System Dynamics simulation applied to Product-Service Systems: a literature review

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Abstract: Manufacturing companies are increasingly offering Product-Service Systems (PSS) to their customers in view of the ability of these solutions to generate added value. The development and delivery of PSS are oriented to adapt the offering to the evolving customer requests, allowing companies to differentiate from competitors, gain higher customer loyalty and trust, and generate new revenues streams. The attention to the customers needs is an essential element of this offer, but to be sustainable for the company it has to be feasible also at the economic level. Thus, it is important to support the identification of the trade-off between effectiveness and efficiency of a PSS and to guide decision-makers. In this context, simulation-based modelling could be exploited as a tool for the decision-making process at strategic level. Among the paradigms of the simulation methodologies, System Dynamics (SD) is a continuous-time simulation approach used to explore complex systems and to make considerations at the strategic level. A literature review focused on the utilization of the SD approach to determine the PSS feasibility is presented. The aim is to provide an insight into the main SD applications related to the PSS context and define the common aspects taken into consideration in the modelling. In this study, SD is presented as a valuable tool to address the structural complexity of PSS and to measure the long-term dynamics of these systems comprehensively.

Keywords: PSS, System Dynamics, decision-making process.

I. Introduction

The rapid evolution of market demand towards more sustainable solutions has brought manufacturing companies to explore new business models. Specifically, manufacturing companies felt the urgency to extend their traditional product-centric offerings and portfolios with new service-oriented proposals, based on a mix of tangible products and intangible services able to generate added value [1]. Such a combination, known as Product-Service System (PSS), represents for manufacturing companies a possibility to instantiate new revenue streams, increase customer loyalty, optimise resource consumption in a sustainable fashion and, thus, enable to differentiate from competitors. The term PSS has been defined as *"a marketable set of products and services capable of jointly fulfilling a user's need"* [3], and as a means for achieving sustainability in the three dimensions of the Triple Bottom Line – economic, environmental, and societal dimensions [4]. The complexities in structuring the PSS offering and forecasting its performance are acknowledged, because of the multiple sources of uncertainties related to its adoption, such as the multiple stakeholders involved in the PSS provision, in particular the customers whose behaviours are complex and non-deterministic [2]. To understand this complexity and uncertainty, characterizing the context of PSS and, consequently, to ensure the successful adoption of PSS solutions by manufacturing companies, a powerful tool can be found in simulation modelling [5]. The literature proposes different simulation-based models related to PSS, covering all the three main simulation approaches (i.e., System Dynamics (SD), Discrete-Event (DES), and Agent-Based (ABS) simulation). However, each of them is suited to different problems and purposes. SD operates at high abstraction level and is mostly used for strategic modelling. DES is a process-centric approach and supports medium and medium-low abstraction. ABS is used to model agents' behaviours and can vary from very detailed to high level of abstraction. Thus, in the PSS context, where the processes have non-linear relations and different feedbacks determine its success, the System Dynamics approach suits best to support decisions at strategic level [6].

This work intends to investigate how simulation-based modelling can be exploited as tool for the decision-making process at strategic level. Specifically, it focuses on the System Dynamics simulation approach, identifying the knowledge available on its application to PSS. It has been selected as the object of more detailed research in this study because SD simulation addresses the complexity and uncertainty characterizing complex systems and it is particularly suitable for supporting decisions at high, strategic level. Furthermore, the attention during the investigation of the applications of SD in the PSS context has been oriented to the sustainability dimension involved, to highlight future areas of research.

The work is structured as follow: Section 2 presents the methodology used to perform the review and the preliminary analysis; Section 3 discusses the results of the full review of the selected papers delineating the common aspects and gaps. Finally, Section 4 concludes the papers, highlighting the results and future developments.

II. Methodology

A. Literature Review

Being one of the major research databases, SCOPUS was used to conduct the literature review. Two separate research were performed: the first one focused on the topic of simulation used as tool enabling to support decision makers in taking PSS-related decisions, without any distinctions on the simulation paradigm; instead, the second one was more focused on the use of System Dynamics in the PSS context, since it is applied with the scope of supporting decisions at strategic level.

The keywords utilised to construct the queries, along with the operators "AND" and "OR" were, respectively:

- ("PSS" OR "Product-Service System") AND ("simulation") AND ("decision-making process" OR "decision makers"), for the first query;
- ("PSS" OR "Product-Service System") AND ("continuous simulation" OR "System Dynamics"), for the second query.

Following, the search results were refined using SCOPUS filters aimed to limit the selection of papers to the research interests. The values used to filter both the two search results are the following:

- Subject area: "Engineering", "Computer Science", "Mathematics", "Business, Management and Accounting", "Decision Science";
- Language: "English"

The obtained set of papers was exported as separate .csv files. At this point, the authors started to read the papers' title, and all the papers not explicitly related to PSS were removed. Then, the abstracts were reviewed and, once again, the papers having abstracts not in line with the research were discarded. The filtered .csv files were converted and merged in a single Microsoft Excel file, and the title of the papers was used as a proxy to remove duplicates. The authors downloaded the full text of the remaining papers and started reading them to obtain the final pool for the detailed analysis. During the reading, following the snowballing procedure, new highly-cited papers were added to the ones already selected [7]. The unavailability of the full texts of some articles led to the full reading of 31 papers for this review.

Table I provides numbers for the analysis, allowing to understand how the final pool of papers was achieved. At this point, Microsoft Excel was exploited to perform a preliminary quantitative and qualitative analysis of the papers' subjects and to have an overview on their content.

TABLE I
PAPERS' NUMBERS AND FILTERS

Filters	Number of papers
Initial pool	141
Title filtering	49 (-92)
Abstract filtering	33 (-16)
Duplicate removal	31 (-2)
Snowballing	+3
Final pool	34
Full reading	31

B. Paper Analysis

The final pool of papers, which cover a time period from 2009 to 2021, highlights, in general, a positive trend in terms of number of publications. Regarding the publishing sources, the results of the analysis show that the Procedia CIRP, publishing papers from CIRP IPSS Conferences, is the most interested to the topic of PSS and simulation, which is not surprising since these conferences are PSS-related. The decrease in terms of conference paper in the last two years might be justified by the fact that the last edition of CIRP IPSS took place in 2019. An analysis of the keywords has been performed, and Fig. 2 shows the most frequent. As expected, there is a strong presence of PSS-related keywords, being the subject of the study. It can be noticed that "Sustainability", and related synonyms, are among the most frequent keywords in the pool. This is coherent with the expectations since the PSS ability of achieving benefits in the Triple Bottom Line has been widely discussed in recent years. Similarly, the Circular Economy and related aspects are frequent, highlighting the correlation between the PSS and the circular business solutions. Then, as expected all the three main simulation approaches (System Dynamics, Agent-Based, and Discrete Event) are discussed in the papers, with a predominance of System Dynamics modelling, which complies with the scope of the review. Finally, it is important to notice the presence of PSS "cost" and "economic" models.

Then, the papers have been classified based on the life cycle phase of application of the simulation methods [8], and of the industrial sector covered. The results of the first classification, presented in Fig. 3, show that simulation techniques are used in several areas of PSS research including the evaluation of the PSS performance, uncertainty modelling across the design and development, the in-service phase and innovation process of the PSS lifecycle. Furthermore, PSS sustainability, mainly the economic dimension, has been object of evaluation through simulation approaches. As shown in Fig. 4, the majority of the papers deal with manufacturing industry, which confirms the increasing trend of manufacturing firms towards adoption of simulation as decision supporting tool for PSS. Related to this, the papers cover a variety of application areas, such as agriculture, energy, washing machine, lighting, and other complex systems. It has been noticed that the public transportation sector is particularly interested in adopting PSS solutions, i.e., e-bike sharing systems, to comply with the sustainability issue.

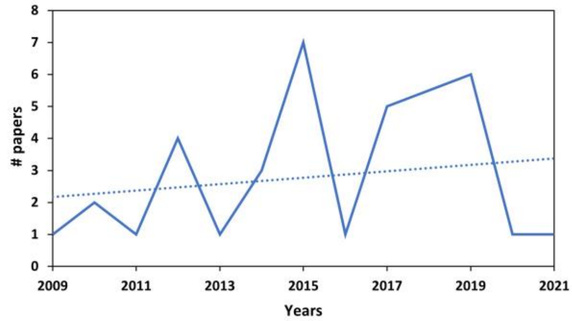

Fig. 1. Publication's Years

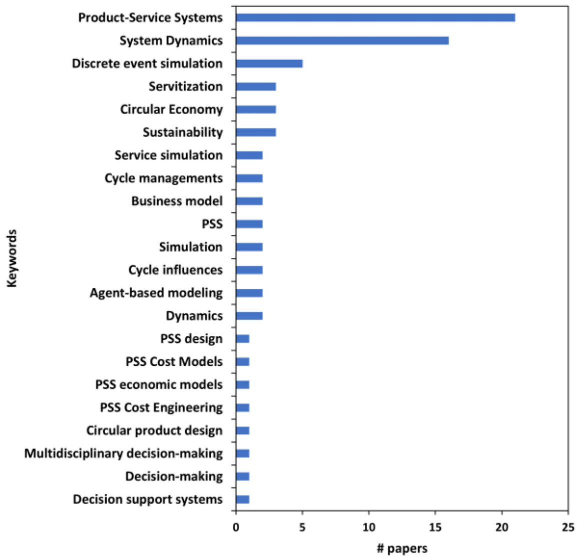

Fig. 2. Keywords Analysis

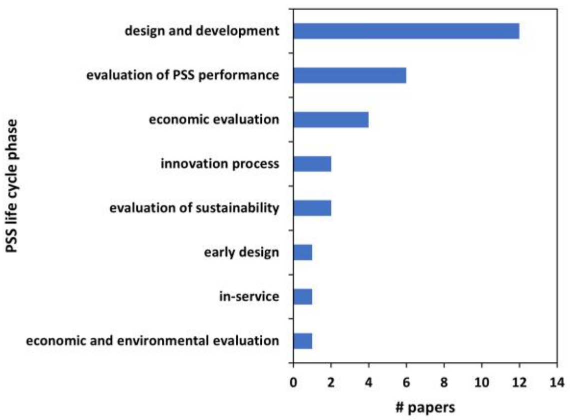

Fig. 3. PSS life cycle phase Analysis

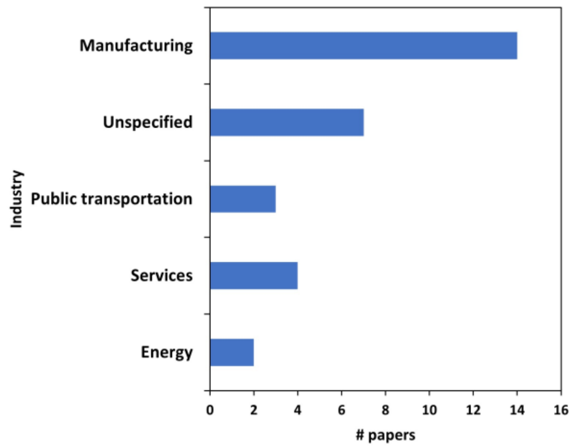

Fig. 4. Industrial sector Analysis

III. Discussion

The full reading of the final pool of papers highlighted common characteristics and barriers related to PSS solutions. Customers and their needs act a central role in the PSS entire life cycle, guiding decisions related to the product and service mix and the business aspect of the PSS solution [4], [9]–[11]. This system helps to establish a long-term relationship favouring to build a win-win solution for both the customer and the provider side. As stated by various authors [2], [4], [12], [13], nowadays customers requests are becoming more and more oriented to sustainable solutions, and PSS shows the potential to generate positive impacts in both the three dimensions of the sustainability (economic, environmental, and societal). More recently, this ability of promoting sustainable consumption has trigged the discussion on PSS as mean to foster the Circular Economy [12], [14], [15]. However, the PSS adoption in the industrial sector faces different challenges mainly due to its complexity (e.g., relationship between multiple stakeholders). This characteristic of PSS is highly discussed in the selected papers. The PSS complexity is due to the involvement of multiple stakeholders in the supply chain, creating a large network of collaborating teams and a dynamic working environment [4], [16]–[19]. In addition, PSS has to deal with different sources of uncertainty:

- customer functional needs which are constantly changing over the entire life cycle;
- customer behaviour which is affected by the fear of risks associated with the unusual PSS offer, and consequently causes variability in the demand; and
- the risks perceived by the provider, especially in economic terms, since the expected returns of implementing a PSS solution do not always cover the costs, mainly due to the lack of in-depth assessment of the service component of PSS (this is called "service paradox") [4], [20].

Thus, manufacturing companies needs to acquire design skills for developing and innovating products and services, as well as be able to develop and maintain a supply network to provide services and transfer value to end-users [21].

To analyze the PSS complexity and to deal with its sources of uncertainty, a powerful tool is simulation modeling. The simulation environment enables to model *as-is* scenario and then analyze the impact of decisions, throughout *what-if* scenarios, in the long-term period [22]. This is very useful for managers that want to implement a PSS solution and need a supporting tool to take informed decisions. From the provider point of view, as previously noticed, the main attention is oriented to reduce the uncertainty influencing the economic costs of PSS delivery. This aspect is highly discussed by many authors, and for that reasons they built evaluation simulation-based models that quantitatively estimate the dynamic economic sustainability of PSS business models [15], [20], [21], [23].

A. *Simulation and PSS*

As previously As previously noticed by the paper analysis, the three main simulation approaches have been used in the PSS context in the last decade with different scopes. System Dynamics (SD) is a simulation approach characterized by differential equations that represent the cause-effect relationships, represented by stocks, flows and decision functions, characterizing complex systems. It is aimed at enhancing the understanding of complex feedback systems while simultaneously supporting the policy formulation process for decision makers [24]. SD does not consider single events but it takes an aggregate view, focusing on policies; it uses global dependencies (i.e., feedback loops), that, usually, are non-linear in the real world, and provide quantitative data for them. Therefore, SD is particularly suitable for applications at high, aggregated, and strategic levels with lower dependency on data. Discrete-Event Simulation (DES) is a computer evaluation of a dynamic system model with discrete events in which operations of the system are performed by a chronological sequence of events. It is process-centric and focuses more on the tactical/operational dimension. This approach supports medium-low level of abstraction [25]. Agent-Based Simulation (ABS) is a simulation approach that focuses on examination of systems from the perspective of individual, interacting components that could evolve over adaptive mechanisms in a changing environment [34]. It allows to make consideration at both low and high level of abstraction. In Appendix A, the three approaches are discussed, highlighting scopes and criticalities in their application to PSS.

In addition to the classical simulation approaches, other mixed models have been proposed. The approach used by [33] is the hybrid simulation, combining ABS and SD approaches, but the constructed simulation model enables to analyze the PSS performance only on the basis of one measure efficiency indicator (i.e., the number of services performed), without quantifying the advantages of the PSS solution from a cost or environmental perspective. [20] utilized an economic simulation platform called PS3A (PSS Scenario Analyzer) to support the quantitative simulation of the economic performance of real industrial PSS value networks, but the authors proposed its integration with an uncertainty assessment framework to deal with the source of incertitude characterizing the PSS environment. However, SD and DES are the mainly adopted in supporting PSS decision-making processes.

In the next section SD applications have been investigated in detail, since the ability of this simulation approach of capturing cause-effect relationships, dealing with uncertainty, and, thus, providing support at strategic level.

B. *System Dynamics and PSS*

Among the paradigms of simulation, this review is aimed to explore the System Dynamics approach in the PSS context. As it can be observed in Appendix A, SD is the simulation method that better deals with PSS complex dynamics and uncertainties. In this section, the authors have analyzed how SD has been utilized in PSS context highlighting the application area, the stakeholders involved and the sustainability dimension.

Among the papers under review, it has been noticed that different authors have used SD approach to study the transition from Product-Oriented towards PSS solutions in the market. [21] modelled the dynamic influencing PO manufactures to start proposing PSS offerings. In particular, they wanted to capture the important relationships and trade-offs in economic and social terms. From the simulation results the authors obtained that new business strategies oriented to PSS can be strongly facilitated by stakeholders' perception and attitude of PSS, as well as economic incentives for the PSS adoption. Also [29] exploited SD to analyze the PSS (use-oriented) adoption in the market, with respect to the traditional purchasing offer, under a policy program. They, specifically, assumed the customer point of view and concluded that high social contagion among PSS potential customers (the so-called "word-of-mouth" effect) reinforces the PSS adoption, reducing the uncertainties by increasing the knowledge on PSS. These models do not provide strategic support for the implementation of a particular service in the PSS model. However, they can be exploited by managers to make strategic decisions for incrementing the customer acceptance of PSS. On the contrary, multiple authors exploited the SD approach as strategic modelling for developing new PSS business models and adapting existing business models in the PSS life cycle. The approach of [6] provides a consideration at management level for new policy introduction related to services. They proposed a SD model for evaluating the introduction of preventive maintenance (PM) contracts to improve service performance and deal with the "service paradox". With this approach they succeed in demonstrating that the company under study gets benefits from the PM – even though the company incurs in higher operational costs, this is balanced by the improvement of several results, such as the overall service profit, the reduction of the inactive personnel costs and the reduction of the spare parts backlog costs. Also, [9] used SD to develop an availability-oriented PSS business model including Total Productive Maintenance (TPM). It focused on modelling the revenue stream on the basis of the availability index (e.g., OEE of machines). The same approach has been used by [11]. The approach of [10] used SD for the strategic personnel capacity planning of PSS. Two models are presented, the so-called resource model and the adaptation model. Once again, liquid asset and cash flows are utilized to demonstrate PSS performance. However, these papers do not take into account the exogenous uncertainties coming from the stakeholders (e.g., word of mouth effect), which, as already stated, affect the adoption of PSS. They consider only the manufacturers' perspective. Other authors exploited SD simulation to evaluate PSS business model concepts, to support the design process phase. In particular, [26] modelled the complex relationships characterizing the PSS in six system dynamics templates replicating the subsets of business model canvas: customer acquisition, channel acquisition, profit creation, resource acquisition, PSS provision and partnership patterns. The same approach has been used by [15], which aimed to evaluate the economic sustainability of PSS business models. The division in the six templates enables a structured identification of the parameters and variables affecting the PSS. The cost structure, revenue stream and PSS provision capacity are the main outcomes. Moreover, as business models are operated with participation of various stakeholders, distributions of costs and profits on service provision with partners have been represented. The strength of this modelling approach lies in the ability of addressing all the aspects of complex PSS business model simultaneously, in a simplified representation. In addition, [15] proposed four KPIs specifically to perform the economic evaluation, which are computed on the basis of the simulation results. They are the net present value (NPV), the return on investment (RoI), the benefit-cost ratio (B/C Ratio), and the break-even point (BEP). The results of the evaluation confirm the economic barrier perceived by manufacturing companies in introducing a PSS solution; in the early stages of the business, the total profit had negative value due to the initial investment cost for PSS, but then they start increasing in the long-term period as the early service increased.

Even though the economic evaluation of PSS performance is a priority for manufacturers willing to adopt PSS solutions, some authors suggested a more comprehensive evaluation of their sustainability – economic, environmental, and societal – since the design phase. The method proposed by [4] helps evaluating the PSS sustainability in the three dimensions of the triple bottom line (TBL). The authors suggested a TLB-based SD approach to support the dynamic and multidimensional evaluation of PSS; more specifically, they used the TBL as the conceptual framework and SD as the measurement tool. It is particularly interesting because it provides a stepwise method for building a complex causal-loop diagram (CLD) for SD (CLDs represents the feedback structures existing in dynamic systems and are used in the conceptualization phase of SD method) by suggesting the concept of building partial CLDs, one for each sustainability dimension. This helps to identify more parameters and variables of the model, and thus have a comprehensive evaluation of the PSS performance. Also [12] investigated the impacts of PSS solution (i.e., leasing contracts) on the three main dimension of the TBL, specifically to show the potentiality of PSS as suitable business model for a transition to CE. However, in their paper, the authors only provided the CLDs showing the feedback loops that affects the PSS adoption, without performing the quantitative simulation. Both the papers suggest the reduction of resource consumption and emissions, as KPIs for the environmental assessment of PSS solutions.

All the above-mentioned papers exhibit the need of more robust indexes, parameters and pattens behaviours to construct SD models of PSS. To comply with these limitations, the literature research must be supported by historical real-world data, obtained through in-dept market and customer analysis, as well as specific company data related to costs and environmental benefits of the PSS solution.

Appendix B summarizes the main evidence obtained by the review. SD applications in the PSS context are mainly oriented to support decisions at strategic level. None of the analysed papers propose SD for supporting operational decisions. Moreover, the performance of PSS that is mainly evaluated by manufactures is its economic performance. However, the review has shown the potential of SD of proving a comprehensive sustainability assessment of PSS, which can be exploited by companies to strength the acceptance of this new business models in the market environment and, consequently, to address the "service paradox". Further developments should focus on the identification of economic, environmental and social variables to build robust models for evaluating the sustainability of PSS and validate them in different markets.

IV. CONCLUSION

The adoption of PSS solutions in the manufacturing sector, even if is increasing, still faces challenges due to their uncertainty and dynamics characteristics. To deal with these challenges, managers could exploit supporting tools that assist the decision-making process related to the transition towards PSS, in particular they can be supported by simulation. Among the main simulation paradigms, SD simulation method is able to incorporate the dynamics of the actors involved in PSS network and the source of uncertainty by means of feedback loops. The literature review has shown that SD can be exploited to drive decisions at strategic level related to the implementation of new PSS business models. Manufacturers focus on the economic dimension of the PSS sustainability to fulfil with the service paradox and thus, they focus on predicting all the costs and revenues stream, main outputs of the SD models. The integration of environmental and social dimensions in these models can provide a powerful supporting tool for strategic decisions towards sustainable PSS implementation and represents an area of future development for SD in PSS context.

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Appendix A. SIMULATION APPROACHES APPLIED TO PSS

Simulation Approach	Simulation approach in PSS context	Disadvantages	Reference
System Dynamics (SD)	Method to recognize patterns in complex structures and their change over time, enabling the evaluation of PSS with a systemic overview and thus supporting the decision-making process in the long-term perspective. Moreover, as a computer-based simulation technique, it can test various changes of uncontrollable factors, copying with the uncertainty of PSS.	Disadvantages of SD are the simplified models and assumptions that decrease usability of results, in particular in the PSS context where there are different stochastic influences (uncertainties) related to the service component (e.g., stakeholder interactions, lifecycle of objects, different revenue stream). Indeed, model parameters are often difficult to be quantitatively populated.	[4], [6], [9]–[12], [14]–[16], [18], [19], [21], [26]–[29]
Discrete Event Simulation (DES)	Method for decision finding and comparison of traditional business models to a PSS-model, specifically oriented to analyze a capacity management for scenarios and strategies in a production system.	Disadvantage of this approach is that a complex dynamic system can be only represented by a sequence of discrete events over time with passive entities through it, thus the individual entities have only passive behaviour. Moreover, there is no real randomness, but only a forced uncertainty based on stochastic probabilities. These do not permit decentralized decisions.	[2], [5], [25], [30]–[32]
Agent Based Simulation (ABS)	Method to map agents by state diagrams, such as machines and technicians, during the PSS-use, so that uncertainty and time factors of capacity planning could be evaluated in customer service. It could be a well performing approach to manage criticalities in the PSS provision process.	Disadvantages of ABS are that the output is always dependent on the model accuracy and completeness of entries, therefore the results from qualitative insights to quantitative values for decision-making support can vary. Moreover, the individual perspective of ABS in large systems can be time consuming and require extensive computational resources.	[13]
Hybrid simulation	Method that combines two or more of the main approaches, working at different levels of abstraction, and exploiting at the same time the strengths of each method. For these reasons, the hybrid model has been considered as a possible way to deal with the complexity and the dynamics of the PSS.	It inherits the disadvantages of the three main simulation paradigms.	[33]

Appendix B. SYSTEM DYNAMICS IN PSS CONTEXT

Scope	PSS Life Cycle	Industrial sector	TBL			Performance measure	Reference
			Economic	Environmental	Society		
Strategic support	Evaluation of PSS performance	Manufacturing	X		X	# PSS adopters	[21]
	Design and development	Manufacturing	X			Costs (operational cost, inactive personnel cost, and spare parts backlog cost) and revenues	[6]
		Manufacturing	X			Liquid asset	[10]
		Services	X			Availability index (i.e., OEE of machines)	[9], [11]
		Manufacturing Services	X		X	# PSS adopters Costs and revenues NPV, RoI, B/C ratio, BEP	[26], [15]
	Evaluation of sustainability of PSS	Manufacturing Public transport	X	X	X	Profitability of the individuals, energy consumption, emissions saving, human health status, # PSS adopters	[4], [12]