Abstract

Servitisation is recognized as a key business strategy for Original Equipment Manufacturers willing to move up the value chain. However, several barriers have to be overcome in order to successfully integrate products and services. Many of these barriers are caused by the technical challenges associated with the design and management of the product-service systems, such as life cycle service level and cost estimation, risk management, or the system design and pricing.

Asset management presents itself as a key research area in order to overcome these barriers as well as to integrate product-service systems within the manufacturers' operations management. It is the scope of this paper to provide theoretical and practical insights with regards to the alignment of asset management and product-service system research areas. To support the alignment between both areas, a management framework which gathers specific technologies, including reliability analysis, simulation modelling and multi-objective optimisation algorithms, is presented. The purpose of the framework is to provide manufacturers with a decision-support tool that facilitates the main managerial challenges faced when implementing a servitisation strategy.

The paper contributions are successfully applied to case studies in the railway and wind energy sectors based on real field data, thereby demonstrating their suitability for both facilitating manufacturer's decision-making process and better satisfying stakeholders' interests.

Managerial relevance statement

Shifting from product-oriented to service-oriented business models could become critical for those manufacturers aiming at moving up the value chain for a better future market position. However, such business models imply to assume the ownership of the products that they used to sell, and in rather unknown scenarios. Thus, products become manufacturers' assets, which need to be managed for them to provide value to their businesses over their entire life cycle.

The lack of asset management capabilities at manufacturers' side may develop a serious risk that is further translated into barriers hindering service-oriented business models adoption. Such barriers are related to difficulties, for instance, to properly define the product-service system contracts or to fulfil stakeholders' requirements during the system life cycle in highly uncertain scenarios.

In this context, the present paper proposes a management framework to provide manufacturers some of the capabilities needed to overcome above mentioned barriers, helping them to design and manage successful

product-service systems.

The framework designed consists of analytical and empirical models providing advanced capabilities for product-service systems management. Likewise, the paper helps manufacturers understand the managerial insights that such capabilities may provide them along their different decision processes, which are further illustrated through wind energy and railway case studies.

Asset management framework and tools for facing challenges in the adoption of Product-Service Systems

A. Erguido, A. Crespo Márquez, E. Castellano, A.K. Parlikad and J. Izquierdo

Abstract

Servitisation is recognized as a key business strategy for Original Equipment Manufacturers willing to move up the value chain. However, several barriers have to be overcome in order to successfully integrate products and services. Many of these barriers are caused by the technical challenges associated with the design and management of the product-service systems, such as life cycle service level and cost estimation, risk management, or the system design and pricing. Asset management presents itself as a key research area in order to overcome these barriers as well as to integrate product-service systems within the manufacturers' operations management. It is the scope of this paper to provide theoretical and practical insights with regards to the alignment of asset management and product-service system research areas. To support the alignment between both areas, a management framework which gathers specific technologies, including reliability analysis, simulation modelling and multi-objective optimisation algorithms, is presented. The purpose of the framework is to provide manufacturers with a decision-support tool that facilitates the main managerial challenges faced when implementing a servitisation strategy. The paper contributions are successfully applied to case studies in the railway and wind energy sectors based on real field data, thereby demonstrating their suitability for both facilitating manufacturer's decision-making process and better satisfying stakeholders' interests.

Index Terms

Servitisation, Asset management, Product-Service System, Management framework, Simulation Modelling, Multi-objective optimisation.

I. Introduction

Original Equipment Manufacturers (OEMs) have traditionally been focused on adding value to their products through improvements in terms of quality and cost. Thus, their investments in research and

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development have mainly been oriented towards products and production processes' design. Nonetheless, manufacturing industries have been undergoing a severe shift of paradigm over the last years, being increasingly challenged by new producers able to offer acceptable quality standards at a low-cost labour base [1]. Therefore, if OEMs want to retain their manufacturing competitiveness, they are advised to "move up the value chain", avoiding to compete uniquely in product and quality offer [1].

In this context, an offer based on the delivery of knowledge-intensive products and services can provide several advantages from a competitiveness point of view [1], [2]. This fact has led to the emergence of Product-Service System (PSS), where both product and services conform a single offer [3], [4], and the business model is no longer selling "only product" but selling an "integration of product and services" [5], [6]. In this new business model, the ownership of the product and its use are decoupled, thus customers (a more suitable term for the users of these products) will not typically buy the product, but its availability or capability [7].

The use of PSSs is expected to bring additional value to an organisation's stakeholders, providing advantages such as: recurrent incomes exceeding the profit margins of new equipment sales [8]; customized and differentiating products [9], and increased customers' satisfaction and loyalty [10], [11]. Nonetheless, and besides the cultural and financial challenges related to the ownerless consumption of products, manufacturers have to face technical challenges associated to the management of PSSs within their operations [1], [12]. Such technical challenges are usually a consequence of having to own and manage their advanced and complex products as own assets in rather unknown and risky scenarios; and they are often the reason of the PSS adoption barriers [13]–[15]. In this context, physical asset management (AM) can acquire a key role in order to facilitate the management of such products (now assets) and maximize their value [16], facilitating PSS design and its performance.

Whereas PSS and AM have been widely researched as independent topics, the impact that the development of accurate AM strategies might have when integrating PSSs in manufacturers' operations has not been previously studied yet. Consequently, the present paper aims to fill this gap in the literature by exploring how developing and improving AM capabilities might help overcome some of the traditional barriers that hinder PSSs' adoption. To this aim, the paper presents a novel management framework, supported by analytical and simulation models, as well as optimisation algorithms, which allows manufacturers optimize their AM decisions and achieve successful PSS scenarios.

From a methodological perspective the research performed can be considered as both explanatory and exploratory [17]. From the explanatory point of view, a literature review has been performed on PSS and AM. This explanatory research provides a fresh perspective in already researched fields, emphasizing on the relationship between both PSS and AM and the gaps to be bridged under an integrated perspective (see Section II).

Subsequently, in order to bridge identified literature gaps, exploratory research has been performed. The investigation focuses on developing new methods that help exploiting asset management capabilities and facing some of the main technical challenges entailed by PSS. These methods should not only consider how can AM capabilities enhance PSS offer, but also how chosen PSS business models condition AM decisions to be made. This research has led to the development of the management framework proposed, as well as of the specific mechanisms it gathers (see Section III).

Finally, proposed developments have been applied to two different case studies based on real field data provided by manufacturers who are facing some of the technical challenges entailed by service-oriented business models. In particular, the simulation models developed, which have been verified and validated (V&V) adopting the approach proposed by Sargent [18], have enabled to quantitatively assess the case studies. Therefore, the results have been analysed from both a qualitative and quantitative perspective, facilitating the discussion concerning the suitability of the developed framework and mechanisms, as well as its limitations (see Section IV).

The research methodology adopted is summarised in Figure 1, which is a graphic guiding line for the remainder of the paper. In section 2 a summary of the exhaustive literature review is presented. Section 3 presents the proposed management framework and describes its main modules and their implementation. Section 4 demonstrates the suitability of the framework through two different case studies in two leading sectors such as wind energy and railway, based on real field data. Finally, Section 5 summarizes the concluding remarks and future research lines.

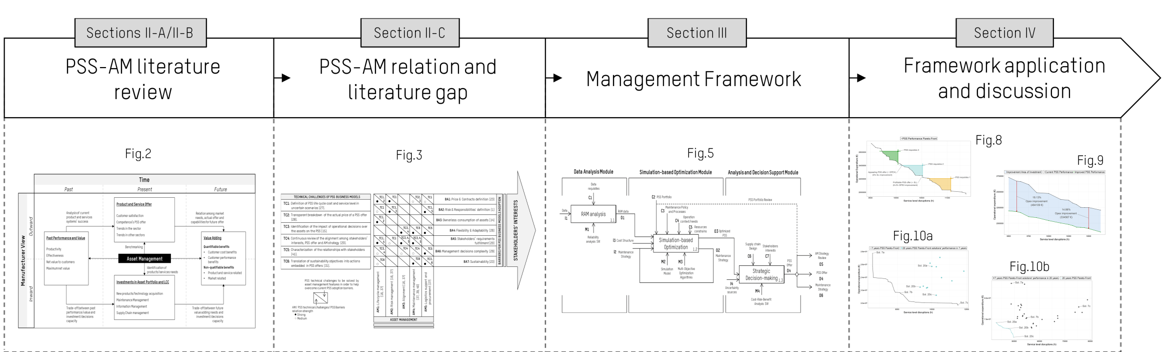


Fig. 1. Research Methodology

II. Literature Review

A. PSS and barriers for its adoption

The integration of products and services has emerged as a new manufacturing strategy for organisations in order to become more competitive, particularly aiming at three objectives: (1) customer satisfaction, (2) economic viability and (3) sustainability [1]. In this context, Tukker [19] highlights that the economy based on purchasing products (*"pure products"*) converges in an economy based on the use of those products (*"pure services"*). This shift, known as *servitisation*, has led to the creation of PSSs, where product ownership and use are decoupled in order to sell the result of their combination [20]. Accordingly, the products provide the technical functions to the customers [13], while the services ensure that customers' demands are met [21]. PSS might be classified into three different PSS business models [19]:

- Product-oriented, where some services to be provided by the manufacturer are included within the product sale (e.g. warranties) [13].
- Use-oriented, where the business model is to sell the availability of the product whilst the product ownership remains within the manufacturer (e.g. car renting services) [13], [22].
- Result-oriented: where the business model is to sell the outcome or capability provided by the product, again owned by manufacturers (e.g. pay-per-print) [19].

The choice of the business model will directly determine *how* value is delivered by the manufacturer and perceived by the customer [23], [24], which will lead to different results in terms of competitiveness and differentiation [25]. Likewise, depending on the PSS business model pursued, products and services will have to be differently combined and implemented by manufacturers within their operations management. To this respect, manufacturers will have to make decisions in several tactics that will determine *how much* value is delivered by the chosen business model [25].

Reim et al. [23] categorize these tactics as follows: i) *contracts*, to define the responsibilities of the stakeholders, for instance in terms of asset's downtimes or service pricing [26]–[28]; ii) *marketing*, to guide the decisions related to the communication between the stakeholders [26], [29]; iii) *network*, to define the interactions with the stakeholders involved in the PSS, such as suppliers, dealers, customers or service partners [26]; iv) *product and service design*, to identify how manufacturers should design both their products and services portfolio to successfully implement the PSS [30], [31] and v) *sustainability*, to meet legal and market environmental conditions through new technologies and solutions [32], [33]. The complexity of making decisions in such diverse domains has translated into several barriers which hinder PSS business models adoption. These barriers (BA) are summarized as follows:

BA1. Price and contracts definition, requiring to handle and fulfil the interests of each involved stakeholder in a long-term relationship [34].

BA2. Risk and responsibilities definition, requiring to guarantee the product performance along its life cycle and the role of each stakeholder within the PSS [1].

BA3. Ownerless consumption of assets, requiring to transparently design the PSS terms, avoiding the conflicts of interests that may appear among the stakeholders [14].

BA4. Flexibility and adaptability, requiring to ensure that service or/and product specifications satisfy the needs of the stakeholders during the whole contractual relationship [26].

BA5. Stakeholders' requirements fulfilment, requiring both to translate customers' requisites into PSS requisites and to align physical products' characteristics to the service [20].

BA6. Management decisions complexity, requiring non-traditional business networks and changes in relationships with actual stakeholders, identifying how decisions made affect them [29].

BA7. Sustainability, requiring to ensure a compromise between economic and environmental benefits [35].

B. Asset management and related capabilities

The complexity of making decisions in such diverse tactics in order to overcome the barriers entails that manufacturers striving for offering a successful PSS have to develop several capabilities ranging from relationship building to technical or management capabilities [36]. Particularly, from a technical point of view, manufacturers often struggle to realize value from the products which they have to manage as own assets in PSS scenarios [15]. To this respect, AM can provide manufacturers with useful insights for enhancing the value that assets can provide to the organization and its stakeholders [37]. In fact, AM is considered to sit the needed meeting point between technical and business performance of assets, making especial emphasis on balancing assets' costs, risks and benefits, over different timescales [37].

Especially when managing products -as assets- in a servitisation context, it becomes strategically critical to assess the four AM perspectives proposed by Tao et al. [38]. The perspectives in Tao et al. [38] have been further complemented and adapted in order to address the case of manufacturers facing a PSS scenario. In Figure 2, the aforementioned perspectives are classified according to their timing, i.e. past, present or future, and their position with regards to the manufacturer, i.e. inward or outward:

- **Past performance and value.** Performance history of products and services are measured in order to analyse whether stakeholders' expectations are being met in terms of effectiveness, efficiency or/and created value.
- **Investments in asset portfolio and LCC.** Products' and services' needs are assessed in order to make decisions either about investments, such as new technology acquisition or development, or about management, such as supply chain or maintenance.
- **Product and service offer.** Stakeholders' interests, as well as competitors and markets' trends are assessed in order to guide future decisions.
- **Value adding.** New products and/or services developments are sought in order to add value to the organisation's offer, both in quantifiable (e.g. cost or service level) and non-quantifiable terms (e.g. market leading image). Future value adding seeks a compromise between internal capabilities and external trends and demands.

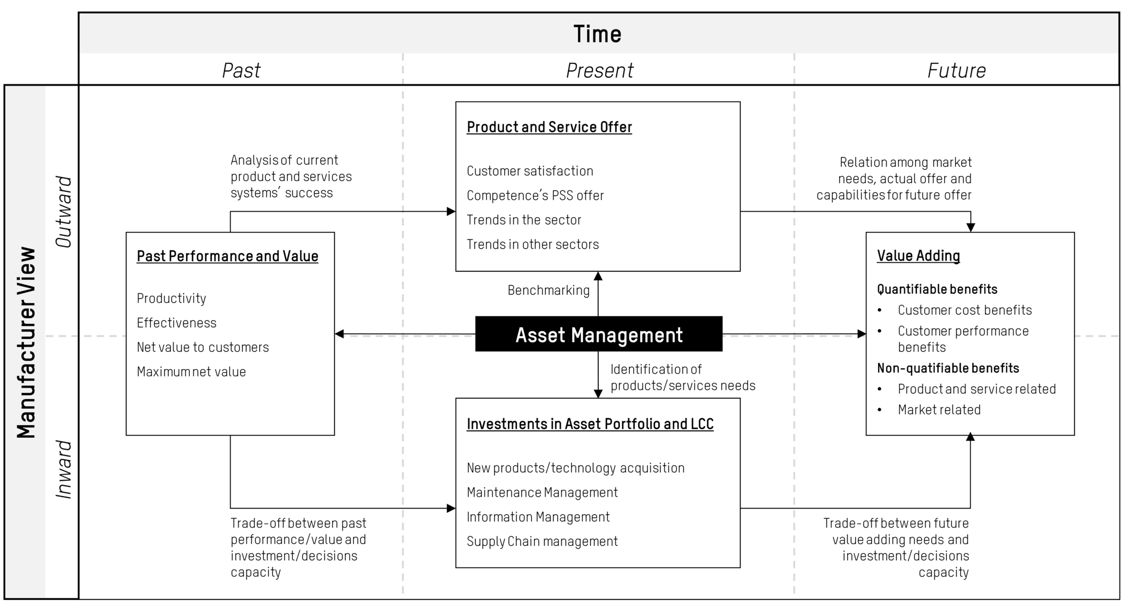


Fig. 2. Asset management perspectives for Original Equipment Manufacturers

In general terms, past view identifies what value has been provided by the products in order to guide present decisions and ensure their efficient and effective management; thus leading to an increase of customers' future value perception [38]. Likewise, inward and outward views help ensure a balance between organisations' capabilities and market trends when making decisions. Therefore, in order to optimize organisations' AM decision making process, it is critical not to consider the stated views independently, but as an interconnected system (see the interactions in Figure 2).

For facilitating such decision processes, physical AM emphasizes on developing technical capabilities in the following domains to enhance assets' value (see [16], [37], [39], [40]):

AM1. Life cycle management, to find a trade-off between initial investment and the value added by the asset, considering the whole life cycle of the asset.

AM2. Risk-based management, to evaluate the decisions not only from a technical perspective but in a risk-based approach, addressing how uncertainty sources might jeopardize organizational objectives.

AM3. Alignment between organisational and asset management objectives, to ensure that decisions made over the assets are directed towards enhancing organisations' objectives.

AM4. Maintenance management, to operate and maintain assets within acceptable performance indicators such as, reliability, safety or cost.

AM5. Logistics support and procurement, to ensure that resources needs for asset management and operation are available.

C. PSS-AM relation and literature gap

Considering the strategic role that AM may play in service-oriented business models, manufacturers could benefit of such capabilities in order to face some of the main technical challenges (TC) that actually hinder their servitisation process. According to the literature review performed, some of the main technical challenges to be faced when adopting PSS business models are as follows:

TC1. Definition of PSS life cycle cost and service level in uncertain scenarios [27].

TC2. Transparent breakdown of the actual price of a PSS offer [28].

TC3. Identification of the impact of operational decisions over the assets on the PSS [15].

TC4. Continuous review of the alignment among stakeholders' interests, PSS offer and AM strategy [20].

TC5. Characterization of the relationships with the stakeholders [41].

TC6. Translation of sustainability objectives into actions embedded in PSS offers [31].

To date, there have been several researches that have focused on developing asset management capabilities in order to face specific technical challenges of PSS, which help manufacturers overcome the barriers cited in Subsection II-A. For instance, total cost of ownership and life cycle cost analysis methods have been widely developed and used for estimating the actual price of the PSS offer (see [42]), considering as well uncertain scenarios [43], thus addressing TC1 and TC2.

Likewise, researchers have investigated how maintenance optimisation may enhance operational decisions over the assets in order to guarantee the effective fulfilment of PSS contracts (TC3). Among others, Teixeira et al. [15] studied the impact of optimising predictive maintenance decisions, supported by online simulation in PSS; and Jin et al. [44] explored the transition of the maintenance paradigm from product-oriented to result-oriented PSS. Furthermore, many authors have focused on ensuring that the supply chain is able to support AM activities in service-oriented business models (TC5), specially in terms of providing needed spare parts for maintenance (see [45]).

According to TC4, there is a large volume of published studies focused on identifying stakeholders' requisites at both product and service level in order to convert them into functional requirements of the PSS, so that the overall performance of the PSS is enhanced (see [20]). When analysed in detail, it can be observed that many of the new design characteristics pursued by researchers are strongly related to asset management, namely the ability to be maintained, upgraded, remanufactured, etc. [23], [46]. Moreover, these new design characteristics of the PSS facilitate the implementation of circular economy practices [46], which would ensure a sustainable PSS offer (TC6).

Even if, as reviewed, there is a growing body of literature optimising AM capabilities to enhance PSS performance, researches mainly focus on addressing specific technical challenges of PSS. On the contrary, there are no works that enable to comprehensively link AM capabilities with the technical challenges to be faced by manufacturers implementing PSS. Drawing this link would enable to exploit such capabilities and face the technical challenges with a wider perspective, thus achieving more competitive PSS designs.

Accordingly, Figure 3 provides a deeper insight into the relation between AM capabilities and PSS.

The information included in the figure is the result of the research conducted to address the literature gap that connects servitisation barriers with AM features (classified as “strong”, “medium” or “none”). In line with the cited literature gap, it is the aim of the present research to provide specific models and tools that take advantage of AM capabilities in order to face the technical challenges of PSS and overcome the barriers for their adoption, therefore linking both research domains.

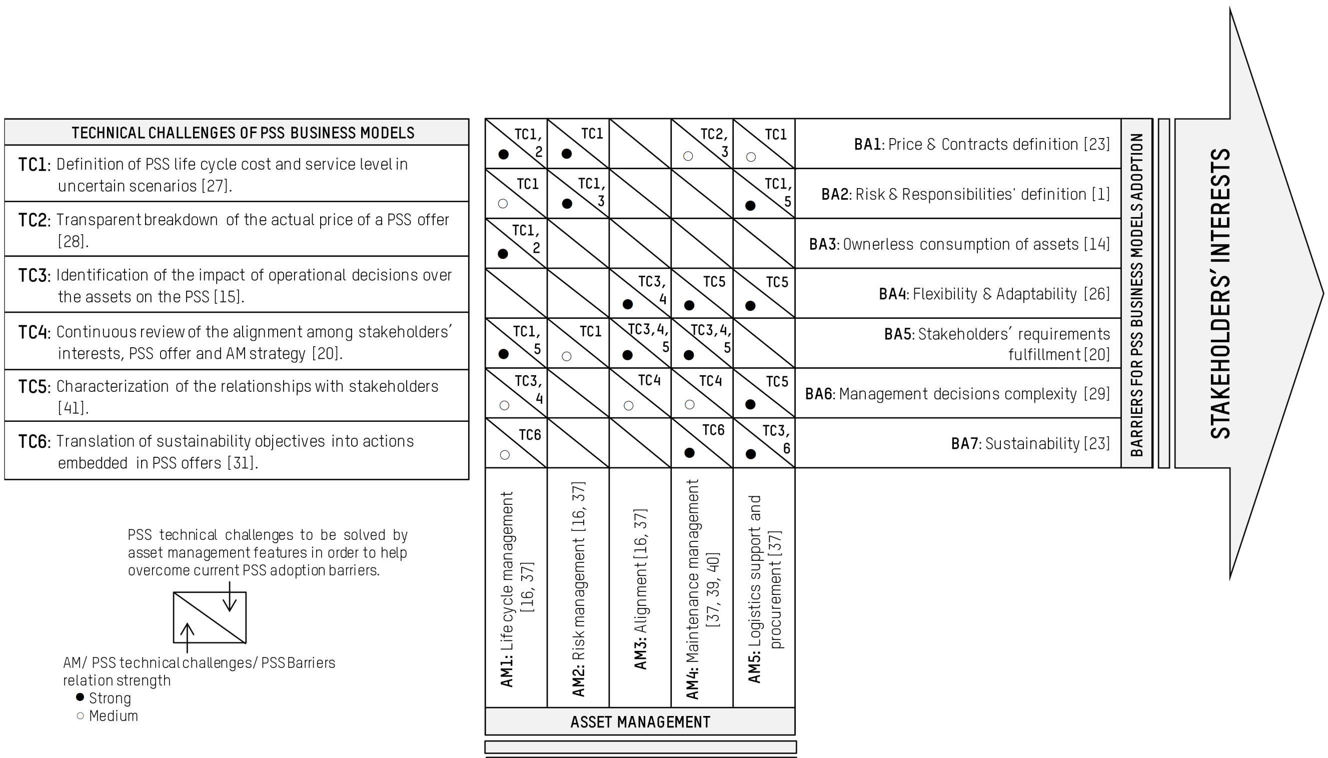


Fig. 3. Matching key features of Asset Management and servitisation barriers

III. Management Framework for Product-Service System design and management

As a result of combining products' and services' characteristics with the specific customers' demands, the potential PSS business scenarios that manufacturers may face are almost infinite. Furthermore, these scenarios are rather unknown for manufacturers, since their PSS portfolios are still under development [47]. In this context there is a clear need of models, methods and tools that can systematically help to design and manage the PSS offering [13], [37], [38], [47], which has led to the development of a management framework inspired in IDEF methodology [48] (see Figure 4).

Defined by functions and ICOMs interfaces (Inputs, Controls, Outputs and Mechanisms), and with a particular focus of enhancing aforementioned AM capabilities, the management framework allows modelling manufacturers' decisions and actions in a servitisation context. To this aim, the management framework translates PSS and AM related data (I) into specific decisions concerning what PSSs should be offered and how should they be defined, what AM strategies are more suitable for enabling such PSSs, and what maintenance decisions should be made in order to fulfil customers' expectations (O). Such decisions will be optimised by means of analytical and simulation models (M), which will consider the specific context of manufacturers in a servitisation context, as well as their customers' interests and the requisites of the mechanisms (C).

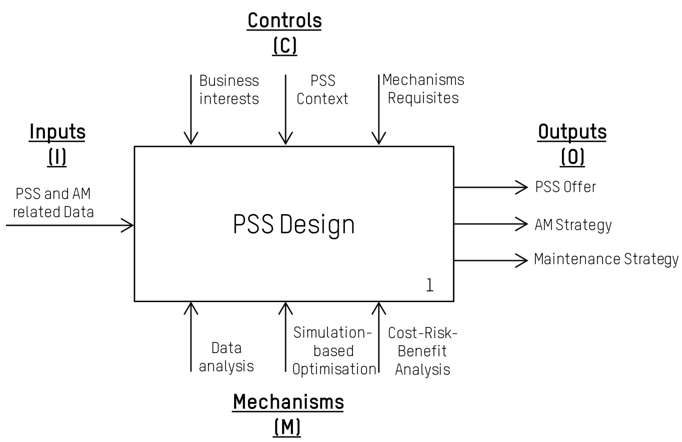


Fig. 4. Overview of Management Framework for Product-Service System design and management

Given the complexity of the problem under consideration, the management framework has been divided in three modules (see Figure 5). These modules, further described in the next Subsections, are as follows:

- **Data analysis module**, aiming at analysing the operational data of already deployed products in order to assess the past performance of AM and to lay the foundations for enhancing manufacturers' AM decisions and PSS design.
- **Simulation-based optimisation module**, aiming at optimizing the long-term performance of manufacturers' PSS and the AM strategies; considering AM inward and future views. It should be noted that this module emphasizes in AM1, AM4 and AM5 capabilities.
- **Analysis and decision support module**, aiming at facilitating manufacturers' final decision-making process, finding a compromise among adopted risks, costs and stakeholders' benefits; it addresses AM outward and future views. It should be noted that this module emphasizes in AM2 and AM3 capabilities.

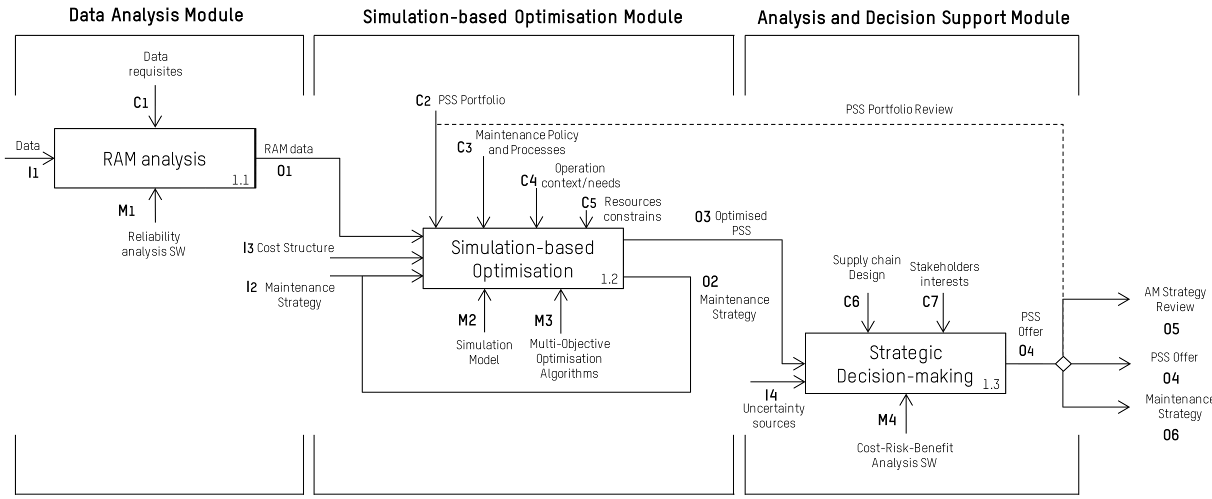


Fig. 5. Management Framework for Product-Service System design and management

A. *Data analysis module*

Currently manufactured original equipments, especially in the context of the Industry 4.0, enable gathering a large amount of data [49]. These data, however, should be translated into useful information with regards to assets' past performance in order to supports manufacturers' decisions related to the servitisation process [50]. This is indeed the purpose of the *data analysis module*.

As described in Section II, decisions made in AM domains have a positive impact on PSSs; decisions that usually regard to [39]: inspections, maintenance, retrofitting, new products development, new technology inclusion, etc. Accordingly, in order to facilitate such decisions it is especially relevant to analyse past performance of sold products according to their reliability, availability and maintainability [42], [51], i.e. a RAM analysis of the products that in service-oriented business models have to be managed as assets by manufacturers.

In particular, much of the current literature on RAM analysis pays attention to the modelling and accurate estimation of reliability [52], [53]. This attention is motivated by the importance of such analysis when making decisions to improve operational safety and economical efficiency of the assets in a risk-based approach. In fact, being a wide research area, reliability models that regard either to operational or strategic decision-making process have been presented [52], [54], [55].

For the framework implementation (see case studies of Section IV), the authors have performed the necessary statistical analyses to determine the reliability of the failure modes of the products to be servitised. In order to avoid the usual and rather unrealistic assumption of identically and independently distributed (iid) failure distributions, which may lead to sub-optimal or even wrong results [55], the general renewal process (GRP) has been implemented [56]. The GRP considers that repair activity *j* may return the system *i* to an operation condition worse than the new one but better than just before the maintenance task is performed, i.e. imperfect maintenance [56], based on two main concepts:

1) Virtual Age (VA). The calculated age of the system immediately after repair process.
2) Rejuvenation parameter (q). The effect of the repair process in the virtual age of the systems.

It should be noted that a value of $q = 1$ leads to a perfect maintenance ($VA = 0$, failed component returns to as good as new condition), whereas $q < 1$ leads to an imperfect maintenance (Eq.1). In this context, before making any decision concerning the servitised asset, failure probability conditioned to the survival of the new virtual age has to be estimated (Eq.2). Due to the widespread application of Weibull distribution in the industry, the conditioned failure probability has been particularized to such distribution in Eq.3 (see Yañez et al. [56] for further details on the reliability and GRP modelling and fitting).

$$VA_i^{new} = VA_i^{old}(1 - q_{ij}) \tag{1}$$

$$F\left(t|VA_i^{new}\right) \quad = \quad P\left[T_i \leq t|T_i > VA_i^{new}\right] = \frac{F\left(t\right) - F\left(VA_i^{new}\right)}{1 - F\left(VA_i^{new}\right)} \tag{2}$$

$$F\left(t|VA_i^{new}\right) = 1 - exp\left[\left(\frac{VA_i^{new}}{\alpha_i}\right)^{\beta_i} - \left(\frac{t}{\alpha_i}\right)^{\beta_i}\right] \tag{3}$$

This reliability analysis, along with the less complex maintainability and availability statistical analyses, lays the foundations for analysing assets' past performance and tackling the convoluted problem of making AM and servitisation decisions in a risk-based approach. Therefore, as shown in Figure 5, the IDEF0 formalization of the data analysis module has been defined as follows: input data related to failures (I); RAM analysis mechanisms (M1), which based on aforementioned algorithms, are able to translate assets' operational data into useful RAM information (O1) for facilitating subsequent AM and PSS decision-making processes; and controls (C1), understood as the traditional requisites for performing the different statistical analyses, such as data sample or quality (see Figure 5).

B. Simulation-based optimisation module

As reviewed in Section II-A, the adoption of PSSs entails making decisions on several and diverse tactics, having often to consider stochastic processes and changing environments within the decision making process, such as: unexpected failures or maintenance actions, changes in customers' expectations and requisites, new competitors, etc. In this complex context, simulation modelling becomes a powerful tool in order to analyse the long-term impact of decisions to be made through life cycle analyses [14], [57], [58], thus reducing assumed risks by OEMs adopting PSS business models [59].

Simulation tools, which have already been successfully utilized to solve engineering problems [60], allow modelling *as is* scenarios and then analyse how different decisions would affect those situations (*what if* scenarios). Based on this concept, simulation models have been implemented for optimising decisions regarding both PSSs design [61], [62] and AM, especially in terms of maintenance and spare parts supply [45], [58]. Likewise, some researches have been focused on optimising specific AM problems, such as prognostics or health management, in the context of PSS [15]. However, according to the literature review, little effort has been focused on the use of simulation models as a decision support tool for making AM decisions depending on the specific PSS business model chosen, which is the aim of the simulation model within the present framework.

It should be noted that simulation models should be both validated and verified in order to ensure their suitability for making decisions. Whereas the verification process ensures that the computer program of the computerized model and its implementation are correct, the validation process confirms that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model [18]. To this aim, the approach presented by Sargent [18] can be adopted, where the whole V&V process is described, from the problem entity analysis to the conceptual model definition and the computerized model implementation. Likewise, in their work the authors suggest the different techniques that can be used in the V&V process, such as degenerate tests, parameter variability, event validity, extreme condition tests, internal validity, etc. [18]

Based on the validated and verified simulation model (M2), the simulation-based optimisation module will evaluate AM (inward view) and PSS performance, for instance in terms of operational expenditure and service-level [42]. Then, based on an optimisation algorithm (M3), which enables to iteratively analyse selected what if scenarios following the logic underlying behind the algorithm [58], the decision-making process of manufacturers will be optimized in order to achieve pursued objectives.

In the particular context of PSS business models, there are several stakeholders involved which usually present conflicting interests, e.g. PSS service level and cost. Thus, decisions should achieve a compromise among the different objectives to be optimised. To this respect, multi-objective optimisation search techniques, able to provide a set of non-dominated set of solutions, should be implemented, such as Newtonians methods or multi-objectives meta-heuristics [15], [58], [63]. For the presented management framework implementation the evolutionary Non-Sorted Genetic Algorithm II (NSGA II) has been selected [64], adopting the optimisation process presented in Figure 6 (note that the population is represented by the decision variables of the asset management and service related decisions to be optimised).

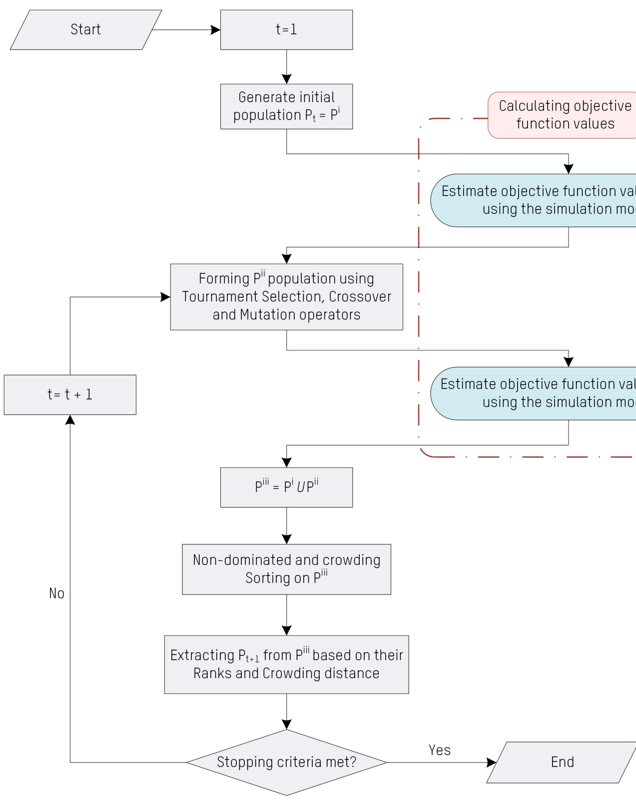


Fig. 6. Simulation-based Optimisation Mechanism for NSGA II (adapted from Attar et al. [58])

In order to illustrate the suitability and potential of the simulation-based optimisation mechanism for facilitating decisions, and given the key role that maintenance management plays both in asset management and servitisation context [39], [62], [65], a maintenance optimisation problem has been derived and implemented. Accordingly, based on the described RAM information from the previous module and the maintenance cost structure (I3), the simulation-based optimisation mechanism will focus on optimizing the maintenance strategy until the stopping criteria are met (I2 and O2, iteratively, see Figure 5). The mathematical formulation is summarized as follows:

1) **Objective functions.** Operational expenditure (OPEX) and service-level disruptions along the time period under study (T) are calculated (see Eq. 4 and 5). They are directly determined by the maintenance strategy adopted, and they depend on the number of preventive and corrective maintenance activities carried out, the maintenance resources cost and the penalizations for not meeting the established objectives.
2) **Maintenance strategy adopted.** Based on the reliability analysis implemented in the data analysis module, a multi-level opportunistic maintenance strategy driven by reliability thresholds has been defined. These reliability thresholds, which are associated to the different failure modes, conform the decision variables to be optimised (see Table I), and each of them triggers a specific maintenance decision (see Eq. 6):

    a) MRT_{ik}, perfect preventive maintenance $(j = 2)$ is compulsory performed in failure mode *k* of system *i* $(y_{ik2t} = 1)$.

    b) PRT_{ik}, perfect preventive maintenance $(j = 2)$ is performed in failure mode *k* of system *i* $(y_{ik2t} = 1)$ if corrective $(z_{ikt} = 1)$ or preventive maintenance $(y_{ikjt} = 1)$ has to be performed in the same system.

    c) IRT_{ik}, imperfect preventive maintenance $(j = 1)$ is performed in failure mode *k* of system *i* $(y_{ik1t} = 1)$ if corrective $(z_{ikt} = 1)$ or preventive maintenance $(y_{ikjt} = 1)$ has to be performed in the same system.

3) **Capacity constraints.** They allow modelling some of the controls (C) to be considered within the simulation-based optimisation module, such as resources constraints. As an example, Eq. 7 limits

TABLE I
VARIABLES UTILISED IN THE MAINTENANCE MATHEMATICAL MODEL

Decision variables	***Intermediate binary variables***
$MRT_{ik} = Minimum\,Reliability\,Threshold\,of\,FM\,k\,of\,system\,i$	$y_{ikjt} = \begin{cases} 1 & if\,PM\,j\,is\,performed\,in\,FM\,k\,of\,system\,i \\ & in\,period\,t \\ 0 & otherwise \end{cases}$
$PRT_{ik} = Perfect\,Reliability\,Threshold\,of\,FM\,k\,of\,system\,i$	
$IRT_{ik} = Imperfect\,Reliability\,Threshold\,of\,FM\,k\,of\,system\,i$	$z_{ikt} = \begin{cases} 1 & if\,FM\,k\,of\,system\,i\,happens\,in\,period\,t \\ 0 & otherwise \end{cases}$

the maintenance tasks according to their maintainability $\left(m_{ik}^{c}, m_{ikj}^{p}\right)$ and the available resources, which depend on the number of maintenance workers (NT) and their working time (T^{wt}).

4) **Maintenance restrictions.** Only one maintenance activity per FM and period of time can be performed (Eq. 8); considered as controls as well.

$$Minimize\ OPEX\left(MRT_{ik}, PRT_{ik}, IRT_{ik}\right) \tag{4}$$

$$Minimize\ Service\,level\,disruptions\left(MRT_{ik}, PRT_{ik}, IRT_{ik}\right) \tag{5}$$

$$S.T.$$

$$0 \leq MRT_{ik} \leq PRT_{ik} \leq IRT_{ik} \leq 1\ \ \forall i \epsilon I, \forall k \epsilon K \tag{6}$$

$$\sum_{i}\sum_{k}\sum_{j} m_{ikj}^{pr} \cdot y_{ikjt} + \sum_{i}\sum_{k} m_{ik}^{c} \cdot z_{ikt} \leq NT \cdot T^{wt}\ \ \ \forall t \epsilon T \tag{7}$$

$$\sum_{j} y_{ikjt} + z_{ikt} \leq 1\ \ \forall i \epsilon I, \forall k \epsilon K, \forall t \epsilon T \tag{8}$$

$$z_{ikt}, y_{ikjt} \epsilon \left\{0,1\right\}\ \forall i \epsilon I, \forall k \epsilon K, \forall j = \{1,2\}, \forall t \epsilon T$$

It is worth noting that whereas the simulation-based optimisation mechanism allows enhancing some of the decisions to be made in the context of servitisation, such as mentioned maintenance management, there are some business decisions to be made which are out of the scope of the optimisation tools. These decisions usually refer to specific PSS restrictions or customer requirements, and thus, they have to considered as controls (C) within the IDEF0 definition of the module. It is the case, for instance, of the PSS business model to be adopted (C2), the specific maintenance processes (C4) and context of PSS (C4) or the resources to be deployed (C5) in terms of logistics and procurement (see Figure 5).

Certainly, these controls define the specific PSS adopted and will act as boundaries of the optimal decisions provided by the simulation-based optimisation mechanism, conforming the so called optimised PSS (O3) (see Figure 5). As a consequence, if decision-makers wanted to address strategic decisions with regards to controls, they should address them using the simulation-based optimisation mechanism to identify and compare different optimised PSS scenarios. Such decisions are specifically addressed in the analysis and decision support module.

C. Analysis and decision support module

In order to facilitate the final decision-making process and to help manufacturers overcome previously presented barriers for PSSs adoption, this last module focuses on analysing the information gathered in the preceding modules. Based on this analysis, decision-makers will not only be aware of the feasibility of the designed PSSs, but also of what AM strategies, including maintenance strategies, should be adopted to satisfy their stakeholders' interests.

Within this module, along with the stakeholders' interests to be fulfilled and the limitations related to the supply chain design (C6, C7), it is critical to consider a risk-based decision approach that assesses how the different uncertainty sources might condition the organisational objectives [66]. Accordingly, it has to be quantified how the uncertainty propagates from the model input variables (e.g. RAM data), through the system model (e.g. simulation model), to the quantities of interest (e.g. objective functions) [67]. As illustrated in Figure 7, where the optimal Pareto Front to be obtained from the previous module is shown, the uncertainty will imply a variability in the quantities of interest of the PSS solutions, which should be considered in order to design a less risky yet appealing PSS offer.

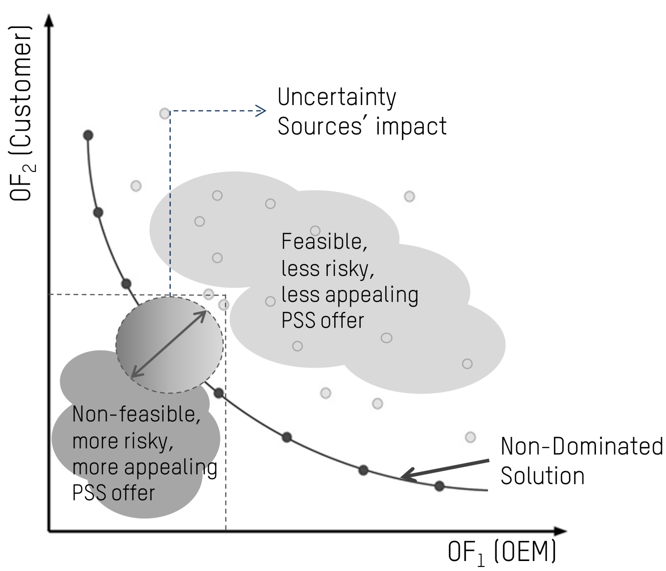


Fig. 7. Uncertainty impact in PSS offer [68]

In order to facilitate such risk-based decision process, the *strategic decision support* function has been provided with a cost-risk-benefit mechanism (M4). This mechanism iteratively evaluates the optimised PSS solutions (O3) under different uncertainty sources' influence (I4), which will let analyse the variability of the outcome of the Optimised PSS; thus enabling to design a feasible PSS offer (O4) with its associated maintenance strategy (O6), that meets stakeholders' interests at an admissible risk adoption (see Figure 7).

The cost-risk-benefit mechanism implements numeric expressions, which based on the foundations of probability, estimate the likelihood of uncertain events [69]. These statistical analyses will provide manufacturers with confidence intervals [43], [70], letting them define specific rules that will restrain adopted risks, e.g. a maximum variability on an specific objective Z $(\sigma^2(z) < Variability Threshold)$ or a minimum value of such objective with a probability $(P\left[Z > z_s\right] \geq Probability Threshold)$ [67] (see authors' paper [68] for further details on this mechanism implementation and application).

Once the outcome of the decisions is assessed within the *strategic decision support* function, in case of non-feasible PSS requirements or a non-appealing offer (see Figure 7), decision-makers will be able to review (in an iterative process) their AM strategy (O5) or/and the controls that characterize the PSS (O4→C2) in order to find new and enhanced PSS scenarios (see feedback loop in Figure 5 and case study II). This *analysis and decision support module* represents the final step on the designing of the PSS.

IV. Framework application and discussion

The present section seeks to exemplify and validate, through a multi-sectorial case study based on real field data, the usefulness of the described management framework to exploit AM capabilities and to help manufacturers face some of the servitisation technical challenges. These case studies assess different decisions to be made in service-oriented business models based on the application of the presented framework and developed technical solutions (see case studies description in Tables II-IV). In particular, data available has been provided by wind turbines and railway rolling stock manufacturers, whose customers are now demanding for services along with the products they acquire.

The result analysis is mainly supported by the Pareto Front provided by the implemented NSGA II optimisation algorithm. As described in Subsection III-B, the Pareto Front shows the set of non-dominated optimal maintenance strategies within the defined control boundaries of the PSS. Finally, it should be noted that costs considered in the case studies are related to the operational expenditures, specifically concerning those critical components for which failure and cost data were available.

Case study I: Designing result-oriented PSS

TABLE II
CASE STUDY I CHARACTERIZATION

Case study description	Design of result-oriented business model, where assets' outcome (service-level) is sold rather than the assets themselves.	
Faced challenge	Life cycle cost and service level estimation (TC1), operational decisions (maintenance) impact identification (TC3), and alignment between PSS and AM strategy (TC4).	
Barriers to be overcome	Price and contracts definition (BA1), flexibility and adaptability (BA4), and stakeholders' requirements fulfilment (BA5).	
Framework objective	To identify the optimal maintenance strategies for sold products, as well as the expected PSS operational expenditure and service-level outcomes. To provide manufacturers' with insights to define the contracts according to their business objectives.	
Framework ICOMs	*I*	Failure and cost data of a fleet of 21 light-rails, 4 systems (brake, traction, heating and ventilation air conditioning and gates) with 2-3 failure modes each.
	C	Specific maintenance process and constraints considered. Result oriented PSS design. Reliability analysis and optimisation constraints' consideration.
	M	Weibull reliability analysis per failure mode (α, β), Imperfect reliability-based opportunistic maintenance strategy optimisation, agent-based simulation model in Anylogic®, NSGA II multi-objective optimisation algorithm implemented.
	O	Optimised result-oriented PSS for rolling stock, with a portfolio of maintenance strategies (defined by reliability thresholds).
Authors' related work	[71]	

If rolling stock manufacturers were to offer a profitable and successful result-oriented PSS, they should not only be able to estimate their products' performance during the life cycle, but to identify how their decisions affect such performance as well (TC1, TC3). To this respect, as illustrated in Figure 8, the *simulation-based optimisation module* of the management framework provides valuable insights, identifying the operational expenditure and service level to which the optimal maintenance strategies lead within the boundaries of the designed PSS (see case study characterization in Table II).

Once manufacturers have this information, they will be able to balance, through the definition of the contract terms and the AM decisions they make, the profitability and appeal of the PSS offered according to their customers' requisites and interests (TC4). Thus, as well as facing some of their main technical challenges and related barriers (BA4, BA5), they will convert contracts' definition from a barrier (BA1) into a business competitive advantage. As illustrated in Figure 8 for the "PSS requisites 2" (in blue), manufacturers may choose different PSS scenarios:

- *Appealing PSS for the customer*, since within the cost limits established by customers, a better service level may be provided (e.g. 5% improvement).
- *Profitable PSS for the manufacturer*, since within the service level limits established by customers, costs may be minimized and thus manufacturers' profits enhanced (e.g. 6.4% of the OPEX is improved).
- *Intermediate win-win scenarios*, where both customers' expectations and manufacturers' profits may be enhanced in a balanced way.

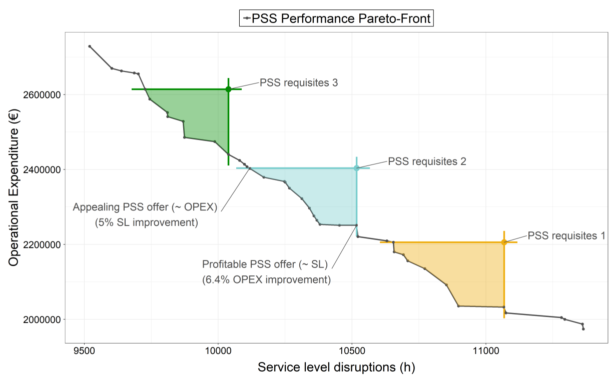


Fig. 8. Representation of feasible PSS boundary

Case study II: Making decisions on PSS improvements

TABLE III
CASE STUDY II CHARACTERIZATION

Case study description	Making decisions on PSS improvements in order to identify how changes in the PSS inputs and controls may affect its outcomes, further analysing investments' suitability.	
Faced challenge	Life cycle cost and service level estimation (TC1), and alignment between PSS and AM strategy (TC4).	
Barriers to be overcome	Stakeholders' requirements fulfilment (BA5), and management decisions complexity (BA6).	
Framework objective	To facilitate strategic decisions regarding PSS potential improvements by comparing and analysing different scenarios.	
Framework ICOMs	*I*	Current and enhanced failure and cost data of a fleet of 21 light-rails (reliability and maintainability of two failure modes enhanced), 4 systems (brake, traction, heating and ventilation air conditioning and gates) with 2-3 failure modes each.
	C	Idem to Case Study I (see Table II)
	M	Idem to Case Study I (see Table II)
	O	Comparison between current and enhanced optimised result-oriented PSS for rolling stock.
Authors' related work	[71]	

Besides the maintenance-related decision-making process, the management framework proposed allows facilitating other AM decisions to enhance the PSS performance, facing TC1 and TC4. Such enhancements in the PSS, which are analysed in the *decision support module* based on the optimised PSS, might have diverse sources: changes in assets' portfolio and/or technology, new terms in relationships with providers, modifications in supply chain processes, etc. In order to analyse their suitability, the inputs and controls defined in the management framework of Figure 5 should be updated, and subsequently evaluate and compare the different PSS alternatives according to stakeholders' interests (see BA5, BA6).

As an example (see case study characterization in Table III), the impact of respectively enhancing the reliability and maintainability of two critical failure modes has been analysed ($\simeq 35\%$ of improvement respectively). As shown in Figure 9, the new PSS pareto optimal would outperform the current one both in terms of operational expenditure and service level. Nonetheless, since these improvements will usually come at an investment cost, decision-makers should consider such cost in order to identify their real profitability.

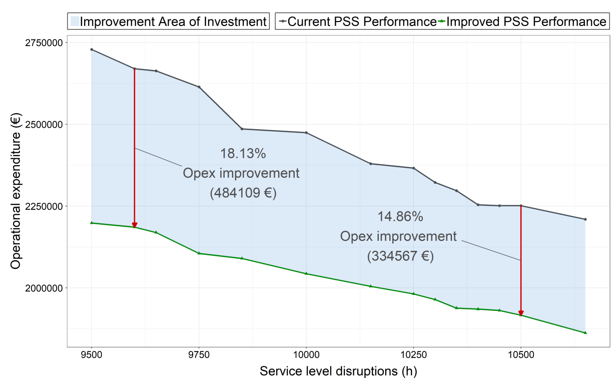


Fig. 9. Representation of investments' impact on PSS performance

To this respect, the improvement area of the new PSS, which has been highlighted in Figure 9, determines as well the maximum profitable investment per expected PSS sale (in present value). For instance, for a service-level disruption of 9600 hours, the OPEX of the PSS would be improved by a 18,13% ($\simeq 484000$€), while for a 10500 hours service-level disruption, the OPEX of the PSS would be improved by a 14.86% ($\simeq 335000$€). Therefore, from an economical point of view (to be afterwards complemented by qualitative managerial insights), if the same service-level was to be offered to the customers of the PSS in each of the cases, the investment cost per PSS should not exceed 484000€ and 335000€ respectively.

Case study III. Designing complex and customizable PSS

TABLE IV
CASE STUDY III CHARACTERIZATION

Case study description	Transparent design of complex and customized PSS profitable and appeal for both customers and manufacturers.	
Faced challenge	Life cycle cost and service level estimation (TC1), and transparent breakdown of complex PSS price (TC2)	
Barriers to be overcome	Price and contracts definition (BA1), ownerless consumption of assets (BA3), stakeholders' requirements fulfilment (BA5), and management decisions complexity (BA6).	
Framework objective	To provide manufacturers with insights for transparently designing complex PSS along with customers in order to overcome the mistrust caused by the conflict of interests.	
Framework ICOMs	*I*	Fleet of 70 wind turbines, 4 systems (gearbox, blades, pitch and yaw system) with 2 failure modes each.
	C	Specific maintenance process and constraints considered. Result oriented PSS design. Reliability analysis and optimisation constraints' consideration.
	M	Weibull reliability analysis per failure mode (α, β), Imperfect reliability-based opportunistic maintenance strategy optimisation, agent-based simulation model in Anylogic®, NSGA II multi-objective optimisation algorithm implemented.
	O	Optimised result-oriented PSS for wind turbines operating 7 and 20 years, with a portfolio of maintenance strategies (defined by reliability thresholds).
Authors' related work	[68], [72]	

PSS terms are often complex to define and they might entail a conflict of interest between manufacturers and customers, which usually brings customers' mistrust and avoids the actual PSS implementation (see BA1 and BA3). In this context, the customized and transparent design of the PSSs' terms by manufacturers and customers plays a key role on the final PSS implementation and success.

For instance, in the wind energy sector, manufacturers have traditionally base their business model on the wind turbines' sale and a further 3-5 years-period warranty, i.e. product-oriented PSS. However, once the established warranty period is over, wind farms are managed by the operators, who struggle on this management process due to a lack of product knowledge. In this context, the management framework presented may help transparently design a customized PSS attractive for both manufacturers and operators (facing TC1 and TC2).

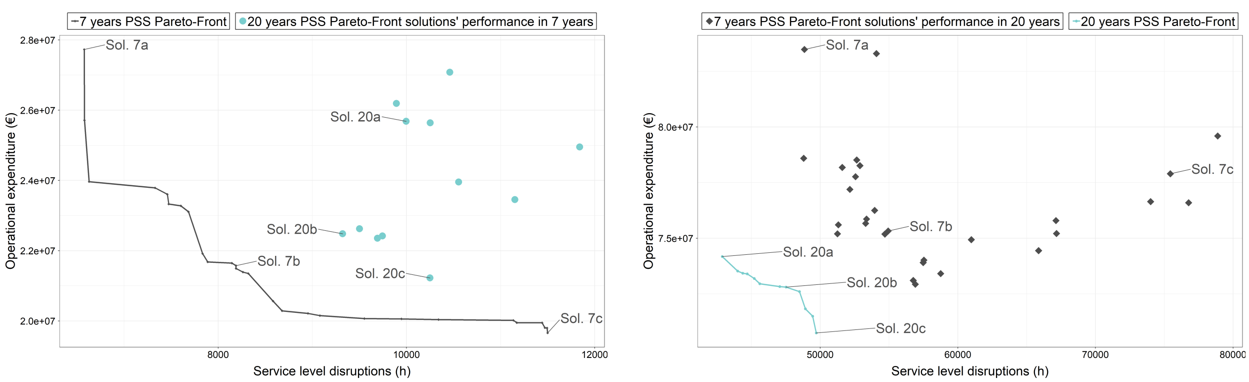
In order to demonstrate the usefulness of the framework, the following complex PSS scenario where both manufacturers are operators could enhance their profits, is designed as an example (see Table IV for case study characterization):

1) Initial 7 years of result-oriented PSS, where manufacturers' incomes can be increased compared to

the previous 3-5 years warranty period.

2) Spare parts' supply product-oriented PSS after the 7th year until the estimated end of life cycle at year 20, where wind farms will be proactively managed by operators according to manufacturers' instructions.

The study of the wind farm performance for 7 and 20 years through the management framework leads to Figure 10. It specifically shows that optimal maintenance solutions considering a 20-year-period (plotted in blue) are not optimal for a 7-year-period, where the optimal Pareto-front is defined by the solutions plotted in gray. Likewise, Figure 10b shows that optimal solutions for a 7-year-period (grey), are not optimal for a 20-year-period (blue). In fact, a more detailed analysis shows that solution 7a, which is the best solution in terms of service level for a 7-years period, is rather inefficient in a 20 year period either in terms of OPEX or service level, dominated for instance by 20a and 20b (see Figure 10b).



(a) Performance of PSS offer for 7 years

(b) Performance of PSS for 20 years

Fig. 10. Performance comparison between 7 and 20 years PSS offers

Therefore, Figure 10 exemplifies the conflict of interest between manufacturers and operators and justifies the mistrust that may arise at operators' side, i.e. manufacturers could adopt the optimal maintenance solutions of 7-year-period, which according to the aforementioned PSS clauses would enhance their results in the initial 7 years of result-oriented PSS (better service level at lower OPEX) and also from year 7 to 20 (since more spare parts would be needed while worse OPEX and service level are achieved). In this context, transparently designing a customized PSS based on the management framework outputs and selecting the 20-year-period solutions (see Figure 10b), would give customers the confidence that the PSS protects their long-term interests; further ensuring win-win PSS implementation.

Limitations of the framework

Even if PSS business models' indicators have traditionally been based on reliability engineering indicators [73], as in the presented framework, the success of the PSS does not exclusively rely on such indicators. In fact, evidence shows that manufacturers should pay special attention to the social and organisational factors that can jeopardize the actual success of the PSS [74]. Whereas it is not within the scope of the paper to deepen on how to deal with such factors, the literature suggests to consider the following social and organisational factors when designing and implementing PSS:

- To ensure a common enterprise perspective among stakeholders, managing the supply chain from a whole system perspective rather than from an individual company perspective [75].
- To preserve the relationships among companies involved in the PSS, especially in terms of communication and interaction [76].
- To ensure that the processes of the stakeholders are understood and that data/information flows properly among them [77], [78].
- To guarantee that internal management processes support the service decisions [74].
- To avoid incongruences between data and operators experience guaranteeing an integrated view of the equipment performance [74].

Consequently, if manufacturers were assessing their decisions based on the information provided by the framework, which is restricted in its scope to help face the technical challenges (see Subsection II-C), they should consider as well mentioned social and organisational factors within their decision-making process.

V. CONCLUDING REMARKS

The present research addresses how the development of asset management capabilities can enhance the design and integration of services within the strategic and operative management of organisations, respectively facing and overcoming some of the main technical challenges and barriers that product-service systems' implementation require.

To this aim, a management framework, which draws the decisions and actions to be considered for the practical alignment and integration of asset management and product-service systems, is proposed. This framework has been provided with specifically developed technical solutions, such as reliability algorithms, maintenance optimisation problems and simulation-based optimisation mechanisms, which have proven to be useful and valuable in both the railway and wind energy case studies based on real-field data.

Within these case studies some of the main technical challenges to be faced in the context of product-service systems are analysed and discussed based on the framework utilization. In particular, each of the three case studies addresses a specific decision to be made by manufacturers, where results obtained validate the usefulness of the developed framework.

Firstly, the definition of product-service systems' contracts and maintenance strategies is addressed, where results show that the framework ensures a profitable yet appealing offer both for manufacturers and customers. Secondly, the framework proves useful for assessing the suitability of investments when improving product-service systems, it allows comparing between the current and the enhanced product-service systems and quantify their expected outcome. Finally, the design of complex product-service systems is studied, demonstrating that the framework provides valuable insights for meeting both manufacturers' and customers' interests while overcoming the conflicts of interests that may appear.

The presented research opens a new research line, where the role that asset management has in product-service systems has been drawn. If this novel proposal was to be fully exploited, further investigation specifically regarding each of the diverse topics mentioned in the paper should be addressed. Among others, there are still unanswered questions about the particular affection of supply chain management decisions to the product-service system or about the fulfilment of the expectations that each stakeholder might have in the different product-service system scenarios. In the same vein, as highlighted in the results discussion, efforts should be placed in researching how to consider the social and organisational factors when designing and implementing the PSS according to the information provided by the framework. Likewise, since the management framework allows designing rather complex product-service system scenarios, as the one exemplified in the third case study, further win-win scenarios for both manufacturers and customers should be explored.

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