Hybrid simulation modelling as a supporting tool for Sustainable Product Service Systems: a critical analysis

1 Introduction

In today's increasingly competitive markets, a growing number of traditional manufacturing companies, whose core business hinged for decades on providing products to the customers, are attempting to move towards a Product-Service-System (PSS) business model, enlarging their value proposition by providing services in addition to their products (Kowalkowski et al. 2015). The advantages and the benefits claimed in the introduction of a PSS business model have been discussed from several points of view (Braax and Visintin 2017). Greater differentiation from competitors and the possibility to 'lock-in' customers and 'lock-out' competitors (Neely 2008) together with the enhancement to a more efficient sustainable offering (Tukker 2015) are probably the most appealing.

Nevertheless, the shift from a traditional product-oriented to an innovative PSS-based business model poses relevant challenges: traditional companies embarking in the *servitization* process have to review their entire organization, facing different levels of risks and uncertainties (Neely 2008; Ng and Yip 2009; Song, 2017). Indeed, PSS entails dynamic interactions among the tangible and intangible components of the PSS, namely the product, the service(s), the customer(s), the provider(s) and the entire infrastructure (Phumbua and Tjahjono 2012) that are complex to design and monitor. Therefore, at least two crucial steps to support companies in this transition can be identified: i) the design of proper PSSs in terms of product and service components, and ii) the assessment of the PSS during the design phases in terms of performance perceived by the customers, company efficiency and effectiveness, and environmental performance (Chou, Chen, and Conley 2015). However, models and tools specifically supporting the development of sustainable PSSs are still lacking (Vasantha et al. 2012). The adoption of models based on the PSS culture, as well as new design, assessment and costing methods, is depicted as one of the internal barriers to success during the implementation of a sustainable PSS business model (Vezzoli et al. 2015). Indeed, companies need to carry on with their traditional product design approach and, concurrently, they have to integrate it with proper service design activities as a mean to develop a marketable PSS.

This study aims at contributing to the PSS research field suggesting a method to design and assess the PSS service component: the service provision process. This method must be then integrated with traditional product engineering methods in order to design the final PSS solution. More in detail, the work proposes the adoption of Business Process Simulation (BPS) to support the design and assessment of the PSS's service provision process according to three main key indicators defined as crucial: performance perceived by the customers, company efficiency, and environmental performance.

The paper is structured as follows: Section 2 reports an analysis about the main critical features of the sustainable PSS provision process that require the adoption of BPS. A cross comparison of the most widespread BPS approaches (discrete events, system dynamics and agent based) against the PSS critical features has been carried out in Section 3, together with the identification of hybrid modelling as a good mean for supporting PSS provision process design and assessment. In Section 4, the effectiveness of hybrid BPS has been tested through a test case in which it has been compared with a traditional discrete event simulation approach. Conclusions and further developments are reported in Section 5.

2 Analysing the complexity factors in sustainable PSS design and assessment

Moving toward PSS business models, many companies suffered poor revenues and scarce return on the investment, thus originating the so-called 'service paradox' (Gebauer, Fleisch, and Friedli 2005; Kuijken et al., 2017). These difficulties mainly relate to the lack of a systematic design and in-depth assessment of the service component of PSS, which usually requires capabilities that are not available in the traditional manufacturing companies. Service characteristics - such as intangibility, perishability and uncertainty (Jaw, Lo, and Lin 2010), together with the dynamic management of infrastructures (Mont 2002), and the continuous involvement of heterogeneous customers in operations (Boßlau 2012) - must be integrated in an effective way into the product design process. PSS indeed are "are mixed product-service offerings with features of heterogeneity, interaction, stakeholder participation and customization, which makes the PSS requirement difficult to be captured, analyzed, concretized and forecasted" (Song 2017). Such service features definitely make the design and the assessment of a PSS provision process a complex task (Rondini et al., 2015).

The following critical features related to the PSS service component, contributing to the system complexity have been identified.

- **Customers have different preferences, behaviours and attitudes** (Lee, Han, and Park 2015). They can be considered as heterogeneous stakeholders that usually do not behave in a standard way. This implies high uncertainty about the demand and in how they act during the service provision process.
- **Resources and customers involved throughout the process are human beings.** As such, they have different preferences, attitudes towards collaboration (Duckwitz, Tackenberg, and Schlick 2011) and the outcomes of their interaction can be unpredictable (Phumbua and Tjahjono 2012). This makes the uncertainty in the service provision process even more critical to manage.
- **Customer and company interaction.** Due to the service features *inseparability* and *perishability*, during the value creation process, the customer and the company interact to generate the offer and the value for themselves (Phumbua and Tjahjono 2012). The PSS provision is not the mere delivery of a traditional product: it implies the relentless participation of the customer in the provider's processes and their continuous interaction. Given such interaction, and the different types of customers involved, the final PSS provision results in a plethora of possible outcomes depending on many factors (e.g. customer needs, company's resources, features of the external business environment).
- **Provider resources operate at customer's premises.** This can cause dynamism and uncertainty. Indeed, the service provision process is usually performed at customers' premises when the customer is present.

Therefore, having an available resource when and where it is needed is quite complex to manage (Lagemann, Boßlau, and Meier 2015), given the distance of customer premises from provider factory and the time that the resources move there.

- **Resources' skills and qualifications are diverse** (Lagemann, Boßlau, and Meier 2015), and this contributes to increase the difficulty in designing and managing the service process.
- **Sustainability as a critical design feature**. According to Tukker (2015), a PSS is not by definition more resource efficient and sustainable than the sole product; therefore, it is relevant to evaluate sustainability since the design phase. Recent papers outlined how the PSS design and process management complexity increase when sustainability issues have to be considered during the PSS design (Vezzoli et al. 2015; Chou, Chen, and Conley 2015). Few efforts could be outlined to integrate sustainability issues in a PSS (Lee et al. 2012; Vasantha et al. 2012).

By analysing the state of the art (Cavalieri and Pezzotta 2012; Tukker 2015; Reim, Parida, and Örtqvist 2015; Phumbua and Tjahjono 2012; Vezzoli et al. 2015; Vasantha et al. 2012; Boehm and Thomas 2013; Qu et al. 2016; Annarelli et al., 2016), it emerges that there is no PSS design and assessment method taking into account all the above mentioned critical features from an holistic perspective. Moreover, in the majority of cases, those features are included in the PSS service process through the adoption of qualitative approaches. In this context, the authors argue that these dynamic features can be managed through BPS and that BPS could properly support a holistic, quantitative-based PSS service provision process design by assessing the efficacy, the efficiency and the sustainability of the process. At the same time, BPS can be used by designers to study the system complexity and to deal with the dynamism at different levels of abstraction.

3 Simulation modelling in sustainable PSS design and assessment: a brief analysis

3.1 Literature review about simulation modelling for PSS

Recent studies applied BPS in the PSS context, as summarised in Table 1. They mainly refer to three different simulation paradigms: System Dynamics (SD), Discrete Event Simulation (DES) and Agent Based Modelling (ABM).

System Dynamics dates back to 1950, and is largely used to analyse the dynamics of a system (Sterman 2000; Leopold 2016). In SD, the real-world processes are represented as stocks and flows. It supports the highest level of abstraction (Borshchev and Filippov 2004).

Discrete Event Simulation is arguably the most used technique in practice (Brailsford and Hilton 2001). It is process-centric and focuses more on the tactical/operational dimension, based on entity flows, resource sharing and sequences of activities: entities can only have a passive behaviour. It supports a medium-low abstraction (Borshchev and Filippov 2004; Weidmann et al. 2015; Hirth et al. 2015).

Agent Based Modelling is a recent approach, more effective in modelling individuals' behaviour, through a bottom-up perspective in which agents have their own rules and become active elements of the model (Maisenbacher et al. 2014). In ABM, the global system behaviour is not defined; it emerges as a result of many individuals, each following its own rules (Borshchev and Filippov 2004).

Next to the three 'pure' methodologies, hybrid modelling grew out of the need to combine the features and the advantages of two or more of these approaches, integrating in one model specific features from the different techniques (Lättilä, Hilletofth, and Lin 2010). This allows attaining higher flexibility at different levels of abstraction, exploiting at the same time the strengths of each method (Wang, Brême, and Moon 2014).

Table 1 summarizes the existing works in the area of BPS and PSS.

Table 1: Summary of the adoption of Simulation to model PSS

<Include here Table 1>

The state of the art confirms that some attempts to evaluate the performance perceived by the customers, the company efficiency and the PSS environmental performance through BPS already exist, and that simulation techniques can potentially help to gather the dynamics of a PSS provision process. Seminal works based on DES, SD and even on the newest ABM can be found. Instead, even though hybrid modelling is recommended to combine the strengths of more paradigms, only one of the investigated works adopted it. In order to identify which of the BPS approaches is more suitable to support the sustainable design and the assessment of the PSS provision process, in the following section a cross-comparison of PSS provision process critical features and BPS approaches properties is presented and discussed.

3.2 Theoretical cross-comparison of BPS approaches and PSS critical features

The PSS's provision process critical features identified in section 2 outlined the high level of uncertainty generated during the PSS provision process as one of the main source of criticality. Hereafter how BPS approaches can support companies in better assessing the PSS service process based on the analysis of the main critical features previously listed is discussed considering the characteristics of each approach.

1. **Model a variety of possible customers' behaviours.** The uncertainty entailed by a PSS is also related to the wide range of possible behaviours on the customer side. ABM responds directly to the necessity of defining individual rules and behaviour, and describes a decentralized system as agents that can behave independently from one another. Agents would perfectly work in representing various human beings with different preferences, skills and attitudes.
2. **Describe inner behaviour uncertainties for resources and customers.** The use of stochastic variables in DES allows simulating process-related uncertainties (e.g. customer arrival rate, duration of activities, reliability of resources, etc.) (Weidmann et al. 2015), while ABM allows to extend the uncertainty to the

human factor through a direct modelling of behaviours. Being based on differential equations, SD may not be the best choice (Borshchev and Filippov 2004).

3. **Describe customer and company interaction.** As much of the complexity entailed in a PSS arises from the value generation process, in which the customer is actively involved, a simulation model should be able to describe this interaction. This can easily happen in an ABM. In a DES, where entities can only have a passive behaviour, the interaction can be defined a priori and can be represented by the company activities interacting with the customer who can be considered as the entities to be processed. Based on stocks and continuous flows rather than on discrete entities, SD can describe interactions only at a high level of abstraction.
4. **Model resources' availability in time and space** and **Model different resources' skills.** Both DES and ABM can respond to these two requirements. In DES, resources' modelling is mainly related to their availability over time, but it can also capture spatial factors (Karnon et al. 2012), while ABM can be used to model resources as active agents if the modeller wants to give higher relevance to their active inttion within the system (Maisenbacher et al. 2014). The high detail level of SD would not fit the scope.
5. **Monitor and evaluate sustainability**. According to the specific needs and features of the system analysed, either DES or SD can be used to give a measure of the system sustainability (e.g. resource consumption in DES, sustainable cause-effects loops in SD), even though none of them has been conceived with this specific aim.

The analysis of these dynamics-related requirements suggests that ABM could be a well performing approach to manage several criticalities in the PSS provision process. However, companies' operations and organization require a certain level of standardization to foster efficiency and responsiveness. This would push the modeller towards the use of DES due to its process-oriented nature that can better fit the modelling of standard processes and activities. On the contrary, a SD model could support strategic decision making giving insights on long-term dynamics, but the analysis shows that it might not be the best choice for PSS provision process.

Since ABM and DES appear complementary (Table 2), a possible solution is the adoption of hybrid simulation in which agents can be used to model the individual behaviour of customers and their interaction with the PSS provider, while the 'standardized' provision process can be described through DES. This allows representing the service delivery process of a PSS as a system where entities move through queues and activities. The use of DES to depict the general process can help in capturing process complexity that results from the possible combinations of many random agents. These theoretical considerations suggest that hybrid simulation modelling is a possible BPS approach to gather the complexity behind the provision process of a PSS. In order to test these theoretical results, a test case has been used. It aims at showing how the combination of ABM and DES can be used to assess a PSS provision process. Moreover, a comparison of this hybrid model against a pure DES approach, which represents the most adopted one in literature, is presented to highlight the former's main benefits or disadvantages.

Table 2: Cross comparison of BPS approaches and the critical features of a PSS provision process

<Include here Table 2>

4 The tests case analysis

In order to test the validity of the theoretical outcome, hybrid simulation (ABM and DES) and pure DES have been compared in a test case. Starting from a real case in the automotive sector, two simulation models have been developed taking into account the main observations and BPS requirements defined in Section 3: a DES model, using the software Arena®, and a hybrid model, integrating DES with ABM, using the multi-environment software Anylogic®. The models have been analysed and validated according to a face validity method (Sargent 2003), thanks to workers operating in the company upon which the case is based, that acted as domain experts, providing their knowledge on the actual processes. Moreover, workers operating in the company upon which the case is based validated the results against the actual processes. The company carries out truck maintenance services for commercial and private customers. Forced by the current market, the company has introduced a maintenance service based on original equipment as well as refurbished spare parts. All the data (e.g. customers' arrival rate and preferences, activities' duration) have been collected from the company. An overview of the two models is shown in figures 1 and 2. Both models follow the same logic in the representation of processes and activities and, although characterized by different structures and features, have been both validated against reality by the experts. Whereas the pure DES model works as a traditional DES with entities entering into a set of activities (Figure 1), the hybrid model jointly utilises ABM to model customers and DES to model the maintenance process. The specific working mechanism and the interaction between the agents and the process are presented hereafter in relation to the PSS features.

< include here figure 1>

Figure 1: General overview of the discrete part of the hybrid simulation model

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Figure 2: General overview of the pure DES simulation model

4.1 Models hypotheses and structure

The system has been modelled taking into account the critical PSS provision process features described in Section 3.

1. ***Model a variety of possible customers' behaviours***. The company manages two main customer categories: customers with a single truck (A) and customers with a truck fleet (B). The customer category A is usually unable to wait for long times: if the expected cycle time for the maintenance activities exceeds a given threshold, they might be willing to leave the company, seeking for a faster alternative. The customer type

B, instead, can accept longer cycle times since he may have backup trucks to put at work. When a customer arrives, the workshop foreman shows him the plan of maintenance with an estimated cycle time. Each customer decides whether to accept or leave the workshop without any intervention, according to a personal rule based on his needs. To measure customer satisfaction, the average operation and waiting times, together with the number of customers leaving the systems, are monitored during the simulation. In the hybrid model, this feature has been modelled through ABM. Each customer corresponds to an agent of type A or type B, and is modelled through the agent state-chart showed in Figure 3 that captures the customer's state. The agent enters the discrete event section of the hybrid model (Figure 1) and, according to the activity it goes through (duration, resources), it changes its status in the agent state chart (Figure 3). Then, the agent's state chart sends back information to the process facilitating the analysis of results and the representation of the decisions taken throughout the process. E.g., once the customer enters the system and is received by the receptionist (figure 1) it moves into the state "received" (figure 3). According to what is happening in the single activity, if the customer is waiting or is receiving a service, the customer moves into the agent state chart in "served" or "waiting". Then in the agent state chart the maximum time that the customer is willing to wait is set (clock in the figure 3) and based on this if the customer is waiting in an activity more than what allowed, the customer moves to the area "unsatisfied". The maximum waiting time is different for customers A and B. The customers in the "unsatisfied" state leave the system in the following part of the DES process, as shown in figure 4.

In the pure DES model, different customers are represented by different entity types and the specific features are added to the customer through entity attributes. Every time the process differs based on the different type of customer decisions, this has to be distinguished through decision modules inside the process (figure 5). The maximum time that the customer is willing to wait before exits the queue is set through an attribute and based on the queue system. Since it is not possible to change the state of an agent, multiple decision nodes are set to distinguish the cases. For example, it is necessary to identify the kind of customer that is going through an activity and the attribute assigned to the specific customer at the beginning of the process. In order to change or modify something in the customer decisions, additional attributes have to be defined or new values for old attributes must be set through the process.

2. ***Describe inner behaviour uncertainties for customers***. In the case, both type A and type B customers can opt either for new or for refurbished spare parts. Later, in case of unplanned issues (e.g. a stock out of a new spare part), customers who decided at first not to buy refurbished products can change their initial decision if the estimated cycle time is longer than they could accept. In the hybrid model, these features have been modelled through ABM, using parameters and variables belonging to each agent, which influence the path of the entity (customers). Again, in the hybrid, this information is directly sent to the process whenever an agent reaches an activity. In the state chart in Figure 3, the variables are included into the invoices or into the clocks.

In the pure DES model, these uncertainties and decisions have to be modelled through a sequence of "if-then" blocks, considering all the possible options as different paths in the process. How the customer behaves and decides is identified through decisional points. This increases the complexity of the model shown in figure 2, as well as of the modelling process. In other words, the customer behaviour and decisions that in the hybrid model is represented by the automatic interaction between the process (figure 4) and the state chart (figure 3), in the pure DES need to be modelled by multiple decisional paths. Figure 5 shows the corresponding part of the DES realized that was used to model multiple decisions for the two types of customers.

< include here figure 3>

Figure 3: Customer's state chart in the hybrid model

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Figure 4: Decision making part in the DES process of the hybrid model

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Figure 5: Customer's choice modelled in the DES model

3. ***Describing customer and company interaction.*** From the previous points, it is clear that the customer's needs and inclinations lead his decision process, which is also based on the information about the state of the service given by the service provider. Thus, this interaction is crucial for the definition of the PSS offer for each customer: through its modelling, different customer's preferences and needs are considered in the test case. The hybrid model itself describes this interaction; ABM has been used to model customers, with attention to their preferences and needs, while the maintenance process has been modelled through DES, based on the operation times and arrival rates observed in the real case. Customers as entities go through the DES process, following precise rules. At the same time, as agents with their own rules and characteristics, they can interact during the process. Their path is not exclusively determined by the sequence of activities defined, as in the pure DES model, but is defined by the interplay of the service state (e.g. long waiting queues, spare parts availability, forecast of total service time) and the customer's needs (e.g. time availability, willingness to use refurbished parts). Figure 6 graphically shows the logic behind

the model functioning and explicates the interaction among DES and ABM: all the components related to customers and their behaviour and choices, as well as the functioning of spare parts stocks, have been modelled through ABM, while DES describes process activities and waiting times.

In the pure DES model, this interaction between customers and company is not clearly represented. Customers are the entities that enter the activities of the process. From the general model, it is not possible to clearly distinguish customers and company roles into the model. Customers are the entities and activities and resources represent the company. How the different attribute change over time (e.g. how much time customers have to wait before served) is defined by entity statistics. In the DES model, the collection of statistics about population of different type of customers (e.g. how many customers type A are waiting on average in the entire system) requires manual definition of variables, statistics that often are quite critical to set.

< Include here figure 6 >

Figure 6: Exemplification of the hybrid model functioning in the case

4. ***Model resource's availability in time and space*** and ***Model different resources' skills.*** Three different types of human resources have been considered in this test case: four technicians; one receptionist; one workshop foreman. All resources follow a fixed work schedule, and the duration of their activities is modelled through triangular distributions, as it depends on both the resource's particular condition (e.g. tiredness, physical and psychological conditions…) and the type of intervention required. Given the necessity of standardization inside the company, resources have been associated to company's activities using DES in both the models.

5. ***Monitor and evaluate sustainability***. The use of refurbished parts allows for savings of CO_2 emissions due to production and transportation, compared to new ones. New and refurbished spare parts have separate orders and inventory systems. During the simulation, the number of stock outs is monitored as a KPI of the process efficiency, while the CO_2 avoided emissions due to the use of refurbished parts has been considered as an indicator for environmental sustainability. In the hybrid model, the stocks for new and re-furbished parts have been modelled as agents, to facilitate the modelling of the inventory management (Figure 7): while the stock for new parts is monitored and new orders are issued when necessary, the stock of refurbished parts depends highly on which used parts the service provider receives daily. The two dynamics are modelled using ABM state charts and variables whose interaction with the process works as described for the customers. In the DES model, the spare part stocks are represented by variables and they are filled by smaller DES processes that are connected to the service delivery one through signals. Checks and controls to verify the level of stocks and the number of used spare parts have been manually defined. The

usage of different kind of spares, by different kind of customers is modelled through multiple decision's points. The interactions between the maintenance process and the inventory fulfilment processes were set manually. It is up to the model designed to represent into the process all the possible situations.

< include here figure 7 >

Figure 7: New spare parts state chart in the hybrid (a) and in the pure DES (b)

4.2 Discussion

Both the models, although characterized by different structures and features as previously explained, are representing the service delivery process as it is, and they have been validated by experts in the field. Moreover, in both models, some service provision process KPIs have been monitored to measure the system's performance, that are:

- *Efficiency oriented KPIs,* including workspaces utilizations (identified by the company as potentially critical resources) and number of stock-outs for both new and refurbished spare parts inventories.
- *Customer oriented KPI*s, including the total customer waiting time, total service time, and the percentage of customers leaving the system, together with the number of customers recovered by offering refurbished parts when new ones are not available.
- *Environmental sustainability oriented KPI,* expressed in terms of CO_2 avoided emissions when a customer buys a refurbished part compared to a new one.

Table 3 shows the way in which the KPIs have been measured into the two models.

The results obtained, that are not reported since they are not the focus of this research, are consistent between the two models, meaning that the two approaches can effectively be compared.

According to the model features and construction, the test case demonstrated that hybrid modelling can cope with all the critical features of a PSS provision process identified in theory, while DES presents some criticalities mainly related to customers' and company interaction and to the necessity of modelling customers' preferences and behaviour. In particular, the customer's choice on the opportunity of selecting refurbished parts when new ones are not immediately available is easily represented in the hybrid model through ABM, using the agent's parameters to enable the choice functions. In the pure DES model, this has been much more complicated, involving the use of different decision blocks to model a decisional tree. More in general, all the possible situations where very kind of customers can make different kind of choices in the pure DES model have to be manually designed and analysed while in the hybrid model they are the result of the automatic interaction between agent state chart and the process, The modeller has to set decisional points and process paths in order to cover all the situations.

Table 3: Example of KPIs measured through the two models

<Include here Table 3>

Summarizing, even if both models allow the analysis of the selected case, some advantages for hybrid simulation can be highlighted based on our experience:

- **Models segregation**: the model of the process and the model of the involved entities (i.e. operators and customers) are clearly separated, allowing for a better description of the different aspects via using the appropriate modelling notation (i.e. DES for the process and multi-agent for the entities). From an operational point of view, this separation also allows for a cleaner attribution of the responsibility over the different models: once the interface between the DES and the agent-based models is defined, it is possible to develop the models separately, even attributing the development responsibility to different modellers. It is no longer required to have a single modeller (or a single responsible for the model development) that must have a deep knowledge of both the simulation paradigms simultaneously.
- **Flexibility**: although in general it is possible to model customers and operators behaviour using the DES alone through a long and complex sequence of "if-then" blocks (e.g. representing customer behaviour or spare parts type), the segregation of the models allowed by the hybrid approach entices a higher flexibility, especially when new entities must be modelled. In fact, the introduction of, say, a new customer in a DES model often requires to change the portion of the model describing the customers' behaviour and the possible entities entering into the system. By moving the customer behaviour model into the agent-based model, it could be possible to introduce new entities without changing the model of the process (i.e. the DES model).
- **Detection of emergent phenomena**: the interactions between entities in the system can result in emergent phenomena (i.e. performance, outcomes…) that cannot be detected by analysing the parts of the model separately. These emergent phenomena can be related to the interaction of several entities with the process or to the interaction between the entities. In summary, the hybrid approach allows for the identification of results and outcome that would be extremely difficult to detect via a DES approach alone. The higher the number of customers or other variables, the higher the difficulty of the pure DES to identify additional outcomes.
- **Simplicity/effectiveness**: due to its nature, agent-based modelling should allow for a better and simplified modelling of the entities behaviour, eliminating the necessity of modelling decision making processes (i.e. the behaviour of the entities) via complex DES constructs, as shown for the description of customers behaviours.
- **Visualization of entities behaviour**: separating the models, it should be possible to better understand the behaviours of the entities operating in the process model. This is immediately understandable looking at figure 1 and 2.

5 Conclusions and further developments

This paper illustrated the adoption of BPS approach to support the design and assessment of the service component of a sustainable PSS. First, a literature analysis helped to draw a list of the features characterizing the complexity of a PSS design process. BPS has been considered suitable to capture such complexity, and a literature analysis on BPS approaches has been carried out showing that DES, ABM and SD have been rarely applied to design the service component of PSSs. The hybrid BPS revealed to be still largely unexplored in PSS environment, though it entails a powerful combination of the other paradigms' strengths, revealing the potential to satisfy most of the PSS requirements identified. A theoretical cross-comparison between the critical features of a PSS provision process and BPS approaches confirmed that hybrid BPS is a good approach to grasp all the features identified. In order to demonstrate how it can be used to support PSS provision process design and assessment, as well as its advantages with respect to traditional DES, it has been applied in a test case in the automotive maintenance sector. The model integrates ABM (modelling customers) and DES (representing the standard service process and activities). At the same time, a pure DES model has been developed to grasp advantages and disadvantages of the hybrid approach.

The test case shows that both the hybrid and the DES approaches could support the design and assessment of PSS provision process since they allow the measurement of the KPIs defined. However, the test case applications show that a combination of DES and ABM tools can have some benefits with respect to a pure DES model. In particular, according to the experience in the test case, the adoption of hybrid model allows a clear distinction of customer behaviour and company process making the whole model more flexible, easy to design and maintain and easier to visualize.

At present, the results obtained are limited to the single case used in this research; hence, no generalizability can be claimed from the results. However, the case has been chosen as a clear and common example of PSS process with the main features described in section 2. Therefore, even though it is a single case, it can be representative of other PSS delivery processes that entail the same general features. For this reason, hybrid modeling could be successfully applied to model and assess PSS with those features.

Further developments could be oriented in different directions: first, the hybrid approach can be applied in a more complex case study with more than two types of customers in order to verify or not the advantages highlighted. Adding more cases to the study could also support the generalizability of results that is currently limited. Second, considering that the current work only focuses on the PSS delivery process the hybrid approach could be integrated with product development methods in order to grant a holistic PSS design and assessment. Third, the current analysis is limited to the comparison between the pure DES and the hybrid simulation approaches but it can be expanded to other kinds of simulations such as system dynamic or lifecycle simulation. An interesting development of the work could be also related to the analysis of the specific case study and to the definition of improvement scenarios. It could be worth exploring the generation of scenarios based on the hybrid simulation paradigm.

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