sustainability

MDPI

Article

A Methodology for a Performance Information Model to Support Facility Management

Rossella Marmo [1,*], Maurizio Nicolella [1], Francesco Polverino [1] and Andrej Tibaut [2]

1 Department of Civil, Architectural and Environmental Engineering of the University of Naples Federico II, 80125 Naples, Italy; nicolell@unina.it (M.N.); polverin@unina.it (F.P.)
2 Faculty of Civil Engineering, Transportation Engineering and Architecture of the University of Maribor, 2000 Maribor, Slovenia; andrej.tibaut@um.si
* Correspondence: rossella.marmo@unina.it

Received: 10 October 2019; Accepted: 6 December 2019; Published: 8 December 2019

check for updates

Abstract: Current facility management practice relies on different systems which require new technologies to integrate and manage information more easily. Building information modeling offers a good opportunity to improve facility information management by providing a unified platform for various data sources rather than an intuitive information interface. Although current research trends reveal that there is a continuously growing interest in facility management aided by building information modeling, an integrated model is still hard to obtain. This paper aims at developing a novel methodology based on building information modeling and facility management systems integration, underpinned by a performance information model. The implementation process of a performance information model is described, including information technologies involved, the data and process requirements, and the building performance assessment methods used. A first pilot case-study has been conducted with regards to surgery rooms in healthcare buildings. The proposal can support condition-based maintenance work schedule, as well as the achievement of organizational, environmental, and technical requirements. Among the practical implications found: Improved technological and environmental performances assessment; better visualization of building condition; improved decision-making process; facilitated maintenance tasks planning and maintenance records management.

Keywords: building information modeling (BIM); building performance assessment (BPA); key performance indicators (KPIs); facility management (FM); operation and maintenance (O&M); operating room (OR)

---

1. Introduction

The International Organization for Standardization (ISO) defines facility management (FM) as the "organizational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business" [1].

Facility management has to support a wide range of activities (commonly referred to as non-core business) which enhance the work environment and well-being of people; enable the organization to deliver effective and responsive services; make the physical assets highly cost-effective, allowing also future changes; enhance the organization's image and culture [2] (pp. 36–37).

Particularly in the healthcare facilities sector, a facility manager has to consider many factors when making a strategic decision. The identification of a set of specific key performance indicators (KPIs) [3,4] helps the performance assessment and strategic planning. An integrated healthcare facility management model has been proposed [5] to hierarchically analyze healthcare FM core parameters, showing that an analytical quantitative model may significantly contribute to a better understanding of facility management performance.

Based on studies conducted by several authors [6–9], it is possible to identify different clusters of services and competencies within the FM domain. These tasks are carried out through different strategies (insourcing, total FM, public private partnership, etc.) but mostly through outsourcing [10].

Among the competency areas, the operation and maintenance (O&M) service plays a key role. It is meant to let the facility and its required systems function efficiently, reliably, safely, securely in a manner consistent with existing regulations and standards [9].

Building maintenance activities requires a comprehensive information system to capture and retrieve data related to building equipment [11]. The current FM practice relies on different systems (i.e., building energy management systems (BEMS), building automation systems (BAS), computerized maintenance management system (CMMS) [12], computer aided facilities management (CAFM), document management system (DMS)), which utilize new technologies to integrate and manage information more easily [13]. Studies on maintenance issues reveal that the most frequent problem is the information accessibility [14].

Building information modeling (BIM) can be considered as a tool or a method to face information management challenges throughout a building life cycle. It has been defined as the "use of a shared digital representation of a built asset to facilitate the design, construction and operation processes to form a reliable basis for decisions" [15]. BIM is semantically-based and object-oriented; it has 3D modeling capabilities and allows users to retrieve comprehensive information represented by objects and their attributes [16]. BIM provides a unified platform (Figure 1) for various data sources needed for daily O&M activities [11,17–19], so that data regarding technical specification, planned activities, and building performances (simulated or monitored) can be integrated to facilitate the decision-making process.

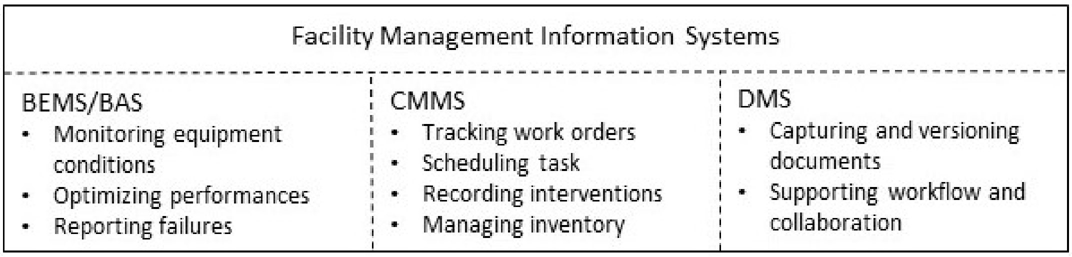

Figure 1. Facility management (FM) information systems.

Recent studies regarding BIM application in O&M activities indicates that energy management has been relatively analyzed by researchers, followed by emergency management and maintenance and repair [19].

Although current research trends reveal that there is a continuously growing interest in facilities information management using BIM [19–21], a seamless information process between BIM and FM systems does not exist yet [18]. Data exchange and interoperability remain problematic topics [18,19,22] while a lack of real-life examples of BIM-FM applications [17,23] and a lack of demonstrated benefits of BIM in FM [22] are among the key barriers to BIM implementation in FM.

Within the condition-based maintenance, monitoring of physical variables related to symptoms of failures is needed. The condition-based maintenance aids facility managers in identifying anomalies early enough to minimize the impact of operational interruptions [24]. Building performance assessment (BPA) provides for a better knowledge of an asset, so to make correct decisions at the right time. The performance assessment enriches BIM models with the purpose of evaluating the residual performances, so that coherent interventions can be selected [25]. For example, when certain spaces are performing under a certain threshold the integrated model can make suggestions regarding maintenance planning.

An improvement that is expected from BIM-FM integration is the systematic generation of information, such as KPIs [8]. Developing an FM benchmarking framework enables organizations to identify best practice and strategies improvement [26].

The aim of this paper is to propose a methodology that integrates FM systems, BIM, and BPA, to support maintenance planning and organizational requirements achievement.

To do so, the following research objectives are defined: (i) Analyzing FM and BPA processes and requirements; (ii) identifying relevant performance information which can be translated into KPIs; (iii) developing a framework for BIM-aided FM and BPA based on that information. To better understand the implications of BIM implementation in FM and performance assessment domain an overview of current BIM-FM integration is provided, with particular regard to information communication technologies (ICT) in FM, the impact of BIM in FM systems, and BPA methods.

A systematic literature review related to data and process requirements for BIM-FM integration was carried out via Scopus database with the following keywords: 'Building Information Modeling', 'BIM', 'Information Management', 'Facilit * Management', 'Operation and Maintenance', 'CMMS', 'CAFM', 'case study', 'Building Performance Assessment' in title/abstract/keywords. A total of 60 publications were examined in detail.

As evident, we were also interested in publications describing use cases to better understand the information exchange needs, the challenges to be faced and the expected results of BIM implementation in our research. For the scope of the paper the case studies analyzed concern BIM application in the O&M domain. Table 1 summarizes the analysis of the selected publications according to the following categories: The purpose of the case study; the BIM use purpose; information requirements; information references; information exchange supports; benefits achieved; challenges encountered. In the table, the 'BIM use purpose' is mapped according to [27] where a BIM use purpose is "the specific objective to be achieved when applying building information modeling during a facility's life.".

According to the Table 1, BIM is mostly appreciated for gathering (i.e., to capture, monitor, qualify), communicating (i.e., to visualize), and analyzing (i.e., to coordinate, validate, forecast) data and information. In few cases [28,29] the BIM model is integrated with a benchmarking system to report current performances, while it commonly contains maintenance activities records [13,30,31], asset characteristics and specification [13,32–42], and space management information [29,34,36].

Table 1. Building information modelling-operation and maintenance (BIM-O&M) integration case studies.

Case Study, Year, Ref.	Purpose of the Case Study	BIM Use Purpose	Information Requirements	Information References	Information Exchange Supports and Methods	Benefits	Challenges
Sydney Opera House 2007, [28]	Supporting building system alterations and asset management	To communicate and analyze	Properties of building elements; Building Condition Index	2D CAD drawings and Sydney Opera House specifications	IFC model (integrated data model)	Control of costs and environmental data; support to decision-making	Not discussed
US Coast Guard 2008, [29] (pp. 339–357)	Facilitating better decision-making for strategic planning and facility assessment	To gather	Facility Condition Index; Mission Dependency Index; Space Utilization Index	As-built documents (including 3D models); assessment team data; assessors' data; new BIM objects	Customized systems based on open standards (IFC, XML etc.)	Cost and time savings; standardizing processes and capturing knowledge digitally	BIM-based processes must support the integration of a variety of data and must be accessible to a wide range of users
A campus building 2010, [30]	Integrating facility maintenance data with BIM to support maintenance planning	To communicate and analyze	Maintenance activities information such as replacement, installation and status change	Not discussed except for the work order records	Manual integration of maintenance data into BIM model	Spatiotemporal analysis to optimize future interventions	Data capture and collection; updating the model and related information
Taiwan's school 2011, [31]	Creating a single repository of facility data for facilities maintenance	To communicate and gather	Schedule of planned tasks; results of maintenance works; facilities maintenance documents	3D CAD models; existing FM systems	Application Programming Interface and C# programming language	Improved information accessibility; enhancement of tasks planning and quality of inspection	Information exchange; updating information in BIM models
Norrtälje hospital 2011, [32]	Developing a customized life cycle management system to support proactive maintenance	To gather, communicate, and analyze	Geometrical model; material properties; environmental properties; condition assessment data; degradation model	2D CAD drawings; administrative documents; condition surveys	wrl. file, transformed from a dwg. file by the use of a third software	BIM-based tools serve as information repository for life cycle management; simplified build-up of information; enriched data	Needs for BIM integrated life cycle solution based on open standards
University of Chicago 2013, [33] (pp. 294–314)	Supporting maintenance activities	To communicate and gather	List of asset inventory information and data	Design and construction models; existing FM systems	Spreadsheet (modified version of COBie)	Improved data accuracy; streamlined data acquisition process	Handling with the variety of information resources; need for FM team information expertise

Table 1. *Cont.*

Case Study, Year, Ref.	Purpose of the Case Study	BIM Use Purpose	Information Requirements	Information References	Information Exchange Supports and Methods	Benefits	Challenges
Manchester City Council Town Hall 2014, [8,23]	Investigating the use of BIM in FM domain	Not discussed	Operation and maintenance information	Various FM systems; 3D building information and cloud-based repository for digital documents	Not discussed	Faster maintenance process and shorter service disruption	Need for FM team BIM expertise; limited software interoperability; unclear BIM FM requirements etc.
Kerr Hall, Ryerson University 2015, [34]	Testing how to overcome key challenges while developing 7D BIM	To communicate, gather, and analyze	Space allocation; lighting feasibility calculations; asbestos hazard map	Survey and reports; existing space management systems	Spreadsheet	Improved data updating and assessment of potential energy retrofit	Identify critical information; create/modify BIM models; information transfer; documentation uncertainty
Northumbria University's campus 2015, [13]	Investigating the value of BIM in space management	To communicate, gather, analyze, and generate	Asbestos properties, location, date of removal and survey documentation	DWG floor plans, scans of elevations, JPEG sections, Excel databases	Not discussed	Improved space management and geometric information record	Identifying necessary information; need for FM team information and BIM expertise; interoperability;
University of British Columbia 2015, [35]	Understanding the transition from a paper-based to a BIM-based approach in handover and FM	Not discussed	List of operation and maintenance information	Building management systems; facilities information systems; asset management systems	Not discussed	Not discussed	Methods and process changes
Terrassa Campus 2016, [36]	Investigating the benefits of the integration of maintenance management and BIM	To gather, communicate, and analyze	List of building characteristics, space management, maintenance and building monitoring data	Physical stock and intranet; building management system; maintenance management systems	Definition of a unique identifier (ID) for each object and space	Improved data consistency, intelligence in the model and reports generation; integration of facility systems	Correlating different kind of data sources; information exchanges
Laboratory and office building 2018, [37,38]	Developing more efficient data collection in post-occupancy facilities management	To gather and communicate	Mechanical and electrical asset data	As-built 2D drawings; project documents; asset data list	Comparison among different methods: manual; spreadsheet; CSV; IFC	Not discussed	Data transferring processes
Public University building 2018, [39]	Creating a central facility data repository to support FM tasks	To gather and generate	List of maintenance and equipment information	Owner's guidelines and handover products	COBie and IFC	Easier updating of CMMS thanks to handover BIM models	Data transfer and data quality control; needs for resources and collaboration among teams

Table 1. *Cont.*

Case Study, Year, Ref.	Purpose of the Case Study	BIM Use Purpose	Information Requirements	Information References	Information Exchange Supports and Methods	Benefits	Challenges
Melzo's school buildings, 2018, [40]	Developing a decision support model to define the priorities of refurbishment actions	To gather and analyze	List of information regarding accessibility; energy efficiency; acoustic performance	Legislation and technical standards; thermal simulations;	SQL and Dynamo	Semi-automatic evaluation of the level of compliance of existing buildings, with reduced time and costs	Lack of information suitable to perform a complete assessment in BIM models
Training center 2019, [41]	Merging BIM and Product-Service System to enhance maintenance operations	To gather and communicate	List of ordinary and extraordinary maintenance activities information	Maintenance reports and interviews with customers and suppliers	Not discussed	More effective management of maintenance activities, facilitated data record and tracking	Lack of knowledge and skills concerning the use of BIM tools
Hospitals in Scandinavia and Denmark 2019, [42] (cases A and B)	Investigating the enabling and constraining elements of digital FM in Scandinavia.	Not discussed	Building inventory	Design and construction information	Manual integration of as-built information in FM systems (case A); customized classification system (case B)	Not perceived (case A); time savings thanks to common project library shared by different design teams (case B)	Information exchange; few interests in ICT investment; lack of knowledge concerning ICT implementation; needs for digitalization strategy

1.1. Facility Management (FM) and Information Communication Technologies (ICT)

FM needs high level of interaction and information sharing, currently supported by ICT. Ranging from email documents to BIM, including computerized maintenance management system (CMMS), computer aided facilities management (CAFM), and BAS/BEMS, different tools have supported FM activities during the past decades [43].

The CMMS includes the creation and the management of asset records, bill of materials, and work orders; inventory control etc. [44], thus they support maintenance scheduling, facilities monitoring, and preventive maintenance [45].

The CAFM is a collection of tools used for organizing and managing various activities within the facilities such as space planning and management [45]. CAFM systems are largely based on the 'office suite' tools, including tabulated data, spreadsheet, and 2D drawings [43].

Both CMMS and CAFM have limited visualization capabilities, as traditional utilization of paper based or digital 2D plans limits the facility manager to identify the exact maintenance location context and the history of modifications [43].

The BEMS are regularly applied to the control of active systems, i.e., heating, ventilation, and air-conditioning (HVAC) system, determining their operating times. While sensors send feedback and alarms to these controlling systems, facility managers can monitor and change any benchmark or override the information [12].

In order to guarantee the required building operational performance, facility managers must check technical and environmental conditions. In this sense, building sensors and controllers can inform maintenance activities.

The complexity of BEMS can be integrated to CAFM, BIM and Maintenance Management System to control the operating equipment [45].

1.2. Benefits of Building Information Modelling-Facilities Managament (BIM-FM) Integration

BIM model might interact with the systems described above, as a source for data input, providing material/spatial data, reports or technical analyses, or as an interface for a repository, providing data capture, monitoring, processing, and transformation [34,46].

The main expected benefits from BIM-FM integration are cost reduction, thanks to ready to use data provided at the handover phase; performance improvement, it is to say more accessible FM data allows faster analysis and correction of problems; integration of several information technologies [33] (pp. 1,2).

BIM promises to provide a reliable database and integrated views across all facility systems [30] so that facility managers can base their decision on a more comprehensive knowledge of the building systems. BIM also provides 3D spatial information; therefore, it supports visualization and spatial analyses of various maintenance activities. Such analyses might not be easily performed with traditional databases [30].

Owners can use a BIM model to quickly populate an FM database [29] (pp. 108–111). As-built BIMs can enable the transfer of facility information from the design and construction phases to the operational phase. Retrieving necessary facility information from a BIM model and importing them into CMMS allows relevant costs savings, avoiding recapturing and transferring information by architects, engineers, and contractors [30].

Owners can also use a BIM model strategically and effectively to manage facility assets. They can evaluate the impact of retrofit or maintenance works or associate each building object with a condition assessment over time, supporting critical analyses [29] (pp. 108–111) such as maintenance planning and sustainability management [33] (pp. 11–13).

However, the BIM implementation in FM systems is not currently achieved without challenges, as described below.

1.3. Challenges of BIM-FM Integration

Three major category of issues can be defined [30]: Challenges encountered by the facility team or facility owners (i.e., lack of knowledge about how to use BIM in their practice); challenges encountered by the designers and contractors (i.e., lack of guidance about data requirements and delivery); technical issues (i.e., interoperability).

To connect BIM data to FM systems, FM teams can face the interoperability issue in several manners [37]. As different companies are involved either in the design or in the operational phase, common data exchange formats can be considered an effective strategy for exchanging data between BIM models and FM systems. Examples of open standards are the Construction Operations Building Information Exchange (COBie) [47] or the Industry Foundation Classes (IFC), in particular the FM Handover Model View definition [48]. They define standard structure and minimum data fields to support facility management [2].

Other BIM-FM linking approaches concern manual integration of data (i.e., through spreadsheets) and proprietary middleware [49].

Due to the simplicity of their inherent structure, spreadsheets are useful means of moving data (text and numbers) between software [28]. They are generally used in CAFM/CMMS or BAS, plus they are linkable to BIM objects. With a customized application, it is possible to read/write and import/extract data from a BIM based platform that also supports spreadsheet-based documents. For example, Dynamo, a tool for visual programming, which works within the Revit environment, can act as a bidirectional link from Revit to an Excel spreadsheet [38].

However, the transfer of data at the handover phase is commonly limited to graphical spatial information (i.e., room areas and attributes) and building inventory. Facility managers hardly update information from small projects, work orders, and major renovations in as-built BIM [33]. In order to enhance the maintenance planning there is a need of capturing information about maintenance and repair works during the operational phase. Retrieving this information facilitates project financial analysis and maintenance works prioritization [50].

In addition, an as-built model that is developed without early guidance is not effective for operational purposes [51]. In early project phases, designers and contractors have to know what information the FM team will need, as well as what organizational standard structure for information inventories is needed [52], which is not commonly known by the owners [53].

Defining the BIM-FM integration goals and developing the BIM-FM information collection and related information exchange process are necessary steps to effectively design the integration of BIM for FM [54]. The strategic identification of operational information is critical; thus facility managers need to detail and prioritize their information requirements [13,34], identifying by whom and when the data should be provided throughout the project life cycle [17]. This data will depend on specific user systems, organizational structure, and scope of the model.

In conclusion, owners might not be accustomed to the technological side of building management issues and not educated on BIM, how to request it, or how to adopt it to their practices. At the same time, few contractors are willing to perform BIM that does not directly benefit their daily work process without charging significant additional costs [55].

For these reasons, the cost of BIM-FM integration can be high, requiring investment in infrastructure, training, and new software and hardware [30].

1.4. Building Performance Assessment Methods

The performance evaluation of buildings and their components has always been a very complex and controversial topic. The problem arose when it was necessary to introduce assessments on the duration of the components, within the wider topic of scheduled maintenance. If we assume that every maintenance intervention must be associated with a performance threshold, and that the status of failure must be identified and coded also for those components for which performance is not measurable, then methods and tools to evaluate the performances are needed.

For the assessment of building performance, it is very important to evaluate whether it is necessary to intervene [56], because there is the risk that maintenance interventions may have high costs if not necessary or urgent [57].

In the last decades, however, the concept of performance evaluation has strongly moved towards those concerning the environment and sustainability [58–60]. In this sense, we can say that building performances have a strong integration with building users [61], and the reference methods have therefore become those that prefer aspects such as quality, health, safety, security, comfort, without neglecting others such as the social ones [62].

Among them, there are the POE (post occupancy evaluation), that is a method developed in the 1960s, conceived to measure the performances of buildings that have been built and occupied for a set time duration, and the BPE (building performance evaluation), that is a method conceived in the 1990s that was developed for upgrading POE and to improve the quality of decisions made at every phase of building life cycle [63–66]. These methodologies mostly tend to evaluate the performance of the whole building, and not those of the single components, essentially using analyses of users' satisfaction.

Similarly, KPIs propose performance assessments indirectly, mainly investigating the satisfaction of users and are detected through non-material indicators such as psychological or perceptive or performance indicators, defined in facility management contracts.

Many researchers have emphasized the importance of measuring building performances through KPIs [67], and many others have categorized them—at operational level—into the following ones: Technical, functional, behavioral, aesthetic, environmental [56].

Performance indicators are useful for measuring status and plan improvement activities and continuously assess changes over time [68]. Technical performance indicators are considered the most critical, and within this category structural resistance to fire and stability are two important indicators to be considered [69], while other researchers [70] identified asset failures and the severity of their consequences as an indicator.

It has been highlighted [71] that performance categories and examples of operational indicators, on the basis of studies conducted by several authors (such as Straub, 2003; Hovde and Moser, 2004; Lützkendorf and Lorenz, 2006; Preiser and Nasar, 2008; Yan et al., 2015), can be summarized as shown in Table 2.

Table 2. Categories of indicators.

Performance Category	Example of Indicator
Technical	Good lay-out of evacuation routes Structural condition [number of defects, severity]
Functional	Suitability of spaces [occupation/m^2] Air quality [CO_2 level]
Behavioral	Thermal comfort [number of complaints about temperature year]
Aesthetic	Façade appearance [peeling defects on façade/m^2]
Environmental	Waste generation [kg/year] Energy consumption [kWh/m^2/year]

From the publications reviewed in this research it is possible to demonstrate that building performance assessment could be limited to safety and efficiency, health and comfort, space functionality, and energy performance.

Some researchers [72] consider methods such as the BREEAM (Building Research Establishment Environmental Assessment Method) or approaches such as LEED (Leadership in Energy and Environmental Design) as real performance evaluation tools, although they refer to performances in a more than qualitative way but in any case codified by means of scores and/or attributes.

There are also possibilities, widely exploited, to use BIM as a source of data for a prediction of performance indicators of the planned building. That is for obtaining quantifiable predictions that can help in identifying strategies, tools, and methods to improve the overall building performances, and in particular the energy efficiency.

BIM-based computational analysis tools provide possibilities for integrating design and analysis process from the earliest stages of design and can also assist in design decision making [73]; some researchers [74] have emphasized the effectiveness of building performance-based design method compared to traditional method.

Recent publications have defined BIM-based workflows to compute and compare KPIs in order to make a qualitative assessment of the building and its parts [75] and to automate the monitoring of buildings during their regular operation [76]. In both cases the digital model becomes the mirror of the building and stores its actual performances to support facility managers in making decisions.

1.5. Interpretation and Discussion

Starting from the review of existing ICT tools for FM, the use cases analysis of BIM implementation for O&M purposes and the review of BPA methods it has been demonstrated that BIM can enhance different FM activities, even though with some challenges.

BIM as a repository tool, able to support different analysis, has been tested in several applications. For example, BIM can support proactive maintenance through gathering information about materials, environmental, and condition data so that a BIM-based life cycle management system can be developed [32]. The prioritization of refurbishment actions can be improved too, developing a decision support model based on accessibility, energy efficiency and acoustic performance information [40]. Three-dimensional data visualization allows analysis to optimize future interventions planning [8,13,23,30,31]. Faster maintenance processes and shorter periods of disruption have been proved [15,18] and tested merging BIM and product-service system [41].

At the same time, it appears that a lack of BIM expertise among the FM team and the owners [8,13,23,33,41,42] and the information exchange processes [8,13,23,31,32,37,38] are major challenges.

Furthermore, it can be deduced that a preliminary analysis of the FM process and policies, both currently adopted or expected, is necessary. In fact, the sources of required information for facility maintenance mostly involve the existing FM documentation, FM personnel's experience, and building management systems [19]. Interviews with the owner and the FM team allow to better understand the organization's information requirements. The analyzed case studies involved the owner and other relevant stakeholders in order to define data needs based on current and future goals of O&M activities [13,34–39,41].

Finally, the integration of operational conditions and performances in BIM models is a lesser-known topic, even if it can facilitate the decision making for facility planning and assessment. For this purpose, a specific set of information for a complete BIM-aided performance assessment must be defined [40], a wide variety of data and a wide range of users must be involved in BIM processes [29], and BIM-FM links must be based on open standards [32].

1.6. Research Contribution

The BIM-based approach presented in this paper includes the definition of FM and BPA information requirements, involves a wide range of data and users, and is based on open standard data format, in order to facilitate the analysis of current building performances, reduce corrective maintenance and emergency repairs.

The methodology is underpinned by a performance information model (PIM), which links facility management information systems, FM workflow repository and BIM's common data environment (CDE) (Figure 2).

The methodology addresses the interoperability issue with the latest IFC 4×2 data schema. Novelties in the schema like the entities IfcFacility and IfcFacilityPart along with IfcBuildingStorey and IfcSpace provide for detailed spatial breakdown of built facilities which can support location context information in the FM systems. The IFC schema can support also organizational requirements like IfcActionRequest for maintenance work orders through the IfcProjectOrder entity, which supports different maintenance types (corrective, condition based, planned corrective, scheduled). The IFC schema could support assessment of environmental conditions with the use of the property Pset_Condition, which determines the state or condition of a physically existent object like IfcElement (i.e., IfcSensor), at a particular point in time. Therefore, our methodology is intended to resource to BIM technologies for building performance assessment and facility maintenance information. Also, Business process modelling notation (BPMN) is considered for the FM workflow automation.

A pilot implementation of the methodology has been conducted in a use case, which includes surgery rooms of a healthcare facility. The case study concerns the environmental quality assessment, considered as a major performance feature to be monitored in such an environment. To easier control and quantify this performance feature a new KPI has been defined. Evaluation of the environmental performance indicator is related to technical and equipment conditions, consequently it can facilitate the identification of maintenance works eventually needed.

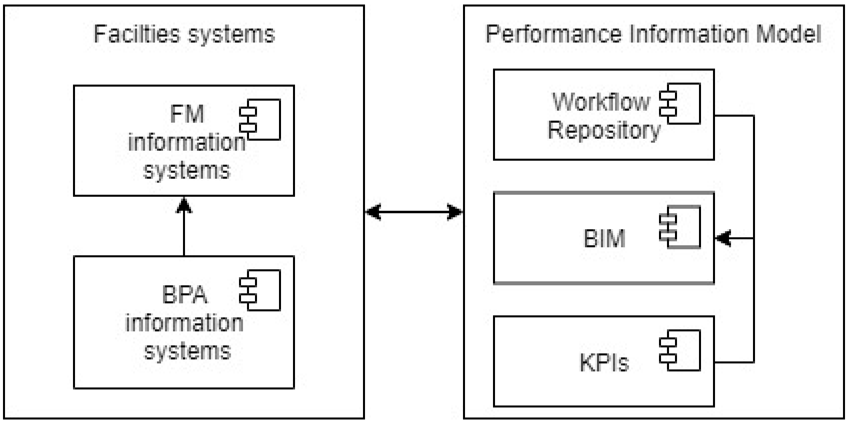

Figure 2. Organization of performance information model (PIM) elements.

2. Methodology for Developing a Performance Information Model (PIM)

In the context of the maintenance information modeling the BIM-aided BPA takes place. The PIM is achieved by the following workflow:

Identify building performances to be monitored and FM information requirements. To achieve a deep understanding of the required information to be gathered and managed through BIM we acquired and studied: Tender specifications about facilities management, in particular specification on O&M management and surgery units environmental condition assessment; reports on the monitoring process and results; adjustment plans; organizational documents on risk assessment. The collected data regard a public hospital in the province of Salerno, South of Italy. Interviews and focus groups were conducted among the FM personnel and the prevention and safety team. The interviews were carried out in person and involved two different Italian public healthcare authorities. These interviews resulted in deeper understanding of: the information needed to control performances and conditions; processes and systems in use to obtain and gather those information; the means by which to communicate the results. Furthermore, aimed by the contractors, we achieved and studied the CMMS database, in particular the history of corrective maintenance intervention, planned and preventive maintenance tasks and schedule, register of work orders. This process of information enrichment led to the definition of the stakeholder's information requirements, a crucial knowledge to inform the BIM model efficiently. Databases used in this research protect patients' privacy. They regard only maintenance and monitoring activities and patient-related information were not collected. Analyzed data are the outcome of maintenance activities carried out according to the Italian regulation, furthermore processes and environments analyzed in this paper were not modified for the scope of this study.

Establish methods of performance assessment. To identify how to achieve the performance assessment, procedures and systems currently in use among the healthcare facilities were analyzed. KPIs have been chosen as performance measurement tool because their functionality is already well-known within the organization involved in this study and they best facilitate the achievement of the BIM-aided BPA as they can be managed in form of objects parameters within the BIM platform. For each performance to be assessed a KPI must be set. In the context of this research an environmental condition index (ECI) was defined ex-novo. Such ECI is a weighted average of control parameters values. The weights are related to the criticality of the parameters in relation to the environmental quality. First, it was necessary to identify which parameters describe the KPI, then their weights. To do so the local health authority of Salerno and the University Hospital of Verona were involved. The list of measurable control parameters was achieved by two focus groups with expert panels from the above-mentioned healthcare authorities. To achieve an agreement on the criticality of each parameters referred to operating room air quality, a Delphi method was conducted. Then the criticality weights were obtained by a combination of Delphi method and analytical hierarchy process (AHP). The Delphi involved a panel of 17 experts including engineers and other technicians, doctors, nurses, and a chemist, all experts of maintenance and condition assessment of surgery rooms. The Delphi allowed to achieve the pair comparison matrix related to the control parameters, then the vector of the weights was calculated by AHP. The pair comparisons referred to the Saaty's values scale.

Link the monitored performances to preventive/corrective activities. According to certain performance values the interventions needed can be identified. From the environmental performance assessment, the performance of the technical systems can be deducted. The links were defined with the collaboration of mechanical systems and indoor air quality experts, taking into account the way by which the environmental quality is monitored and the type of installed plants. These relationships can be translated in a deterministic logic and then transposed in a BIM platform to inform and update the model utilizing IfcActionRequest (description of maintenance request), IfcApproval (approval of maintenance request) and IfcActor (person or organization(s) fulfilling the request such as a facilities manager or contractor.).

Define the BIM use purpose and PIM requirements. Establishing the potential value of BIM use on the project helps to identify the BIM implementation goals and the specific BIM uses. Once the BIM uses are identified then the model requirements can be defined, i.e., in terms of parameters to be inserted in the model, customized dataset, links to maintenance database, level of development required, implementation process needs, etc. Once the implementation process has been established then the information exchanges can be defined. The exchange files contain instances of a subset of entities compliant with the IFC schema, such as IfcActionRequest, which are addressing the PIM requirements. For consumption of the exchange files a customized software needs to be developed.

Implement the PIM. PIM input data come from facility information management systems, including the BPA process. The actual condition of the facility is also required, so that the model to which the FM attributes refer can be created. Monitoring information were pulled in the model in an automatized manner, creating a link between the model and the Excel spreadsheets used to handle the monitoring results. The output data are the required inspection tasks associated with the failed systems. They are visualized in the model in the form of text shared parameters, but they can be exported or linked to CMMS to inform future work orders.

3. Performance Information Model: Use Case of Hospital Surgery Rooms

Considering international guidelines [77–80] and literature analysis, a proposal of PIM process development is deducted (Figure 3).

The proposed process provides for the operational condition assessment of a building and its elements. The monitored data can be gathered in the model, then analyzed and translated in the form of performance indicators. Relevant information can be generated, such as the interventions needed to satisfy the necessary requirements. The KPIs, in form of objects properties, are visualized in the digital model, allowing further spatiotemporal analysis and supporting decision making tasks of subcontractors and FM team. According to the monitored conditions different performances of the building during its lifecycle can be assessed and managed (i.e., sustainability, affordability, energy consumption, safety, efficiency, environmental quality, etc.). Building information modeling can play a key role as it allows collaboration and information exchange among the operators, shows the building actual performances and related suggested interventions, supports the maintenance planning, and facilitates the asset inventory management.

The local health authority has recently provided new contractors for FM and prevention and safety activities for hospitals under its responsibility. No existing BIM models were held by the authority or the FM contractors, and the processes currently in use among them were not BIM-oriented. This is a common situation within the Italian built environment. Therefore, recent laws and regulations [81–83] regarding the digitalization of the information process in the construction sector require to face the digitalization of existing buildings and related services. In such context this case-study constitutes the first step taken to a BIM-aided FM.

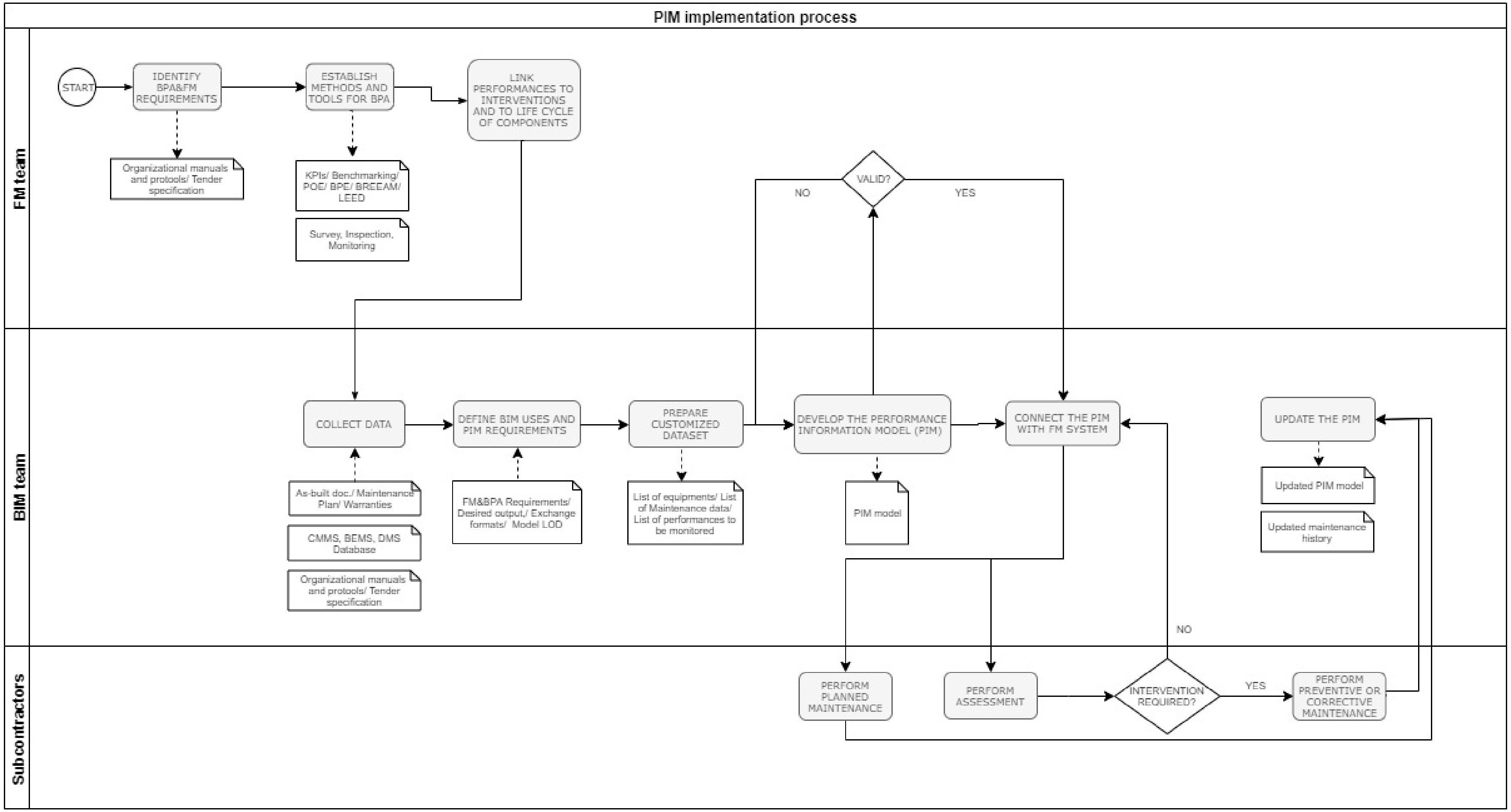

Figure 3. Performance information model (PIM) implementation process in business process modelling notation (BPMN) standard. The PIM approach has been validated by a surgery rooms BIM model, regarding a public healthcare building in Italy. A surgery room is a very complex system, it has to comply with a set of requirements [84] which can be transposed in performances to be assessed.

3.1. Building Performance Assessment (BPA) and FM Information Requirements

Especially when no BIM exists yet, it is crucial to do the prior analysis of stakeholders' information requirements to optimize geometric modeling and information handling effort. Prior to modelling, local health authority's specifications on surgery rooms (related to maintenance, risk management and work organization) have been examined.

The list of collected data related to preventive and corrective maintenance tasks is reported in Table 3.

Table 3. List of preventive and corrective maintenance information that can fill the model as objects properties.

Work Orders History	
WorkOrderID	Description
BuildingID	DateOfRegistration
DateOfCompletition	Duration
Requests for Intervention	
RequestID	Created by
Reported by	Description
Location	ContractualAuthority
SiteID	BuildingID
FloorID	UniteID
RoomID	Equipment
DateRequestCreated	UrgencyLevel
UrgencyTimeConstraints	ProblemType
InterventionType	ResolutionType
InsuranceDeductable	ExpectedCompletitionDate
MaintenanceCompany	DateOfCompletition
Notes	StatusID

Monitoring significant parameters related to the condition of hygienic/engineering/structural systems allows healthcare facilities to adopt preventive procedures. The risk management team, according to the performance assessment and risk evaluation results, informs the FM team in order to align findings to the required condition. The local health authority commissioned a specialized company to evaluate, analyze, and report the environmental and equipment condition of surgery areas. The hospital has no BAS, but the quality control is performed according to a planned schedule of activities. The list of information to be monitored is reported in Table 4.

Table 4. Monitored conditions in surgery rooms.

Parameter Name	
Particle concentration	Air volumes/air exchange
Microbiological concentration	Noise
Anesthetic gases	Recovery time
Microclimatic conditions	Water quality
Pressure gradient	Lighting intensity

3.2. Key Performace Indicator (KPI) for Surgery Rooms: Environmental Condition Index

Using a set of established KPIs simplifies the evaluation process and helps the management team to make strategic decisions towards the organization's mission.

We proposed a novel environmental condition index (ECI), which has the following Formula (1):

$$\frac{\sum_i^n P_i \times W_i}{\sum_i^n W_i} \tag{1}$$

where:

- ECI_{UAk} = environmental condition index referred to the surgery room k. It varies from 0 (best scenario) to 1 (worst scenario). As an example, the ECI for the orthopedic surgery room resulted to be 0.09, while for the general surgery room it was equal to 0.21. In both cases the 'noise' and the 'contamination at rest' controls were not satisfied, but in the latter case also the 'microclimatic condition in operational' was not fulfilled;
- P_i = value of each environmental quality factor. It is evaluated on a binary scale: P_i is equal to 0 if the control associated to it is fulfilled, otherwise it is equal to 1. As an example, for the orthopedic surgery room the value 1 was associated with the parameter's 'noise' and 'contamination at rest', while the value 0 was associated with the remainder;
- W_i = criticality weight of each factor. The sum of all the weights is 1 (100%). In the orthopedic room case, the sum of the products was 0.09 as the 'noise' and the 'contamination at rest' weigh respectively 4% and 5%.

The ECI has the following features:

- It eliminates overlapping and redundant information, as some parameters are grouped when depending on the same equipment element. Then the identification of the required intervention was simplified;
- It expresses each relevant aspect of the system assessed. The list presented in Table 3 was discussed in two focus groups to select seven parameters necessary and sufficient to evaluate a surgery room environmental quality;
- It provides for a wide applicability across the authority FM systems, as it is based upon their requirements;
- It is expressed by a number, which values can vary from 0 to 1. This is a consequence of two factors: The formula which expresses the KPI and the evaluation mechanisms.

The Delphi method provided for the pair comparison matrix (consistency ratio equal to 0.07). Each expert involved in the Delphi expressed his opinion regarding parameters confronted two by two with respect to their contribution to the environmental quality of operating rooms. The AHP was used to deduce the parameters priorities with respect to the above-mentioned criterion. These weights have been deducted by calculating, in the MATLAB programming platform, the main eigenvector associated to the main eigenvalue of the pair comparison matrix. The results are reported in Table 5.

Table 5. Pair comparison matrix and criticality weights.

		1	**2**	**3**	**4**	**5**	**6**	**7**	**Weights %**
Contamination at rest	1	1.00	0.19	0.64	0.40	0.26	0.15	0.93	4
Contamination in operational	2	5.27	1.00	4.57	0.73	0.44	0.27	4.78	14
Microclimatic conditions at rest	3	1.57	0.22	1.00	0.20	0.19	0.15	0.51	4
Microclimatic conditions in operational	4	2.48	1.37	4.94	1.00	0.26	0.21	2.64	12
Air volumes/Air exchanges/Recovery time	5	3.90	2.27	5.39	3.78	1.00	0.27	2.47	21
Anesthetic gases concentration	6	6.65	3.71	6.65	4.72	3.66	1.00	5.62	40
Noise	7	1.08	0.21	1.98	0.38	0.40	0.18	1.00	5

3.3. Correlation Between Environmental and Technical Performances

In order to integrate BPA with maintenance planning and to enhance the value of the ECI use, a link was established between control parameter values and the interventions required. These interventions are defined in terms of inspections and checks to be performed in order to verify possible failures or inadequate operational conditions within the technological and functional system. Table 6 proposes the correlations list.

Table 6. Links between environmental and technological system.

N° Parameter	Parameter Name	N° Task	Task Description
1	Contamination at rest	1.1	HEPA filters inspection
		1.2	HVAC pipes inspection
2	Contamination in operational	2.1	Behavioral protocols check
3–4	Microclimatic conditions at rest and in operational	3.1	Project condition check
		3.2	ATU supplied power control
5	Air exchanges/Recovery time	5.1	Filters inspection
		5.2	Load loss check
		5.3	Forced air volume calculation
		5.4	Mixing and ventilation efficiency control
6	Anesthetic gases concentration	6.1	Pipes fitting controls (high- and low-pressure systems)
		6.2	Gas evacuation system controls
7	Noise	7.1	Air-cooled inspection
		7.2	HVAC ducts inspection
		7.3	ATU inspection

3.4. PIM Implementation

The PIM methodology was tested on a healthcare building in the province of Salerno, south of Italy (Figure 4). In this case study BIM was used to gather information related to the environmental control, to communicate the monitoring results, and to analyze the condition assessment in terms of maintenance interventions required. The controls discussed in this study concern the risk management associated with surgery rooms activities. We accessed the database containing the surgery units' environmental controls, which regard air quality. Other factors and engineering devices were not monitored. The methods used to perform those tests respect the Italian regulations and are based on the Italian guidelines regarding the assessment of the efficiency of the preventive measures adopted by the prevention and safety department of healthcare organizations. The PIM described here has a basic geometric development (a BIM model with LOD 200) [85] but contains specific non-graphical information for facility management. The geometric model was created in Autodesk Revit 2019, starting from 2D CAD plans regarding the architectural and HVAC systems. Autodesk Revit allows different types of analysis when combined with other software, such as Green Building Studio to conduct energy performance simulation [86] or Dynamo, as illustrated below.

Figure 4. Location of the case study: building and surrounding.

The case study is focused on the environmental systems management, so it was enriched by the definition of rooms and related properties (i.e., environmental condition index).

We analyzed the database of the monitoring results related to one semester of activities (last semester of 2018 year) carried out in three operating rooms. In this database the results were individually presented for each type of test. The authors provided to translate them in a summarized Excel sheet to make them easier to read by Dynamo (Table 7). The results were translated to Boolean values to define the failure (1) or the fulfillment (0) of each control in each room.

Table 7. Monitoring results associated to each surgery rooms presented as Boolean values.

Orthopedic Surgery Room	1	0	0	0	0	0	1
General Surgery Room	1	0	0	1	0	0	1
Pediatric Surgery Room	1	0	0	0	0	0	1

The input data in Excel sheets (Figure 5) can be easily updated when BPA activities are conducted. The data concern all the results enabling to calculate the ECI for each surgery room (i.e., the value of control parameters, their respective weights, and the value of the resulted ECI).

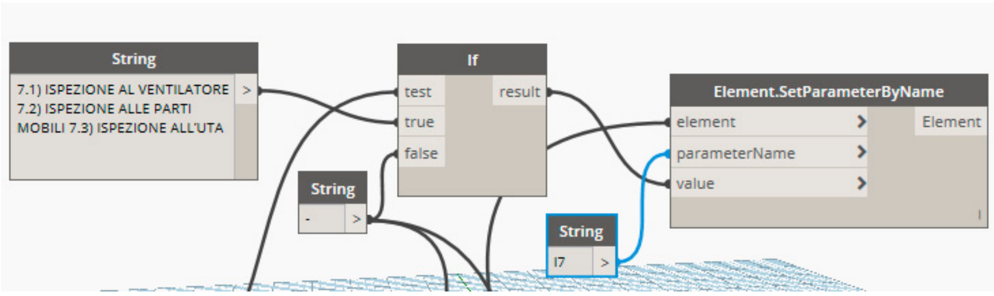

Figure 5. Conditional logic in Dynamo.

Dynamo was used to create bidirectional links between the model and external data, as systems integration tool. The Excel.ReadFromFile node was used to connect the BPA results spreadsheet-based with the model parameters. The 'If' statement was used to check the needs of intervention according to the monitoring activities results. The 'If' statement contains a Boolean statement so that the 'true' condition was associated with the failure of environmental controls. The results of the performance assessment were transposed in the model through the node Element.SetParameterByName (Figure 6). The BPA results and maintenance tasks needed are visualized in the model in the form of shared parameters, furthermore it is possible to visualize the performance assessment by thematic drawings. The Figure 7 shows the thematic plan of three surgery rooms and the properties associated to them, in terms of ECI, controls (I1, I2, etc.) and interventions required (1.1, 1.2, etc.). In this case, which regards the general surgery room, the controls I1, I4, and I7 are not fulfilled, so the corresponding required interventions are reported in the model (1.1 HEPA filters inspection, 1.2 HVAC pipes inspection; 3.1 Project condition check, 3.2 ATU supplied power control; 7.1 Air-cooled inspection, 7.2 HVAC ducts inspection, 7.3 ATU inspection).

The corresponding fragment of the IFC file shows an example of the custom IfcPropertySet 'Environmental Condition Index' for the use case.

#836 = IFCPROPERTYSET('3DF3k2$9z3HRdciX9bgXts',#59,'Environmental Condition Index',$,(#850,#854));
#850 = IFCPROPERTYSINGLEVALUE('Description',$,IFCLABEL('1.1 HEPA filters inspection, 1.2 HVAC pipes inspection; 3.1 Project condition check, 3.2 ATU supplied power control; 7.1 Air-cooled inspection, 7.2 HVAC ducts inspection, 7.3 ATU inspection'),$);
#854 = IFCPROPERTYSINGLEVALUE('Value',$,IFCREAL(0.217256),$);

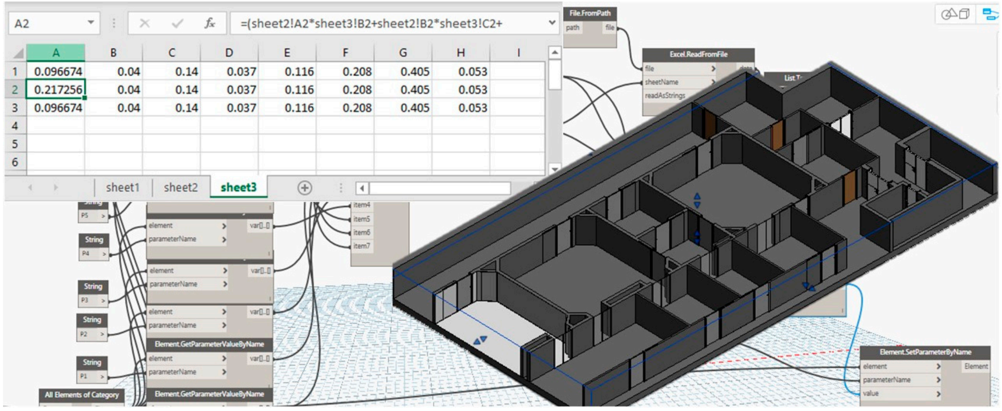

Figure 6. Excel-Dynamo-Revit links.

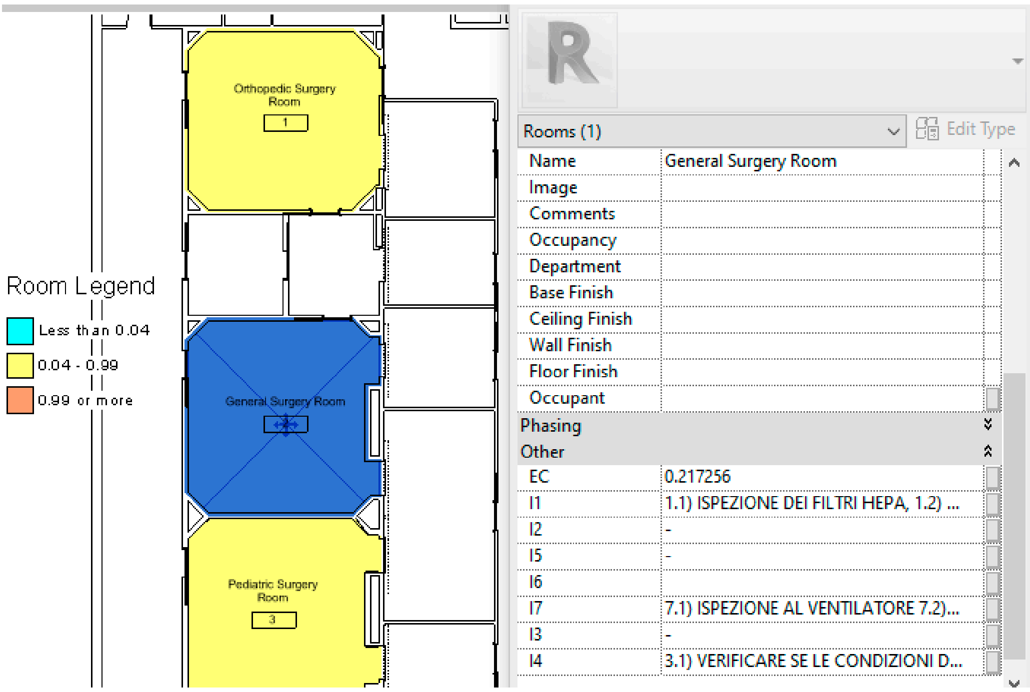

Figure 7. Thematic plans of orthopedic, pediatric and general surgery rooms. ECIndex and inspections required are reported in the model as rooms properties.

4. Analysis and Discussion

In this section, a synthesis of findings and their analysis is presented. The purpose of the synthesis is to assess the stability of results.

The performance information model tested on surgery rooms provides for:

1. Proposing a workflow for PIM implementation based on BPMN model (Figure 3),
2. Listing maintenance related information which can be added to the BIM model as the IFC object properties (Table 2),
3. Defining a new KPI for surgery rooms, measuring the environmental and functional performances (Formula (1)),
4. Correlating the measured performances to required maintenance intervention in terms of inspections and controls (Table 3),
5. Implementing a conditional logic and the information systems integration (Figure 6).

This application demonstrates the positive impact that BIM can have on analyzed FM and BPA processes.

The prevention and safety department is in charge of measuring the air quality of the surgery units, with the support of an external contractor. The results inform the maintenance department with a list of suggested interventions. The maintenance department is in charge of the maintenance planning and require the intervention, if needed, of the maintenance provider, an additional contractor.

A performance information model in such context can act as a tool to facilitate the analysis of building performances, through KPI definition (Figure 7), and as a system to speed-up the information exchange process among the different parties. A PIM can also support the maintenance works and assessment activities record, information that are rarely captured in BIM models nowadays. Figure 8 shows the instance of PIM implementation, starting from the already developed model (see Figure 3). The requests for intervention and related approvals are omitted in order to simplify the diagram interpretation.

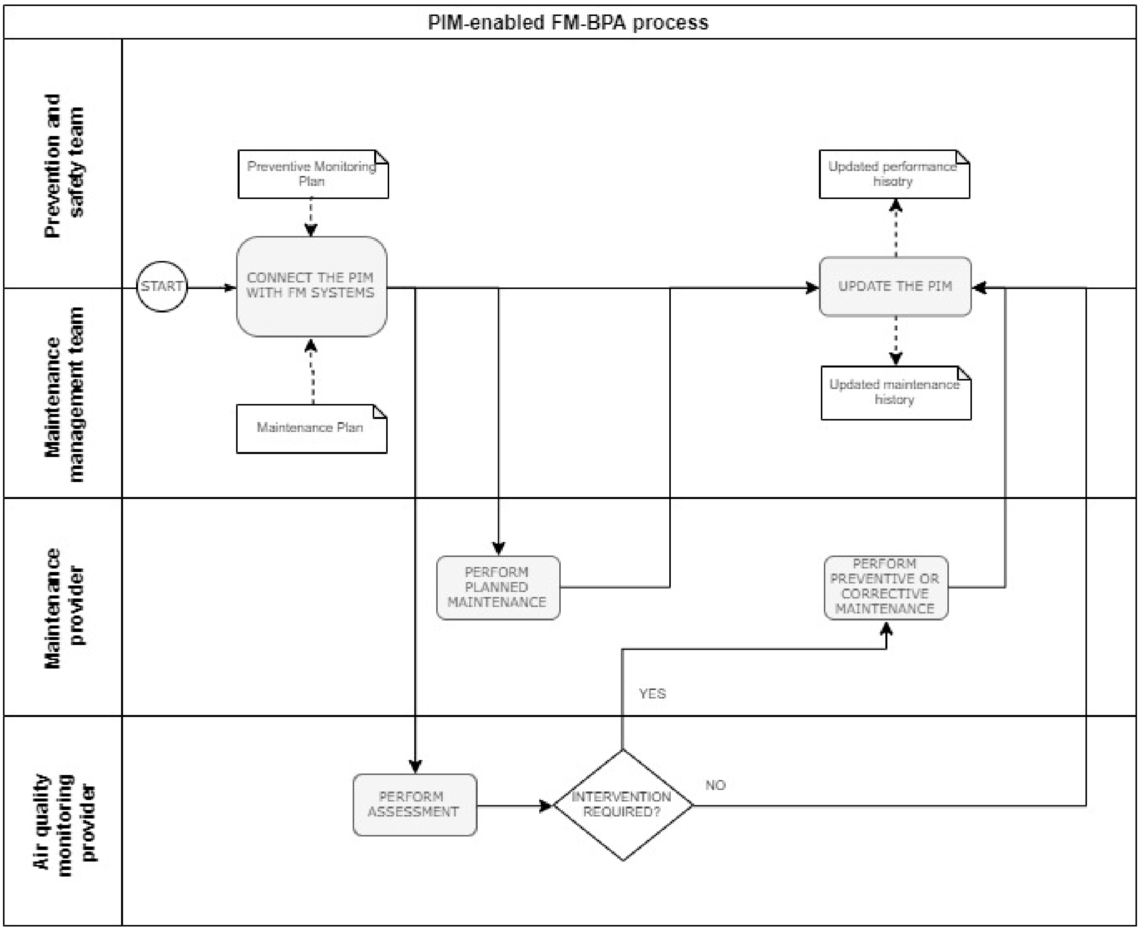

Figure 8. Instance of the PIM application process.

From the case study analysis, it is possible to deduct that a comprehensive PIM, extended to maintenance management and further systems control, has at least the following application benefits:

1. Improved technological and environmental performances assessment,
2. Integrated visualization of the operating condition of building and its elements,
3. Inventory management of building components, spaces, furniture and documents,
4. Automation of the quantity take-off,
5. Support to identify and schedule future maintenance interventions,
6. Management of historical data about previous maintenance.

5. Conclusions

Current research trends reveal that there is a continuously growing interest in facilities information management using BIM, which offers a good opportunity for a technical platform to integrate various data sources needed for daily O&M activities. An improvement that is expected from the BIM-FM integration is the systematic generation of information, such as KPIs to identify best practice and improvement strategies. Even though such an integration process has promising potential benefits, for example relating performance thresholds to maintenance planning, in very few cases the benchmarking of performance was tested.

Surveys aiming to develop the common BIM data requirements for O&M are limited and more focused surveys for specific building types and for specific O&M tasks have to be conducted [19].

Within this context, this article aimed at developing a methodology to integrate BIM, BPA and FM systems, supporting organizational, environmental and technical requirements achievement.

It contributes to the body of knowledge by defining a comprehensive approach to achieve this systems integration and has proposed a novel performance information model as decision-making support tool.

Furthermore, it explores in detail the healthcare buildings sector, with particular regard to operating rooms, reporting specific information requirements which can be used for future O&M tasks.

As no existing BIM models were held by the authority or the FM contractors, the starting point for the PIM development was the owner's and FM team's needs investigation, which resulted in modeling the environmental system and related attributes. As the BPA and FM process were not BIM oriented, we created a link between the existing FM systems and BIM model by customized application and commercial software tools.

At the moment the PIM implementation is limited to operating room environmental system. Other engineering systems (i.e., fire protection, electrical systems, energy consumption meters, weather station etc.) were not monitored.

Further research will be conducted to achieve a more comprehensive as-built model in order to enrich the PIM with maintenance information related to technological system elements (i.e., mechanical plant elements as ducts, pipes, filters, etc.; architectural elements as floor, ceiling, doors etc.; structural elements as pillars, columns, beams, etc.).

Further research and development of the proposed methodology concern automation of the information exchange, development of a prototype application in Python with an API that utilizes IfcOpenShell and a customized database, integrated with a BPMN automation support. In the development, preventive and corrective maintenance information from the Table 2 will be mapped to the corresponding objects from the asset BIM models using the standardized IFC entities identified as relevant for FM. The prototype application will be tested on several case studies to deeper analyze the proposed approach and for developing a more powerful and generally applicable BIM-based solution for FM and BPA activities.

Author Contributions: Writing—original draft preparation, R.M.; writing—review and editing, M.N. and A.T.; supervision, F.P.

Funding: This research received no external funding.

Acknowledgments: The authors want to acknowledge the local health authority of Salerno and the University Hospital of Verona for the support given to the development of the case study discussed in this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. ISO 41011:2017. Facility Management—Vocabulary. Available online: https://www.iso.org/obp/ui/#iso:std:iso:41011:ed-1:v1:en (accessed on 4 August 2019).
2. Atkin, B.; Brooks, A. *Total Facility Management*, 4th ed.; John Wiley & Sons: Chichester, UK, 2015.

3. Shohet, I.M.; Lavy, S. Facility maintenance and management: A health care case study. *Int. J. Strateg. Prop. Manag.* **2017**, *21*, 170–182. [CrossRef]
4. Lavy, S.; Garcia, J.A.; Dixit, M.K. KPIs for facility's performance assessment, Part I: Identification and categorization of core indicators. *Facilities* **2014**, *32*, 256–274. [CrossRef]
5. Lavy, S.; Shohet, I.M. A strategic integrated healthcare facility management model. *Int. J. Strateg. Prop. Manag.* **2007**, *11*, 125–142. [CrossRef]
6. Chotipanich, S. Positioning facility management. *Facilities* **2004**, *22*, 364–372. [CrossRef]
7. Roper, K.; Payant, R. *The Facility Management Handbook*; AMACOM Division of American Management Association International: New York, NY, USA, 2014.
8. Kiviniemi, A.; Codinhoto, R. Challenges in the Implementation of BIM for FM—Case Manchester Town Hall Complex. In *Computing in Civil and Building Engineering*; Issa, R., Flood, I., Eds.; American Society of Civil Engineers (ASCE): Orlando, FL, USA, 2014; pp. 665–672.
9. International Facility Management Association. Competency Guide. Available online: https://www.fm.training/sites/collabstore/files/images/Competency_Guide_Context_Public_v1_7-12-18.pdf (accessed on 4 August 2019).
10. Ancarani, A.; Capaldo, G. Supporting decision-making process in facilities management services procurement: A methodological approach. *J. Purch. Supply Manag.* **2005**, *11*, 232–241. [CrossRef]
11. Motawa, I.; Almarshad, A. A knowledge-based BIM system for building maintenance. *Autom. Constr.* **2019**, *29*, 173–182. [CrossRef]
12. Shalabi, F.; Turkan, Y. IFC BIM-Based Facility Management Approach to Optimize Data Collection for Corrective Maintenance. *J. Perform. Constr. Facil.* **2016**, *31*. [CrossRef]
13. Kassem, M.; Kelly, G.; Dawood, N.; Serginson, M.; Lockley, S. BIM in facilities management applications: A case study of a large university complex. *Built Environ. Proj. Asset Manag.* **2015**, *5*, 261–277. [CrossRef]
14. Liu, R.; Issa, R.R.A. Survey: Common Knowledge in BIM for Facility Maintenance. *J. Perform. Constr. Facil.* **2015**, *30*. [CrossRef]
15. International Organization for Standardization. ISO 19650-1:2018—Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling. Part 1: Concepts and Principles. Available online: https://www.iso.org/obp/ui/#iso:std:iso:19650:-1:ed-1:v1:en (accessed on 9 October 2019).
16. Jeong, W.S.; Kim, K.H. A performance evaluation of the BIM-based object-oriented physical modeling technique for building thermal simulations: A comparative case study. *Sustainability* **2016**, *8*, 648. [CrossRef]
17. Becerik-Gerber, B.; Jazizadeh, F.; Li, N.; Calis, G. Application Areas and Data Requirements for BIM-Enabled Facilities Management. *J. Constr. Eng. Manag.* **2012**, *138*, 431–442. [CrossRef]
18. 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**, *24*. [CrossRef]
19. Gao, X.; Pishdad-Bozorgi, P. BIM-enabled facilities operation and maintenance: A review. *Adv. Eng. Inform.* **2019**, *39*, 227–247. [CrossRef]
20. Ilter, D.; Ergen, E. BIM for building refurbishment and maintenance: Current status and research directions. *Struct. Surv.* **2015**, *33*, 228–256. [CrossRef]
21. Edirisinghe, R.; London, K.A.; Kalutara, P.; Aranda-Mena, G. Building information modelling for facility management: Are we there yet? *Eng. Constr. Archit. Manag.* **2017**, *24*, 1119–1154. [CrossRef]
22. Pärn, E.A.; Edwards, D.J.; Sing, M.C.P. The building information modelling trajectory in facilities management: A review. *Autom. Constr.* **2017**, *75*, 45–55. [CrossRef]
23. Codinhoto, R.; Kiviniemi, A. BIM for FM: A Case Support for Business Life Cycle. In *Product Lifecycle Management for a Global Market*; Fukuda, S., Bernard, A., Gurumoorthy, B., Bouras, A., Eds.; Springer: Berlin/Heidelberg, Germany, 2014; pp. 64–74.
24. Hao, Q.; Xue, Y.; Shen, W.; Jones, B.; Zhu, J. A Decision Support System for Integrating Corrective Maintenance, Preventive Maintenance and Condition-based Maintenance. In Proceedings of the Construction Research Congress 2010, Banff, AB, Canada, 8–10 May 2010.
25. Bruno, S.; De Fino, M.; Fatiguso, F. Historic Building Information Modelling: Performance assessment for diagnosis-aided information modelling and management. *Autom. Constr.* **2018**, *86*, 256–276. [CrossRef]
26. Kensek, K. BIM Guidelines Inform Facilities Management Databases: A Case Study over Time. *Buildings* **2010**, *5*, 899–916. [CrossRef]

27. Kreider, R.G.; Messner, J.I. *The Uses of BIM: Classifying and Selecting BIM Uses*; The Pennsylvania State University: State College, PA, USA, 2013; pp. 6–8.
28. CRC. *Adopting BIM for Facilities Management: Solutions for Managing the Sydney Opera House*; Cooperative Research Centre (CRC) for Construction Innovation: Brisbane, Australia, 2007.
29. Eastman, C.M.; Teicholz, P.; Sacks, R.; Liston, K. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*; John Wiley & Sons: Hoboken, NJ, USA, 2008.
30. Akcamete, A.; Akinci, B.; Garrett, J.H. Potential utilization of building information models for planning maintenance activities. In Proceedings of the International Conference on Computing in Civil and Building Engineering, Clearwater Beach, FL, USA, 17–20 June 2012.
31. Su, Y.C.; Lee, Y.C.; Lin, Y.C. Enhancing Maintenance Management Using Building Information Modeling in Facilities Management. In Proceedings of the 28th International Symposium on Automation and Robotics in Construction (ISARC 2011), Seoul, Korea, 29 June 2011; pp. 752–757. [CrossRef]
32. Hallberg, D.; Tarandi, V. On the use of open bim and 4D visualisation in a predictive life cycle management system for construction works. *Electron. J. Inf. Technol. Constr.* **2011**, *16*, 445–466.
33. Teicholz, P. *BIM for Facility Managers*; John Wiley & Sons: Hoboken, NJ, USA, 2013.
34. 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]
35. Cavka, H.; Staub-French, S.; Pottinger, R. Evaluating the Alignment of Organizational and Project Contexts for BIM Adoption: A Case Study of a Large Owner Organization. *Buildings* **2015**, *5*, 1265–1300. [CrossRef]
36. Bortolini, R.; Forcada, N.; Macarulla, M. BIM for the integration of Building Maintenance Management: A case study of a university campus. In Proceedings of the 11th European Conference on Product & Process Modelling (ECPPM), Limassol, Cyprus, 7–9 September 2016.
37. Thabet, W.; Lucas, J. Asset Data Handover for a Large Educational Institution: Case-Study Approach. *J. Constr. Eng. Manag.* **2017**, *143*. [CrossRef]
38. Lucas, J.; Thabet, W. Using a Case-Study Approach to Explore Methods for Transferring BIM-Based Asset Data to Facility Management Systems. In Proceedings of the Construction Research Congress (CRC 2018), New Orleans, LA, USA, 2–4 April 2018. [CrossRef]
39. 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]
40. Carbonari, A.; Corneli, A.; Di Giuda, G.; Ridolfi, L.; Villa, V. BIM-Based Decision Support System for the Mangement of Large Building Stocks. In Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC), Berlin, Germany, 20–25 July 2018. [CrossRef]
41. Fargnoli, M.; Lleshaj, A.; Lombardi, M.; Sciarretta, N.; Di Gravio, G. A BIM-based PSS approach for the management of maintenance operations of building equipment. *Buildings* **2019**, *9*, 139. [CrossRef]
42. Koch, C.; Hansen, G.K.; Jacobsen, K. Missed opportunities: Two case studies of digitalization of FM in hospitals. *Facilities* **2019**, *37*, 381–394. [CrossRef]
43. Aziz, N.D.; Nawawi, A.H.; Ariff, N.R.M. ICT Evolution in Facilities Management (FM): Building Information Modelling (BIM) as the Latest Technology. *Procedia—Soc. Behav. Sci.* **2016**, *234*, 363–371. [CrossRef]
44. Márquez, A.C.; De León, P.M.; Fernández, J.F.G.; Márquez, C.P.; Campos, M.L. The maintenance management framework: A practical view to maintenance management. *J. Qual. Maint. Eng.* **2009**, *15*, 167–178. [CrossRef]
45. Mohanta, A.; Das, S. ICT-Based Facilities Management Tools for Buildings. In Proceedings of the International Conference on ICT for Sustainable Development, Ahmedabad, India, 3–4 July 2015; pp. 125–133.
46. 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]
47. What Is COBie? Available online: https://www.thenbs.com/knowledge/what-is-cobie (accessed on 9 October 2019).
48. MVD Database. Available online: https://technical.buildingsmart.org/standards/mvd/mvd-database/ (accessed on 9 October 2019).
49. Ibrahim, K.F.; Abanda, F.H.; Vidalakis, C.; Woods, G. BIM for FM: Input versus Output Data. In Proceedings of the 33rd CIB W78 Conference, Brisbane, Australia, 31 October–2 November 2016.
50. Klammt, F. Financial Management for Facility Managers. In *Facility Design and Management Handbook*; McGraw-Hill Companies Inc.: New York, NY, USA, 2001; pp. 510–537.

51. Lui, R.; Zettersten, G. Facility Sustainment Management System Automated Population from Building Information Models. In Proceedings of the Construction Research Congress, San Juan, Puerto Rico, 31 May–2 June 2016; American Society of Civil Engineers (ASCE): Reston, VA, USA, 2016.
52. Mayo, G.; Giel, B.; Issa, R. BIM use and requirements among building owners. In *Computing in Civil Engineering*; ASCE: Reston, VA, USA, 2012; pp. 349–356.
53. Keady, R. *Equipment Inventories*; Wiley: Hoboken, NJ, USA, 2013.
54. Lin, Y.-C.; Chen, Y.-P.; Huang, W.-T.; Hong, C.-C. Development of BIM Execution Plan for BIM Model Management during the Pre-Operation Phase: A Case Study. *Buildings* **2016**, *6*, 8. [CrossRef]
55. Gleason, D. Getting to a facility management BIM. In *Lake Constance 5D-Conference*; Trimble Navigation: Constance, Germany, 2013.
56. Talon, A.; Boissier, D.; Chevalier, J.L.; Hans, J. Temporal quantification method of degradation scenarios based on FMEA. In Proceedings of the 10th International conference on durability of building materials and components, Lyon, France, 17–20 April 2005.
57. Silva, A.; de Brito, J.; Gaspar, P.L. *Methodologies for Service Life Prediction of Buildings*; Springer International Publishing: Basel, Switzerland, 2016. [CrossRef]
58. Isaac, A.; Meir, I.A.; Garb, Y.; Jiao, D.; Cicelsky, A. Post-Occupancy Evaluation: An Inevitable Step Toward Sustainability. *Adv. Build. Energy Res.* **2019**, *3*, 189–220. [CrossRef]
59. Built to Last: Measuring the Life Cycle of a Facility. Available online: http://www.greenerbuildings.com/feature/2008/04/10/built-last-measuring-life-cycle-a-facility (accessed on 9 October 2019).
60. Meir, I.A.; Motzafi-Haller, W.; Krüger, E.L.; Morhayim, L.; Fundaminsky, S.; Oshry-Frenkel, L. Towards a comprehensive methodology for Post Occupancy Evaluation (POE): A hot dry climate case study. In Proceedings of the 2nd PALENC and 28th AIVC Conference, Crete, Greece, 27–29 September 2007; pp. 644–653.
61. Wahab, A.M.; Kamaruzzaman, S.N. Building Performance and Evaluation Methods: A Preliminary Review. In Proceedings of the 2nd International Conference on Project and Facilities Management, Kuala Lumpur, Malaysia, 16 September 2011.
62. Vischer, J.C. Applying knowledge on building performance: From evidence to intelligence. *Intell. Build. Int.* **2009**, *1*, 239–248. [CrossRef]
63. Preiser, W.F.E. Post-occupancy evaluation: How to make buildings work better. *Facilities* **1995**, *13*, 19–28. [CrossRef]
64. Preiser, W.F.E. Building performance assessment- from POE to BPE: A personnel perspective (post occupancy evaluation and building performance evaluation). *Archit. Sci. Rev.* **2005**, *48*, 201–204. [CrossRef]
65. Sanni-Anniber, M.O.; Hassanain, M.A.; Al Hammad, A.-M. POE of Housing Facilities Overview & Summary of Methods. *J. Perform. Constr. Facil.* **2016**, *30*, 1–9. [CrossRef]
66. Menon, R.; Gilbert, J.; Bridgestock, M. Development of Post Occupancy Evaluation for Evaluation of Innovative Low Carbon Social Housing Projects. Available online: http://www.cicstart.org/fs03.htm (accessed on 9 October 2019).
67. Sinou, M.; Kyvelou, S. Present and future of building performance assessment tools. *Manag. Environ. Qual.* **2006**, *17*, 570–586. [CrossRef]
68. Talamo, C.; Bonanomi, M. *Knowledge Management and Information Tools for Building Maintenance and Facility Management*; Springer International Publishing: Basel, Switzerland, 2015. [CrossRef]
69. Lützkendorf, T. A comparison of international classifications for performance requirements and building performance categories used in evaluation methods. In Proceedings of the 11th Joint BIM International Symposium, Helsinki, Finland, 13–16 June 2005.
70. Weber, A.; Thomas, R. *Key Performance Indicators—Measuring and Managing the Maintenance*; Iavara Corporation: Burlington, ON, Canada, 2005.
71. Bortolini, R.; Forcada, N. Facility managers' perceptions on Building Performance Assessment. *Front. Eng. Manag.* **2018**, *5*, 324–333. [CrossRef]
72. Amasuomo, T.T.; Atanda, J.; Baird, G. Development of a building performance assessment and design tool for residential buildings in Nigeria. *Procedia Eng.* **2017**, *180*, 221–230. [CrossRef]
73. Aksamija, A. BIM-based building performance analysis: Evaluation and simulation of design decisions. In Proceedings of the 2012 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA, 12–17 August 2012.

74. Aksamija, A. Analysis and Computation: Sustainable Design in Practice. *Des. Princ. Pract. Int. J.* **2010**, *4*, 291–314. [CrossRef]
75. Re Cecconi, F.; Maltese, S.; Dejaco, M.C. Leveraging BIM for digital built environment asset management. *Innov. Infrastruct. Solut.* **2017**, *2*, 14. [CrossRef]
76. Bonci, A.; Carbonari, A.; Cucchiarelli, A.; Messi, L.; Pirani, M.; Vaccarini, M. A cyber-physical system approach for building efficiency monitoring. *Autom. Constr.* **2019**, *102*, 68–85. [CrossRef]
77. CIC Research Group. *BIM Project Execution Planning Guide—Version 2.1*; The Pennsylvania State University: University Park, PA, USA, 2011.
78. Common BIM Requirements. Series 12. In *Use of Models in Facility Management*; BuildingSMART Finland: Helsinki, Finland, 2012.
79. PAS 1192-3:2014. *Specification for Information Management for the Operational Phase of Assets Using Building Information Modelling*; BSI Standards Limited: London, UK, 2014; ISBN 978-0-580-86674-6.
80. U.S. General Service Administration Public Buildings Office of Design and Construction. *GSA Building Information Modeling Guide Series: 08—GSA BIM Guide for Facility Management*; General Services Administration: Washington, DC, USA, 2011.
81. Minister of Transport and Infrastructure. Ministerial Decree n.560/2017. Available online: http://www.mit.gov.it/normativa/decreto-ministeriale-numero-560-del-01122017 (accessed on 9 October 2019).
82. UNI 11337/1-4:2017. Building and Civil Engineering Works—Digital Management of the Informative Processes. Available online: http://www.uni.com (accessed on 9 October 2019).
83. President of Italian Republic. Legislative Decree n.50/2016. Gazzetta Ufficiale della Repubblica Italiana. 2016. 91, 1–378. Available online: https://www.anticorruzione.it/portal/rest/jcr/repository/collaboration/Digital%20Assets/anacdocs/MenuServizio/English%20section/ITALIAN_PUBLIC_CONTRACT_CODE%2015%20giugno%202018_sito%20(2).pdf (accessed on 7 December 2019).
84. President of Italian Republic. Presidential Decree 14/01/1997. *G.U.* **1997**, *42*, 1–70.
85. AIA. *AIA Document G202–2013, Project Building Information Modeling Protocol Form*; American Institute of Architects: Washington, DC, USA, 2013.
86. Ozarisoy, B.; Altan, H. Low Energy Design Strategies for Retrofitting Existing Residential Buildings in Cyprus. In *Proceedings of the Institution of Civil Engineers–Engineering Sustainability*; ICE Publishing: London, UK, 2018; pp. 1–15. ISSN 1478 4629. E-ISSN 1751 7680. [CrossRef]