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A BIM-based PSS Approach for the Management of Maintenance Operations of Building Equipment

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Abstract: The service-centered economy has grown considerably in the last few years, shifting from product-based solutions towards service centered offerings, i.e., Product-Service System (PSS) solutions. Such an approach is also emerging in the context of building equipment, where maintenance activities play a fundamental role in facility management. In this field, Building Information Modeling (BIM) based tools are diffusely used to improve the performances of facility management. However, few studies have addressed the above issues while considering a shift from product-based approaches in favor of more advanced servitization models. The study aims at integrating BIM based approaches in a PSS context for the improvement of the management of maintenance operations of building equipment. A general framework for maintenance management has been developed, merging the implementation of the PSS components in a BIM model for the definition of maintenance management. A first application of this methodology to a real case study concerning the elevators of an existing building has shown the efficacy of the proposed approach. The study highlighted the benefits that can be achieved, especially in terms of reduced periods of equipment unavailability, reduced costs and augmented customer satisfaction, while enhancing the information exchange between the PSS actors. Hence, although further research is still needed for its validation, the proposed approach can offer practical insights for the development of promising BIM-based PSS solutions for facility management in the construction industry.

Keywords: building information modeling (BIM); product service system (PSS); maintenance management; facility management; building equipment; industry 4.0

1. Introduction

In recent years the need to provide more efficient solutions for the production and management of products has been fostering companies to implement strategies that consider the whole life cycle of products [1,2]. As a matter of fact, the proper design and management of all the product's functions during its life cycle allows not only an improvement of its environmental performances [3,4], but also a positive impact on the producer's bottom line [5,6]. Accordingly, particular attention has been paid to the use phase of products in order to optimize the activities related to the proper functioning of products, such as repair and maintenance [7–9].

The implementation of a Product-Service System (PSS) approach can allow an improvement of the product's value during its whole lifecycle, especially in the case of application-oriented systems, such as high-tech and heavy investment equipment [10], where operation activities play a fundamental role for the correct functioning of the equipment. This is the case of the equipment usually installed in buildings, such as elevators, escalators or centralized heating/cooling systems. In fact, in such a context the presence of multiple stakeholders (i.e., the manufacturer, the provider, the building manager, and the building users), as well as the need to operate in regulated markets, where some maintenance services are usually guaranteed by the equipment providers, make the implementation of the PSS approach a very promising solution [11]. Moreover, the use of modern technologies, such as remote monitoring systems [12], cloud computing and data storage systems, as well as the possibilities offered by the so-called "Industry 4.0" [13] can augment the effectiveness of adopting PSS solutions for the management of building equipment.

In literature, several studies have considered the implementation or augmentation of the services related to building equipment. For instance, in the case of elevators, Song and Sakao [14] proposed a design framework for the development of customization-oriented PSS solutions, focusing on the analysis of the customer activity cycle. Van Ostaeyen et al. [15] illustrated the benefits (mainly in terms of economic revenues) for the manufacturer that can be achieved by adopting different PSS approaches. Similarly, Hara et al. [16] depicted the service activities related to an elevator, showing how to enhance the users' satisfaction by adding additional functions such as providing advertisement/information. Further, Cortesi et al. [17] showed the environmental benefits that can be obtained when implementing a PSS approach, discussing a design experience with an elevator manufacturer.

Besides, other studies discussed the integration of digital technologies by means of Building Information Modeling (BIM) [18] based approaches to augment the performances of facility management [19,20], especially focusing on the optimization of maintenance operations [21]. However, despite these potential benefits, the integration of the PSS theory with the opportunities given by the new information technologies and tools has still been scarcely investigated [22]. In particular, the need for more practical studies to support companies and building managers in overtaking product-based approaches in favor of more advanced servitization models has been stressed by Ardolino et al. [23].

Hence, the present study aims to address this gap by means of the development of a BIM based PSS approach for the enhancement of maintenance operations of building equipment. into provide further detail, in the following section the theoretical background and motivations of the study are discussed, while in Section 3 the research method is presented. Such an approach was verified in Section 4, where a case study concerning the management of maintenance and repair operations of the elevators of an already existing building is described. The results achieved are discussed in Section 5, while Section 6 concludes the paper.

2. Research Background and Motivations

2.1. The PSS Approach

The PSS approach relies on the awareness that providing not only the product but also services related to its proper functioning during its whole life cycle has the potential to offer a more effective and efficient solution than a stand-alone product [24,25]. Indeed, it has been proved that this type of solutions can augment customer satisfaction and value, while reducing costs and environmental burdens [26–28]. As remarked by Tukker [29], this type of integration can be classified into three main models:

- Product-Oriented (PO) PSS, when the product's ownership belongs to the customer, who receives some services such as warranty, maintenance and customer support, which are able to increase the product's value through the augmentation of its effectiveness and efficiency.
- Use-Oriented (UO) PSS, which differs from the previous model since the ownership of the product is retained by the manufacturer, while the customer usually purchases "per time use" or "per unit use" PSSs.

- Result-Oriented (RO) PSS, when the ownership of the product is retained by the manufacturer, who provides the customer with functions (intangible goods) only, rather than with tangible goods.

In the literature, numerous studies have investigated the application of PSSs in different industrial contexts [30,31], providing PSS models and tools to support manufacturers in the implementation of integrated solutions [32,33]. In particular, a large number of studies have focused on the Use-Oriented PSSs (i.e., when the company provides the product's functions rather than the ownership of the product), since the manufacturer's interventions to optimize the use phase of the product can be very beneficial not only for the PSS stakeholders but also in terms of environmental performances [34,35]. This means that when considering an integrated product-service offering as a functional product (or a "total care product" as per Alonso-Rasgado et al. [36]), a long-term relationship between the provider and the customer can be established. Compared to a traditional product based scheme, in this type of business model the provider is in a continuous interaction with the customer [37]. Hence, several advantages for both can be achieved: e.g., customized functions, an increased knowledge of the product performances, a better understanding of technical and customer care requirements, a constant cash flow, and an augmented availability of the system.

This is especially true when the redesign options of the physical parts of a PSS are limited, as in the case of high-tech products requiring significant efforts for their development [38], as well as in those sectors where the provision of some services is usually included in the offering [10,39]. In such a context, life cycle maintenance activities, including the product's upgrade and replacement, can enhance eco-efficiency [17], augmenting customer value at the same time [40]. Accordingly, when dealing with the provision of complex products such as building equipment, a use-oriented PSS approach should be considered [10,11], where the provider retains the ownership of the equipment and provides all maintenance interventions aimed at guaranteeing the proper equipment's availability during the whole contract period. These activities include inspection, monitoring and diagnosis, maintenance task execution, as well as evaluation of maintenance results and update of the equipment safety documents [7]. Moreover, as noted by Ulaga and Reinartz [5], when customers consider the provision by the manufacturer of a set of basic product-oriented services as being necessary, shifting to more integrated offerings such as the use oriented PSS model provides businesses with the opportunity to expand their business, generating more value and reducing costs.

In recent years, these issues have also received greater attention in the construction sector, focusing on the development of solutions for sustainable buildings [41]. In fact, most studies have investigated the application of a life-cycle thinking approach to improve the environmental performances of buildings [42]. Whereas a few studies have addressed facility management by means of the PSS approach, discussing its integration with BIM solutions has only occurred thus far at a general level [43,44].

2.2. The BIM Approach

BIM is a complex system of information, including 3D visual aids, whose performances depend on the level of detail of data implemented in it [45–47]. In fact, the effectiveness of BIM in supporting the assessment of design features, as well as the management of a flow of information of all operations related to constructions, relies on its databases containing both geometric and non-geometric data [48–50]. As remarked by Jiang et al. [51], the use of BIM has been shifting from its initial use for the design of construction features towards the support in managing all the activities related to the building's life-cycle, such as environmental issues and safety checking. Accordingly, it can foster collaboration between different actors for operation and maintenance of the building's assets [52], especially when considering its extensions that in consolidated literature are classified as "type three" BIM models [18,53]. The use of BIM is fostered to support managers/designers in complex decision making, as it can allow them to manage large amounts of information in a common data environment [54]. Such a tool can enhance the creation and exchange of knowledge related to the whole building's life-cycle, providing information to monitor the operational phases of a building [55]. In the facility management field, numerous studies have discussed the use of BIM solutions. In particular, Dong et al. [56] developed a BIM enabled information infrastructure for the management of Fault Detection and Diagnostics (FDD) of building Heating, Ventilation and Air-conditioning (HVAC) systems, where based on a BIM model developed through the AutoDesk Revit software [57] a dynamic building operational information system was designed. Similarly, a BIM-based automatic maintenance work order scheduling algorithm was proposed by Chen et al. [21] with the goal of optimizing maintenance operations' scheduling. Other works addressed the management of mechanical equipment status considering the BIM authoring perspective [58]. However, as far as the management of the buildings' equipment is concerned, most studies focused on refurbishment methods based on BIM [59], while research on their life cycle maintenance activities is poorly addressed [42].

As noted by Hosseini et al. [60], the role of BIM for the enhancement of facility management activities, such as the maintenance of building's components and equipment, needs to be further investigated considering a multi-disciplinary approach. In particular, the characterization of the different actors (and their requirements) involved in these processes emerged as a winning approach to be addressed in further research works.

2.3. Research Issues

A response to the above research clues can be found in the use of BIM to support PSS in the maintenance management of building equipment. Such an integration can benefit from the combination of the specific characteristics of these approaches:

- the life-cycle perspective and multi-stakeholder approach provided by the PSS business model, shifting the ownership and operation and thus the responsibility of the equipment to the provider; and
- the detailed information flow concerning the operations management of the building's facilities, which can be achieved through the BIM model and its dynamic augmentations.

In literature, the combination of these issues is still scarcely considered, although the integration of such features is recommended for the proper development of operation and management (O&M) of facilities management [61]. Hence, the aim of the present study consists in providing a possible answer to the following research question: how can BIM and PSS models be merged to enhance maintenance operations of building equipment?

With this goal in mind, in the following section the development of a generic framework integrating BIM and PSS characteristics for maintenance management is discussed.

3. Research Approach

The supplier of building equipment (e.g., elevators, escalators, etc.) usually provides the equipment for the customers in return for a monthly fee that takes into account the cost of the product and the activities related for its functioning for a certain period, such as: scheduled and extraordinary maintenance interventions, customer care service, training of the technical staff of the building. Additionally, the upgrading of the system, as well as disposal activities can be included. In such a context, different actors can be involved. Adopting the black box approach proposed by Hubka and Eder [62], the PSS Black Box can be drawn up to illustrate the PSS model from a functional perspective, as shown in Figure 1.

In detail, when implementing a PSS model, the starting point is represented by the request of the customer (input), which is transformed in an operating PSS (output) through a transformation process on which the operators interact (i.e., the PSS actors, as well as the information systems and the technical means). In practice, the PSS provider can be split into different actors, as it is not uncommon for the equipment manufacturer to differ from the retailer, the company providing maintenance operations, or the company providing the customer care. Similarly, the PSS receiver is represented by different actors such as the building managers, their technical staff, and the users of the building. Accordingly, the flow of information can be achieved by different types of systems. The interactions between these different stakeholders can be schematized by means of the view model proposed by Sakao and Shimomura [24], as illustrated in Figure 2.

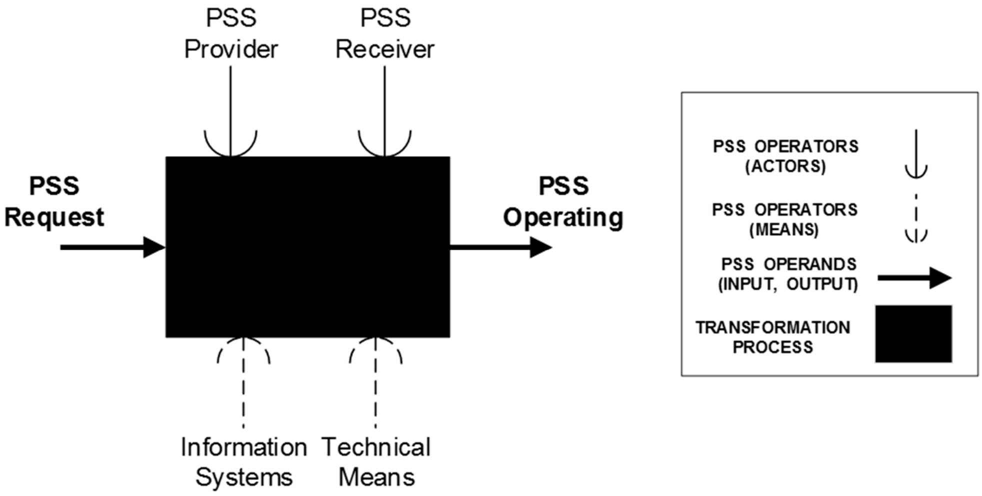


Figure 1. The PSS Black Box.

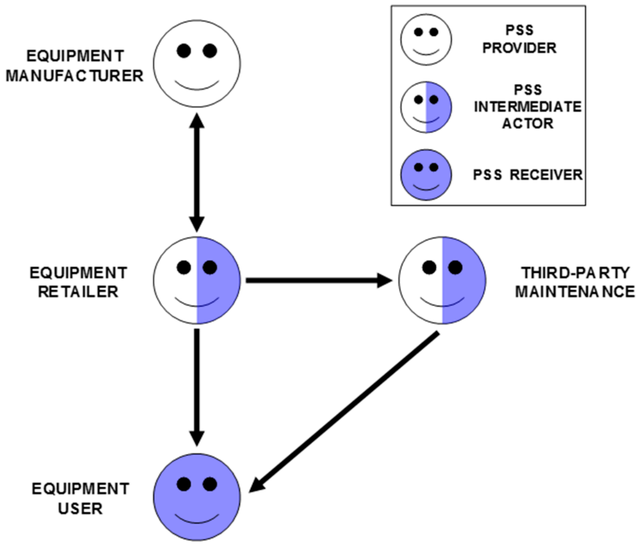


Figure 2. The PSS view model (adapted from reference [24]).

In the case of building equipment, usually companies providing maintenance services (including those requested by safety regulations) are not linked to the equipment manufacturer. Hence, these situations cannot be considered in the ambit of the above-mentioned PPS models properly. Conversely, in a PSS context the manufacturer of the equipment also provides services related to the proper equipment functioning through its retailers/third party maintenance services. In other words, following a PSS approach the flow of information (and responsibilities) is always linked to the manufacturer, while in the traditional maintenance of building equipment such a relationship is not always guaranteed.

The use of BIM tools can enhance this information flow, improving the communication exchange between the different actors. In fact, as remarked by McArthur [63], such an exchange of information is based on a "push and pull" mechanism, where the BIM model provides updated information of the system, while maintenance management data are pulled to update the BIM model. Accordingly, Pishdad-Borzogi et al. [64] provided a practical scheme of interoperability for exchanging information between BIM tools and maintenance management tools, such as the CMMS (Computer Maintenance

Management System) software. In such a context, Chen and Jupp [65] remarked the key role of feedback information for a continuous monitoring of data, suggesting a set of software and platform for their management to support BIM-enabled operations and maintenance phases. Similarly, Love et al. [66] clarify that in order to create and deliver value through BIM, the key factor is represented by the proper definition of "data needs" for the operation and maintenance of facilities: these data include both technical information (i.e., constructive details) of the system and customer requisites on the execution plans of maintenance management.

It has to be noted that in a PSS context the customer is not only represented by the final user of the equipment, but also by the building manager and the building owner, who receive and benefit from the maintenance services [67].

Based on this, to implement a PSS approach in the context of maintenance management of building equipment a procedure containing the following activities can be depicted from the extant PSS theory [30,37]:

1. Definition of the PSS context, such as the equipment characteristics, the characteristics of the place of installation, the customer requirements concerning the maintenance operations, e.g., in terms of availability and operability expected features.
2. Definition of the maintenance operations' technical characteristics, such as the response time in case of malfunctioning, the operational time of technical support, etc.
3. Definition of the PSS actors, as for example the role of building managers and their staff for the solution of minor malfunctioning problems, the presence of third-party maintenance operators, etc.
4. Definition of the PSS components, which include the physical components of the equipment as well as the service components that can be distinguished in information and service tools [38]: e.g., maintenance operations' database and malfunctioning detection's instruments.
5. Definition of the workflow processes, such as the ordinary maintenance operations (scheduled interventions), the training activities for the building managers and their staff, the flows of information in case of extraordinary interventions (unscheduled interventions, such as restore damaged equipment), etc.
6. Definition of the feedback processes, which are aimed at monitoring and improving the PSS performances.

Then, specific tools aimed at supporting the development of the above-mentioned activities at a practical level can be used. In particular, as far as the service features are concerned, the Service Blueprint [68] or the Business Process Map and Notation (BPMN) [69,70] tool can be used in order to represent the flow of the requested service activities. In this way it is possible to highlight the domain of the different stakeholders involved in maintenance activities and their mutual interactions [48]. Besides, the information concerning both the equipment and the places where they are installed plays a fundamental role to define the way maintenance activities have to be performed and their proper provision during the contract period. For this purpose, a BIM model can be employed, where tools such as Autodesk Revit [57] allow a description of the physical characteristics of both the building and the equipment, as well as of the maintenance operations' features [56]. Accordingly, Revit can represent the means for integrating the information related to the maintenance operations with the BIM-based data through supporting standards such as Industry Foundation Classes (IFC) [21].

From the PSS side, the use of tools such as the quality function deployment and its augmentations for product service system development [71] can support managers in capturing and eliciting customer needs related to the provision of the equipment and the related maintenance services. This type of analysis is important in order to define the expected performances of maintenance activities (e.g., "time of response in case of malfunctioning"), providing fundamental information for the definition of both the maintenance management databases (e.g., the definition of customized IFC entities and attributes) and the roles of the different stakeholders. In fact, since the PSS approach transfers the responsibilities for the system availability from the customer to the supplier [72], the role of each actor involved in the maintenance processes needs to be well defined and mapped, providing a clear flow of information to avoid document losses or redundancy, as well as mistakes in operations or delays in interventions. A more detailed list of these activities and the related tools used in the present study are reported in Table 1.

Table 1. Activities and tools for the development of an integrated BIM-PSS maintenance framework.

Activities	Outputs	Tools
Definition of the context	Customer needs	Interviews; BIM model of the building and the equipment.
Definition of the maintenance operations' technical characteristics	PSS Characteristics	Reliability and maintenance data; Interviews.
Definition of the PSS components	PSS Components	BIM model of the equipment; BIM databases.
Definition of the PSS actors	Actors involved in the processes	Interviews.
Definition of the workflow processes	Map of processes	BPNM.
Definition of the feedback processes	Map of processes	BPNM.
Definition of the PSS schedules	Maintenance schedules	BIM databases; Detection and monitoring systems.

Note: Building Information Modeling (BIM); Product Service System (PSS); Business Process Map and Notation (BPMN).

The final output of these activities consists in the definition of a proper PSS solution for maintenance management, merging the service needs of the PSS receiver with the technical characteristics of both the equipment and the necessary operations to guarantee its availability. At the same time, the use of customized IFC attributes can represent the basis for the implementation of detection and diagnostics means, which can make the BIM model dynamic (e.g., providing remote control monitoring, updating maintenance database automatically, updating components database, etc.) [73], augmenting the effectiveness and efficiency of maintenance operations.

Hence, based on the above considerations, a model for the management of maintenance activities of building equipment can be depicted in the BIM-PSS Maintenance Management Framework illustrated in Figure 3, where the flow of the PSS development activities is interrelated with the ones concerning the development of BIM components.

In summary, such an approach allows the implementation of a use-oriented PSS approach, where the BIM role is twofold:

1. In the PSS implementation stage, information on the equipment's components is integrated with the one related to the expected characteristics of maintenance services. In other words, the PSS provider needs to analyze customer needs and expectations in order to define the characteristics of the PSS (i.e., product and service characteristics), and then translate them into PSS components, which can be split into "product components", "information components" and "service components" [74]. On the one hand, data on "product components" are usually at the provider disposal and can be directly provided by means of a BIM module (as schematized in Figure 3). On the other hand, data related to the components of the maintenance services (e.g., the response time in case of malfunctioning, the customer care characteristics, etc.) are elicited through the analysis of customer requirements [75,76]. Hence, such an approach can allow a better understanding and management of customer needs, making the information in the BIM model more complete and satisfactory for the customer.
2. In the maintenance management stage, contextual and use data from BIM can be used to optimize maintenance operations and the related information exchange between the provider and the customer. In fact, data related to maintenance operations derived from the previous stage are put

into practice through the definition of maintenance plans and schedules adapted to the needs of the customers. Accordingly, BIM tools can improve the flow of information during these activities by means of improved data sharing and information control [77]. In fact, maintenance operations can be easily tracked and the related data can be stored through the creation of a database on maintenance activities that is capable of providing updated data and reports at the disposal of both the provider and the customer. The practical implementation of the BIM system can be carried out using different software solutions [68] as the definition of a specific set of tools for the implementation of BIM depends on whether a pre-existing BIM is already available or not [78]. As better explained in the case study section, we adopted the use of Autodesk Revit [57] to describe the physical characteristics of the system and the features of the maintenance operations. This can facilitate a further implementation of the building information model to obtain Construction Operations Building Information Exchange (COBIE) or Computerized Maintenance Management Systems (CMMS) deliverables [79].

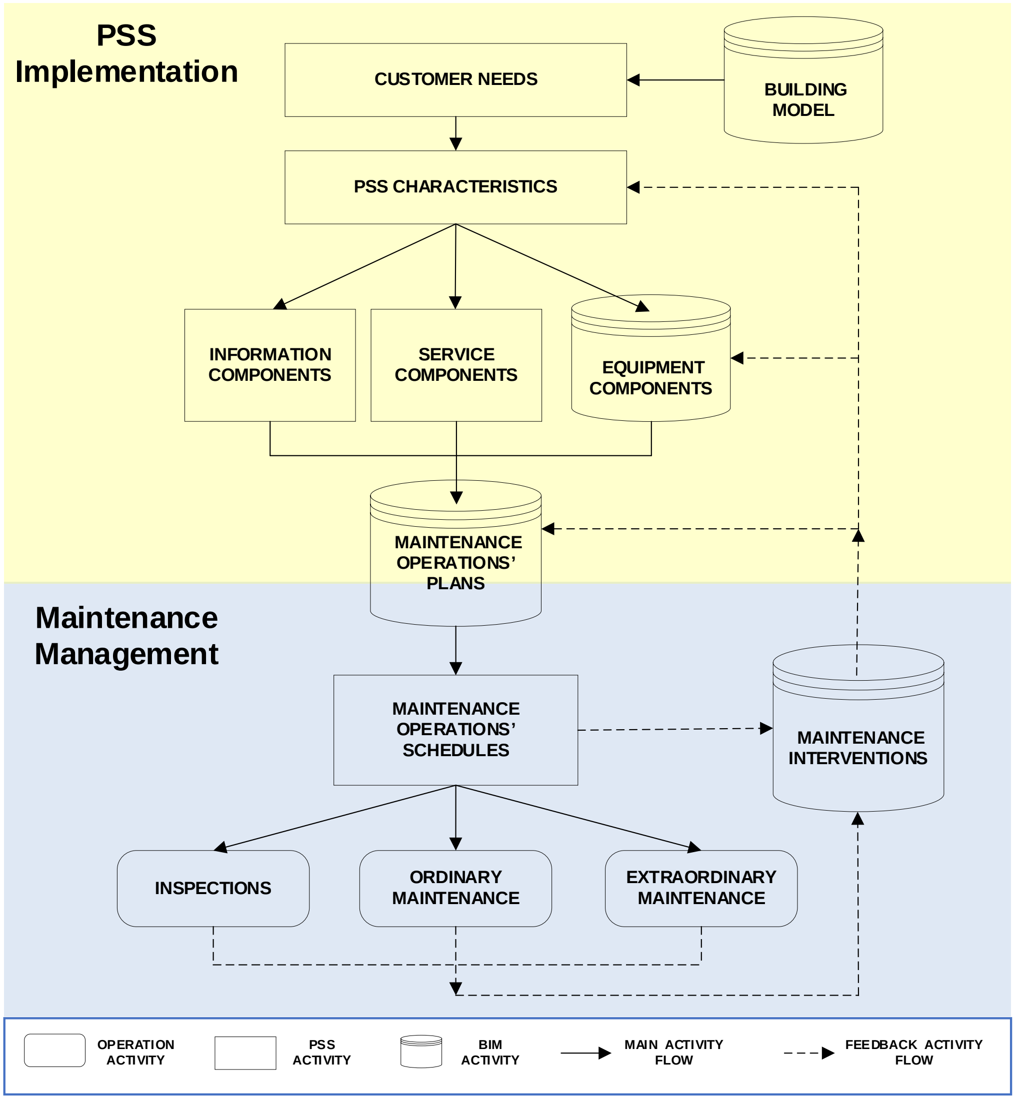


Figure 3. The BIM-PSS Maintenance Management Framework.

4. Case Study

A first verification of the proposed approach has been applied to a practical case study regarding the management of maintenance activities of the elevators in a building serving as a training center of a government body, indicated as Company "A" due to privacy concerns. In particular, the five floor (including the basement and the crawl space) building object of the study is more than 100 years old, and it is equipped with 4 elevators. Company A owns the equipment, while the maintenance service is provided by an external company specialized in maintenance services. Company A is aiming at replacing the elevators due to their obsolescence and to the fact that in recent years the building has been used as a training center, hence the flow of people using the facilities every day has increased. Therefore, a feasibility study regarding the implementation of a PSS solution for the provision and maintenance of four identical elevators was carried out in collaboration with the building manager and the technical staff of Company A.

The first step of the study consisted in analyzing the needs of the customers, which here are represented both by the Company A (the building manager and the technical staff) as well as by the final users of the elevators, i.e., the administrative personnel of the training center.

Then, a series of interviews was carried out, in order to understand what type of elevators are needed and how maintenance activities are managed. This activity allowed us to define the expected performances of the elevators as well the type of drive system suitable for the building's dimensions (i.e., the existing elevator's shaft). Based on this, the software DigiPara® Elevatorarchitect for Autodesk® Revit® [80] was used to choose a new model of elevator fitting with the above characteristics: in particular, the "OFFICE TYPE" parameters were selected among the different options provided by the software. It has to be noted that legislative requirements concerning safety and accessibility issues were considered, including those concerning the accessibility of persons with disability. It has to be also noted that since the four elevators are identical, hereafter we will focus on only one of them.

Further, the maintenance processes were mapped in order to define the flow of information and activities. In Figure 4 a simplified scheme of extraordinary maintenance operations is reported, where both the customer care service and the maintenance operations are managed by the same actor, i.e., the provider.

Company A currently adopts a conventional maintenance contract with a third-party company, according to which for a monthly fee:

- two inspections every month are foreseen, in order to verify the proper functioning of the elevator's components, including those for the compliance with safety requirements;
- a prompt intervention in case of malfunctioning is guaranteed to restore safety conditions of the equipment;
- interventions requiring the replacement of small parts or similar activities such as the refill of the hydraulic system's oil, or the cleaning of the pit are included in the contract, while other repair interventions are paid for separately.

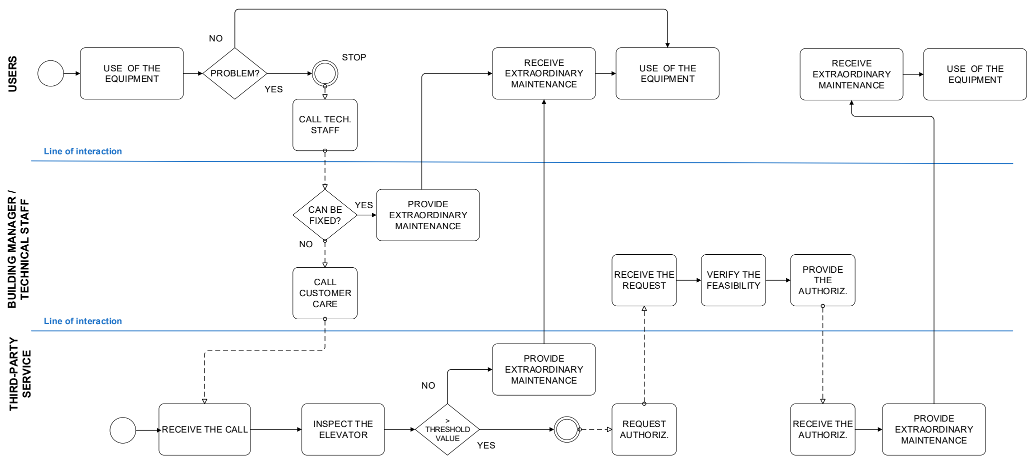


Figure 4. BPMN map of the existing extraordinary maintenance processes.

As far as the latter aspect is concerned, it has to be pointed out that interventions whose cost is under a certain threshold value are carried out directly, while if the estimated costs are higher a specific request for authorization is submitted to the building manager, who needs to approve the expenditure authorizing the maintenance company to operate. Hence, an inspection of the equipment is provided by the maintenance technicians before deciding whether the intervention costs are higher than the threshold value or not. In Figure 4, such an activity is summarized in the gateway action of the third-party service due to simplicity reasons.

Thus, analyzing the maintenance documents related to the last five years (2013–2018), during which the same type of contract as the current one was stipulated with two different maintenance providers, it was found out that the main critical aspects concerned the following issues:

- In the case of interventions over the threshold value, an average period of about a week passed between the request for intervention and the authorization to proceed, during which the elevator was out of service.
- In the period analyzed, seven interventions over the threshold value happened involving the four elevators of the building.
- No maintenance plans were provided to the building manager, while maintenance schedules were communicated mainly by fax a few days before the interventions.
- Several times, not only was more than one elevator out of service simultaneously, but also the same elevators were unavailable for three days in a month due to regular inspection activities.

The next step of the analysis consisted of defining the system components: from the product-side, the BIM model of the elevator was completed, including its components. In practice, this activity was performed by adding information to a specific Revit abacus (Figure 5).

In addition, other two abaci were implemented in order to include the components of ordinary and extraordinary maintenance activities respectively. For each component, several fields were implemented. For example, in the abacus related to ordinary maintenance operations, we included among others the following fields:

- Type of maintenance intervention;
- Date of the maintenance intervention;
- Start time of the maintenance intervention (hour);
- End time of the maintenance intervention (hour);
- Duration of the maintenance intervention (end time– start time);
- Elements checked (the components of the elevators inspected);
- Problems identified (specify);
- Solution adopted (for the each problem);
- New components installation (specify);
- Verification of the compliance with mandatory safety requirements (e.g., periodic checks).
- Inspection of safety systems (specify);
- Inspection of emergency systems (specify);
- Inspection of the remote monitoring system (specify);
- Name/code of the operator;
- Date of the next inspection, etc.

Based on this, new maintenance plans were implemented, providing the proper parameters for each field of the abaci. In Figure 7 an example of this activity is given: Figure 7a shows the implementation of the sub-parameters "start of the maintenance intervention" and "end of the maintenance intervention", which contribute to the definition the parameter "duration of the maintenance intervention (end time– start time)" as in Figure 7b.

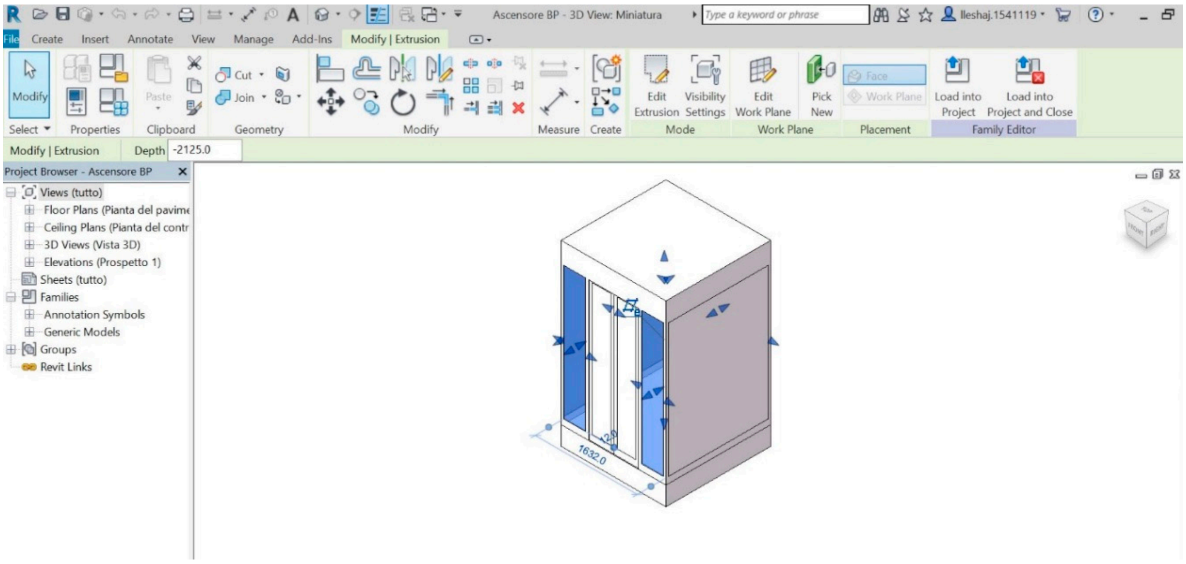
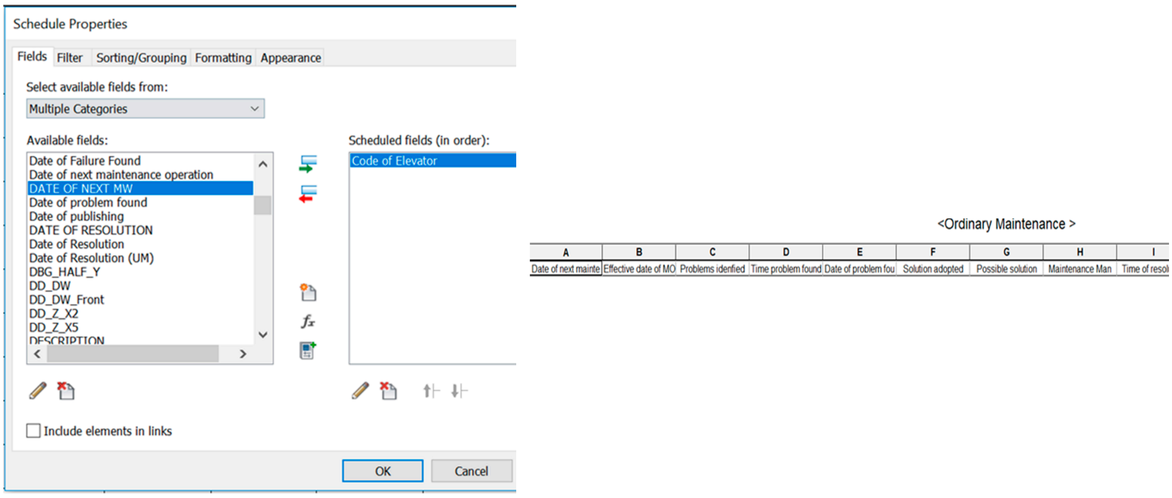


Figure 5. BIM model of the elevator.

In Figure 6 the Revit interface for the abacus implementation (a) and an excerpt of its fields for ordinary maintenance activities (b) are shown.



(a) (b)

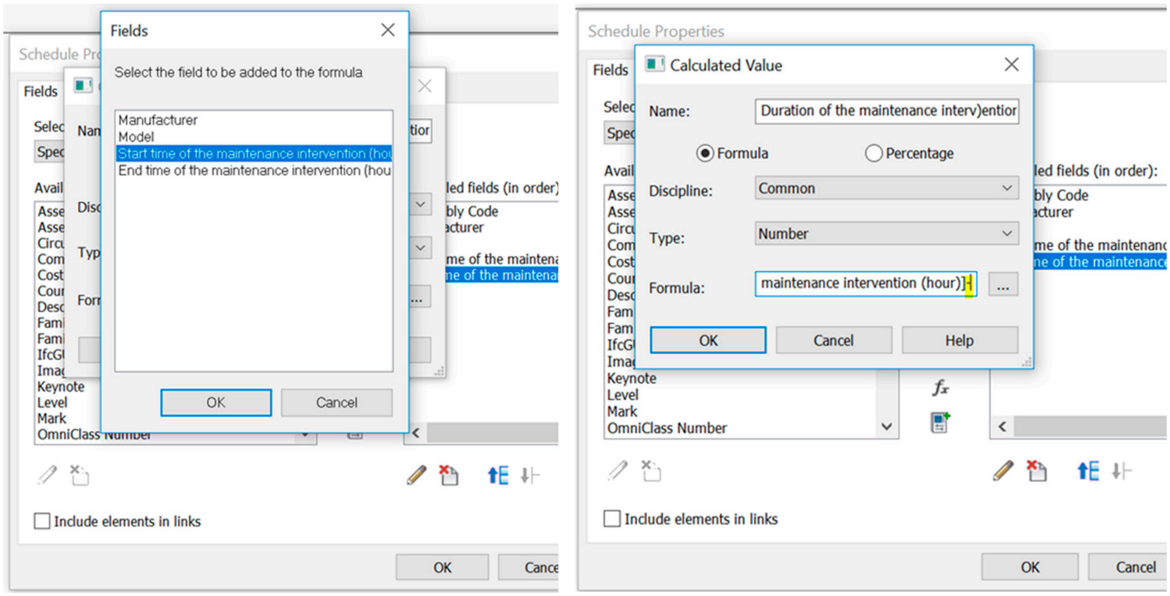
Figure 6. (**a**) Revit abacus implementation; (**b**) list of fields included in the abacus concerning ordinary maintenance operations (excerpt).

Then, data provided by the building manager by means of MS Excel® spreadsheets were used to fill in the various fields of the Revit abaci. This allowed us to create a platform for a database containing all data on maintenance operations, which can also facilitate the implementation of a Structured Query Language (SQL) automated notification and alert system [81,82] that are able to: update maintenance intervals for each component/part of the elevator; update the intervention plans, notify both the provider and the building manager; update the calendar of inspections and maintenance interventions; optimize the scheduling of intervention reducing the down time of the equipment. This database is managed by the provider and shared with the building manager, who can extract data and reports.

Accordingly, the use of an alert system together with doors and floor sensors for an automated signaling of a malfunctioning is also foreseen, notifying the need for an intervention to both the service provider and the building manager through the BIM server.

Lastly, the plans of maintenance activities were updated providing improved workflows of the related activities. In Figure 8 the BPMN model of extraordinary maintenance interventions is summarized.

At the moment, the management of Company "A" is verifying the feasibility of the proposed solution for maintenance management, hence due to a non-disclosure agreement, detailed information on technical results cannot be provided.



(a) (b)

Figure 7. Maintenance schedules implementation: (**a**) definition of the sub-parameters; and (**b**) parameter "duration of maintenance intervention".

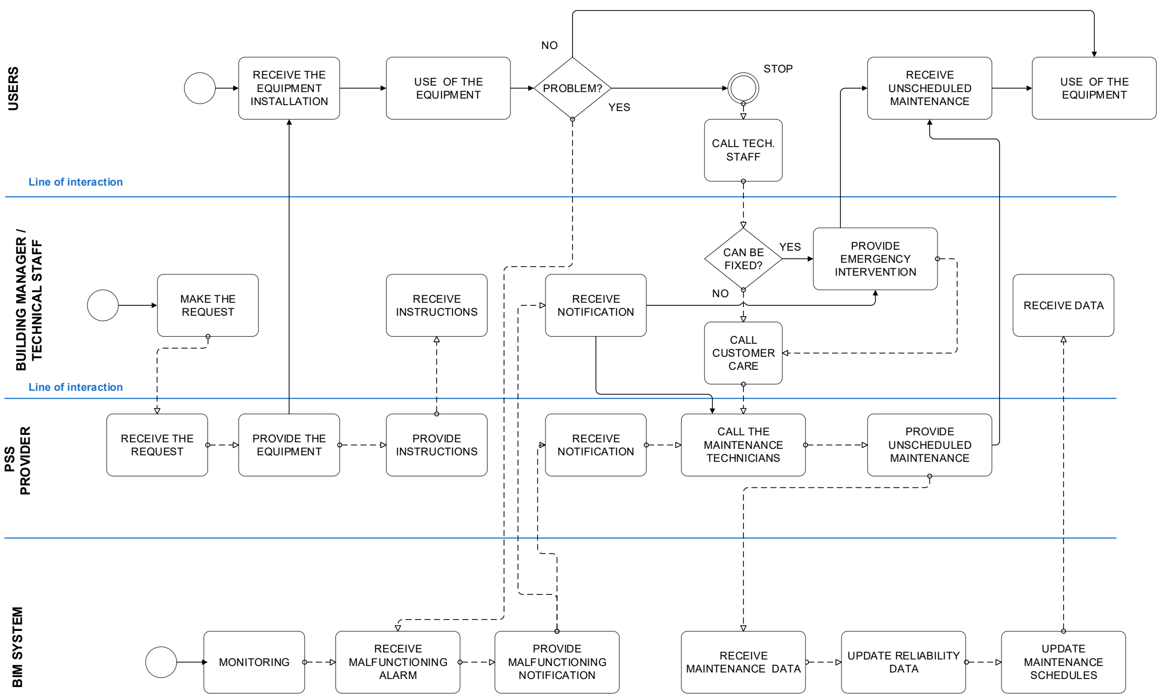


Figure 8. BPMN map of the new extraordinary maintenance processes.

5. Discussion of Results

Although only simplified data could be provided in the previous section, the first results of this study showed the potential benefits of the integration of BIM for the development of PSS solutions for the improvement of maintenance activities. In fact, following the PSS approach it was possible to define those service components that were considered relevant for the customer, such as "remote control of the elevator parameters", "database of maintenance interventions", "database of replaced components", "safety compliance assessment data", etc. Then, the use of BIM allowed us to implement them in the abaci for the creation of a database aimed at making maintenance management more effective.

In practice, analyzing data collected in the study and comparing them with the solution proposed to the company, it emerged that:

- 35 working days of unavailability due to the exchange of communications in case of extraordinary maintenance interventions requiring costs over the threshold value could be avoided.
- 30 days of partial unavailability for each elevator could be avoided, since almost 50% of inspections and ordinary maintenance activities were carried out in three different days per months instead of two.
- From the analysis of the half-year reports provided to the building manager, it was found that in 5 cases ordinary maintenance interventions were skipped and the service company had shifted these activities in the following months, increasing the number of elevators being unavailable in those periods. In this case, the proposed model would have avoided these "missing routines", providing at the same time a prompt information to the building manager.
- The BIM-based model would have reduced the elevators' unavailability due to the supply of spare parts (21 working days of delay in providing the interventions were registered).
- The costs of all the interventions in the five-year period were estimated equal to the cost of a new elevator with similar characteristics as the ones installed.
- 3 times the building manager had to request the half-year report concerning maintenance activities and related costs, as documents were missing.

Moreover, we have to highlight the troubles caused by this large number of days of unavailability of the equipment to the final users and consequently their unsatisfaction significantly impacted both on the building manager and building owner.

Therefore, the inclusion of BIM within a PSS model allows a more effective management of maintenance activities, where:

- Ordinary maintenance interventions can be provided timely and all the operations are registered, updating the information related to the equipment components automatically. In this way, redundant or missing activities can be avoided, reducing costs for both the service provider and the building manager, as well as augmenting the availability and life span of the equipment.
- The interventions for extraordinary maintenance can be provided faster and in a more effective manner, since BIM technology allows a direct information exchange between the service provider and building manager. Hence, a short response time in case of malfunctioning can reduce the equipment downtime, while augmenting customer satisfaction.
- Maintenance technicians can get information on the type of components and the repair actions needed more easily, reducing the time invested in field trips and supply of the new components [83].
- The BIM system allows the storage of all data related to maintenance and repair information, updating the maintenance schedules continuously: this type of information can be used to monitor the reliability of the equipment and its components, as well as to facilitate the implementation of predictive maintenance techniques, further augmenting the equipment availability.

In addition, the benefits that can be achieved in terms of safety should be outlined. In fact, on the one hand incorporating also the information related to the mandatory safety checks into a BIM model can reduce the risks of data loss, facilitating data record and tracking (e.g., the logbook in which repairs and, where appropriate, periodic checks can be noted) especially when BIM is combined with smart technologies as pointed out by Wetzel and Thabet [84]. Accordingly, it can also support the implementation of a knowledge management system for the implementation of an occupational health and safety management system [85,86]. On the other hand, since in a PSS context the responsibilities of maintenance activities are shifted from the building manager and building owner to the equipment provider, who is the owner and the manager of this type of information, it is expected that the possibility of mistakes while performing maintenance activities is further reduced [72,87], guaranteeing the proper safety and availability level of the equipment [88].

At a more general level, the present study has shown a possible way of integrating BIM and PSS. Answering our research question, this can contribute to reduce the research gap remarked among others by Chowdhury et al. [89], who fostered the adoption of information technologies as a key factor for companies to succeed in service-based businesses, enabling value creation through the establishment of new organizational capabilities.

In line with Gao [61], the merit of this study consists of augmenting the knowledge on BIM-based facility management through the PSS approach, since the use of information technologies in this field will be a pressing issue. Accordingly, the proposed approach also accomplishes the need for specific maintenance management BIM applications remarked by Volk [78] in the context of facility management of existing buildings, providing a generic framework that can be adopted in different contexts and can represent a promising platform for Industry 4.0 business model applications [90], e.g., through cloud computing, mobile computing, RFID/QR technologies, etc. [20,91].

Beside these positive aspects, some limitations of the present study also need to be pointed out. Firstly, the implementation of the proposed approach is at an initial stage of development and practical results of its application are currently being analyzed. Hence, despite the first positive results in terms of maintenance schedules' optimization and data storage of operations, a data validation [64] as well as a life cycle cost analysis are needed to verify its feasibility.

Moreover, the problem of the lack of knowledge and skills concerning the use of BIM tools has not been addressed. In fact, even though the PSS approach shifting the responsibilities of maintenance activities to the provider partially solves this problem, the interface with building managers and third-party maintenance technicians needs to be further analyzed [61], especially for what factors impact on data exchange among the different stakeholders [92,93].

Accordingly, the use of supporting methods has not been discussed in detail. In fact, a further investigation on the application of tools for facilitating both the analysis of PSS components (e.g., The Quality Function Deployment for PSS and the Axiomatic Design methods [33,94]), as well as the interoperability between the various actors (e.g., CMMS [95] and COBIE [96,97] tools) is necessary.

6. Conclusions

The provision of integrated offerings, merging tangible and intangible goods, is emerging as one of the most successful business models in the Architecture Engineering Construction (AEC) sector, especially for the provision and management of the building's equipment. The use of BIM capabilities can certainly foster the implementation of such an approach, providing a support for collecting, managing and exchanging information among the different stakeholders of the equipment lifecycle, increasing customer satisfaction and value on the one hand; and companies' profitability on the other.

Therefore, the present study proposes a methodology for modeling the maintenance management activities of building equipment through the synergic use of these approaches, providing a general framework relying on the development of the PSS components (both tangible and intangible) through a BIM tool for the definition of effective maintenance management activities, augmenting the flow of information between the service provider and the building manager.

The framework was verified by an application concerning the improvement of the management of maintenance operations of the elevators of a building in collaboration with the building manager and his technical staff. The comparison between the current situation and the application of the proposed approach showed potential benefits, especially in terms of reduced periods of equipment unavailability, reduced costs and augmented customer satisfaction. In addition, this article provides some new substantial insights for servitization of building equipment through BIM.

Hence, this work can represent a basis for further investigations by researchers and practitioners to support companies and building managers in overtaking product-based approaches in favor of more advanced servitization models, in the light of the ever-increasing spread of Industry 4.0 solutions.

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References

1. Tukker, A. Product Services for a Resource-Efficient and Circular Economy—A Review. *J. Clean. Prod.* **2015**, *97*, 76–91. [CrossRef]
2. Organisation for Economic Cooperation and Development (OECD). *Business Models for the Circular Economy: Opportunities and Challenges for Policy*; OECD Publishing: Paris, France, 2019. [CrossRef]
3. Matschewsky, J.; Kambanou, M.L.; Sakao, T. Designing and providing integrated product-service systems–challenges, opportunities and solutions resulting from prescriptive approaches in two industrial companies. *Int. J. Prod. Res.* **2018**, *56*, 2150–2168. [CrossRef]
4. Umeda, Y.; Takata, S.; Kimura, F.; Tomiyama, T.; Sutherland, J.W.; Kara, S.; Herrmann, C.; Duflou, J.R. Toward integrated product and process lifecycle planning-An environmental perspective. *CIRP Ann.* **2012**, *61*, 681–702. [CrossRef]
5. Ulaga, W.; Reinartz, W.J. Hybrid offerings: how manufacturing firms combine goods and services successfully. *J. Mark.* **2011**, *75*, 5–23. [CrossRef]
6. Fargnoli, M.; De Minicis, M.; Tronci, M. Product's life cycle modelling for ecodesigning product-service systems. In *DS 70, Proceedings of the DESIGN 2012, the 12th International Design Conference, Dubrovnik, Croatia, 21–24 May 2012*; Marjanovic, D., Storga, M., Pavkovic, N., Bojcetic, N., Eds.; International Design Conference: Dubrovnik, Croatia, 2012; pp. 869–878.
7. Takata, S.; Kirnura, F.; van Houten, F.J.; Westkamper, E.; Shpitalni, M.; Ceglarek, D.; Lee, J. Maintenance: changing role in life cycle management. *CIRP Ann.* **2004**, *53*, 643–655. [CrossRef]
8. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
9. Ploeger, H.; Prins, M.; Straub, A.; Van den Brink, R. Circular economy and real estate: the legal (im)possibilities of operational lease. *Facilities* **2019**. [CrossRef]
10. Gao, J.; Yao, Y.L.; Zhu, V.C.Y.; Sun, L.Y.; Lin, L. Service-oriented manufacturing a new product pattern and manufacturing paradigm. *J. Intell. Manuf.* **2011**, *22*, 435–446. [CrossRef]
11. Oliva, R.; Kallenberg, R. Managing the transition from products to services. *Int. J. Serv. Ind. Manag.* **2003**, *14*, 160–172. [CrossRef]
12. Grubic, T. Remote monitoring technology and servitization: Exploring the relationship. *Comput. Ind.* **2018**, *100*, 148–158. [CrossRef]
13. Frank, A.G.; Mendes, G.H.; Ayala, N.F.; Ghezzi, A. Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. *Technol. Forecast. Soc. Chang.* **2019**, *141*, 341–351. [CrossRef]
14. Song, W.; Sakao, T. An environmentally conscious PSS recommendation method based on users' vague ratings: A rough multi-criteria approach. *J. Clean. Prod.* **2018**, *172*, 1592–1606. [CrossRef]
15. Van Ostaeyen, J.; Van Horenbeek, A.; Pintelon, L.; Duflou, J.R. A refined typology of product–service systems based on functional hierarchy modeling. *J. Clean. Prod.* **2013**, *51*, 261–276. [CrossRef]
16. Hara, T.; Arai, T.; Shimomura, Y.; Sakao, T. Service/Product Engineering: a new discipline for value production. In Proceedings of the 19th International Conference on Production Research, Valparaiso, Chile, 29 July–2 August 2007; Volume 29, ISBN 9563107519.

17. Cortesi, S.; Vezzoli, C.A.; Donghi, C. Case study of the design of Eco-Efficient Product-Service-System for KONE Corporation, using the MSDS method and tools. In Proceedings of the Sustainability in Design: Now!—Challenges and Opportunities for Design Research, Education and Practice in the XXI Century, Bangalore, India, 29 September–1 October 2010; pp. 1201–1211, ISBN 9781906093556.
18. Succar, B. Building information modelling framework: a research and delivery foundation for industry stakeholders. *Autom. Constr.* **2009**, *18*, 357–375. [CrossRef]
19. Hernández, J.; Martín Lerones, P.; Bonsma, P.; van Delft, A.; Deighton, R.; Braun, J.D. An IFC Interoperability Framework for Self-Inspection Process in Buildings. *Buildings* **2018**, *8*, 32. [CrossRef]
20. Wong, J.K.W.; Ge, J.; He, S.X. Digitisation in facilities management: A literature review and future research directions. *Autom. Constr.* **2018**, *92*, 312–326. [CrossRef]
21. Chen, W.; Chen, K.; Cheng, J.C.; Wang, Q.; Gan, V.J. BIM-based framework for automatic scheduling of facility maintenance work orders. *Autom. Constr.* **2018**, *91*, 15–30. [CrossRef]
22. Bertoni, A.; Larsson, T. Data mining in product service systems design: Literature review and research questions. *Procedia CIRP* **2017**, *64*, 306–311. [CrossRef]
23. Ardolino, M.; Rapaccini, M.; Saccani, N.; Gaiardelli, P.; Crespi, G.; Ruggeri, C. The role of digital technologies for the service transformation of industrial companies. *Int. J. Prod. Res.* **2018**, *56*, 2116–2132. [CrossRef]
24. Sakao, T.; Shimomura, Y. Service Engineering: a novel engineering discipline for producers to increase value combining service and product. *J. Clean. Prod.* **2007**, *15*, 590–604. [CrossRef]
25. Cavalieri, S.; Pezzotta, G. Product service systems engineering: state of the art and research challenges. *J. Clean. Prod.* **2012**, *63*, 278–288. [CrossRef]
26. Matschewsky, J.; Sakao, T.; Khanagha, S.; Elfving, S.W. What's in it for the Provider? The Case of a Telecom Vendor's Value Capturing from the Transition to Product-Service Systems. *Procedia CIRP* **2016**, *47*, 6–11. [CrossRef]
27. Matschewsky, J.; Lindahl, M.; Sakao, T. Capturing and enhancing provider value in product-service systems throughout the lifecycle: A systematic approach. *CIRP J. Manuf. Sci. Technol.* **2018**, 1–14. [CrossRef]
28. Bertoni, A.; Bertoni, M.; Isaksson, O. Value visualization in Product Service Systems preliminary design. *J. Clean. Prod.* **2013**, *53*, 103–117. [CrossRef]
29. Tukker, A. Eight types of product service system: eight ways to sustainability? Experiences from Suspronet. *Bus. Strategy Environ.* **2004**, *13*, 246–260. [CrossRef]
30. Vasantha, G.V.A.; Roy, R.; Lelah, A.; Brissaud, D. A review of product service-systems designs methodologies. *J. Eng. Des.* **2012**, *23*, 635–659. [CrossRef]
31. McAloone, T.C.; Pigosso, D.C. From ecodesign to sustainable product/service-systems: a journey through research contributions over recent decades. In *Sustainable Manufacturing. Sustainable Production, Life Cycle Engineering and Management*; Stark, R., Seliger, G., Bonvoisin, J., Eds.; Springer: Cham, Switzerland, 2017; pp. 99–111. [CrossRef]
32. Qu, M.; Yu, S.; Chen, D.; Chu, J.; Tian, B. State-of-the-art of design, evaluation, and operation methodologies in product service systems. *Comput. Ind.* **2016**, *77*, 1–14. [CrossRef]
33. Bertoni, M. Multi-Criteria Decision Making for Sustainability and Value Assessment in Early PSS Design. *Sustainability* **2019**, *11*, 1952. [CrossRef]
34. Metz, P.; Burek, S.; Hultgren, T.R.; Kogan, S.; Schwartz, L. The Path to Sustainability-Driven Innovation: Environmental sustainability can be the foundation for increasing competitive advantage and the basis for effective innovation. *Res. Technol. Manag.* **2016**, *59*, 50–61. [CrossRef]
35. Lingegard, S.; Sakao, T.; Lindahl, M. Integrated product service engineering factors influencing environmental performance. In *Design for Innovative Value towards a Sustainable Society*; Springer: Dordrecht, The Netherlands, 2012; pp. 386–391. [CrossRef]
36. Alonso-Rasgado, T.; Thompson, G.; Elfström, B.O. The design of functional (total care) products. *J. Eng. Des.* **2004**, *15*, 515–540. [CrossRef]
37. Haber, N.; Fargnoli, M. Design for product-service systems: a procedure to enhance functional integration of product-service offerings. *Int. J. Prod. Dev.* **2017**, *22*, 135–164. [CrossRef]
38. Sakao, T.; Song, W.; Matschewsky, J. Creating service modules for customising product/service systems by extending DSM. *CIRP Ann.* **2017**, *66*, 21–24. [CrossRef]
39. Trevisan, L.; Brissaud, D. Engineering models to support product–service system integrated design. *CIRP J. Manuf. Sci. Technol.* **2016**, *15*, 3–18. [CrossRef]

40. Fargnoli, M.; Haber, N.; Sakao, T. PSS modularisation: a customer-driven integrated approach. *Int. J. Prod. Res.* **2018**, 1–17. [CrossRef]
41. Liu, S.; Meng, X.; Tam, C. Building information modeling based building design optimization for sustainability. *Energy Build.* **2015**, *105*, 139–153. [CrossRef]
42. Hossain, M.U.; Ng, S.T. Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. *J. Clean. Prod.* **2018**, *205*, 763–780. [CrossRef]
43. Maskil-Leitan, R.; Reychav, I. A sustainable sociocultural combination of building information modeling with integrated project delivery in a social network perspective. *Clean Technol. Environ. Policy* **2018**, *20*, 1017–1032. [CrossRef]
44. Mauger, C.; Blessing, L.T.M.; Qureshi, A.J.; Gericke, K. Transdisciplinary Research-Buildings as Service-Oriented Product-Service Systems. In *The Future of Transdisciplinary Design: Proceedings of the Workshop on "The Future of Transdisciplinary Design", University of Luxembourg 2013*; Springer International Publishing AG: Cham, Switzerland, 2013; pp. 124–135, ISBN 978-3-319-06381-2.
45. Zou, R.R.; Tang, L.; Goh, M. Assessment of information maturity during design, operation and maintenance stages within BIM use environment. In Proceedings of the 19th International Conference on Engineering Design, ICED13, Seoul, Korea, 19–22 August 2013; pp. 41–52, ISBN 978-1-904670-49-0.
46. Verghote, A.; Al-Haddad, S.; Goodrum, P.; Van Emelen, S. The Effects of Information Format and Spatial Cognition on Individual Wayfinding Performance. *Buildings* **2019**, *9*, 29. [CrossRef]
47. Dasović, B.; Galić, M.; Klanšek, U. Active BIM Approach to Optimize Work Facilities and Tower Crane Locations on Construction Sites with Repetitive Operations. *Buildings* **2019**, *9*, 21. [CrossRef]
48. Zhang, S.; Teizer, J.; Lee, J.K.; Eastman, C.M.; Venugopal, M. Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules. *Autom. Constr.* **2013**, *29*, 183–195. [CrossRef]
49. Denis, F.; Vandervaeren, C.; De Temmerman, N. Using Network Analysis and BIM to Quantify the Impact of Design for Disassembly. *Buildings* **2018**, *8*, 113. [CrossRef]
50. Ramaji, I.J.; Memari, A.M. Extending the current model view definition standards to support multi-storey modular building projects. *Archit. Eng. Des. Manag.* **2018**, *14*, 158–176. [CrossRef]
51. Jiang, Y.; Liu, X.; Liu, F.; Wu, D.; Anumba, C. An analysis of BIM web service requirements and design to support energy efficient building lifecycle. *Buildings* **2016**, *6*, 20. [CrossRef]
52. Antwi-Afari, M.F.; Li, H.; Pärn, E.A.; Edwards, D.J. Critical success factors for implementing building information modelling (BIM): A longitudinal review. *Autom. Constr.* **2018**, *91*, 100–110. [CrossRef]
53. Ahankoob, A.; Manley, K.; Hon, C.; Drogemuller, R. The impact of building information modelling (BIM) maturity and experience on contractor absorptive capacity. *Archit. Eng. Des. Manag.* **2018**, *14*, 363–380. [CrossRef]
54. Röck, M.; Hollberg, A.; Habert, G.; Passer, A. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Build. Environ.* **2018**, *140*, 153–161. [CrossRef]
55. Eleftheriadis, S.; Mumovic, D.; Greening, P. Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. *Renew. Sustain. Energy Rev.* **2017**, *67*, 811–825. [CrossRef]
56. Dong, B.; O'Neill, Z.; Li, Z. A BIM-enabled information infrastructure for building energy Fault Detection and Diagnostics. *Autom. Constr.* **2014**, *44*, 197–211. [CrossRef]
57. Autodesk Revit. Multidisciplinary BIM software for higher quality, coordinated designs. Available online: https://www.autodesk.com/products/revit/overview (accessed on 14 January 2019).
58. Re Cecconi, F.; Maltese, S.; Dejaco, M.C. Leveraging BIM for digital built environment asset management. *Innov. Infrastruct. Solut.* **2017**, *2*, 14. [CrossRef]
59. Li, J.; Ng, S.T.; Skitmore, M. Review of low-carbon refurbishment solutions for residential buildings with particular reference to multi-story buildings in Hong Kong. *Renew. Sustain. Energy Rev.* **2017**, *73*, 393–407. [CrossRef]
60. Hosseini, M.R.; Roelvink, R.; Papadonikolaki, E.; Edwards, D.J.; Pärn, E. Integrating BIM into facility management: Typology matrix of information handover requirements. *Int. J. Build. Pathol. Adapt.* **2018**, *36*, 2–14. [CrossRef]
61. Gao, X.; Pishdad-Bozorgi, P. BIM-enabled facilities operation and maintenance: A review. *Adv. Eng. Inf.* **2019**, *39*, 227–247. [CrossRef]

62. Hubka, V.; Eder, W.E. *Engineering Design*; Heurista: Zürich, Switzerland, 1992.
63. McArthur, J.J. A building information management (BIM) framework and supporting case study for existing building operations, maintenance and sustainability. *Procedia Eng.* **2015**, *118*, 1104–1111. [CrossRef]
64. Pishdad-Bozorgi, P.; Gao, X.; Eastman, C.; Self, A.P. Planning and developing facility management-enabled building information model (FM-enabled BIM). *Autom. Constr.* **2018**, *87*, 22–38. [CrossRef]
65. Chen, Y.; Jupp, J. Model-Based Systems Engineering and Through-Life Information Management in Complex Construction. In Proceedings of the IFIP International Conference on Product Lifecycle Management, Turin, Italy, 2–4 July 2018; pp. 80–92. [CrossRef]
66. Love, P.E.; Matthews, J.; Simpson, I.; Hill, A.; Olatunji, O.A. A benefits realization management building information modeling framework for asset owners. *Autom. Constr.* **2014**, *37*, 1–10. [CrossRef]
67. Song, W.; Sakao, T. A customization-oriented framework for design of sustainable product/service system. *J. Cleaner Prod.* **2017**, *140*, 1672–1685. [CrossRef]
68. Hara, T.; Arai, T.; Shimomura, Y. A CAD System for Service Innovation: Integrated Representation of Function, Service Activity, and Product Behaviour. *J. Eng. Des.* **2009**, *20*, 367–388. [CrossRef]
69. Kazemzadeh, Y.; Milton, S.K.; Johnson, L.W. Service blueprinting and business process modeling notation (BPMN): a conceptual comparison. *Asian Soc. Sci.* **2015**, *11*, 307. [CrossRef]
70. Ramaji, I.J.; Memari, A.M.; Messner, J.I. Product-oriented information delivery framework for multistory modular building projects. *J. Comput. Civil Eng.* **2017**, *31*, 04017001. [CrossRef]
71. Fargnoli, M.; Haber, N. A practical ANP-QFD methodology for dealing with requirements' inner dependency in PSS development. *Comput. Ind. Eng.* **2019**, *127*, 536–548. [CrossRef]
72. Kimita, K.; Sakao, T.; Shimomura, Y. A failure analysis method for designing highly reliable product-service systems. *Res. Eng. Des.* **2018**, *29*, 143–160. [CrossRef]
73. Grubic, T.; Jennions, I. Remote monitoring technology and servitised strategies–factors characterising the organisational application. *Int. J. Prod. Res.* **2018**, *56*, 2133–2149. [CrossRef]
74. Sakao, T.; Lindahl, M. A value based evaluation method for Product/Service System using design information. *CIRP Ann.* **2012**, *61*, 51–54. [CrossRef]
75. Song, W. Requirement management for product-service systems: Status review and future trends. *Comput. Ind.* **2017**, *85*, 11–22. [CrossRef]
76. Haber, N.; Fargnoli, M. Prioritizing customer requirements in a product-service system (PSS) context. *TQM J.* **2019**, *31*, 257–273. [CrossRef]
77. Ghaffarianhoseini, A.; Tookey, J.; Ghaffarianhoseini, A.; Naismith, N.; Azhar, S.; Efimova, O.; Raahemifar, K. Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges. *Renew. Sustain. Energy Rev.* **2017**, *75*, 1046–1053. [CrossRef]
78. Volk, R.; Stengel, J.; Schultmann, F. Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Autom. Constr.* **2014**, *38*, 109–127. [CrossRef]
79. Whole Building Design Guide (WBDG). Comprehensive Facility Operation & Maintenance Manual. Available online: http://www.wbdg.org/facilities-operations-maintenance/comprehensive-facility-operation-maintenance-manual (accessed on 27 May 2019).
80. DigiPara. DigiPara® Elevatorarchitect for Autodesk® Revit®. Available online: https://www.digipara.com/products/digipara-elevatorarchitect/ (accessed on 14 January 2019).
81. Muller, A.; Marquez, A.C.; Iung, B. On the concept of e-maintenance: Review and current research. *Reliab. Eng. Syst. Saf.* **2008**, *93*, 1165–1187. [CrossRef]
82. Khaja, M.; Seo, J.D.; McArthur, J.J. Optimizing BIM metadata manipulation using parametric tools. *Procedia Eng.* **2016**, *145*, 259–266. [CrossRef]
83. Yang, X.; Ergan, S. Leveraging BIM to provide automated support for efficient troubleshooting of HVAC-related problems. *J. Comput. Civ. Eng.* **2015**, *30*, 04015023. [CrossRef]
84. Wetzel, E.M.; Thabet, W.Y. The use of a BIM-based framework to support safe facility management processes. *Autom. Constr.* **2015**, *60*, 12–24. [CrossRef]
85. Fargnoli, M.; De Minicis, M.; Di Gravio, G. Knowledge Management integration in Occupational Health and Safety systems in the construction industry. *Int. J. Prod. Dev.* **2011**, *14*, 165–185. [CrossRef]
86. Zou, Y.; Kiviniemi, A.; Jones, S.W. A review of risk management through BIM and BIM-related technologies. *Saf. Sci.* **2017**, *97*, 88–98. [CrossRef]

87. Lin, Y.C.; Su, Y.C. Developing mobile-and BIM-based integrated visual facility maintenance management system. *Sci. World J.* **2013**, *2013*, 1–10. [CrossRef]
88. Olatunji, O.A.; Akanmu, A. BIM-FM and consequential loss: how consequential can design models be? *Built Environ. Proj. Asset Manag.* **2015**, *5*, 304–317. [CrossRef]
89. Chowdhury, S.; Haftor, D.; Pashkevich, N. Smart Product-Service Systems (Smart PSS) in Industrial Firms: A Literature Review. *Procedia CIRP* **2018**, *73*, 26–31. [CrossRef]
90. Ardolino, M.; Saccani, N.; Gaiardelli, P.; Rapaccini, M. Exploring the key enabling role of digital technologies for PSS offerings. *Procedia CIRP* **2016**, *47*, 561–566. [CrossRef]
91. Matarneh, S.T.; Danso-Amoako, M.; Al-Bizri, S.; Gaterell, M.; Matarneh, R. Building information modeling for facilities management: A literature review and future research directions. *J. Build. Eng.* **2019**, 100755. [CrossRef]
92. Ramaji, I.J.; Memari, A.M. Information exchange standardization for BIM application to multi-story modular residential buildings. In Proceedings of the Architectural Engineering National Conference 2015: Birth and Life of the Integrated Building, AEI 2015, Milwaukee, WI, USA, 24–27 March 2015; pp. 13–24. [CrossRef]
93. Kim, K.; Kim, H.; Kim, W.; Kim, C.; Kim, J.; Yu, J. Integration of IFC objects and facility management work information using Semantic Web. *Autom. Constr.* **2018**, *87*, 173–187. [CrossRef]
94. Kimita, K.; Akasaka, F.; Hosono, S.; Shimomura, Y. Design Method for Concurrent PSS Development. In *Proceedings of the 2nd CIRP IPS2 Conference 2010, Linköping; Sweden, 14–15 April 2010*; Linköping University Electronic Press: Linköping, Sweden; Volume 77, pp. 283–290, ISBN 978-91-7393-381-0.
95. Shalabi, F.; Turkan, Y. IFC BIM-based facility management approach to optimize data collection for corrective maintenance. *J. Perform. Constr. Facil.* **2016**, *31*, 04016081. [CrossRef]
96. Kensek, K. BIM guidelines inform facilities management databases: a case study over time. *Buildings* **2015**, *5*, 899–916. [CrossRef]
97. Nicał, A.K.; Wodyński, W. Enhancing facility management through BIM 6D. *Procedia Eng.* **2016**, *164*, 299–306. [CrossRef]