stresses the capability shift and mix between products and services and also between stakeholders in order to develop feasible and enduring PSS designs.

The framework emphasizes the importance of taking into account the preferences and views of the stakeholders and the apposite alignment of responsibilities. Organized feedback loops between the various steps aid PSS design modelling and performance evaluation. The framework facilitates the exploration of a wide variety of designs by synthesizing designs that have been identified for various gaps. The generation and evaluation of designs are well structured in the framework. The results of the simulation using ISCL provide good insights into PSS designs. We believe that this framework would facilitate and structure the interactions between the customer, manufacturer and supplier. It also helps in understanding the capabilities of the stakeholders and aids an understanding of the value of PSS designs as appreciated by the customer. The representation of PSS designs through extended IDEF0 was found to be useful in providing a common understanding among the stakeholders.

The application of this framework to a real industrial laser system case study helps to demonstrate the benefits of the framework. This demonstration also helps refine the framework based on the few observed limitations such as the inputs collected and the features in the modelling technique. The demonstration of the framework along with ISCL highlights the important features of ISCL and the modules to be developed to enhance design support. In particular, support for design generation through standardized PSS ontology and the synthesis of different designs generated through Taguchi's factorial method would prove to be especially helpful for PSS designers. Additionally, the implementation of this framework using a step-by-step approach in software could greatly facilitate the design process by decreasing information load on PSS designers. An effective mechanism is required to support PSS designers to specify the conditions and consequences of each development design which are vital inputs for PSS simulation. Since the underpinning expectation that PSS will have a lower environmental impact is yet to be proven, the impact of PSS designs on environmental benefits should be studied separately. There is ongoing work in applying this framework to various case studies which involve other case companies who are in the process of refining the development of their PSS designs.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
GVAV carried out understanding industrial challenges, framework development, case study development, framework evaluation and manuscript preparation. HK participated in the framework development, Service CAD integration with the framework and manuscript preparation. RH participated in understanding industrial challenges and assisted in the framework development, case study development and framework evaluation. RR was the principal investigator of this project and assisted in all the phases of the work especially on the framework development and framework evaluation. TT supported in Service CAD integration with the framework. SE and AT participated in the framework development and framework evaluation. SW supported in the laser case study development and framework evaluation. All authors read and approved the final manuscript.

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References

1. Neely, A: Exploring the financial consequences of the servitization of manufacturing. Operation Management Research **1**, 103–118 (2008)
2. Annamalai Vasantha, GV, Roy, R, Lelah, A, Brissaud, D: A review of product–service systems design methodologies. J. Eng. Des. **23**(9), 635–659 (2012)
3. Mont, OK, Plepys, A: Customer satisfaction: review of literature and application to the product-service systems. Final report to the Society for Non-Traditional Technology, Japan. International Institute for Industrial Environmental Economics, Lund University, Lund, (2003)
4. Komoto, H, Tomiyama, T: Integration of a service CAD and a life cycle simulator. CIRP Ann. Manuf. Technol. **57**, 9–12 (2008)
5. Komoto, H, Tomiyama, T: Design of competitive maintenance service for durable and capital goods using life cycle simulation. Int. J. Automot. Techn. **3**(1), 63–70 (2009)
6. Umeda, Y, Nonomura, A, Tomiyama, T: Study on life-cycle design for the post mass production paradigm. Artificial Intelligence for Engineering Design, Analysis and Manufacturing **14**, 149–61 (2000)
7. Sakao, T, Shimomura, Y: Service engineering: a novel engineering discipline for producers to increase value combining service and product. J. Clean. Prod. **15**(6), 590–604 (2007)
8. Shimomura, Y, Hara, T, Arai, T: A service evaluation method using mathematical methodologies. CIRP Ann. Manuf. Technol. **57**(1), 437–440 (2008)
9. Shimomura, Y, Hara, T, Arai, T: A unified representation scheme for effective PSS development. CIRP Ann. Manuf. Technol. **58**(1), 379–382 (2009)
10. Maussang, N, Zwolinski, P, Brissaud, D: Product–service system design methodology: from the PSS architecture design to the products specifications. J. Eng. Des. **20**(4), 349–366 (2009)
11. Alonso-Rasgado, T, Thompson, G, Elfström, B: The design of functional (total care) products. J. Eng. Des. **15**(6), 515–540 (2004)
12. Alonso-Rasgado, T, Thompson, G: A rapid design process for total care product creation. J. Eng. Des. **17**(6), 509–531 (2006)
13. Zhao, Y, Harrison, A, Roy, R, Mehnen, J: Aircraft engine component deterioration and life cycle cost estimation. In: Hesselbach, J, Herrmann, C (eds.) Globalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, pp. 657–662. Springer, Berlin (2011)
14. Neaga, EI, Henshaw, M, Yue, Y: The influence of the concept of capability-based management on the development of the systems engineering discipline. In: Proceedings of the 7th Annual Conference on Systems Engineering Research (CSER 2009), Loughborough University, Loughborough, 20–23. (2009)
15. Matzen, D: A systematic approach to service oriented product development. DTU Management Engineering, Technical University of Denmark, PhD dissertation (2009)
16. Tan, AR: Service-oriented product development strategies. PhD thesis, Department of Management Engineering, Technical University of Denmark. (2010)
17. Hussain, R, Lockett, H, Annamalai Vasantha, GV: A framework to inform PSS conceptual design by using system-in -use data. Computers in Industry, Special Issue: Product Service System Engineering: From Theory to Industrial Applications **63**, 319–327 (2012)
18. Tucker, A, Tischner, U: New Business for Old Europe - Product-Service Development. Competiveness and Sustainability, Greanleaf, Sheffield (2006)
19. NASA: NASA Systems Engineering Handbook: NASA/SP-2007-6105 Rev1. , NASA, Washington, D.C (2007)
20. Annamalai Vasantha, GV, Hussain, R, Cakkol, M, Roy, R, Evans, S, Tiwari, A: An ontology for product-service systems. In: Xu, Y (ed.) Decision Engineering Report Series. Cranfield University, Cranfield (2010)
21. Annamalai Vasantha, GV, Roy, R, Cakkol, M: Problem definition in designing product service systems. In: Proceedings of the 3rd CIRP Conference on IPS2, Braunschweig, 5–6 May 2011. ( )
22. Roy, R: A Primer on the Taguchi Method. Society of Manufacturing Engineers, Dearborn. ( )
23. Supply-Chain Council: Supply-Chain Operations Reference-Model: SCOR Version 7.0 Overview. Supply-Chain Council, Cypress. (2005)
24. Komoto, H, Tomiyama, T: Systematic generation of PSS-concepts using a service CAD tool. In: Sakao, T, Lindahl, M (eds.) Introduction of Product/Service-System Design, pp. 71–91. Springer, Berlin (2010)
25. ISCL software. (2005). http://staff.aist.go.jp/h.komoto/iscl_en.html (2011). Accessed 20 Aug 2013

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