Article

Supporting Facility Management Processes through End-Users' Integration and Coordinated BIM-GIS Technologies

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Abstract: The integration of facility management and building information modelling (BIM) is an innovative and critical undertaking process to support facility maintenance and management. Even though recent research has proposed various methods and performed an increasing number of case studies, there are still issues of communication processes to be addressed. This paper presents a theoretical framework for digital systems integration of virtual models and smart technologies. Based on the comprehensive analysis of existing technologies for indoor localization, a new workflow is defined and designed, and it is utilized in a practical case study to test the model performance. In the new workflow, a facility management supporting platform is proposed and characterized, featuring indoor positioning systems to allow end users to send geo-referenced reports to central virtual models. In addition, system requirements, information technology (IT) architecture and application procedures are presented. Results show that the integration of end users in the maintenance processes through smart and easy tools can overcome the existing limits of barcode systems and building management systems for failure localization. The proposed framework offers several advantages. First, it allows the identification of every element of an asset including wide physical building elements (walls, floors, etc.) without requiring a prior mapping. Second, the entire cycle of maintenance activities is managed through a unique integrated system including the territorial dimension. Third, data are collected in a standard structure for future uses. Furthermore, the integration of the process in a centralized BIM-GIS (geographical information system) information management system admit a scalable representation of the information supporting facility management processes in terms of assets and supply chain management and monitoring from a spatial perspective.

Keywords: facility management; maintenance; BIM; indoor mapping; geo-referencing; digital communication; GIS

1. Introduction

Facility management is a growing interest for both academic studies and construction industries [1]. The increasing impact of information technology (IT) systems requires more reliable and flexible studies for the improvement of techniques and instruments in practice. Indeed, the term facility management includes an enormous area of action. A first overall definition of facility management

is contained in [2] and defined as "an integrated approach for operating, maintaining, improving and adapting building and infrastructure assets to support the primary objectives of occupants, owners and facility managers". This overall approach is focused on the needs of the different actors involved in the life cycle of goods. Two other interesting definitions are reported in [3,4] highlighting the importance of non-core services. Thus, the goal of facility management is to provide a suitable environment to conduct the core businesses. Hence, "communication" between building elements (including spaces) and facility managers is fundamental for this scope [2,5]. Previous research shows a tendency on integration of sensory systems and database management systems (DBMS) to support facility management activities, based on detection of environmental conditions, room occupancy data, and/or functioning status of plants. Nevertheless, facility management only constitutes a branch, jointly representing real estate market with property management [6,7] and asset management [8] (Figure 1).
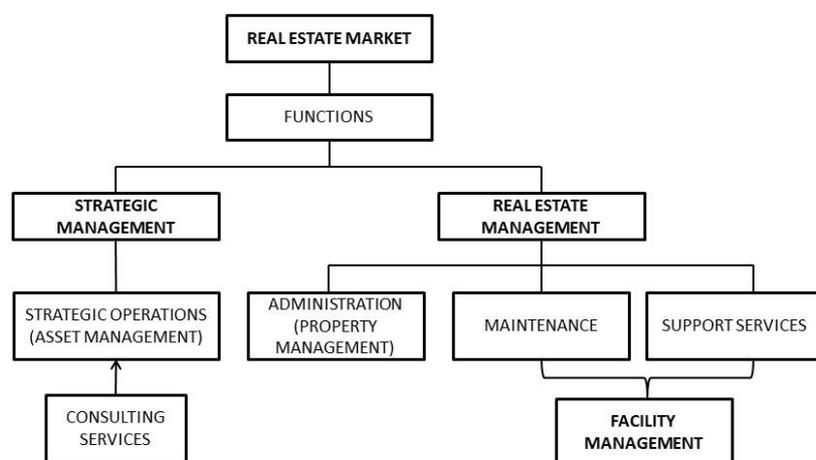

Figure 1. Real Estate Management—Asset, Property, Facility.

Asset management, monitoring, and traceability within an organization represent a significant cost element in terms of dedicated resources (times and people) [9]. Hence, in the development of methods and systems devoted to support the real estate management process, it is critical to consider an overall vision including maintenance operations, asset traceability and space management [2,10,11]. Tag systems based on barcodes are usually adopted by organizations to trace the assets, but they could also be integrated with DBMS to report communication and equipment failures. For instance, physical building elements (e.g., doors and windows) cannot be equipped with hardware systems capable of monitoring their functionality and consequently report any damages via signals. Even if barcode technologies could support both property management and facility management activities, including tags on spaces and physical elements, some issues cannot overlap, especially those referring to the exact damage localization on wide elements (e.g., walls and floors). For instance, an onerous number of tags would be necessary to map out these elements, which would have its drawbacks due to barcode maintenance needs and possible aesthetic defects. The scope of this research is to define a technological system, and the related process, capable of supporting both property management and facility management components, supporting asset traceability, damage detection and reporting, and communication of failures in building elements (communicating damages). The system will also include and be used for wide building elements by means of end-user involvement. This objective is pursued with specific reference to old buildings, characterized by a high number of daily users (e.g., schools or oratories) and where it is difficult to install sensors devoted to plant monitoring. In this context, end-users are intended as the habitual users of a real estate, who have been trained on the usage of a specific reporting application. The scope is pursued through the definition of an integrated process based on building information modelling (BIM) and indoor localization systems for end-users, providing a dynamic system that allows further developments. Hence, end-users can report failure modes by transmitting data through mobile apps

and a building information model that is connected to an external DBMS allowing the integrated management of both geometrical and alphanumerical information. The proper integration of end-users in the process represents a critical point that can reduce the time laps between the damage and its notification and repair.

This research focuses on the phase of communicating damages in corrective maintenance processes. Meanwhile, the theorized system is studied to support the entire maintenance work until the work order is closed and the model is updated. Furthermore, the information collected in a systematic way should enrich the building information models, ensuring the efficiency of the system over time. During the life-cycle of real estate management, one of the most important advantages of BIM is that it can provide precise geometric and semantic information [12–17]. On the contrary, the geographical information systems (GIS) have strong capability on large spatial scale modelling and geospatial analysis for the geographical objects and spatially distributed assets [18–22]. Thus, as a fast-developing trend, BIM-GIS integration can provide a valuable support, offering geovisualization-based decision making and geospatial modelling [23].

Figure 2 shows a flowchart synthetizing how organizations generally manage a corrective maintenance work order, from the initial request until the end of the maintenance work [24]. This schema underlines the problems connected to a traditional management of the maintenance process. There is a considerable lack of efficiency due to an ineffective communication flow, which does not guarantee the correct transfer (and storage) of the needed information from the client to the maintenance company passing through the facility management. Gallaher et al. [25] underlined this point estimating the annual costs associated to inadequate interoperability in the U.S. capital facilities industry in $15.8 billion.
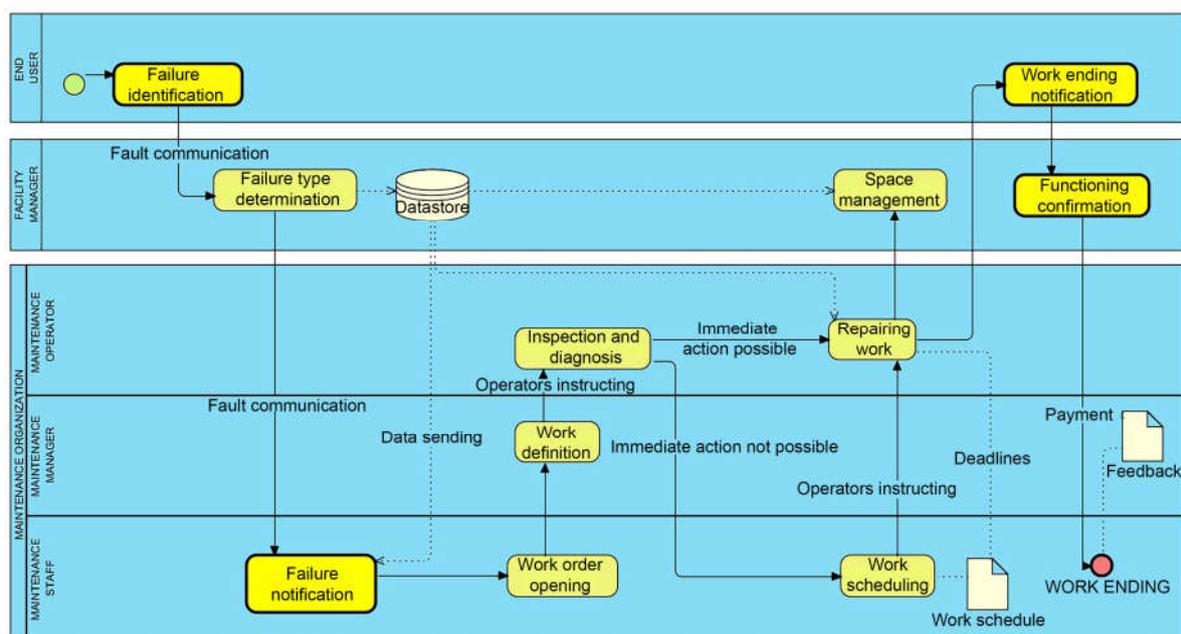
Figure 2. Corrective maintenance workflows, flowchart-type.

In this research, the initial processes for facility management support system were studied to understand their strengths and limitations. Then technologies were investigated to implement and adapt a system suitable for the defined scope. The focus of this research was based on old buildings with the involvement of end-users, which required easy to use devices for failures identification and low maintenance of required systems in a very crowded building occupied also by children.

This article is structured in six sections. Section 2 reports a brief literature review about the actual methods used in facility management and the previous research developed on the integration of facility management practices and BIM. Section 3 proposes the applied research methodology. Section 4 presents the proposed method and the structure of the connected system. Section 5 contains

a case study that was developed to test the studied processes and the developed system. This section includes a discussion about academic and practical contributions. Finally, Section 6 is a summary of the obtained results with some suggestions about possible development of future research.

2. Supporting Methods for Maintenance Operations: Literature Review

Facility management includes many activities coming from different fields. The efficiency of the management, based on cost reduction and optimal value, could be achieved through the implementation of integration strategies [26]. Therefore, technological tools are needed to support the facility manager in monitoring all the management aspects of a real estate. This section synthesizes the methods, systems, and technological tools most used for facility management objectives, managing both alphanumeric and geometric data.

2.1. CAFM Systems and BIM

Widespread systems used to support facility management activities are computer aided facility management (CAFM) [27] or other similar systems as computer maintenance management systems (CMMS), electronic document management systems (EDMS) and building automation systems (BAS) [28]. These management systems are based on alphanumeric data management, capable of uploading data and technical documentation, creating job lists and schedule activities, identifying resources, tools and materials needed to manage the real estate [29].

Generally, traditional management systems fail in accessing and controlling the information effectively because data coming from different sources is modified several times during the building life cycle without an automated synchronization between servers [30]. Another relevant limitation is the inability to control the building performances and lacking 3D building visualization since CAFM systems are usually linked with 2D building drawings allowing merely the space management [31]. Thus, CAFM systems are ineffective in managing all the information and they lack the ability to integrate the geometrical information along with the technological ones.

The integration between BIM and other technologies and techniques used in the market is progressively changing facility management processes. BIM can be viewed as an approach applied to the building process, based on the creation of a centralized information platform for building knowledge shared among different users during the entire building life cycle, from planning to the management stage [32]. The building information model applied to the facility management can be interpreted as a building information system connected to a DBMS that provides the ability to process the geometric information and the non-geometric information including performance, regulations, materials, and management [33]. Hence, the building information model and the related DBMS constitute a memory storage platform, shared by players involved in the maintenance process, which enable the traceability of each building component in terms of location, technical features and total cost [34].

2.2. BIM-Based Facility Management Supporting Methods

The integration of facility management and BIM has been explored in recent research [3]. One of the major components of the maintenance policy is the reaction time required between a defect occurring and a repair being carried out [35]. As stated in the introduction, the communication between all the parties involved assumes a critical position for maintenance objectives. Recognizing the importance of communication along with its central role in maintenance processes, different IT tools and methods, including BIM, can be found in the literature.

The first case is based on a central building information model managed by a facilities manager. The system has supporting BIM tools and cloud access to communicate damages by the end-users, the maintenance crew, and the consulting staff. It can be integrated with virtual reality applications [36]. The interface between different servers (i.e., models and facility management databases) can be reached using open standards and data specifications (e.g., IFC and COBie) or by implementation of

proprietary formats linked with interconnected platforms, for the definition of Asset Information Models [37].

Another application that has been used in the research field in the last few years consists of mapping building elements with barcodes that are linked with building management databases and building information models [38]. Barcode is the most widely used technology to trace products and assets, especially in the industrial and manufacturing sectors [39]. The most common types are the Quick Response (QR) code [40] and Radio Frequency Identification (RFID) code [41–43]. According to this method, end-users can report a failure to the facility manager by scanning the QR code through a mobile device, activating the maintenance process [30].

In the last years, the technological developments in home automation have brought to propensity a condition-based maintenance approach, based on efficiency status monitoring [44]. This maintenance process is based on Building Management Systems (BMS) ensuring service control (e.g., lighting, fire and air conditioning) monitoring over time status indicators in order to ensure living comfort, plant efficiency and sustainability [45], and to report and manage failures [37].

A BMS can reduce the need of human intervention and through a data-logger [46] it allows recording environmental indicator measurements (e.g., temperature, humidity and using time) [47]. Building information models related with the BMS allow creating a link between the design and the real use of the building-plant system by the end-users.

Table 1, reports a matrix of comparison between each case, namely (case 1) central building information model for the facility manager and cloud building information model for the end users and maintenance staff, (case 2) QR code mapping linked with building information models and DBMS, (case 3) BMS combined with building information models. The advantages column reports the main functionalities of each method, while in the disadvantages column are identified open issues and features that can hinder the application of the method.

Table 1. Resuming comparison between facility management (FM) supporting methodologies.

	FM Methodology	Advantages	Disadvantages
Case 1:	Central building information model for the facility manager and cloud building information model for the end users and maintenance staff.	BIM cloud applications for the visualization of building information models are used both for failure communications from the end-users and consultation during the operations for the maintenance operators. A unique technology used during all the maintenance process from the failure report until the end of the maintenance work [34,35].	a) Awkward browsing in BIM mobile devices for the end-users; "ease of use" requirement not guarantee. b) A structured method to synchronize the players involved in the process using cloud building information models has to be implemented. c) No automation and geo-referencing of the fault communication phase: the facility manager is not informed automatically about the failure position because mapping or localization systems are not provided.
Case 2:	QR code mapping linked with building information models and DBMS.	Building components are mapped with barcode tags; end-users can communicate a failure scanning barcodes. A central building information model connected with a DBMS manages the failure reports and archives maintenance data. Identification data about components is directly stored in barcodes [38].	a) Barcode mapping can be onerous if it is used for all the building components. b) Barcodes need periodical maintenance especially in busy buildings. c) Difficult localization about failure reports on wide building elements (e.g., walls and floors). d) Barcodes can be seen as aesthetics defects.

		Systems and spaces are equipped with sensors capable of monitor functioning status and environmental conditions. The connection between BMS and building information models combines precision of field data acquisition and 3D localization [35,43].	a) Onerous costs of installation and maintenance especially in the case of old buildings do not equipped with modern systems.
Case 3:	BMS combined with building information models.		b) The management of not-sensorized building elements is not possible. Barcodes system integration is necessary.

3. Research Methodology

Starting from the objectives defined in the area of interest of the research that is focused on old buildings, characterized by a high number of daily users, a first analysis of traditional corrective maintenance processes and of the existing research in the literature has been defined. Highlighted by the limitations of the existing technologies and techniques, a possible process framework has been proposed identifying the suitable technologies through a compared study of the existing solutions. Finally, starting from the proposed framework, a case study has been developed identifying available commercial partners for the implementation of the proposed technological framework. Figure 3 shows the research path highlighting the passages above described and the outputs of each passage (on the right) identifying the main results of the research.
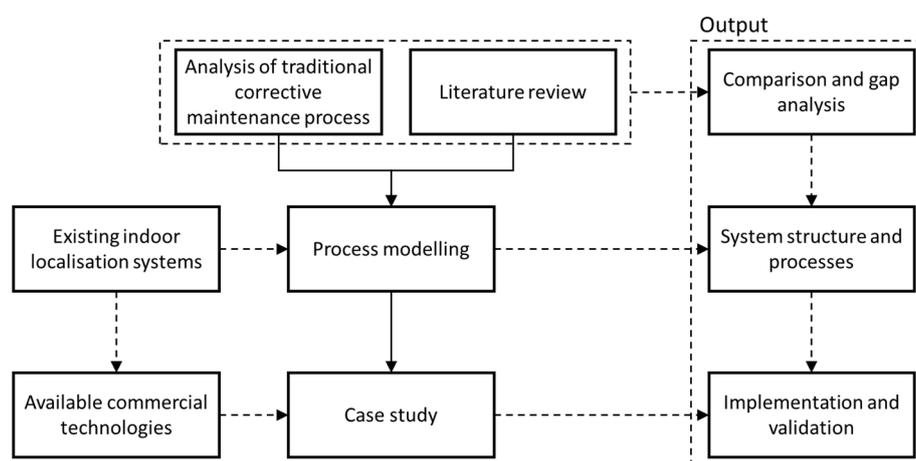

Figure 3. Schematic flowchart of research methodology.

4. End-User Integration and Coordinated BIM-GIS Technologies to Support Management and Maintenance Operations

Real estate management includes several integrated functions and traceability of the assets is an important prerequisite to support maintenance and management activities. A considerable part of the facility management activities is related to the management of the corrective maintenance about both plant systems and physical building components. Starting from the existing methods and practices analyzed in Section 2, an alternative method is proposed according to the stated objectives, with the aims of allowing the management of corrective maintenance for wide building components integrating technologies usually adopted for building assets traceability from the organizations. The proposed method is based on the digital communication between mobile apps managed by end-users on smart devices directly localized on the building information models of a real estate when reporting a failure.

Nowadays the majority of the population has a mobile device and according to a study conducted in 2014 by the International Data Corporation, about 3.5 billion people in 2017 (46% of the entire world population) will have an internet connection and 64% of them will access the mobile network [48]. Mobile devices are nowadays used daily and could be useful as communication tools to improve the quality of real estate and urban management [49] involving end-users.

In this direction, as shown in the case studies reported in [48], some administrations in Europe, such as the Barcelona Metropolitan Area, and some Britannic organizations are developing mobile platforms, involving the citizens in reporting urban problems, in order to improve the quality of the city. These tools are useful to support the urban management, but they are inapplicable in indoor environments due to limitations of the global positioning system (GPS) technology that they are based on. Despite these limitations of GPS technology, the concept behind these applications is efficient and can be extended to indoor environments combining mobile apps for faults communication with indoor positioning sensors as demonstrated in [50].

4.1. Indoor Localisation Systems for Fault Messages

The proposed system is composed of three main components:

- Real Estate central building information model, structured for the facility management scopes.
- Real Estate cloud models.
- Indoor localization systems for user localization.

The first two parts are the virtual models used to collect and share all the maintenance information. As proposed in the literature [51–53], the definition of the model must follow the objectives defined by the as built philosophy. A building information model developed for maintenance purposes should focus primarily on the correct individuation of the elements that would need maintenance. In this sense, the localization of each relevant object in the overall building information model must be assured. Nevertheless, it is not necessary to have a high level of geometrical detail for each specific object included in the model while the informative part must be dedicated to all the information needed for maintenance purposes [54].

The third part is conversely a physical part dedicated to the construction of the geo-referencing system for indoor localization [55]. In this direction, there are several technologies that can be used, namely infrared, RFID, Wi-Fi fingerprint, ultrasound, and Bluetooth. In particular, Bluetooth indoor localization systems are technologies structured with indoor localization sensors linked to mobile apps for mobile devices allowing the user localization and the specification of points of interest [56]. Compared to other solutions, Bluetooth technologies are embedded in common mobile devices. Furthermore, the required indoor localization sensors are easy to install and they have long-life batteries. Lastly, the inherent connection to the required mobile application guarantees the direct integration of the entire process presented in Section 4.2.

Table 2 reports a comparison between the main localization system technologies, highlighting for each one the characteristic functionalities and the connected disadvantages, summarizing the literature review [50,55,56].

Table 2. Resuming comparison between most used localization systems for indoor assets.

|	Localization System	Functioning	Disadvantages
Sol. 1	Infrared technologies	Emitter with fixed position in the room, which is associated with a unique ID and signal receiver.	a) Short transmission range. b) Eye contact necessary between emitter and receiver. c) No automation and geo-referencing in complex and labyrinthine environments, many devices are needed.
Sol. 2	RFID	Based on localization through radio frequencies.	a) Signal disorders can produce multipath propagation phenomena. b) Close contact between two devices is needed.
Sol. 3	Wi-Fi fingerprint	It is part of the localization techniques based on Received Signal Strength Indication (RSSI). Access point return the position of an antenna device.	a) Signal disorders can produce multipath propagation phenomena. b) Not suitable for environments subjected to variations over time, because moving the access point involves variations across the system.

Sol. 4	Ultrasound	Used as counting sensors, it is based on ultrasonic emissions and triangulation of lens transducers, which locate the persons' position.	a)	Obstructions that reflect sound waves hinder the performance of the system.
Sol. 5	Bluetooth (beacons)	Infrastructure availability because Bluetooth is integrated into common smartphones. IOS and Android compatible hardware. They work with long lasting batteries; not invasive, they can be positioned everywhere.	a) b)	Proximity sensors, high margin of error. An application for mobile devices is needed to capture signals from beacons.

The implementation of the Bluetooth-based technology can be divided in three main parts [57]. The hardware portion is constituted by the so-called Bluetooth Low Energy (BLE) beacons. They are transmitters using the Bluetooth technology to individuate smartphones presence and localize them through triangulation of signals. To allow the localization of mobile devices, it is required to have them equipped with a communication protocol (that constitute the second main part of the system) like Eddystone of iBeacons, contained in specific apps. Finally, the software part (the third one) is dedicated to the interpretation of data. This last portion constitutes the core of the system allowing the management of the entire maintenance process, including the creation of the fault notification, the communication with the facility manager along with the maintenance company and the final validation of the executed work.

In this environment, data extracted from the building information model are geolocalized and integrated with GIS information. This can support supply chain management [45] minimizing the time laps between damage and repair actions. Furthermore, the standard data structure embedded in the system allows maintenance data visualization in a geospatial environment for further quantitative analysis.

4.2. Structure of the System

In the proposed system, the identification of elements in the building is done through indoor localization systems. As already stated, several problems exist for barcodes including the high number of required labels and their maintenance, especially for wide physical elements such as walls and floors. Furthermore, tagging elements with lots of barcodes can produce aesthetic defects. In the proposed system, end-users are involved in the reporting phase through intuitive mobile tools that allow recognizing the position of the elements instead of the bar code scanning procedure. All the physical elements identified in this research are available in the market but their integrated usage to support the facility management phases has not been studied. A first layer is defined to regulate the specific services available through the mobile app, identifying three main user types: (a) end-user; (b) maintenance operator and (c) facility manager as shown in Figure 4.
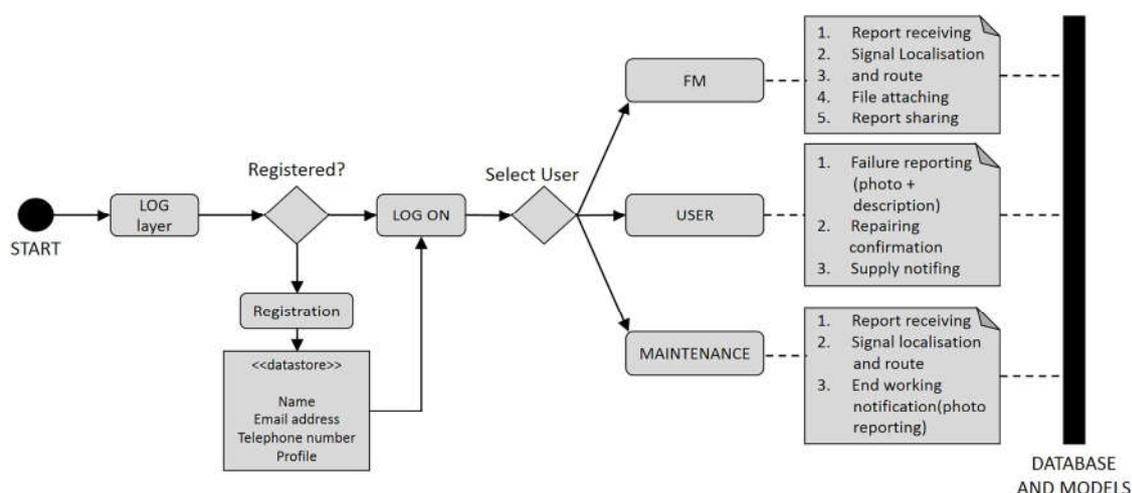
Figure 4. Indoor localization app: registration interface.

The process is divided in three main areas: (a) the Input phase, in which the end-user can identify a specific damage and communicate it through the mobile app; (b) the Intermediate phase, in which the message is forwarded from the end-user to the facility manager; and (c) the Output phase, in which the work order is closed after being verified by the maintenance person and the end-user.

INPUT phase: damage reporting

This phase starts with the identification of a damaged building element or system by end-users. After the log-in phase, the end-user can transmit the image of the faulty object through the dedicated mobile app adding any additional comments. Every fault communication is identified through a unique ID code that is automatically generated by the system when the end-user sends the message. Through the interface between the dedicated app, the localization system and the virtual model, the fault communication generates an "alert object" in the building information model. This object will show up in the building information model according to the position of the end-user; i.e., where the photo was taken—and will contain the photo along with comments from the end-user. This phase is the most delicate. In general, two main aspects can hinder the effectiveness of the system. Firstly, the accuracy of the localization system is not sufficient to distinguish between two similar features that are close to each other. Furthermore, the location of the signal is performed on the mobile device and not on the specific object. Secondly, the error identification phase is based on comments from an end-user who is not a professional. The first issue can be addressed by training end-users in taking photos near the damaged component. Furthermore, the photo can be enriched with a viewfinder to point the damaged element helping the facility manager in identifying the object in the virtual model. The second issue can be partially overcome because of inherent informative content of the objects contained in the virtual model. In fact, all the technical information related to the identified object are available in the building information model. Thus, even if the end-user has no competencies, he or she must explain the situation, leaving it to the facility manager's interpretation.

INTERMEDIATE phase: fault message forwarding

At the end of the INPUT phase, the fault message is received by the facility management office that can localize the fault object on the virtual model and from it read all the connected information. Thus, the facility manager can query the identified object in the digital model and read all the technical and maintenance data from which he or she can obtain the information about the maintenance company commissioned for the specific item.

The localization is performed by the facility manger combining the position of the signal in the model (defined through the automated creation of an "alert object"), and the attached photo that points to the element. The IT structure allows two different actions from the facility manager. On the one hand, the fault object can contain all the information about the defined maintenance company. In this case, the system allows forwarding the message to the maintainer with any additional information added by the facility manager. On the other hand, if there is not a defined maintenance company, the facility manager can consult a list of selected maintainers and select the most suitable on a map where all the suppliers are geo-localized.

OUTPUT phase: work order closing

The message is sent to the maintenance company using the same mobile app and sharing the building information model through the cloud to allow the maintainer viewing the position of the element and all its technical specifications. When the maintenance company receives the fault message, it has the complete information about the faulty object. Thus, the maintainer can prepare all the materials needed to proceed with the reparation. At the end of the work, the maintainer can notify the parties about the executed task through the dedicated application sending a message to both the end-user and the facility manager. During this phase, the system allows the maintainer to attach a photo of the repaired item along with the description of the activity carried out in a message. The question of correct execution is automatically generated by the system as the maintainer notifies that the work has been completed. If the end-user confirms the correct execution, the facility manager receives a notification of "work done" and can directly pass the task to the accounting office. On the

other hand, if the end-user does not confirm the correct execution of the work, the fault is notified again and the process restart from the first phase.

In addition to the management of the fault reports, the same structure can be used to manage the non-core services. For example, the system can be integrated with counting sensors distributed in common use rooms. These devices can detect the number of people occupying a specific room and communicate through WIFI, USB [58] or 4G technologies with the localization system that can send a signal to the virtual model when maximum occupancy is reached. Through this automated communication, the facility management can optimize the non-core services such as rooms cleaning, without the end-user's involvement. This example shows how the proposed system can be integrated with existing and/or additional components or sensors centralizing in a single digital environment the information flow. Figure 5 resumes the logical structure of the entire process.
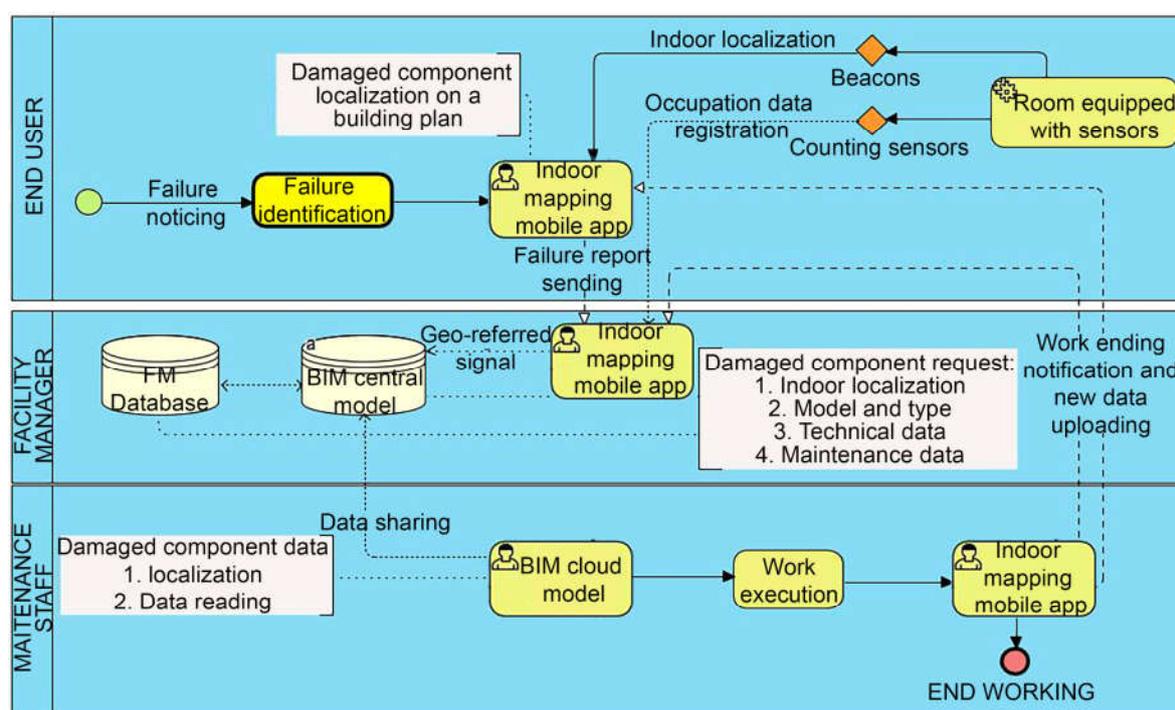

Figure 5. Indoor localization system: process flowchart.

5. Implementation and Validation Through a Case Study

5.1. BIM Model of the Real Estate Case Study, for Management and Maintenance Scope

The validation of the proposed system and of its procedures has been made through a practical case study focused on a parish real estate sited in Baranzate in Milan province (Italy). The considered real estate was composed of four buildings: a church, a manse, an oratory, and a school; it had a total area of 3.172 m² allocated respectively in 438 m², 518 m², 1901 m² and 315 m². After a first step of surveying dedicated to the collection of geometrical and non-geometrical data, we modelled all the buildings of interest (Figures 6 and 7).
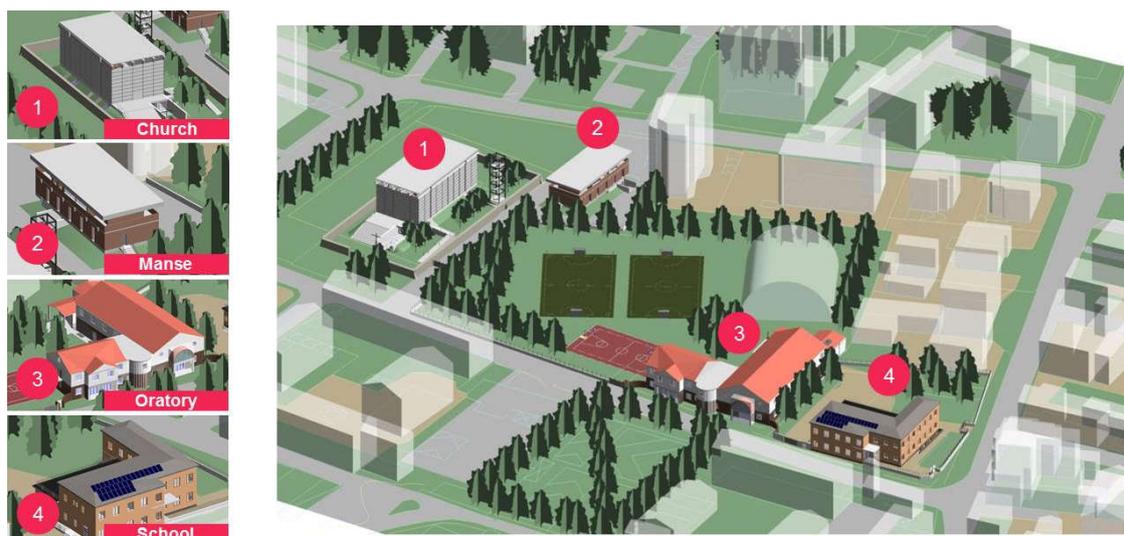
Figure 6. Case study real estate geometric modelling.

Figure 7. Real estate BIM modelling, internal view.

The objective of the developed model was to support the facility management activities. Thus, all the objects contained in the model were characterized by a low level of development in the geometrical representation related to the scope of the model. This allows for a more dynamic modelling phase and, as a result, a final model with modest dimensions in terms of hard disk memory. On the other hand, the level of development in regards to information content was enriched with all the information obtained from facility operations [59], according to the objectives of the building information model. An external database, related to the building information model, was developed to allow archiving the information on all the maintenance activities during this time. All the objects of interest such as architectural components, MEP components and structural components have been inserted in the building information model (and in the connected database).

The data collected can be divided in three main classes:

- identification data: as the code, type, model, description, maintenance company information;
- technical data: obtained from the technical sheets. This information is useful to complete the component identification and to control the required data in the case of component replacement;
- maintenance data: dates of maintenance visits and deadlines, schedules, maintenance contracts, instructions video URL. This data is useful for the maintenance operators during the work.

*5.2. Application Results on Corrective Maintenance*

BIM in the real estate case study was utilized to apply the facility management supporting method proposed, to assess its applicability to a real prototype, with specific reference to the management of corrective maintenance.

For the application of the theorized processes, a specific app called Nextome developed by Noovle [57] was used. The implementation of the system needed the construction of the indoor localization structure through the installation of several beacons in the real estate. As stated by Noovle, 150 beacons are sufficient for an average area of 8000 m^2 [57]. The real estate configuration led to install 61 beacons, allocated in the following way:

- 9 beacons for the church;
- 10 beacons in the manse;
- 36 beacons in the oratory;
- 6 beacons in the school.

A parish priest was the manager of the real estate used in the case study and represented the facility manger. The priest received a real estate central building information model that was managed by a BIM modeler engaged to realize the survey, design the model, and upload new data periodically. The real estate end-users were the parishioners and according to the theorized system, they were involved in the fault-reporting phase. As shown by the context, the case study included end-users without high technological skills and background, validating the applicability of the proposed method to a wide range of situations. In fact, mobile devices are now available to everyone and the intuitive mobile app structure that was provided to generate reports can encourage end-users to collaborate according to the facility maintenance needs.

Testing the process reported in Section 4.2 with a real component as shown in Figure 8, the message was correctly sent from the end-user to the facility manager that individuated the correct object inside the virtual model and from it extracted all the information required for maintenance activities.
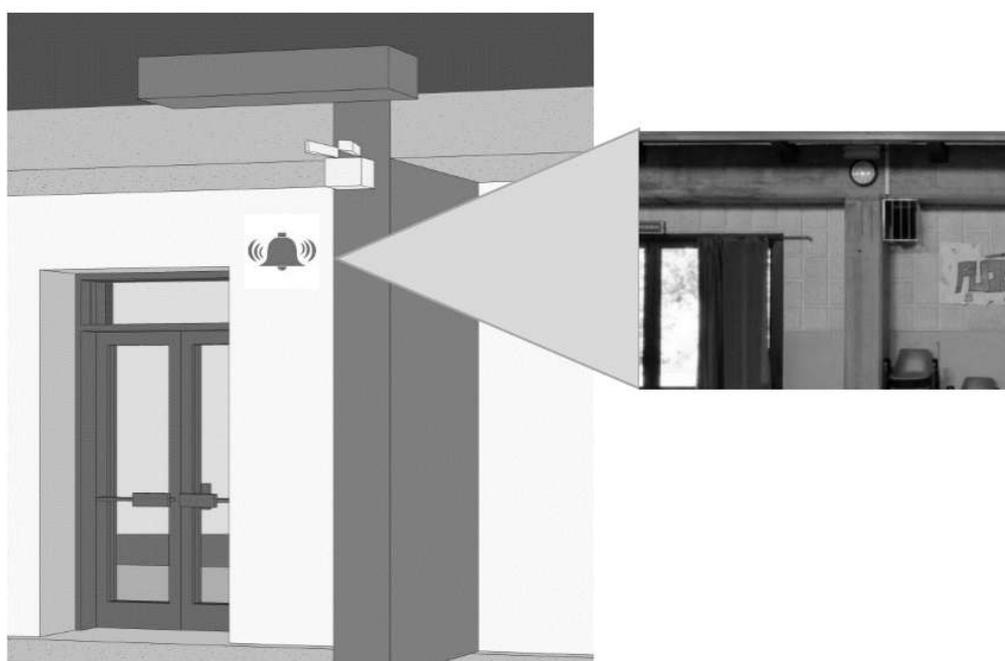
Figure 8. Building information model fault message reporting interface.

In this case, all the information about the maintenance company was already integrated inside the damaged object (Figure 9). Thus, in this context, the facility manager can contact the maintenance company and provide all the essential information needed for an effective maintenance service. Due

to the level of definition of the virtual objects, developed to be useful for the maintenance phase, the maintainer can estimate the possible causes of failure and determine the needed operations, instruments and any logistical constraints. This reduces the needed time for inspections and allows the maintainer to show up on site and ready to proceed with work.

A building management system, based on components equipped with sensors, can detect the cause of failures with high precision, but it would be very onerous for an old property like the one discussed in this case study. Costs for the replacement of plants and systems would not be feasible and physical building components without sensors would need to be tagged with barcodes, integrating two technologies. On the other hand, an approach based uniquely on barcode tags for components and scanning procedures by the end-user for communicating damages could be inappropriate for this case study. In fact, ecclesiastical buildings are very crowded and costs for barcode periodical maintenance would be high.

Parametro	Valore
Dati identità	
Impresa di manutenzione	TESIR s.a.s
Indirizzo	Via Sempione 9, Nerviano (MI)
Numero di telefono	0331-415668
Immagine tipo	
Nota chiave	
Modello	i3F 752x58+16B0
Produttore	Lighting PETRIDIS
Commenti sul tipo	
URL	C:\Users\Francesco\Desktop\TESI\02-MO
Descrizione	2 x Fluorescente lineare T5 (16 mm)
Codice assieme	ILL-EM
Costo	
Descrizione assieme	
Contrassegno tipo	ILL-EM
Numero OmniClass	23.80.70.11.21
Titolo OmniClass	Emergency Lighting
Nome codice	
Fotometrica	
Emissione luminosa	72.00 lm/W
Flusso luminoso	5200.00 lm
Flusso totale	7812.00 lm
Rendimento	62.4000%

Figure 9. Building information model component database example.

However, in old buildings like the ones in this case study, the real estate data is often collected and stored in paper archives, and consequently results in loss of information over a period. For this reason, it is not known if all the geometrical, technical and maintenance data are available during the survey phase and if the first building information model can be effective and applicable for the proposed process. Thus, the proposed process could perform poorly in the early phases of its application due to the unavailability of data in most of the building elements. The experimentation showed that feedback from end-users during the input phase could help the maintainer in identifying possible causes of faults and damages by combining the feedback with the information in the virtual object. In the case of objects with poor informative content, the maintainer is not generally able to understand the probable causes of faults and/or damages directly. This aspect shows the importance of a continuous update of the building information model after each maintenance activity. A structured uploading process is important to improve the efficiency of the system during the years increasing the database. In this scope, it is thought to regulate the communication between the maintainer and the real estate BIM modeler. At the end of the work, the maintainer can take a photo of the product's barcode, send it to the facility manager allowing him to access the product technical sheet and to upload the data in the central building information model (Figure 10). Furthermore, the double check provided by the system in the closing phase guarantees the correct fault resolution. As a result, the proposed method configures a valid alternative to the ones presented in Section 2 for supporting facility management activities, specifically for case studies like the one showed in this paper. Furthermore, not only the proposed system by itself is able to support the corrective

maintenance for all building components, both systems and physical ones, but also it is easily integrated with other technologies such as sensors for space management.

During the experimentation of the process, the limited precision of the localization system proved to be a critical point. While in rooms with high internal height and in the case of large and/or well-spaced elements, the process shows an effective identification of the fault object in the virtual model. In other cases, the correct identification of a specific object required a reiteration of the procedure by the end-user with caused poor performances. Nevertheless, during the experimentation several private companies were working on new devices for indoor localization, opening the perspective to possible future improvements.
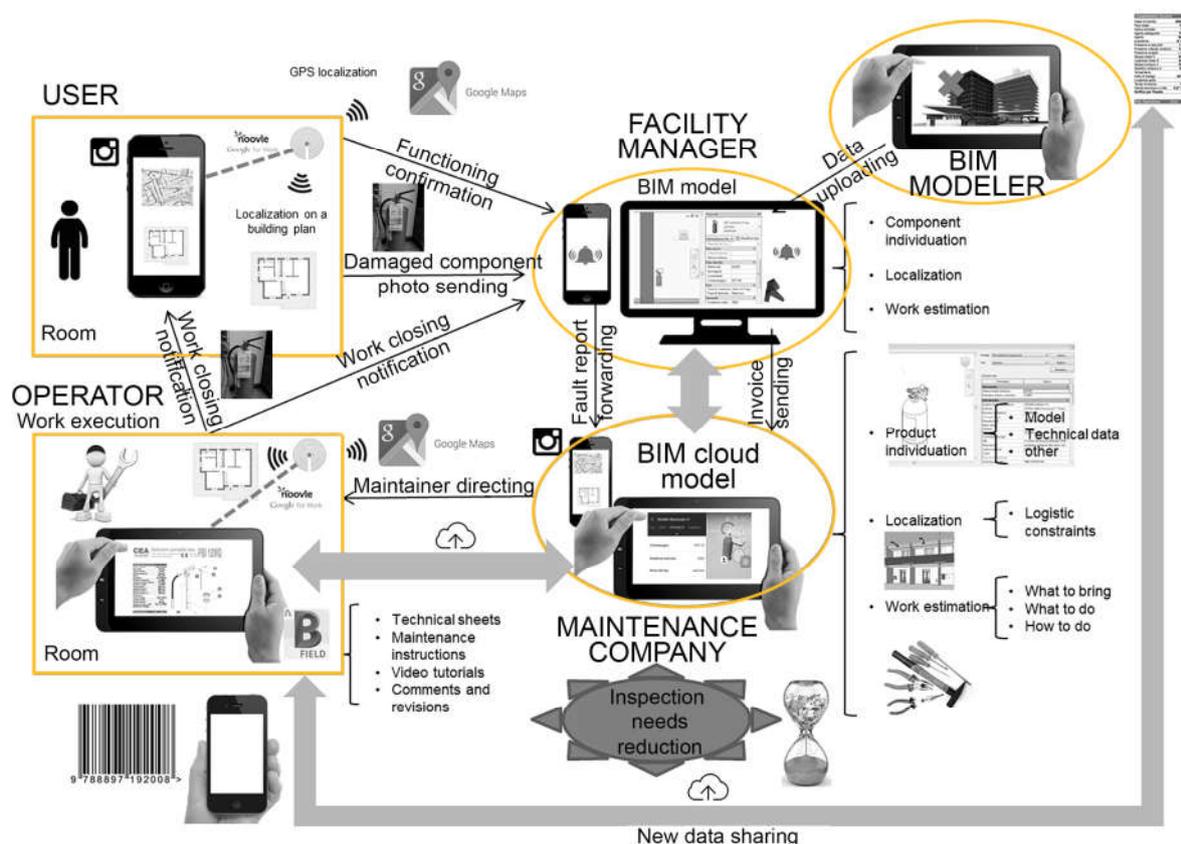

Figure 10. Flowchart of the process implemented in the case study.

5.3. Academic and Practical Contributions

This research shows how end users' involvement and integrated BIM-GIS technologies can support FM activities with a specific focus on old buildings that are characterized by a high number of daily users. The findings of the approaches and applications include:

- The integration of BIM and indoor localization systems that are managed through a central digital environment allows the identification of every element of an asset in a digital environment without requiring a prior mapping.
- No mapping systems are required for reducing maintenance efforts.
- The use of a standardized data structure, inherently defined by the system, allows the update of future data analysis that are still undervalued.
- The integration of standardized information in a BIM-GIS environment allows quantitative analysis for distributed assets.
- Integrating data in a BIM-GIS logic can improve the supply chain management processes.

Starting from the findings above listed, it is possible to define a comparison analysis between the proposed framework and the existing methodologies analyzed in Section 2.2. The benefits and differentiations are summarized as follows (Cases 1, 2 and 3 refer to Table 1):

- In the proposed framework, the end users are not required to use complex systems and/or instruments to identify faults. This principle improves the usability of the system in comparison with Case 1 and it is aligned with the methodology applied in the case of QR codes (Case 2).
- Compared to Case 1, the proposed framework allows the localization of the elements in an integrated system facilitating the identification of the faults.
- Compared to Case 2, the proposed framework allows the localization and management of every element of the building. The only requirement is the introduction of the element in the building information model. This peculiarity allows the management of wide building elements such as walls and floors. In fact, the application of QR codes on wide building elements can pose several issues, namely the definition of the number of QR codes on a specific element that can present different characteristics in different points (e.g., layers, thickness, materials) and the correct identification of localized damages on the specific element. Through the proposed framework, both the above-mentioned issues are overcome.
- Furthermore, in the case of changes in the building (e.g., the introduction of a new element) the use of QR codes (Case 2) requires the definition of a new QR code, its introduction in the digital system and the physical application of the QR code on the element. The proposed framework requires only the introduction of the new element in the building information model to allow its identification and the consequent activation of the process.
- In comparison with Case 3, all the elements can be identified including both the one connected to the grid and the physical one such as windows, doors, and walls.

The GIS information in the integrated system with a defined and guided data structure allows the management of distributed assets and the inclusion of supply chain management in the system. Nevertheless, the data management defined on multiple asset paves the way for the development of data analytics applications.

In addition, this paper provides an integrated literature review that is analyzed in a systematic manner. The review presents the existing supporting methods for maintenance operations, the related technologies and existing technologies for indoor localization applicable in the support of FM activities.

Finally, the proposed solution can be directly applied in the industry with specific reference to old buildings. The localization system can be reused in different services such as the security and emergency management, including the industry site, hospitals, public spaces, and nursing homes.

There are still limitations in the study. First, the precision in the identification of objects is limited compared to the QR code systems mentioned in the cases in the literature. The direct link between a QR code and the related object allows a precise and unique identification of the element that is more difficult using the proposed framework. Next, in comparison to an integrated BMS and BIM system, the proposed framework is based on the human action in the identification of faults. Hence, the uncertainty of continuous monitoring for plants needs to be further studied. A delay can be registered between the fault, its identification from the end-users, and the consequent activation of the process. Finally, the precise evaluation of the costs related to the effective implementation and maintenance of the system needs to be evaluated on multiple cases to provide a comparison analysis with the existing technologies and techniques. This passage constitutes one of the main directions for future research.

6. Conclusions

The market of Facility Management is increasingly expanding, and efficient systems are necessary to support manger's decisions. Facility managers usually manage maintenance and activities using CAFM systems, which usually cause an inadequate monitoring of building management features. The introduction of BIM processes can improve the efficiency of building

management, linking external databases to a virtual representation of a real estate. However, current research of BIM-based facility management supporting systems shows some open issues especially in the case of old buildings with a high number of daily users. First, the communication between the players involved in the facility management operations needs to be improved allowing a better and useful data transfer. The proposed system provides a platform linking indoor localization systems with building information models structured for the facility management scope. Results of the proposed case study indicated that end-users can report a failure by taking a photo through a mobile device and a facility manager can manage activities and maintenance operations through an interactive building information model connected with the end-user position in the building. This process can be an alternative to the one based on barcode systems and sensing components for localizing indoor failures. For instance, BMS is a good solution for building status monitoring for components connected to the network, but low performances are expected in failure reporting for physical building elements (e.g., walls and floors). Furthermore, the implementation of a BMS would be very onerous, especially for old real estate. The proposed processes showed to be useful even if several issues were highlighted during the validation phase. Furthermore, less maintenance operations for the management-system components are required, compared to the BIM-barcode based system. The system can be integrated with the previous explained technologies and it is structured to support corrective maintenance operations until the work ends. In addition, the system can be updated automatically due to the definition of a circular proactive process allowing data collecting and archiving in the building information model at the end of each maintenance activity. Thus, maintenance activities are managed in an integrated digital environment that includes fault notification, activity management, validation, and closing as well as spatial information for supply chain management and quantitative data analysis.

In conclusion, the proposed framework allows the development of integrated systems to support FM operations providing several advantages in comparison to existing techniques. First, every element of the building can be localized and included in the process (no mapping and/or tag systems required). Second, the entire cycle of maintenance activities is managed through a unique integrated system including the territorial dimension. Third, data are collected in a standard structure for future uses.

Future research will be focused on the study of the performance provided by new localization devices that are now under development, including the definition of more case studies to effectively prove the functionality in the management of predictive maintenance and non-core services maintenance. Meanwhile, more comparisons need to be analyzed for the theoretical frameworks and cases to reveal the gaps between theories and practical issues. Another line of future research is about the cost of implementation. It is known that one of the main limitations of BIM-based processes adoption for the existent building management is the time (and consequently cost) needed to the survey operations and the building information model representation. One of the next steps of research will be the study of the overall costs needed to implement the systems considering IT structure, devices, and virtual components (including models and data). In this direction, laser scanning and augmented reality for indoor navigation are potentially beneficial for the improvement of the support for maintenance operators and facility managers [60].

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