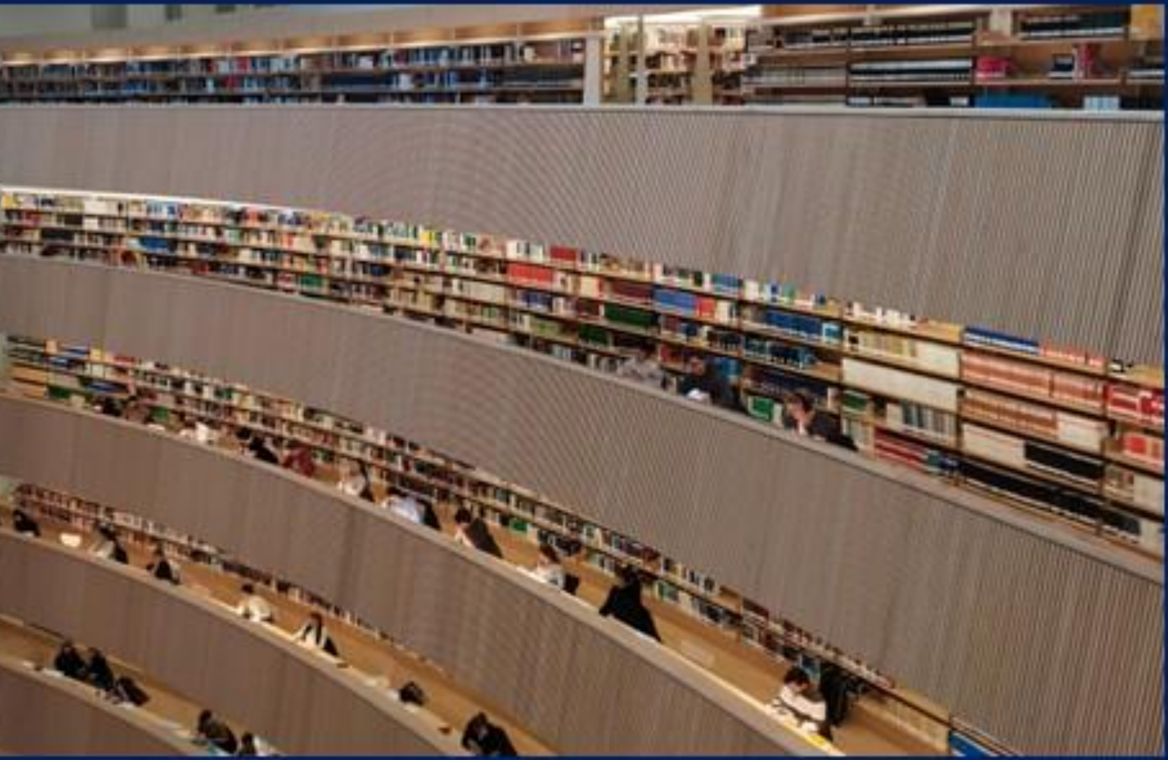
Rossella Marmo

Advancing Facility Management through Building Information Modelling



Federico II University Press

fedOA Press

Università degli Studi di Napoli Federico II

Rossella Marmo

Advancing Facility Management through Building Information Modelling

Federico II University Press

fedOA Press

Advancing Facility Management through Building Information Modelling / Rossella Marmo ; prefazione di Andrej Tibaut. – Napoli : FedOAPress, 2025. – 110 p. ; 25 cm.

Accesso alla versione elettronica: www.fedoabooks.unina.it

ISBN: 978-88-6887-369-1

DOI: 10.6093/978-88-6887-369-1

Le immagini contenute nel presente volume sono opera dell'autore.

Università degli Studi di Napoli Federico II
Centro di Ateneo per le Biblioteche "Roberto Pettorino"
Piazza Bellini 59-60
80138 Napoli, Italy
http://www.fedoapress.unina.it/
Published in Italy
Prima edizione: Settembre 2025

Contents

Preface

Andrej Tibaut
Full Professor at the University of Maribor

Facility Management (FM) stands at a crossroads filled with both challenges and exciting possibilities. Dr Malmo's book, "Advancing Facility Management through Building Information Modelling" dives into the powerful connection between FM and Building Information Modelling (BIM), a digital innovation that is transforming the way architecture, engineering, and construction professionals design, build, and operate buildings.

FM has come a long way from being seen as just a mix of maintenance tasks and cleaning services. It has grown into a strategic discipline that helps improve organizational performance, enhances user comfort, and promotes sustainability. Yet, keeping track of the mountains of data involved in building operations and maintenance can be daunting. That's where BIM shines, offering a rich digital model that brings all this information together in one place, making it easier to share and use throughout the entire life of a building.

This book introduces an exciting concept called the Performance Information Model (PIM). Think of the PIM as a next-level BIM, it goes beyond simply creating design models to include real-time monitoring and performance assessment. By weaving in Key Performance Indicators (KPIs) right into the digital model, the PIM empowers facility managers to keep a close eye on asset health, fine-tune maintenance schedules, and gain deeper insights into how buildings actually perform day to day. Alongside this, the book presents the openPIM database, built on open standards like the Industry Foundation Classes (IFC), which supports smooth, standardized data sharing and collaboration between all parties involved.

Drawing from wide-ranging research and real-world case studies, especially within healthcare settings, this book shows how integrating BIM and FM opens new doors to resilience, smarter risk management, and environmentally responsible operations. While this integration holds great promise, it also comes with hurdles, technical glitches, organizational shifts, and cultural changes that need thoughtful handling.

This journey is crafted for researchers, industry professionals, and decision-makers eager to push forward the digital transformation of FM. It encourages embracing multidisciplinary approaches, leveraging open data standards, and applying cutting-edge technologies to help make better, evidence-based decisions and smooth-running asset management.

Ultimately, the hope is that this work sparks further innovation and inspires wider adoption of performance-focused BIM frameworks, helping us build and maintain environments that are not only smarter and safer but also kinder to our planet.

1. Foundations: Facility Management, Information Systems, and Building Information Modelling

Facility Management (FM) has been defined 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” (International Organization for Standardization, 2017).

Facility Management supports a wide range of activities (commonly referred to as non-core business), which enhance the work environment and the well-being of people; enable the organization to deliver effective and responsive services; make physical assets highly cost-effective, while also allowing for future changes; and enhance the organization’s image and culture (Atkin and Brooks, 2015).

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 partnerships, etc.), but mostly through outsourcing (Ancarani & Capaldo, 2005).

Among the competency areas, the Operations and Maintenance (O&M) service plays a key role. It ensures that the facility functions efficiently, reliably, safely, and securely, in a manner consistent with existing regulations and standards (IFMA, 2025).

Building maintenance activities require a comprehensive information system to capture and retrieve data related to building equipment. Current FM practice relies on various systems (e.g., Building Energy Management Systems (BEMS), Building Automation Systems (BAS), Computerized Maintenance Management Systems (CMMS), Computer-Aided Facilities Management (CAFM), and Document Management Systems (DMS)), which utilize new technologies to integrate and manage information more easily (Shalabi & Turkan, 2016). Studies on maintenance issues reveal that the most frequent problem is information accessibility (Liu & Issa, 2015).

Building Information Modelling (BIM) can be considered a tool or method to address information management challenges throughout a building’s lifecycle. 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” (International

Organization for Standardization, 2018). BIM is semantically based and object-oriented; it has 3D modelling capabilities and allows users to retrieve comprehensive information represented by objects and their attributes (Jeong & Kim, 2016). BIM provides a unified platform for various data sources (**Figure 1**) needed for daily O&M activities (Gao & Pishdad-Bozorgi, 2019), so that data regarding technical specifications, planned activities, and building performance (simulated or monitored) can be integrated to facilitate the decision-making process. The Architecture, Engineering, and Construction (AEC) sector is involved in the “Industry 4.0” era, and it is being innovated starting from digitization processes.

In this context, Building Information Modelling is a relevant actor in the overall sector transformation, aiming to improve collaboration, efficiency, and productivity.

The use of electronic tools such as BIM has been encouraged by the European Parliament for public works contracts through the adoption of the 2014 European Union Public Procurement Directive. In accordance with these European policies, several countries adopted legislative provisions and strategies to lead construction sector innovation. In Italy, the New Procurement Code was the first legislation to include this topic. Ministerial Decree No. 560/2016 set the BIM adoption schedule for Italian public works, which involves the entire public construction sector starting from the year 2025.

The AEC industry transformation has so far focused on optimizing the design and construction phases, while BIM benefits during the operational phase are not well documented (Pärn et al., 2017). In fact, a lack of real-life examples of BIM-FM integration is one of the major challenges to be addressed in order to promote BIM adoption throughout the construction lifecycle (Codinhoto & Kiviniemi, 2014; Becerik-Gerber et al., 2012). Moreover, a seamless information process between BIM and FM systems does not yet exist, and data exchange and interoperability remain problematic topics (Matarneh et al., 2019).

Nevertheless, current research trends reveal a growing interest in facilities information management using BIM. Recent studies indicate that energy management has been relatively well analyzed by researchers, followed by emergency management and maintenance and repair (Gao & Pishdad-Bozorgi, 2019).

A parametric model can establish a knowledge system that can be queried in various ways according to specific needs, allowing FM managers to make better and faster maintenance decisions and provide higher-quality building performance. The model can support building modifications throughout its lifecycle and can serve as a starting point for simulations and intervention evaluations. If the BIM-FM system is kept up to date by operators, it can provide an accurate record of the facility's current conditions. BIM-FM integration is expected to enable the systematic generation of information, such as Key Performance Indicators (Kiviniemi & Codinhoto, 2014). Developing an FM benchmarking framework enables organizations to identify best practices and strategic improvements.

In condition-based maintenance, monitoring physical variables related to failure symptoms is necessary. Building Performance Assessment (BPA) provides better knowledge of an asset, enabling timely and informed decisions. Performance assessment enriches BIM models with the purpose of evaluating residual performance, allowing for the selection of appropriate interventions. For example, when certain spaces are performing below a defined threshold, the integrated model can suggest maintenance planning options.

Particularly in the healthcare facilities sector, a facility manager must consider numerous factors when making strategic decisions. Identifying a set of specific Key Performance Indicators (KPIs) aids in performance assessment and strategic planning. An Integrated Healthcare Facility Management Model has been proposed (Lavy & Shohet, 2007) to hierarchically analyze core parameters of healthcare FM, showing that an analytical, quantitative model can significantly improve the understanding of facility management performance. In this sense, qualitative features can be translated into quantitative analysis. Both technological and financial aspects can be included in an integrated model for FM.

This book presents a comprehensive methodological framework for integrating Facility Management (FM) systems, Building Information Modelling (BIM), and Building Performance Assessment (BPA) to support decision-making and improve organizational performance in facility operations.

At the heart of this approach is a performance-based tool that assists facility managers in assessing building conditions, optimizing maintenance activities, and making informed decisions. Central to the methodology is the use of Key Performance Indicators (KPIs), which provide a structured way to evaluate residual building performance and embed essential, concise data within the BIM model.

The book begins by reviewing FM policies, BPA methodologies, and the role of BIM and digital FM technologies. It then explores the potential and limitations of BIM-FM integration through a critical analysis of published case studies, identifying both the benefits and challenges of such integration.

A novel approach is introduced to enable the integration of real-time building performance data into the BIM environment. This allows FM teams to streamline operations, reduce reactive maintenance and emergency repairs, and improve long-term asset management. The methodology is specifically applied to healthcare facilities and case studies are described in the text.

This book stands for the development of a **Performance Information Model**, a digital framework that connects FM information systems, process repositories, and the BIM Common Data Environment (CDE). Interoperability challenges are addressed through the adoption of the IFC standard, which guides the design of a relational database called **openPIM**. This database serves as a dynamic link between performance monitoring, maintenance records, and the digital building model, ensuring the FM-oriented BIM remains accurate and actionable.

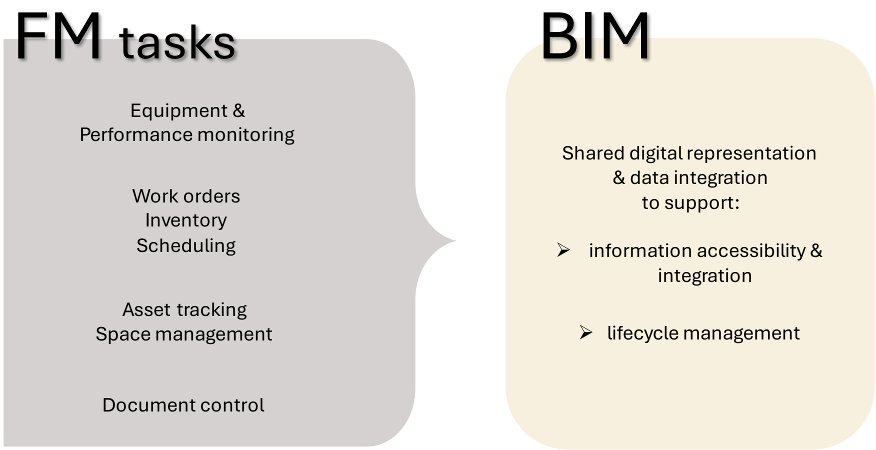


Figure 1. BIM for FM tasks

References

Ancarani, A., & Capaldo, G. (2005). Supporting decision-making process in facilities management services procurement: A methodological approach. *J. Purch. Supply Manag.*, 11, 232–241. https://doi.org/10.1016/j.pursup.2005.12.004

Atkin, B., & Brooks, A. (2015). *Total Facility Management* (Fourth Edition). John Wiley & Sons: Chichester, UK.

Becerik-Gerber, B., Jazizadeh, F., Li, N., & Calis, G. (2012). Application Areas and Data Requirements for BIM-Enabled Facilities Management. *J. Constr. Eng. Manag.*, 138(3), 431–442. https://doi.org/10.1061/(asce)co.1943-7862.0000433

Codinhoto, R., & Kiviniemi, A. (2014). BIM for FM: A Case Support for Business Life Cycle. *IFIP Advances in Information and Communication Technology*, 442, 63–74.

Gao, X., & Pishdad-Bozorgi, P. (2019). BIM-enabled facilities operation and maintenance: A review. *Adv. Eng. Inform.*, 39, 227–247. https://doi.org/10.1016/J.AEI.2019.01.005

IFMA – International Facility Management Association. (2025). What if Facility Management. Available at: https://www.ifma.org/about/what-is-fm/

International Organization for Standardization. (2017). *ISO 41011:2017. Facility management — Vocabulary*.

International Organization for Standardization. (2018). *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*.

Jeong, W.S., & Kim, K.H. (2016). A performance evaluation of the BIM-based object-oriented physical modeling technique for building thermal simulations: A comparative case study. *Sustainability*, 8, 1–27. https://doi.org/10.3390/su8070648

Kiviniemi, A., & Codinhoto, R. (2014). Challenges in the Implementation of BIM for FM—Case Manchester Town Hall Complex, 665–672. https://doi.org/10.1061/9780784413616.083

Lavy, S., & Shohet, I.M. (2007). A strategic integrated healthcare facility management model. *Int. J. Strateg. Prop. Manag.*, 11, 125–142. https://doi.org/10.1080/1648715X.2007.9637565

Liu, R., & Issa, R.R.A. (2015). Survey: Common Knowledge in BIM for Facility Maintenance. *J. Perform. Constr. Facil.*, 30. https://doi.org/10.1061/(asce)cf.1943-5509.0000778

Matarneh, S.T., Danso-Amoako, M., Al-Bizri, S., Gaterell, M., & Matarneh, R. (2019). Building information modeling for facilities management: A literature review and future research directions. *J. Build. Eng.*, 24. https://doi.org/10.1016/J.JOBE.2019.100755

Pärn, E.A., Edwards, D.J., & Sing, M.C.P. (2017). The building information modelling trajectory in facilities management: A review. *Autom. Constr.*, 75, 45–55. https://doi.org/10.1016/j.autcon.2016.12.003

Shalabi, F., & Turkan, Y. (2016). IFC BIM-Based Facility Management Approach to Optimize Data Collection for Corrective Maintenance. *Journal of Performance of Constructed Facilities*, 31(1). https://doi.org/10.1061/(asce)cf.1943-5509.0000941

2. Facility Management and performance assessment

This chapter examines the evolution of Facility Management, exploring its strategic role, information systems, performance assessment methods, and maintenance practices, with a particular focus on how these dimensions integrate to support organizational effectiveness.

Facility Management (FM) has evolved since the 1960s from a cost-centre focused on maintenance and cleaning into a strategic discipline integral to organizational performance. Its scope now includes human factors, operations, sustainability, information technology, risk, and real estate management.

The strategic positioning of FM lies in managing non-core processes, balancing insourcing and outsourcing models, and leveraging integrated service providers to align support functions with core business objectives. Central to FM is the management of diverse information supported by digital tools such as CMMS, CAFM, BAS/BEMS, and increasingly, BIM.

Building performance assessment further strengthens FM's role by linking service delivery with measurable outcomes. Methods such as benchmarking, Post-Occupancy Evaluation (POE), Building Performance Evaluation (BPE), and certification systems enable the definition and monitoring of Key Performance Indicators (KPIs), providing both technical and user-centred perspectives on performance.

Maintenance management, in turn, integrates corrective, preventive, and condition-based approaches, guided by KPIs to ensure safety, compliance, and value preservation across building lifecycles.

2.1 Introduction to Facility Management

The concept of FM emerged in the 1960s in the United States, initially tied to developments in information technology systems and networks (Wiggins, 2014). By the 1970s, Facility Management expanded into space planning, responding to rapid transformations in the office furniture industry. This evolution culminated in the founding of the International Facility Management Association (IFMA) in 1980 (Wiggins, 2014), marking the formal recognition of FM as a profession within the property and construction sectors (Tay & Ooi, 2001).

Initially perceived as a cost-centre associated with non-value-adding activities, such as maintenance and cleaning, Facility Management has since broadened its scope (Codinhoto & Kiviniemi, 2014). The concept of non-core business gained traction, emphasizing FM's role in supporting customer activities linked to space, facilities, and personnel (Curcio, 2003).

Facility Management encompasses a broad set of functions, with overlapping responsibilities that resist strict categorization. IFMA (IFMA, 2025) outlines that facility managers are the people who make sure we have the safest and best experience possible, by coordinating the processes that make the built environment succeed. They hold a variety of roles including:

- Building operations like security, cleaning, maintenance;
- Overseeing energy, materials, waste, and site management;
- Risk management, emergency and disaster mitigation and response;
- Facility and IT management, including cybersecurity and tech upgrades;
- Project management and budgeting;
- Managing property acquisition, use, and disposition.

Facility Management importance grew up together with the complexity of the real estate, including more and more activities and demanding professionals with more skills and wider expertise; from these emerging needs the externalisation of many activities is born, with its benefits and costs.

In general, organisational models for non-core business management depend on the company's strategies and long-term values analysis, as discussed in the section below.

2.2 Strategies for Managing Non-Core Processes

FM strategy spans a continuum between insourcing and outsourcing. Outsourcing involves transferring internal activities to external providers (Chase et al., 2004), while insourcing retains them within the organization (Schniederjans et al., 2015).

Outsourcing offers efficiency and cost benefits but may compromise data control and system oversight. Vertically integrated models (insourcing) provide tighter control but at potentially higher cost. Large organizations typically establish internal FM divisions, led by facility managers who may be internal staff (in-house management) or external consultants (managing agents) (Alexander, 2013).

Service providers in facility management are generally categorized based on the scope and integration of their offerings. At one end, specialized providers deliver individual services, requiring organizations to oversee and coordinate multiple contracts. On the other end, integrated providers offer bundled services managed through coordinated business units, enabling a more streamlined and efficient approach.

Further classification is based on the depth of service provision: partial management operators focus on specific operational tasks; sectorial management operators concentrate on areas such as energy, maintenance, and employee services; and facility management operators provide comprehensive, coordinated solutions typically governed by Global Service contracts.

The integration of facility management, as an effective function for an organisation, can be achieved by recognizing three key characteristics: (1) facility management is a *support role* within an organisation, or a support service to an organisation; (2) facility management must *link* strategically, tactically and operationally support activities and primary activities to create value; (3) within the facility management, managers must be *equipped with knowledge* of facilities and management to carry out their integrated support role (Kincaid, 1994).

2.3 Information management in Facility Management

An efficient approach to information and data management is essential for an organisation to meet various obligations and responsibilities, as well as to derive optimal use and benefits from the facility. Knowledge about the facility holds real value, as the delivery of a service also involves

the delivery of information. In facility management, it is important to have knowledge of the spaces to be serviced, the services to be performed, and the actual performance of those services (Atkin & Brooks, 2015). Information should be accurate, reliable, up to date, and complete.
Different types of information are managed in daily FM operation:

- *commercial information* such as valuations of the real estate, insurance policies and market data;
- *financial information* such as the cost of operating of the facility, performance of services and related work items;
- *technical information* related to the safe and correct operation of the facility;
- *managerial information* include the former, additionally human resources should be considered;
- *as-built information*, as part of the technical information, include information prepared before the handover phase and those produced during the operational phase (i.e., details of defects, maintenance, alterations, etc.). As-built information is made by drawings, specifications and schedules (Atkin & Brooks, 2015).

FM information management is supported by a range of tools and software. From emails to BIM and including systems like Computerized Maintenance Management Systems (CMMS), Computer-Aided Facilities Management (CAFM), and Building Automation/Energy Management Systems (BAS/BEMS), various tools have supported FM activities over the past decades (Aziz et al., 2016).
CMMS support the creation and management of asset records, bills of materials, work orders, inventory control, and maintenance management in general (Marquez et al., 2009). CAFM refers to a set of tools used to organize and manage various facility activities, including space planning and real estate (Mohanta & Das, 2015). Both CMMS and CAFM have limited visualization capabilities, as they often rely on paper-based or 2D digital plans. This limits a facility manager's ability to identify the precise maintenance context or track modification history (Aziz et al., 2016).
BEMS are commonly used to control active systems such as HVAC, managing their operating schedules. Sensors send feedback and alarms to these systems, allowing facility managers to monitor performance and make manual adjustments when necessary (Shalabi & Turkan, 2016).
To ensure optimal building performance, facility managers must monitor both technical and environmental conditions. In this context, building sensors and controllers play a key role in informing maintenance

activities. BIM might interact with the described systems, 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 (McArthur, 2015; Volk et al., 2014).

2.4 Building performance assessment methods

Performance is defined as a “measurable result” (UNI EN ISO 41011:2018) and may relate to activities, processes, or products, encompassing both quantitative and qualitative outcomes. Broadly, performance assessment involves comparing the levels of service delivered to users against agreed standards and targets set in service specifications and service-level agreements. Performance requirements should be defined in the FM strategy and policy and communicated to stakeholders (Atkin & Brooks, 2015).

Building Performance Assessment (BPA) improves knowledge of an asset, which is crucial for understanding building behaviour and making timely, informed decisions. For example, assessing building performance is essential to determine if maintenance is necessary (Talon et al., 2005). Evaluations should be integrated with inspections (Percy & Kobbacy, 2000) and the assessments should yield an index, score, or rating (Roulet et al., 2002; Salim & Zahari, 2011) to help prioritize maintenance, rank buildings within a portfolio, and explore refurbishment scenarios.

Performance is increasingly linked to user experience, emphasizing quality, health, safety, security, comfort, and social aspects (Vischer, 2009; Wahab & Kamaruzzaman, 2011). Consequently, asset management decisions have grown more complex, requiring detailed knowledge of asset conditions (Flores-Colen et al., 2010), which is often difficult to obtain. Managers typically base decisions on limited data (Vanier et al., 2006), leading to ineffective maintenance, but up to one-third of costs may be wasted due to unnecessary or poorly executed interventions (Mobley, 2002).

Various models, methods, and tools assist in measuring performance and identifying areas for improvement. These include: benchmarking, Post Occupancy Evaluation (POE), Building Performance Evaluation (BPE), Critical Success Factors (CSFs), Key Performance Indicators (KPIs).

Benchmarking compares strategies or performances against best practices under similar conditions to identify areas for improvement (UNI

EN 15221-7:2012). Measures may be qualitative or quantitative, at local or international levels, and conducted as one-off, periodic, or continuous exercises.

Post Occupancy Evaluation (POE), developed in the 1960s, assesses building performance after a period of use, primarily through user feedback. **Building Performance Evaluation (BPE)**, introduced in the 1990s, expands on POE to support decision-making throughout the building lifecycle (Preiser & Schramm, 2005). Both POE and BPE generally evaluate overall building performance rather than individual components and rely heavily on user satisfaction data (O Sanni-Anniber, 2016). Some researchers (Amasuomo, 2017) consider certification systems like **BREEAM** and **LEED** as performance evaluation tools too, providing codified, score-based assessments.

Critical Success Factors (CSFs) are essential activities required to meet business goals. Each CSF is associated with one or more KPIs, which help track progress. For KPIs to be effective, they must align with organizational objectives, otherwise, meeting service levels may not support core business goals (Atkin & Brooks, 2015).

Key Performance Indicators propose performance assessments based on what has been agreed on in facility management contracts, some examples are reported in **Table 1**.

Performance indicators are useful for measuring status and plan improvement activities and continuously assess changes over time. Also, KPIs can be used to evaluate user satisfaction via perceptual or psychological indicators.

Developing performance metrics is an important step in the process of performance evaluation, as it includes relevant indicators that express the performance of the facility in a holistic manner. Consequently, it is significant to identify a set of KPIs to establish effective performance evaluation metrics for the facility under consideration (Lavy et al., 2014). However, a large number of KPIs adds a level of complexity and is narrow in perspective, thus lacking quantification and applicability across a range of projects (Shohet, 2006; Neely et al., 1997). The list of KPIs needs to be filtered through a certain set of criteria to identify independent and orthogonal indicators.

Table 1. Examples of Key Performance Indicators

Performance Category	Indicator	Description
Economic	FCI – Facility Condition Index	Represents the economic value of anomalies in a facility.
	AME – Annual Maintenance Expenditure	Measures maintenance expenditure, typically in $/m².
	MEI – Maintenance Efficiency Indicator	Evaluates the economic efficiency of maintenance activities.
Technical	BPI – Building Performance Indicator	Assesses the physical condition of building systems.
	D – Service Life Index	Reflects the age and expected lifespan of building systems.
	A – Degradation Index	Indicates the degree of degradation in building systems.
	LOS – Level of Service	Measures technological performance in relation to environmental quality.
	EC – Environmental Condition	Evaluates the environmental performance of the facility.

According to the UNI EN 15341:2019, an indicator is a "*quantitative or qualitative measure of a characteristic or a set of characteristics of a phenomenon or performance activities, according to defined criteria or a given formula or a questionnaire*". A key performance indicator is an "*indicator considered significant*".

This standard proposes 8 groups of Key Performance Indicators: one for asset management, six for the maintenance sub-functions and the last one for information and communication management (**Table 2**).

The KPIs related to each subsystem are divided in areas, which represent the fundamental contents or characteristics to be measured, controlled and improved. For example, for the Health and Safety Environment (HSE) subsection 22 KPIs are proposed (HSE1-22).

Table 2. Maintenance KPI matrix, based on UNI EN 15341:2019

Sub Functions, Tools and Methodologies	KPIs	Main Areas
Maintenance within physical asset management	PHA_i: Sustainability (i = 1 to 3)	Capacity, Effectiveness, Integrity (i = 4 to 11) Service Level (i = 12 to 13) Economics (i = 14 to 20)
Sub-function 1: Health - Safety - Environment	HSE_i: Laws - Rules conformity (i = 1 to 3)	Statistical Records (i = 4 to 12) Safe Practice (i = 13 to 17) Prevention and Improvements (i = 18 to 22)
Sub-function 2: Maintenance Management	M_i: Strategy (i = 1 to 3)	Function (i = 4 to 10) Technical Assessment (i = 11 to 16) Continuous Improvement (i = 17 to 22)
Sub-function 3: People Competence	P_i: Maintenance Manager (i = 1 to 3)	Maintenance Supervisor/Maintenance Engineer (i = 4 to 9) Maintenance Technician/Specialist (i = 10 to 12) Education (i = 13 to 21)
Sub-function 4: Maintenance Engineering	E_i: Capability, Criticality (i = 1 to 3)	Durability (i = 4 to 9) Preventive Maintenance (i = 10 to 16) Engineering Improvements (i = 17 to 19)
Sub-function 5: Organization and Support	$O\&S_i$: Structure and Support (i = 1 to 2)	Planning and Control (i = 3 to 9) Productivity Effectiveness (i = 23 to 28) Quality (i = 29 to 30)
Sub-function 6: Administration and Supply	$A\&S_i$: Economics (i = 1 to 6)	Budget & Control (i = 7 to 19) Outsourcing services (i = 20 to 25) Materials and spare parts (i = 26 to 29)
Information Communication Technology	ICT_i: Management (i = 1 to 6)	Administration and Supply (i = 7 to 10) Organization and Support (i = 11 to 13) Engineering Improvements (TEC i = 18 to 20)

2.5 Maintenance management

As with Facility Management, various definitions of maintenance have emerged over the past decades. Maintenance comprises a set of interventions (corrective, preventive, condition-based) and the overall structure in which these interventions are organized.

A recent definition by the Technical Committee CEN/TC 319 “Maintenance” (UNI EN 13306:2018) describes maintenance as the combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function. Technical actions include inspection, monitoring, testing, diagnosis, and prognosis.

According to Alner & Fellows (1990), building maintenance objectives are to:

- Ensure buildings and services are safe and fit for use;

- Meet statutory requirements;
- Maintain the building's value;
- Maintain or improve building quality.

Organizations must select the most appropriate maintenance methods based on business objectives. A maintenance strategy must be developed and periodically reviewed, incorporating stakeholder needs and performance assessments. Maintenance strategies can be grouped into three categories:

- Preventive maintenance, which aims to reduce failure probability;
- Corrective maintenance, performed after a fault to restore functionality;
- Improving maintenance, which enhances reliability, maintainability, or safety without changing the function.

Preventive maintenance can be predetermined, condition-based predictive. Corrective maintenance may be deferred or immediate (**Figure 2**).

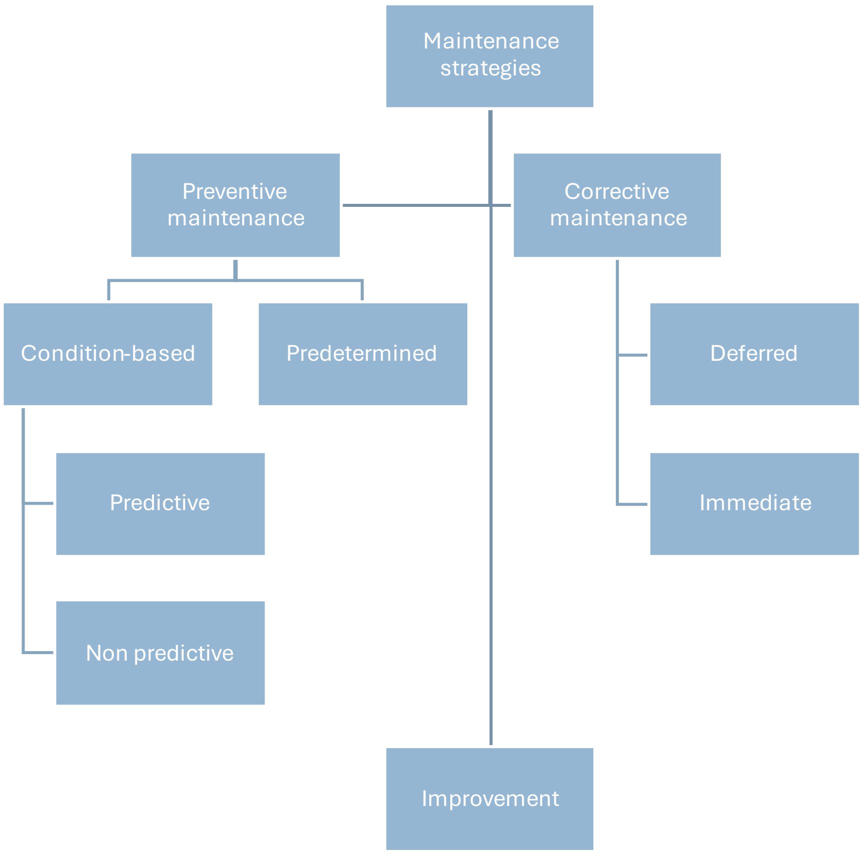


Figure 2. Maintenance strategies

A scheduled maintenance may follow a predetermined or deferred corrective approach. Unscheduled maintenance, conducted immediately after failure detection, aligns with immediate corrective strategies. Opportunistic maintenance, a form of unscheduled maintenance, is carried out during other interventions to reduce downtime or costs.

The link between maintenance methods, performance, and service delivery can be established through KPIs. KPIs help clarify expectations and track achievements, indicating deviations from goals to guide corrective action.

The maintenance process starts with identifying asset requirements. After selecting appropriate methods, resources are allocated, and the maintenance plan is developed. Maintenance planning includes consideration of operational demands and financial factors as well as feedback from past maintenance activities. The plan must then be implemented and monitored.

References

Alexander, K. (2013). *Facilities management: Theory and practice*. https://doi.org/10.4324/9780203475966

Alner, G. R., & Fellows, R. F. (1990). Maintenance of local authority school building in UK: A case study. In *Proceedings of the International Symposium on Property Maintenance Management and Modernisation* (pp. 90–99). Singapore.

Amasuomo, T. T., Atanda, J., & Baird, G. (2017). Development of a building performance assessment and design tool for residential buildings in Nigeria. *Procedia Engineering, 180*, 221–230. https://doi.org/10.1016/j.proeng.2017.04.181

Atkin, B., & Brooks, A. (2015). *Total facility management* (4th ed.). John Wiley & Sons.

Aziz, N. D., Nawawi, A. H., & Ariff, N. R. M. (2016). ICT evolution in facilities management (FM): Building Information Modelling (BIM) as the latest technology. *Procedia - Social and Behavioral Sciences, 234*, 363–371. https://doi.org/10.1016/j.sbspro.2016.10.253

Chase, R. B., Jacobs, F. R., & Aquilano, N. J. (2004). *Operations management for competitive advantage* (10th ed.). Irwin/McGraw-Hill.

Codinhoto, R., & Kiviniemi, A. (2014). BIM for FM: A case support for business life cycle. *IFIP Advances in Information and Communication Technology, 442*, 63–74.

Curcio, S. (2003). *Lessico del facility management*. Il Sole 24 Ore.

Flores-Colen, I., de Brito, J., & Freitas, V. (2010). Discussion of criteria for prioritization of predictive maintenance of building façades: Survey of 30 experts. *Journal of Performance of Constructed Facilities, 24*(4), 337–344.

Kincaid, D. (1994). Integrated facility management. *Facilities, 12*(8), 20–23. http://dx.doi.org/10.1108/02632779410062353

IFMA – International Facility Management Association. (2025). What if Facility Management. Available at: https://www.ifma.org/about/what-is-fm/

Lavy, S., Garcia, J. A., & Dixit, M. K. (2014). KPIs for facility's performance assessment, Part I: Identification and categorization of core indicators. *Facilities, 32*(5), 256–274. https://doi.org/10.1108/F-09-2012-0066

Márquez, A. C., León, P. M. D., Fernández, J. F. G., Márquez, C. P., & Campos, M. L. (2009). The maintenance management framework: A practical view to maintenance management. *Journal of Quality in Maintenance Engineering, 15*(2), 167–178. https://doi.org/10.1108/13552510910961110

McArthur, J. J. (2015). A building information management (BIM) framework and supporting case study for existing building operations, maintenance and sustainability. *Procedia Engineering, 118*, 1104–1111. https://doi.org/10.1016/j.proeng.2015.08.450

Mobley, R. K. (2002). *An introduction to predictive maintenance*. Elsevier.

Mohanta, A., & Das, S. (2015). ICT-based facilities management tools for buildings. In *Proceedings of the International Conference on ICT for Sustainable Development* (pp. 125–133). Ahmedabad, India, 3–4 July.

Neely, A., Richards, H., Mills, J., Platts, K., & Bourne, M. (1997). Designing performance measures: A structured approach. *International Journal of Operations & Production Management, 17*(11), 1131–1152.

Sanni-Annibire, M., Hassanain, M. A., & Al Hammad, A. M. (2016). POE of housing facilities: Overview and summary of methods. *Journal of Performance of Constructed Facilities, 30*(5), 1–9. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000868

Percy, D. F., & Kobbacy, A. H. (2000). Determining economical maintenance intervals. *International Journal of Production Economics, 67*(1), 87–94.

Preiser, W. F. E., & Schramm, U. (2005). A conceptual framework for building performance evaluation. In W. F. E. Preiser & J. C. Vischer (Eds.), *Assessing building performance* (pp. xx–xx). Elsevier Butterworth-Heinemann.

Roulet, C. A., Flourentzou, F., Labben, H. H., Santamouris, M., Koronaki, I., Dascalaki, E., & Richalet, V. (2002). ORME: A multicriteria rating methodology for buildings. *Building and Environment, 37*(6), 579–586.

Salim, N. A. A., & Zahari, N. F. (2011). Developing integrated building indicator system (IBIS): A method of formulating the building condition rating. *Procedia Engineering, 20*, 256–261.

Schniederjans, M. J., Schniederjans, A. M., & Schniederjans, D. G. (2015). *Outsourcing and insourcing in an international context* (Vol. 53). https://doi.org/10.1017/CBO9781107415324.004

Shalabi, F., & Turkan, Y. (2016). IFC BIM-based facility management approach to optimize data collection for corrective maintenance. *Journal of Performance of Constructed Facilities, 31*(1). https://doi.org/10.1061/(ASCE)CF.1943-5509.0000941

Shohet, I. M. (2006). Key performance indicators for strategic healthcare facilities maintenance. *Journal of Construction Engineering and Management, 132*(4), 345–352.

Talon, A., Boissier, D., Chevalier, J. L., & Hans, J. (2005). Temporal quantification method of degradation scenarios based on FMEA. In *Proceedings of the 10th International Conference on Durability of Building Materials and Components* (pp. xx–xx). Lyon, France.

Tay, L., & Ooi, J. T. L. (2001). Facilities management: A "Jack of all trades"? *Facilities, 19*(10), 357–363. https://doi.org/10.1108/EUM0000000005534

UNI EN 13306:2018. *Maintenance – Terminology of maintenance*. European Committee for Standardization.

UNI EN 15221-7:2012. *Facility management – Part 7: Guidelines for performance benchmarking*. European Committee for Standardization.

UNI EN 15341:2019. *Maintenance – Maintenance key performance indicators*. European Committee for Standardization.

UNI EN ISO 41011:2018. *Facility management – Vocabulary*. European Committee for Standardization.

Vanier, D. J., Tesfamariam, S., Sadiq, R., & Lounis, Z. (2006). Decision models to prioritize maintenance and renewal alternatives. In *Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering* (pp. 2594–2603). Montréal, Québec.

Vischer, J. C. (2009). Applying knowledge on building performance: From evidence to intelligence. *Intelligent Buildings International, 1*, 239–248. https://doi.org/10.3763/inbi.2009.SI02

Volk, R., Stengel, J., & Schultmann, F. (2014). Building information modeling (BIM) for existing buildings—Literature review and future needs. *Automation in Construction, 38*, 109–127. https://doi.org/10.1016/j.autcon.2013.10.023

Wahab, A. M., & Kamaruzzaman, S. N. (2011). Building performance and evaluation methods: A preliminary review. In *Proceedings of the 2nd International Conference on Project and Facilities Management*. University of Malaya, Kuala Lumpur.

Wiggins, J. M. (2014). *Facilities manager’s desk reference*. John Wiley & Sons.

3. Building Information Modelling for the operational phase

This chapter provides an overview of Building Information Modelling (BIM), emphasizing its definitions, core concepts, data structures, interoperability standards, and its application in facility and maintenance management.

Building Information Modelling (BIM) has emerged as a transformative methodology in the Architecture, Engineering, and Construction (AEC) sector, offering a digital representation of the physical and functional characteristics of built assets.

Beyond a three-dimensional model, BIM is a knowledge-rich environment where objects, attributes, and relationships are semantically defined, enabling coordinated and non-redundant information management across the project lifecycle. It supports design, analysis, and construction processes, from early conceptualization to cost estimation and compliance verification, while enhancing collaboration through shared or federated models.

Crucially, BIM extends its benefits into the operational phase of assets, serving as a central repository of accurate information for facility management. By integrating BIM with maintenance systems, facility managers can plan proactive interventions, monitor asset conditions, and optimize performance over time. This continuity of data allows informed decisions regarding refurbishment, energy efficiency, and strategic asset management, improving operational efficiency and reducing lifecycle costs.

Standardized exchange formats, such as IFC and COBie, ensure interoperability across platforms, facilitating reliable information sharing among stakeholders. Despite challenges in implementation, BIM represents a paradigm shift toward sustainable, resilient, and intelligent building management, with its operational phase enabling the full realization of lifecycle value.

3.1 Introduction to BIM

A common definition of Building Information Modelling (BIM) is provided by the National BIM Standard-United States: *"Building Information Modeling is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition*." (National Building Information Model Standard Project Committee, 2015). This definition outlines the applicability of BIM during all the lifecycle of a construction and its value in helping the decision making.

Similarly, the US Government General Services Administration defines Building Information Modelling as "*the development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility.*" (U.S. Government General Services Administration, 2007).

Eastman et al. (2008) exclude the notion of lifecycle support but defines BIM as a "*modeling technology and associated set of processes to produce, communicate, and analyze building models*". Building models are characterized by:

- Objects that 'know' what they are, and can be associated with computable graphic and data attributes and parametric rules;
- Components that include information and data describing their behaviour;
- Consistent, coordinated and non-redundant data through all views within the BIM environment.

In the same way, according to BIM Dictionary *"Building Information Modelling is a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a Facility in virtual space. As a term, BIM has grown tremendously over the years and is now the 'current expression of digital innovation' across the construction industry".* (BIM Dictionary, 2019).

BIM can be understood in three ways: as a **product** (the model), a **method** (tools and processes), or a **methodology** (a collaborative paradigm applied throughout the project lifecycle). Different organizations offer varying definitions, but all emphasize BIM's role in enhancing collaboration, supporting decision-making, and design, construction, and operational phases.

A Building Information Model includes 3D typically includes the three-dimensional geometry at a defined level of detail; non-physical objects, such as spaces and zones, a hierarchical project structure and schedules. Objects are semantically enriched and relationships between components are defined too (**Figure 3**).

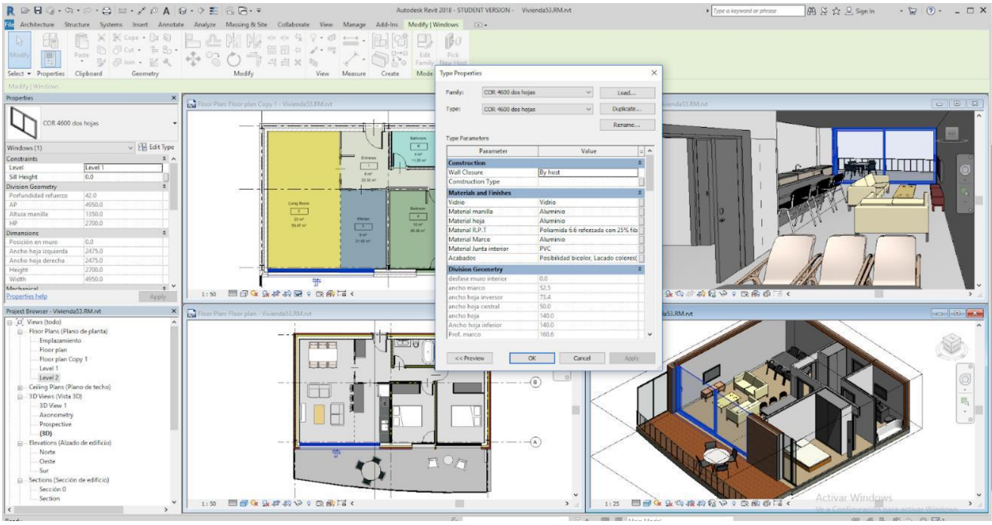


Figure 3. BIModels provide for 3D and 2D coordinated views of an asset, attributes and relationships between the components are set and a hierarchical project structure can be defined.

The building information model is used as a basis for all data exchange within the project. This avoids the need to manually re-enter data and reduces the accompanying risk of errors. The model may contain information to perform several analyses (i.e., structural, cost, lightning, energy, acoustics, etc.) interacting with a variety of other software tools (**Figure 4**).

BIM allows better collaboration among different design teams, which can work on a single shared model or on different sub-model, linked and coordinated among each other (**Figure 5**). In addition, the model can be checked for compliance with codes and regulations, and it can be used to compute a very precise quantity take-off, providing the basis for reliable cost estimations and improving accuracy in the tendering and bidding process (Borrmann et al., 2018).

Positive impacts of BIM on design can be grouped as follows (Eastman et al., 2008):

- At the **conceptual design level**, which typically includes 3D sketching, space planning, environmental analysis, BIM can positively impact the decision-making process (**Figure 38**). None of the tools available today fully support the conceptual design. Technicians have to rely on different software tools with a scarce interoperability between them;
- **Analysis and design of buildings systems** cover many functional aspects of a building's performance and can require the collaboration of various professionals (**Figure 39**). The exchange formats can be reduced to (1) one-way flow from the BIM design tool to analysis application; (2) two-way flow where the design application supports importing and exporting phases. Resulting plans and specific layout have to be coordinated and coherent, and BIM helps in this sense;
- **Construction level models** can be interpreted in two different ways: the model is a detailed design expressing the intent of the designer and the client, so that the contractors are expected to develop their own independent construction model and documents; the model needs to be further detailed for being used in construction and fabrication phases;
- **Design and construction integration** can be achieved by allowing construction considerations to influence the project from the beginning. In this sense a digital twin of the future building facilitates constructability checking to review and improve the design process.

This book focuses specifically on the use of BIM during the operational phase of an asset's lifecycle. It assumes that the reader already possesses a basic understanding of what BIM is and what it is not. For readers seeking more information on BIM terminology, standards, and core concepts, further reference can be made to "*Building Information Modeling*" by Eastman et al. (2008) and "*Building Information Modeling: Technology Foundations and Industry Practice"* by Borrmann et al. (2018) for a comprehensive overview of BIM processes and applications. Among international BIM standards, the most widely adopted is the ISO 19650 Series, which provides the framework for organizing, securing, and exchanging BIM-related information throughout a building's lifecycle.

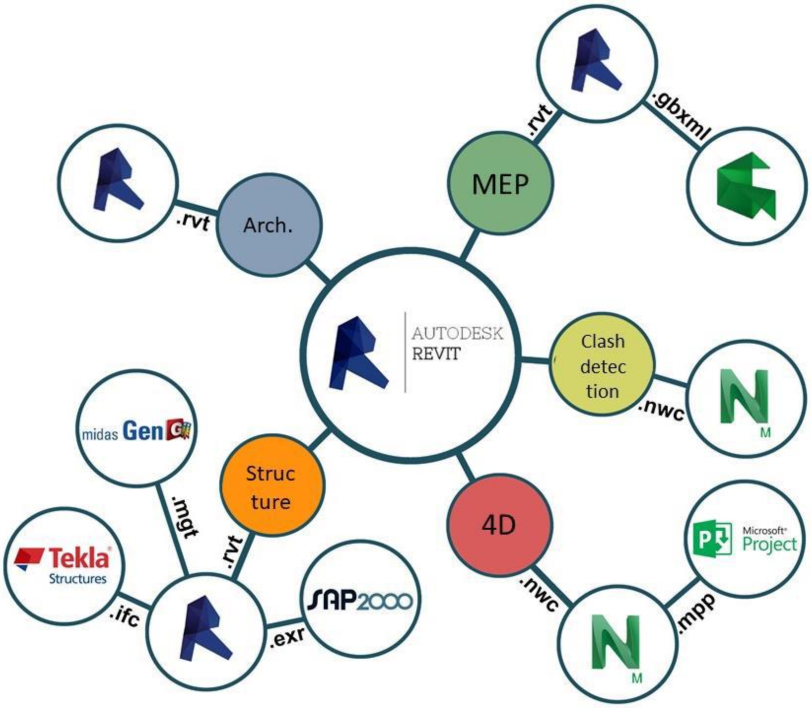


Figure 4. Example of possible information exchange and analysis during the design phase.

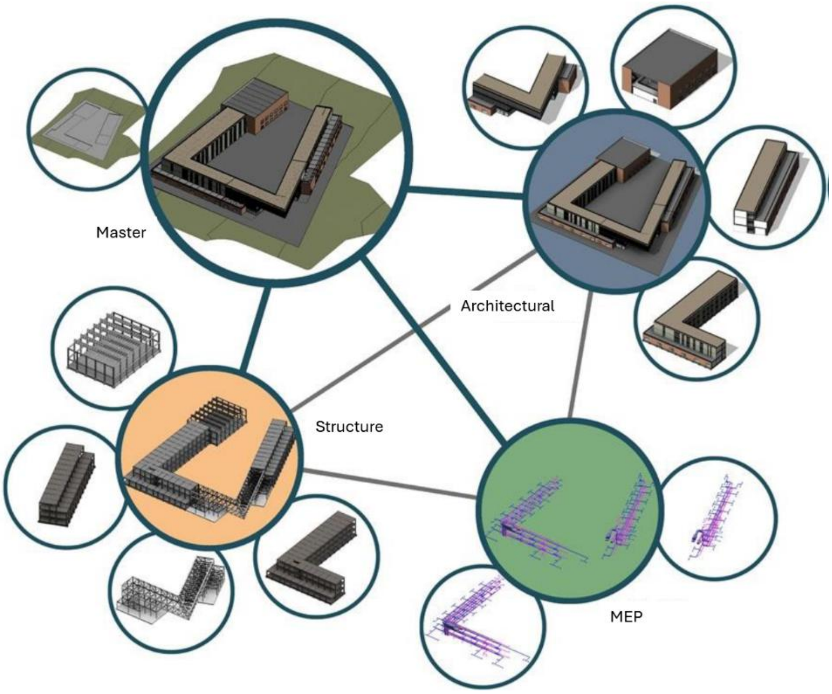


Figure 5. Example of possible sub-models involved in a design project.

3.2 Interoperability

A common data exchange format is required in the AEC domain, as different companies, involved from the design to the operational phase, can require the use of several proprietary data formats, and consequently, risk to miss an effective information exchange.

To achieve the goal of BIG BIM (Borrmann et al., 2018), it became clear that a vendor-neutral, open and standardized data exchange format is needed. Such a format must set out uniform, unequivocal descriptions of geometric and semantic information of building components, including a common classification system, the description of the relationships between them and the definition of their relevant properties (Borrmann et al., 2018).

The international organisation buildingSMART has dedicated many years to the development of the **Industry Foundation Classes** (IFC) as an open, vendor-neutral data exchange format. This is a complex data model with which it is possible to represent both the geometry and the semantic structure of a building model using an object-oriented approach.

The Industry Foundation Classes specify a data schema and an exchange file format structure (International Organization for Standardization, 2018). The data schema is defined in EXPRESS data specification language or XML Schema definition language (XSD). The exchange file formats for exchanging and sharing data according to the conceptual schema include clear text encoding of the exchange structure and Extensible Markup Language (XML).

EXPRESS employs the construct of an entity type as an equivalent to classes in object-oriented theory. For each entity type, attributes and relationships to other entity types can be defined (Borrmann et al., 2018). EXPRESS also implements the object-oriented concept of inheritance (**Figure 6**).

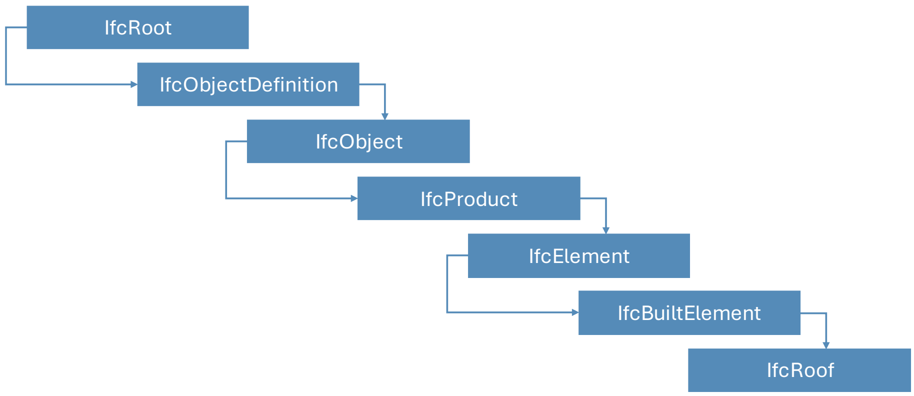


Figure 6. Example of entity inheritance

A relationship (or association) between an object of Type A and an object of Type B is expressed by giving entity Type A an attribute from the type of Entity B. A special characteristic of the EXPRESS standard is the ability to explicitly define inverse relationships. In this case, no new information is modelled; just a relationship in the reverse direction. Attributes that can only contain specific values from a selection of predefined strings are modelled in EXPRESS with the help of the Enumeration Type. In addition, EXPRESS also offers a means of modelling data graphically. The corresponding graphical notation language is called EXPRESS-G (Borrmann et al., 2018).

The data schema architecture of IFC defines four conceptual layers (Building SMART, 2025) as depicted by **Figure 7**.

The Core Layer contains the most elementary classes of the data model. Entities defined in this layer can be referenced and specialised by all entities above in the hierarchy. The core layer provides the basic structure, the fundamental relationships and the common concepts for all further specialisations. All entities defined in the core layer and above derive from *IfcRoot*, having unique identification, name, description, and change control information. The *Kernel schema* represents the core of the IFC data model and comprises basic abstract classes such as *IfcRoot*, *IfcObject*, *IfcProcess*, *IfcProduct*, *IfcProject*, *IfcRelationship*.

Classes defined in the Interoperability Layer are derived from classes in the Core Layer. For example, *IfcSharedBldgElements* defines subtypes of *IfcBuiltElement*, which is defined in the *IfcProductExtension*. Those subtypes are the major elements of the building structure. The *IfcSharedFacilitiesElements* schema defines basic concepts in the

facilities management domain. This schema, along with *IfcProcessExtension* and *IfcSharedMgmtElements*, provides a set of models that can be used by applications needing to share information concerning facilities management related issues. The objective of the *IfcSharedMgmtElements* schema is to capture information that supports the control of project scope, cost, and time. The following are within the scope of this part of the specifications: cost schedules; orders including purchase orders, change orders, and work orders; permits for access and carrying out work; requests to be fulfilled.
Entities defined in the Domain Layer are self-contained and cannot be referenced by any other layer. The defined domains concern architecture, building control, construction management, electrical systems, heating, ventilation and air conditioning, plumbing and fire protection as well as structural elements (such as foundations, pylons, reinforcement, etc.) and structural analysis.
The Resource Layer contains entities which can be referenced by all entities in the layers below. Unlike entities in other layers, resource definition data structures cannot exist independently, but can only exist if referenced (directly or indirectly) by one or more entities deriving from *IfcRoot*.

Figure 7. Extract of the data schema architecture

A subset of the data schema is referred to as a **Model View Definition (MVD)** (Model View Definition (MVD) - An Introduction, 2019). To support BIM interoperability across hundreds of software applications, industry domains, and regions, the IFC schema is designed to accommodate many different configurations and levels of detail. For example, a wall can be represented:

- as a line (or curve) segment between two points;
- as one of many types of 3D geometry for visualization and analysis (such as extruded solids or triangulated surfaces);
- as simple forms or with specific construction detail.

As not every construction domain needs all the same information delivered or received, project delivery contracts may reference exchange specifications. An MVD will describe which objects, representations, relationships, concepts, and attributes are needed for the receiving stakeholder and their software application to accomplish a desired task. In this sense, an MVD will narrow the IFC broad scope depending on the client's information requirements and specific workflows.
However, the specifics of an MVD may be influenced by more general software capabilities or needs. Typically, a BIM-authoring tool has a list of MVD options in their IFC export user interfaces. Depending on the type of BIM tool, the MVD will differ because of the domain the application serves, such as space planning, architectural, structural, or building system MVDs. Examples of MVDs include: Architectural Design to Structural Design; Architectural Design to Quantity Takeoff; Building Envelope Design to Energy Analysis; Construction Operations Building Information Exchange; Basic FM Handover View.
The **Basic FM Handover View**, based on IFC2x3 schema, it is meant to transfer information from planning and design applications to CAFM and CMMS applications, as well as information from construction and commissioning software to CAFM and CMMS applications.
One of the most common MVD used in FM domain is the **Construction Operations Building Information Exchange (COBie)**. This is a non-proprietary data format for the publication of a subset of building information models focused on delivering asset data as distinct from geometric information (NBS, 2018; East, 2016).

3.3 BIM for facility and maintenance management: benefits and challenges

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 Model*’, ‘BIM’, ‘Information Management’, ‘Facilit* Management’, ‘Operation and Maintenance’, ‘CMMS’, ‘CAFM’, ‘case study’, ‘Building Performance Assessment’ in title/abstract/keywords. The query was performed in 2019.

As evident, there was an interest 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 the Operation & Maintenance (O&M) domain. **Tables 3** summarizes the analysis of the selected publications according to the following categories: 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 (Kreider & Messner, 2013) where a BIM use purpose is ‘the specific objective to be achieved when applying Building Information Modelling during a facility’s life’.

According to the **Table 3**, BIM is mostly appreciated for gathering (i.e., to capture, monitor, qualify), communicating (i.e., to visualize) and analysing (i.e., to coordinate, validate, forecast) data and information. In few cases the BIM model is integrated with a benchmarking system to report current performances, while it commonly contains maintenance activities records and space management information.

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 problems correction; integration of several information technologies (Figure 6).

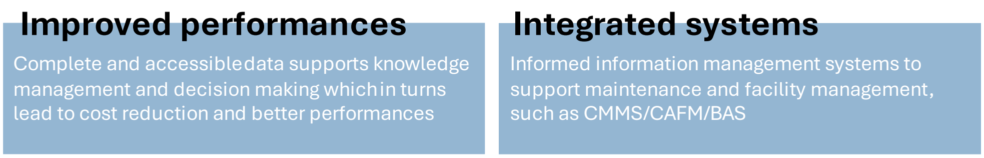


Figure 8. Benefits of BIM-FM integration

Building Information Modelling (BIM) offers owners an effective means to transfer facility data from design and construction into the operational phase, thus bridging what is often a fragmented process.
As-built BIMs allow information to flow directly into Facility Management (FM) systems, avoiding the costly and time-consuming re-entry of data by architects, engineers, and contractors.
When integrated with Computerized Maintenance Management Systems (CMMS), BIM provides not only economic benefits but also a reliable and comprehensive knowledge base of building systems.
Its strength lies in combining detailed databases with spatial intelligence: the 3D environment supports both the visualization and the analysis of maintenance activities. In practice, this enables owners to manage assets more strategically, from routine maintenance planning to evaluating the implications of retrofitting works.
By linking building objects with condition assessments over time, BIM supports decision-making processes that are critical for long-term efficiency, sustainability, and resilience (Eastman et al., 2008; Teicholz, 2013).
An important aspect is the constant upkeep of the digital building model; all changes in the real facility must be recorded in its digital twin. When larger renovations or modifications are required, the building model provides an excellent basis for the necessary design activities. When the built facility reaches the end of its life cycle and is going to be demolished, the digital twin provides detailed information about the materials used in its construction, in order to plan their environmentally-sound recycling or disposal.
However, the BIM implementation in FM systems is not currently achieved without challenges.
Three major categories of issues can be listed (Akcamete et al., 2010): 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 to FM systems, FM teams can face the interoperability issues. Examples of open standards are the Construction Operations Building Information Exchange or the Industry Foundation Classes, in particular the FM Handover Model View Definition. They define standard structure and minimum data fields to support facility management. Other

BIM-FM linking approaches concern manual integration of data (i.e., through spreadsheets) and proprietary middleware.
Due to the simplicity of their inherent structure, spreadsheets are useful means of moving data (text and numbers) between software (CRC, 2007). 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.
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 (Teicholz, 2013). 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 facilitate project financial analysis and maintenance works prioritization (Klamt, 2011).
In addition, an as-built model that is developed without early guidance is not effective for operational purposes (Lui & Zettersten, 2016). 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, which is not commonly known by the owners.
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 (Marmo, 2019). The strategic identification of operational information is critical, thus facility managers need to detail and prioritize their information requirements, identifying by whom and when the data should be provided through- out the project life cycle (Becerik-Gerber et al., 2012). 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 (Gleason 2013). For these reasons, the cost of BIM-FM integration can be high, requiring

investment in infrastructure, training, and new software and hardware (Akcamete et al., 2010).
The analysis of papers regarding BIM implementation for O&M purposes has demonstrated that BIM as a repository tool, able to support different analysis, has been tested in several applications. For example, BIM has been used to support proactive maintenance through gathering information about materials, environmental and condition data so that a BIM-based life cycle management system can be developed (Hallberg & Tarandi, 2011). The prioritization of refurbishment actions can be improved too, developing a decision support model based on accessibility, energy efficiency and acoustic performance information (Carbonari et al., 2018).
In addition to the information exchange processes, it appears that a lack of BIM expertise among the FM team and the owners is a major challenge (Teicholz, 2013; Fargnoli et al., 2019; Koch et al., 2019).
The literature findings suggest 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 involve the existing FM documentation, FM personnel's experience, and building management systems (Gao & Pishdad-Bozorgi, 2019). Interviews with the owner and the FM team are necessary to better understand the organisation’s information requirements, defining data needs based on current and future goals of O&M activities.
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, specific set of information for a complete BIM-aided performance assessment must be defined (Carbonari et al., 2018), a wide variety of data and a wide range of users must be involved in BIM processes (Eastman et al., 2008; Bortolini et al., 2016; McArthur et al., 2015) and BIM-FM links must be based on open standards (Hallberg & Tarandi, 2011).

Table 3. Operation & Maintenance integration case studies

Ref.	BIM use purposes	Information requirements	Information references	Benefits	Challenges
CRC, 2007	Communicate Analyse	Properties of building elements; Building Condition Index	2D CAD drawings and Sydney Opera House specifications	Control of costs and environmental data; support to decision-making	Not discussed
Eastman et al., 2008, pp. 339-357	Gather	Facility Condition Index; Mission Dependency Index; Space Utilization Index	As-built documents (including 3D models); assessment team data; assessors' data; new BIM objects	Cost and time savings; standardizing processes	Integrating diverse data types while making them accessible to a wide range of users
Hallberg & Tarandi, 2011	Communicate Gather Analyse	Geometrical model; material properties; environmental properties; condition assessment data; degradation model	2D CAD drawings; administrative documents; condition surveys	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
Teicholz, 2013, pp. 294-314	Communicate Gather	List of asset inventory information and data	Design and construction models; existing FM systems	Improved data accuracy; streamlined data acquisition process	Handling with the variety of information resources; need for FM team information expertise

Table 3. Operation & Maintenance integration case studies (continued)

Ref.	BIM use purposes	Information requirements	Information references	Benefits	Challenges
McArthur, 2015	Communicate Gather Analyse	Space allocation; lighting feasibility calculations; asbestos hazard map	Survey and reports; existing space management systems	Improved data updating and assessment of potential energy retrofit	Identify critical information; create/modify BIM models; information transfer; documentation uncertainty
Bortolini et al., 2016	Communicate Gather Analyse	List of building characteristics, space management, maintenance and building monitoring data	Physical stock and intranet; building management system; maintenance management systems	Improved data consistency, intelligence in the model and reports generation; integration of facility systems	Correlating different kind of data sources; information exchanges
Pishdad-Bozorgi, 2018	Gather Generate	List of maintenance and equipment information	Owner's guidelines and handover products	Easier updating of CMMS thanks to handover BIM models	Data transfer and data quality control; needs for resources and collaboration among teams
Carbonari et al., 2018	Gather Analyse	List of information regarding accessibility; energy efficiency; acoustic performance	Legislation and technical standards; thermal simulations;	Semi-automatic evaluation of the compliance level, with reduced time and costs	Lack of information suitable to perform a complete assessment in BIM models

References

Akcamete, A.; Akinci, B.; Garrett, J. H. (2010), Potential utilization of building information models for planning maintenance activities. *Proceedings of the International Conference on Computing in Civil and Building Engineering*, Nottingham, Britain, 2010, pp. 151–157.

Becerik-Gerber, B.; Jazizadeh, F.; Li, N.; Calis, G. (2012), Application Areas and Data Requirements for BIM-Enabled Facilities Management. *J. Constr. Eng. Manag.*, 138(3), pp. 431–442. DOI:10.1061/(asce)co.1943-7862.0000433.

BIM Dictionary (2019), Building Information Modelling (BIM), English version. Available at: https://bimdictionary.com/en/building-information-modelling/1 (accessed on 04 November 2019).

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018), *Building Information Modeling: Technology Foundations and Industry Practice*. Springer International Publishing. https://doi.org/10.1007/978-3-319-92862-3_8

Bortolini, R.; Forcada, N.; Macarulla, M. (2016), BIM for the integration of Building Maintenance Management: A case study of a university campus. *Proceedings of the 11th European Conference on Product & Process Modelling (ECPPM)*, Limassol, Cyprus, September 2016.

BuildingSMART International (2025), *IFC 4.3.2.20241204 (IFC4X3_ADD2)*. Available at: https://ifc43-docs.standards.buildingsmart.org/ (accessed on 17th August 2025).

Carbonari, A., Corneli, A., Di Giuda, G., Ridolfi, L., & Villa, V. (2018), BIM-Based Decision Support System for the Management of Large Building Stocks. *Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC)*. https://doi.org/10.22260/isarc2018/0049

CRC (2007), *Adopting BIM for facilities management: Solutions for managing the Sydney Opera House*. Cooperative Research Centre (CRC) for Construction Innovation, Brisbane, Australia.

East, B. (2016), Construction-Operations Building Information Exchange (COBie). Available at:https://www.wbdg.org/resources/construction-operations-building-information-exchange-cobie (accessed on 19th November 2019).

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2008), *BIM Handbook: A Guide to Building Information Modeling*. https://doi.org/10.1093/nq/s7-II.32.110-e

Fargnoli, M., Lleshaj, A., Lombardi, M., Sciarretta, N., & Di Gravio, G. (2019). A BIM-based PSS approach for the management of maintenance operations of building equipment. *Buildings*, *9*(6). https://doi.org/10.3390/buildings9060139

Gao, X.; Pishdad-Bozorgi, P. (2019), BIM-enabled facilities operation and maintenance: A review. *Adv. Eng. Inform. 39*, pp. 227–247. DOI:10.1016/J.AEI.2019.01.005

Hallberg, D., & Tarandi, V. (2011), On the use of open BIM and 4D visualisation in a predictive life cycle management system for construction works. *Electronic Journal of Information Technology in Construction*, 16, 445–466.

International Organization for Standardization. (2018). *ISO 19650 series — Organization and digitization of information about buildings and civil engineering works, including building* *information modelling (BIM) — Information management using building information modelling*. Geneva, Switzerland: ISO.

Klammt, F. (2001), Financial Management for Facility Managers. In *TEICHOLZ E.* (ed.), *Facility Design and Management Handbook*, New York: McGraw-Hill Companies Inc., pp. 5.1–5.37.

Koch, C., Hansen, G. K., & Jacobsen, K. (2019), Missed opportunities: two case studies of digitalization of FM in hospitals. *Facilities*, *37*(7–8), 381–394. https://doi.org/10.1108/F-01-2018-0014

Kreider, R. G., & Messner, J. I. (2013), *The Uses of BIM: Classifying and Selecting BIM Uses*. Version 0.9, September, The Pennsylvania State University, University Park, PA, USA, pp. 6–8.

Lui, R.; Zettersten, G. (2016), Facility sustainment management system automated population from building information models. *Construction Research Congress 2016*, ASCE, Reston, VA.

Marmo, R.; Nicolella, M.; Polverino, F.; Tibaut, A. (2019), A Methodology for a Performance Information Model to support Facility Management. *Sustainability*, 11, 7007.

Model View Definition (MVD) - An Introduction (2019). Available at: https://technical.buildingsmart.org/standards/mvd/ (accessed on 18th August 2025).

National Building Information Model Standard Project Committee (2015), *Frequently Asked Questions – What is BIM?* Available at: https://www.nationalbimstandard.org/faqs#faq1.

NBS (2018). *What is COBie?*. Available at: https://www.thenbs.com/knowledge/what-is-cobie (accessed on 18th August 2025).

Teicholz, P. (2013), *BIM for Facility Managers*. John Wiley & Sons: Hoboken, New Jersey.

U.S. General Services Administration (2007), *GSA Building Information Modeling Guide Series 01 – Overview*. Public Buildings Service, Washington, USA.

4. Performance Information Model

This chapter introduces the concept of a Performance Information Model (PIM), an evolution of Building Information Modelling (BIM) that integrates facility management (FM) and performance assessment throughout a building's lifecycle.

Moving beyond its traditional design-focused role, BIM becomes a dynamic, collaborative environment in which information flows between owners, managers, maintenance staff, and other stakeholders. When enriched with actual performance data, the digital model evolves into a decision-support tool.

The PIM functions as a structured framework for transforming raw data, on energy use, environmental quality, condition state, and more, into actionable knowledge and measurable key performance indicators (KPIs). These indicators support proactive interventions, preventive maintenance, and informed decision-making, enabling the continuous assessment of building performance in terms of sustainability, safety, efficiency, and affordability.

The chapter also outlines a methodological approach for developing a PIM, including identification of performance requirements, KPI definition, linking monitored variables to maintenance actions, defining BIM uses and requirements, and integrating data into a coherent digital model. In this way, the PIM transforms BIM into a living, performance-oriented tool that supports effective and informed facility management.

4.1 Conceptualising a Performance Information Model

Over the past decade, literature has consistently shown that Building Information Modelling (BIM) holds remarkable potential in the field of performance assessment and facility management (FM). Far beyond its traditional role as a design tool, BIM has evolved into a collaborative environment where information flows among facility users and managers, maintenance suppliers, owners, employees, safety officers, and many others. Within this environment, the digital model becomes a living repository: it not only enables simulations of energy use, costs, or safety compliance, but also stores and processes the intrinsic properties of building elements, from thermal performance to mechanical resistance.

The real breakthrough emerges when BIM is enriched with actual performance data. In this way, the model evolves into more than a digital twin of physical assets: it becomes a decision-support instrument for maintenance planning. Conditional logics can be embedded so that, for each monitored variable, the model suggests targeted inspections or interventions. At the same time, the BIM model acts as a digital inventory, automating quantity take-offs and streamlining asset management processes.

In this context, a **Performance Information Model (PIM)** is a BIM model meant to support FM activities by gathering and managing relevant information related to residual performances and operational conditions of an asset and its elements (**Figure 9**).

BIM and FM, separately, may be thought of as a closed model which has evolved into a controlled-dynamical-model, in analogy with dynamical systems with control. According to the monitored conditions different performances of an asset during its lifecycle can be assessed (i.e., sustainability, affordability, energy consumption, safety, efficiency, environmental quality, etc.) and their relative weights may become control/dynamical variables.

A PIM enables performances assessment results and evaluation for better interventions planning in different application areas. As an example, in the housing field several indicators can be defined, moving from architectural, energy and structural criticality to transformability evaluation (Acampa et al., 2021).

Even more than dwellinghouses, technologically advanced environments can benefit from a Performance Information Model. Industrial and manufacturing sites, laboratories and healthcare facilities rely on

specific environmental, structural and technological conditions to function properly. Infrastructures can be digitalised too, to help monitoring and enhancing health and safety conditions. Infrastructure monitoring systems are widely adopted in civil structures, as bridges, tunnels and viaducts, to detect faults before they can lead to severe failures (Hodge et al., 2015). Within the infrastructures field performance-based maintenance contracts may provide several indicators (i.e., condition state, number of accidents, number of defects for track kilometres, maintenance cost per kilometres, etc.) which help evaluating the level of performance of the maintenance process and to quantify benefits of maintenance to traffic operation (Chuo et al., 2024; Famurewa et al., 2013).
To the aim of integrating FM systems, BIM and performance assessment, a methodological approach for a Performance Information Model is presented below.

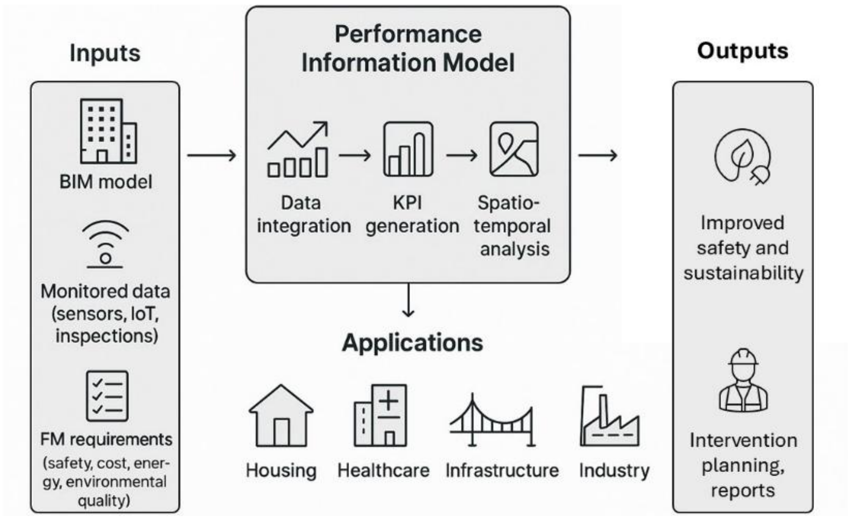


Figure 9. Graphical abstract of the Performance Information Model concept

4.2 Developing a Performance Information Model

In the life cycle of a building, data never stand still. Sensors continuously register energy flows, comfort levels, and system behaviours, producing an ever-growing stream of information. Yet, without structure, this abundance of data risks remaining silent, offering no real guidance to those responsible for maintaining performance. The **Performance Information Model** provides the framework through which such information is transformed into knowledge. As illustrated in **Figure 10**, monitored data are collected, processed, and translated into measurable performance indicators. These indicators reveal when and where interventions are required to satisfy organizational needs, and they become embedded in the digital model as object properties. Within this environment, key performance indicators (KPIs) are not merely numbers: they become navigable elements that allow spatiotemporal analysis, support the decisions of subcontractors, and guide facility management teams. Implementing a PIM thus means more than managing data; it requires defining the precise information needed for assessment, engaging a wide range of actors, and adopting open standards to guarantee that knowledge remains accessible, interoperable, and usable over time. The Performance Information Model is achieved by the workflow described below (Marmo et al., 2019):

- **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 it is crucial to acquire and study several documents and carry out interviews with future users of the model. Client's and users' perspectives are essential to keep in mind which are the objectives they want to achieve. Analysing the facility management policy, maintenance tender specifications and monitoring reports allows to identify information to be managed in order to reach the FM goals.
- **Establish methods of performance assessment.** Policies and systems currently in use have to be analysed in order to identify how to establish the performance measurement methods. KPIs are valuable tools as their functionality is generally well-known and, above all, 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 at least one KPI must be defined.
- **Link the monitored performances to preventive/corrective activities.** According to certain performance values the interventions needed can be identified. For example, from the environmental quality assessment, the condition state of building systems can be deduced. These relationships can be translated in a deterministic logic and then transposed in a BIM platform to inform and update the model, i.e., using: *IfcActionRequest* (description of maintenance request); *IfcApproval* (approval of maintenance

request); *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, level of development required, implementation process needs, etc. Once the implementation process has been established then information exchanges can be defined. The exchange files contain instances of a subset of entities compliant with the IFC data model, such as *IfcActionRequest*, which are addressing PIM requirements. A customized software is needed to improve the efficiency of information exchange.
- **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 can be pulled in the model in an automatized manner, creating a link between the model and the database used to handle the monitoring results (i.e., in form of Excel spreadsheets or relational databases). The output data are the required inspection tasks associated with the failed systems. They can be visualized in the model, i.e., in the form of text shared parameters, but they can also be exported or linked to CMMS to inform future work orders.

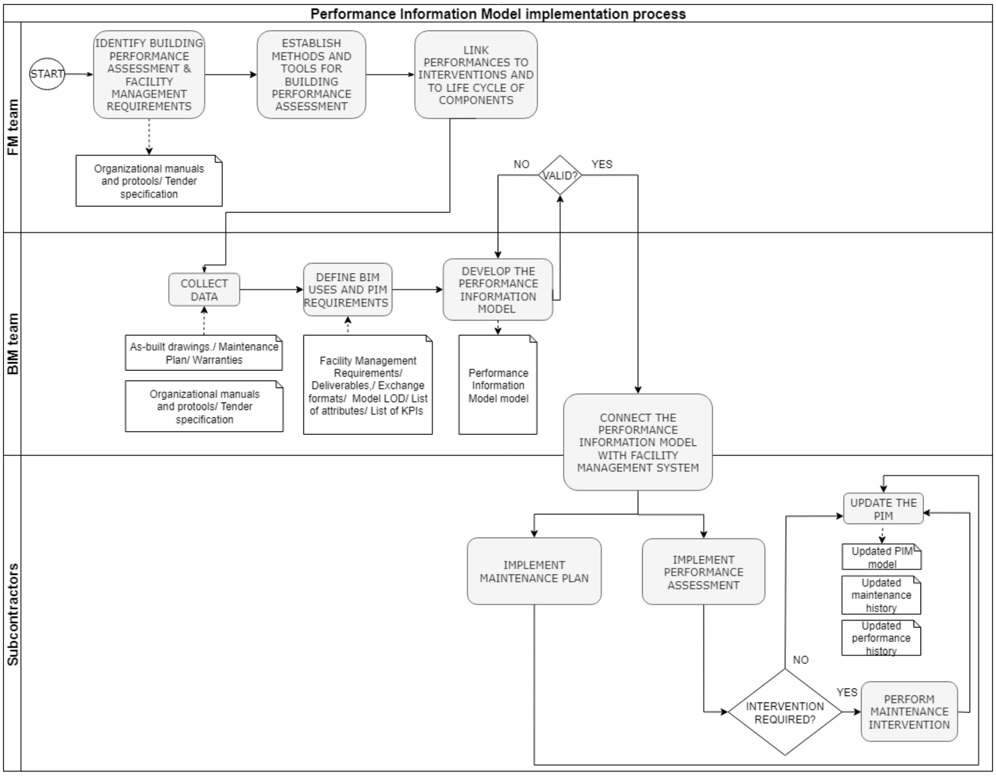


Figure 10. Performance Information Model implementation process in business process modelling notation (BPMN) standard

References

Acampa, G., Diana, L., Marino, G., & Marmo, R. (2021) Assessing the Transformability of Public Housing through BIM. *Sustainability*, *13*(10), 5431. https://doi.org/10.3390/su13105431

Chuo, S., Mehranfar, H., Adey, B. T., & Elshani, G. (2024) *Connecting predictive algorithms to BIM to improve the planning process*. In J. S. Jensen, D. M. Frangopol, & J. W. Schmidt (Eds.), *Bridge Maintenance, Safety, Management, Digitalization and Sustainability* (1st ed., pp. 1479–1486). CRC Press.

Hodge, V. J., O'Keefe, S., Weeks M. , & Moulds, A. (2015) Wireless Sensor Networks for Condition Monitoring in the Railway Industry: A Survey, *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 3, pp. 1088-1106.

Famurewa, S.M., Asplund, M., Galar, D. et al. (2013) *Implementation of performance based maintenance contracting in railway industries*. Int J Syst Assur Eng Manag 4, 231–240. https://doi.org/10.1007/s13198-013-0167-4

Marmo, R.; Nicolella, M.; Polverino, F.; Tibaut, A. (2019) *A Methodology for a Performance Information Model to support Facility Management*. Sustainability, 11, 7007.

5. IFC-based Performance Information Model

This chapter explores the development of **openPIM**, a Performance Information Model grounded in the principles of openBIM and the IFC schema, to support systematic facility management and performance assessment.

OpenBIM promotes interoperability and standardized information exchange, enabling collaborative workflows across design, construction, and operation. Building on this, openPIM translates IFC-based models into a relational database structure, allowing efficient filtering, querying, and analysis of large volumes of data from multiple disciplines while preserving 3D object representations for enhanced decision-making.

The chapter details the structured process of database development, from requirements analysis and conceptual design to implementation. Requirements analysis identifies information needs, actors, and operational workflows, ensuring that maintenance, monitoring, and performance indicators are accurately represented.

The design stage maps IFC entities into an entity-relationship model, normalizes tables, and defines attributes, keys, and relationships.

Implementation involves constructing the relational database, creating tables, indexes, and constraints, and populating it with data to support querying, reporting, and integration with facility management systems.

Finally, the openPIM database can be linked to the IFC model, such as using Dynamo, a visual programming environment, to automate workflows, link parametric design with performance data, and facilitate real-time interaction between the digital model and its operational data.

This integrated approach ensures that performance information is structured, accessible, and actionable, transforming BIM into a powerful tool for informed facility management.

5.1 The OpenPIM

The construction sector is increasingly required to document and share information in a consistent and interoperable way, and this can only be achieved through the adoption of open formats. In this regard, buildingSMART has introduced the IFC schema as the standard for openBIM data exchange. OpenBIM simply means working with BIM using open standards. This is a universal approach to the collaborative design, realization and operation of buildings based on open standards and workflows (BIM dictionary, 2019).

Building upon the principles of openBIM, this book advances the concept of **openPIM**, a Performance Information Model grounded in the IFC schema. The IFC data model can be mapped into a relational database structure, which in turn allows the application of query languages to filter and retrieve relevant data (Preidel et al., 2017). Although this transformation is not yet standardized, it offers significant potential, particularly in facility management, where the processing of large volumes of data from multiple disciplines and stakeholders is essential. In this context, an IFC-based relational database can support users in efficiently filtering and analysing the required information, while simultaneously enabling the integration of 3D object representations within the query process, adding further value to decision-making.

5.2 Developing and processing databases

In relational database theory, data are organized hierarchically: a *data item* (or attribute) represents the smallest unit of information, *records* (rows) are sets of related data items, and *tables* are collections of records of the same type (Teorey et al., 2011).

A database can be understood as an organized collection of interrelated data designed to support the information needs of multiple users within an organization. Unlike simple lists, which are prone to redundancy and modification errors, databases provide structured storage that ensures consistency and reliability. In the relational model, data are distributed across separate tables, with each table dedicated to a single theme or entity. When a table contains data concerning more than one theme, it is decomposed into multiple tables, each addressing only one subject. This process, known as **normalization**, reduces redundancy and enhances data integrity. A relational database takes its name from the fact that each entity (or relation) is presented as a two-dimensional table with special characteristics, as reported below (Kroenke and Auer, 2009):

- Rows contain data about an entity;
- Columns contain data about attributes of an entity;
- Cells of a table hold a single value;
- All entries in a column are of the same kind;
- Each column has a unique name;
- The order of the column is unimportant;
- The order of the rows is unimportant;
- No two rows should be identical.

In order to create, process and administer databases, a *database management system* (DBMS) is used. For each relation of a DBMS it is essential to define the *primary key*, which is the column used by the DBMS to uniquely identify each row in a relation.

It is possible to query and process databases through several approaches, but the *Structured Query Language* (SQL) emerged as the leading technique for this purpose (Codd, 1991). A DBMS receives requests encoded in SQL and translates those requests into actions. DBMS are generally licensed by software vendors. Examples of well-known DBM products are Microsoft Access, SQL Server, MySQL, PostgreSQL (Kroenke and Auer, 2009).

The development of a database can be described as a structured process that unfolds through the following main stages: requirements analysis, design (both logical and physical), and implementation (Kroenke and Auer, 2009).

The first stage, **requirements analysis**, establishes the purpose of the database and defines its scope. At this stage, system users are interviewed, and both data and functional requirements are collected. These inputs form the foundation for creating a **conceptual data model**, which provides an abstract representation of the facility or system under consideration (Teorey et al., 2011).

The second stage, **design**, refines these requirements into a formalized model. Here, data are analysed and represented using methodologies such as Entity-Relationship (ER) modelling or Unified Modeling Language (UML). Once developed, the conceptual model is translated into SQL tables. Each entity corresponds to a table, which must then be normalized to eliminate redundancies, while the relationships between tables are explicitly defined. This process also involves specifying table

and column names, data types, column properties, and the assignment of primary and foreign keys (Kroenke and Auer, 2009).
The final step, **implementation**, involves constructing the database and populating it with data. At this stage, queries and reports are created and tested to ensure functionality. Implementation typically requires the formal schema to be defined using the Data Definition Language (DDL). Once the schema is in place, the Data Manipulation Language (DML) is employed to query, update, and manage the database, including the creation of indexes and the enforcement of constraints. In practice, SQL integrates both DDL and DML constructs: for example, the CREATE TABLE command belongs to DDL, while the SELECT command is part of DML.

5.3 The OpenPIM database development

The development of the openPIM follows four main steps: (a) defining the scope of the database and the information requirements; (b) mapping IFC schema into an entity-relationship model (ERM); (c) creating the openPIM relational database; (d) integrating the IFC model with the openPIM relational database.

Database scope and requirements analysis

The initial stage focuses on defining the database's scope and establishing the information requirements. The primary objective of openPIM is to support the systematic recording of maintenance and monitoring activities while enriching a building model with detailed facility management information. To achieve this, the database has been structured to track several key aspects: corrective maintenance activities, planned maintenance activities, ongoing monitoring tasks, performance assessment outcomes expressed through key performance indicators (KPIs), and the actors involved in these processes.
To ensure alignment with practical operational needs, information requirements are to be established together with the organizations involved. This provides a detailed understanding of the information flows necessary to populate the database and support facility management operations effectively.
For instance, the corrective maintenance process, illustrated in **Figure 11** using the BPMN standard, assumes that an employee detects a failure and contacts the maintenance management team. A project order can be required for certain tasks, but it can be avoided for minor works.

The outcome of the requirements analysis is the list of the main entities to be inserted in the database, as per **Table 4**.

Table 4. Main entities of the PIM-related database

Entities name	
Action request	Measurement
Actor	Product
Approval	Project order
Model	Task
Key Performance Indicator	Work plan

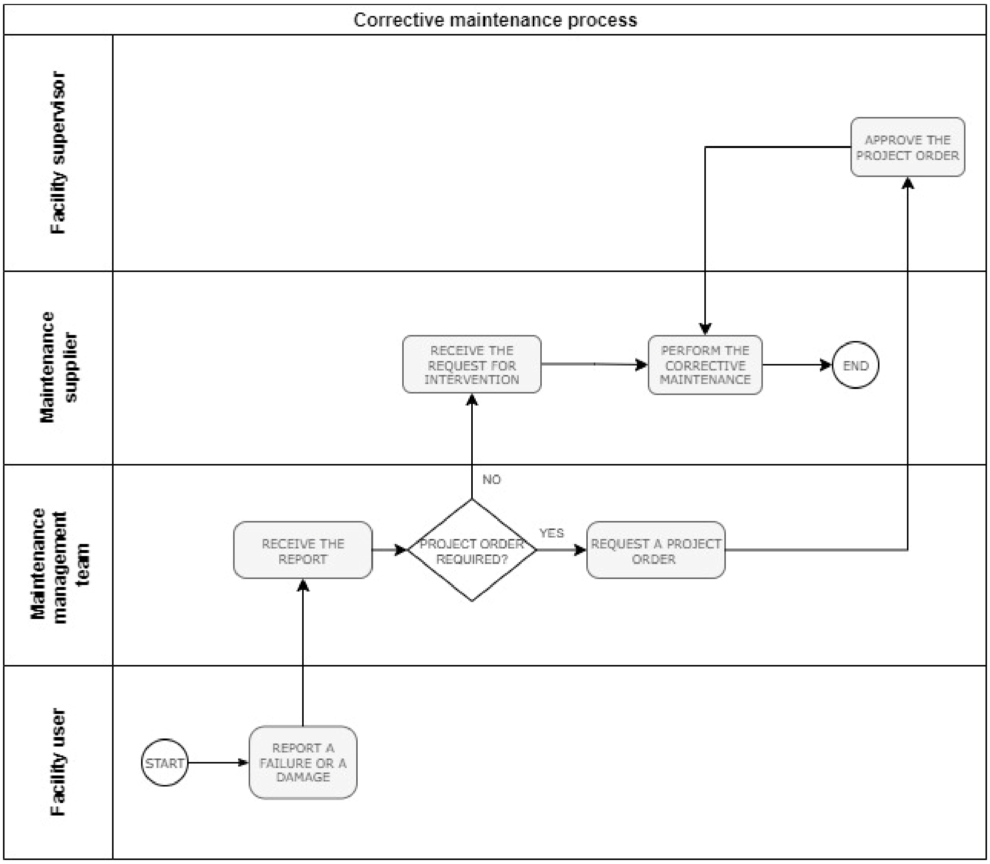


Figure 11. Instance of corrective maintenance process

Entity-relationship database design

Once the main databse entities are identified, the IFC schema support their definition, including relationships and attributes. Identified entities are covered by the international schema except for the *KeyPerformanceIndicator*, the *Measurement* and the *Model*. The *Model* entity has been used to relate each product to the model it belongs to.

An **Entity-Relationship model** (ER model) has been created to provide a conceptual representation of data and their relationships within a system. Its purpose is to help designers, developers, and stakeholders understand, organize, and communicate how data are structured before creating a physical database.

The *IfcActor* defines all actors or human agents involved in a project. It facilitates the use of person and organisation definitions in the resource part of the IFC object model. The *IfcActorResource* schema and related classes are used to define the *IfcActor* entity through *IfcPerson*, *IfcOrganization* and *IfcPersonAndOrganization* entities.

The *ActorRole* indicates a role which is performed by the previous entities. The *Actor* has relationships defined by the *IfcRelAssignsToActor* entity. For example, an actor can issue an action request, so that in the *IfcRelAssignsToActor* relationship the *RelatingIssuingActor* and the *RelatedActionRequest* will be defined (**Figure 12**).

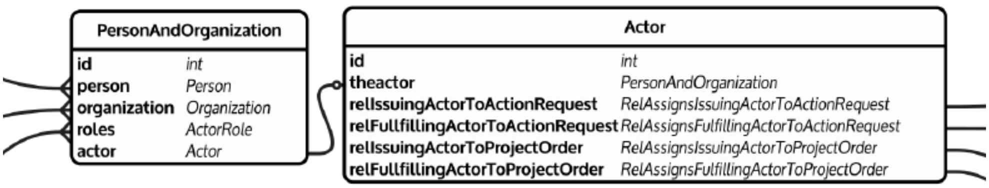


Figure 12. The Actor entity

The *IfcActionRequest* entity is defined as the act or an instance of asking for something. Each *ActionRequest* instance is identified by a unique identification number through the id attribute, inherited by the *IfcControl*. The *ActionRequest* entity is related to the *IssuingActor* and the *FulfillingActor* through the *RelAssignsToActor* relationship. The *ActionRequest* is also related to the *Task* and the *Product* entities. Furthermore, an *ActionRequest* is related to *ProjectOrder* and *KeyPerformanceIndicatorResult* entities as each request can generate a work order or can lead to the quantification of the assessed performances (**Figure 13**).

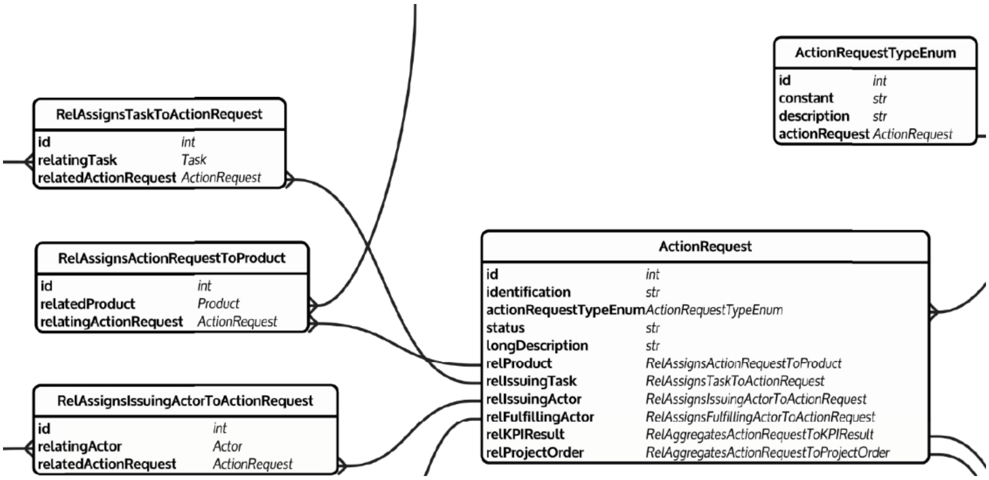


Figure 13. The ActionRequest entity

An *IfcProjectOrder* is a directive to purchase products and/or perform work. The *ProjectOrder* is related to the *Actor* similarly to the *ActionRequest*. The *IfcApproval* entity may indicate the status of acceptance or rejection using the *IfcRelAssociatesApproval* relationship where *RelatedObjects* refers to a *ProjectOrder*. Even though this idea is not included in the openPIM model here presented, action requests and project orders may nest further controls and orders.

The *IfcWorkPlan* entity contains a set of work schedules for different purposes. A *WorkSchedule* is related to the *WorkPlan* through the *IfcRelAggregates* relationship. A *WorkSchedule* controls a set of *Tasks* defined through *IfcRelAssignsToControl*.

The *IfcTask* entity represents an identifiable unit of work to be carried out in a project. The *Task* entity is related to the *WorkSchedule*, to *Product* and *ActionRequest* entities, in order to define the object to which the work schedule is assigned, the product on which a determined task has to be performed, and the action request generated by an instance of a task (**Figure 14**).

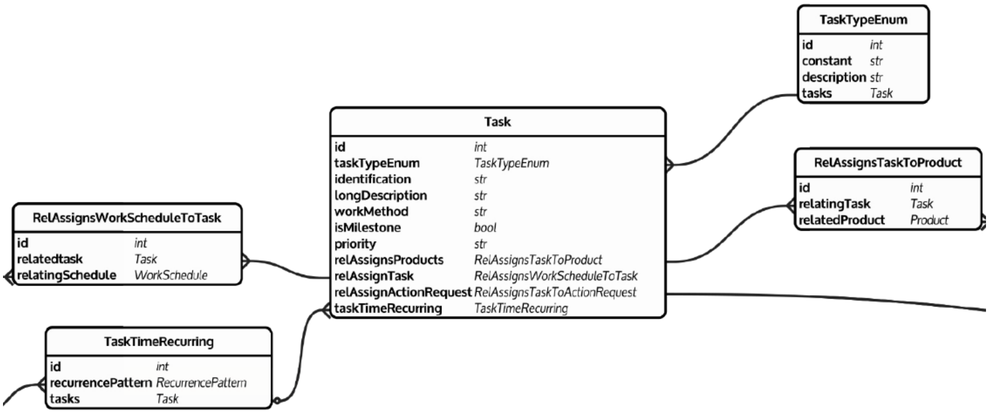


Figure 14. The Task entity

The *IfcProduct* entity is an abstract representation of any object that relates to a geometric or spatial context. For inheritance, attributes such as GUID (globally unique identifier), object type, name, description can be applied. In addition, the *localId* attribute has been added to make the identification of the product in a BIM platform (such as Revit) easier. Each instance of the product entity is related to *Task*, *ActionRequest*, *Measurement* and *IfcModel* through the relationship *RelAssignsToProduct* (**Figure 15**).

The *IFCModel* entity has been added to relate each product to the model it belongs to. In this way the database is aware of the informed model. Each *IFCModel* instance is identified by a unique identification number through the *id* attribute. Additionally, the *modelContent* attribute defines the information contained in the model, for example through the declaration of the discipline treated by the model (**Figure 15**).

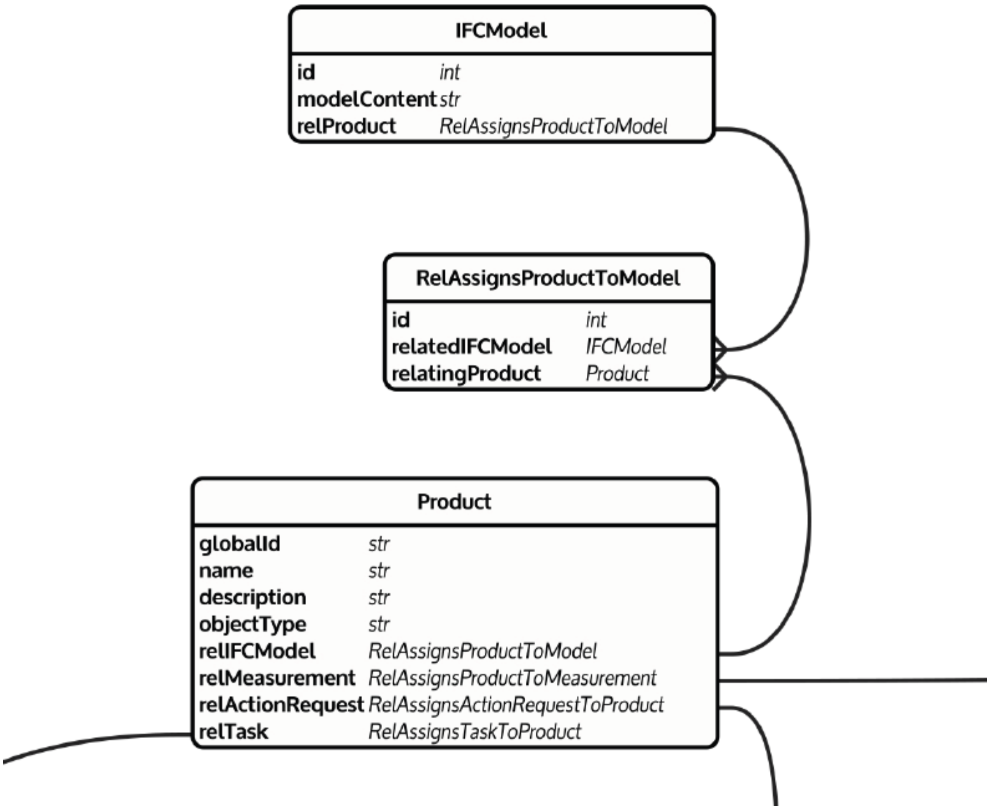


Figure 15. The Product entity

The *IfcMeasurement* entity is meant to describe the monitoring activities and related results. An instance of an *IfcMeasurement* identifies a control variable. Each instance of the *IfcMeasurement* entity is associated with an *IfcProduct*. For example, the measurement of thermal properties can be associated with a wall, the noise intensity to a space etc. The measurement is also related to the *IfcKeyPerformanceIndicatorResult*, as according to monitored parameters values, the related KPI is calculated. In the *IfcRelAssignsToMeasurement* relationship it is possible to define the acceptability of measurement results and their interpretation (**Figure 16**).

The concept of KPI is expressed by the *IfcKeyPerformanceIndicator* entity, so that each KPI is identified by a unique identification number, furthermore its description, its explicit name and its acronym are defined. Each *IfcKeyPerformanceIndicator* instance can be related to an *IfcKeyPerformanceIndicatorResult* instance. The latter is also related to *IfcActionRequest* entity through the

IfcRelAggregatesActionRequestToKPIResult relationship, as the performance assessment through multiple KPIs can be defined by an action request (**Figure 16**).

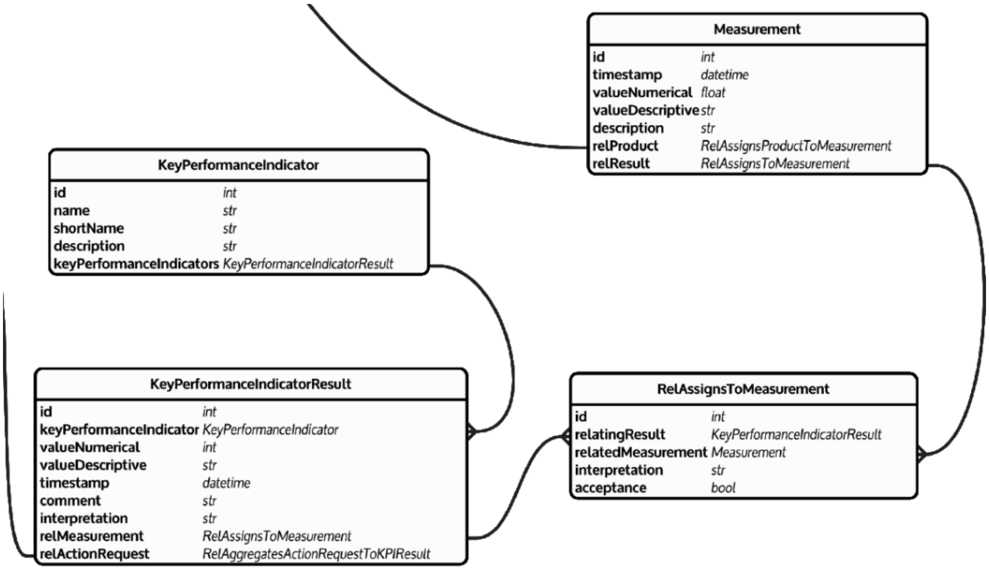


Figure 16. The Measurement and KeyPerformanceIndicator entities

The concepts of measured, derived or simple values are contained in the Resource layer of the IFC schema, through the *IfcValue* select type. Furthermore, the *IfcPerformanceHistory* entity is meant to represent performance assessment results. It can be related to products, controls and measurement values through a system of relationships. To improve the efficiency of the database, it has been decided to define two new tables containing the KPI results and related measurements.

The resulted openPIM database can be referred to as a **customized Model View Definition** for performance assessment and maintenance management.

Creating the OpenPIM database from the ER model

The Entity-Relationship model has defined entities, attributes and relationships. The database defines tables and attributes, specifying properties of attributes (i.e. data types and constraints) and identifying the primary key for each table.

The class of each attribute is specified in: primary key, for an attribute that will be used by the Database Management System (DBMS) to uniquely

identify each row in a table; required, when an instance of the attribute is needed for each row; optional, if the instance of the attribute is not required.
The data type is selected among:

- Str, it stands for string and means a textual attribute;
- Int, it stands for integer and means a numerical attribute;
- Float, it is a shortened term for floating point, and it is used to define numeric values with floating decimal points;
- Decimal, it is used for storing numbers that have fixed precision and scale;
- Datetime, it contains both date and time parts, for example in 'YYYY-MM-DD hh:mm:ss' format;
- Time, it has only the time component, for example in ‘hh:mm:ss' format;
- Timedelta, it represents a duration and can be expressed in different units, such as years, months, days, minutes;
- Bool, it stands for Boolean;
- Longstr, it stands for long string;
- UUID, it stores universally unique identifiers. It is a sequence of lower-case hexadecimal digits, in several groups separated by hyphens, for a total of 32 digits.

The database editor translates queries to Structured Query Language (SQL) using a specific database ‘dialect’. The resulted database consists of 40 tables, listed in **Table 5**.

Table 5. Tables contained in the openPIM relational database

	Item	Item
Entities	ActionRequest	Actor
	ActorRole	Approval
	IFCModel	KeyPerformanceIndicator
	KeyPerformanceIndicatorResult	Measurement
	Organization	Person
	PersonAndOrganization	Product
	ProjectOrder	RecurrencePattern
	Task	TaskTimeRecurring
	WorkPlan	WorkSchedule
Relationships	RelAggregatesActionRequestToKPIResult	RelAggregatesActionRequestToProjectOrder
	RelAggregatesWorkPlanToWorkSchedule	RelAssignsActionRequestToProduct
	RelAssignsFulfillingActorToActionRequest	RelAssignsFulfillingActorToProjectOrder
	RelAssignsIssuingActorToActionRequest	RelAssignsIssuingActorToProjectOrder
	RelAssignsProductToMeasurement	RelAssignsProductToModel
	RelAssignsTaskToActionRequest	RelAssignsTaskToProduct
	RelAssignsToMeasurement	RelAssignsWorkScheduleToTask
	RelAssociateApproval	
Enumerations	ActionRequestTypeEnum	ProjectOrderTypeEnum
	RecurrenceTypeEnum	RoleEnum
	TaskTypeEnum	WorkPlanTypeEnum
	WorkScheduleTypeEnum	

As an example, for creating the *WorkPlanTypeEnum* and *WorkPlan* tables in PostgreSQL the fragment of the DDL is the following:

```
CREATE TABLE "workplantypeenum" (
"id" SERIAL PRIMARY KEY,
"constant" TEXT NOT NULL,
"description" TEXT
);
CREATE TABLE "workplan" (
"id" SERIAL PRIMARY KEY,
"workplantypeenum" INTEGER NOT NULL,
"creationdate" DATE,
"purpose" TEXT,
"starttime" TIMESTAMP
);
CREATE INDEX "idx_workplan__workplantypeenum" ON "workplan"
("workplantypeenum");
ALTER TABLE "workplan" ADD CONSTRAINT
"fk_workplan__workplantypeenum" FOREIGN KEY
("workplantypeenum") REFERENCES "workplantypeenum" ("id") ON
DELETE CASCADE;
```

The CREATE TABLE command is used to create a table. The names of the tables and of each column are defined and all attributes have specified properties.
The CREATE INDEX statement is used to create indexes in tables. Indexes are used to retrieve data from the database more quickly than otherwise. In this case the statement means that index named *workplantypeenum* is created in the table *WorkPlan* for the attribute *workplantypeenum*.
A relationship between the tables exists in the sense that the *WorkPlan* type attribute is selected from the table *WorkPlanTypeEnum*.
The *WorkPlan* table was altered by the ALTER TABLE command in order to insert a foreign key on the *workplantypeenum* attribute which refers to the *id* attribute of the *WorkPlanTypeEnum* table.
Implementing the SQL DDL in a DBMS it is possible to create the database and managing it.
Database schema modifications, such as table name, column name, data type, etc., can be carried out in the DBMS itself. As an example, the

SQL command used to change the datatype of the ‘relatedproduct’ column in the *relAssignsProductToModel* is reported below:

ALTER TABLE "relassignsproducttomodel**" ALTER COLUMN** relatedproduct **TYPE TEXT;**
ALTER TABLE "relassignsproducttomodel**" ADD CONSTRAINT "**fk_relassignsproducttomodel__relatedproduct**” FOREIGN KEY ("**relatedproduct**") REFERENCES** "product" ("globalid") **ON DELETE CASCADE;**

Connecting the openPIM database with the IFC model

The openPIM database and the corresponding IFC model can be connected in several ways. For example, Dynamo, a VPL environment, has been used to connect the IFC model with the openPIM database (Marmo et al., 2020).
Dynamo is a visual programming environment developed by the Autodesk software house that enables to perform parametric design and automate tasks (Dynamo Studio, 2019). Dynamo extends the building information modelling with the logic environment of a graphical algorithm editor (Explore Dynamo, 2019). Dynamo provides for a canvas as a basic workspace. Here the functions (*nodes*) can be arranged and linked to each other by directed edges (also denoted as *wires*) (Preidel et al., 2017). The different functions are usually offered in a library that can be expanded through several packages.

References

BIM Dictionary (2019), *Open BIM, English version*. Available at:https://bimdictionary.com/terms/search (accessed on 10th August 2025).

Codd, E. F. (1991). *The relational model for database management: Version 2*. Reading: Addison-Wesley).

Dynamo Studio. Available at: https://www.autodesk.com/products/dynamo-studio/overview(accessed on 10th August 2025).

Explore Dynamo. Available at: https://dynamobim.org/ (accessed on 10th August 2025).

Kroenke, D. M., & Auer, D., J. (2009), *Database concepts* (4th ed.), Pearson, 2009. ISBN:013460153X 9780134601533

Marmo, R., Polverino, F., Nicolella, M., & Tibaut, A. (2020). Building performance and maintenance information model based on IFC schema. *Automation in Construction*, 118, 103275. https://doi.org/10.1016/j.autcon.2020.103275

Preidel, C., Daum, S. & Borrmann, (2017), A. Data retrieval from building information models based on visual programming. *Vis. in Eng.*, 5(18) . doi:10.1186/s40327-017-0055-0).

Teorey, T., Lightstone, S., Nadeau, T., and Jagadish, H.V. (2011). *Database modeling and design* (5th ed.). Morgan Kaufmann, USA.

6. Applications and case studies

Hospitals are among the most complex settings for facility management, where technical systems, regulations, and organizational processes must operate in harmony to ensure safety and efficiency.
Managing these spaces requires robust methods that translate performance data into informed decisions on maintenance, risk prevention, and compliance.
This chapter presents applications and case studies that address these challenges through two complementary approaches. The first is the **Environmental Condition Index (ECI)**, a performance indicator developed to quantify and assess the environmental quality of surgery units. By integrating regulatory standards and expert evaluations, the ECI links parameters such as air quality and microclimatic condition to targeted maintenance.
The second focuses on the use of **Building Information Modelling (BIM)**, and in particular the **Performance Information Model (PIM)** and **openPIM frameworks**, as tools to support environmental monitoring and risk assessment. Case studies from Italian and European hospitals show how these digital approaches enable the integration of diverse data sources, visualization of performance results, and systematic support for resilience strategies.
Finally, recent advancement and applications of BIM for risk assessment procedures are analysed and discussed.
Together, these applications demonstrate how combining performance indicators with BIM-based workflows can improve decision-making, enhance environmental quality in surgery units, and strengthen hospitals' capacity to manage risks.

6.1 Surgery unit Environmental Quality

The implementation of the PIM process has been tested in the hospital context, a field universally recognised as one of the most demanding and complex within facility management (Lavy & Shohet, 2007; Marmo et al., 2019; Marmo et al., 2025). Hospitals are multifaceted systems where managerial decisions must be taken daily in areas as diverse as maintenance policies, human resource allocation, logistics and supplies, information systems, and safety for both healthcare workers and patients. Each of these aspects, while seemingly independent, contributes to shaping the overall performance and resilience of the healthcare organization (Marmo et al., 2025).

This complexity is heightened by the coexistence of **different categories of data**, which managers must interpret and integrate. On the one hand, there are **quantitative measures**, such as costs of maintenance interventions or environmental performance indicators; on the other, **qualitative assessments**, such as the perceived quality of service or patient satisfaction. Managing these multiple dimensions simultaneously is what distinguishes healthcare facility management from other domains, requiring robust decision-support frameworks.

In response, several attempts have been made in the literature to develop **integrated FM models for healthcare buildings** (Lavy et al., 2014; Lavy & Shohet, 2007). These models typically begin by examining the impact of specific parameters, such as building age or maintenance expenditure, on the performance of the facility and its technical systems. From this starting point, a hierarchical and multidisciplinary knowledge base is constructed, combining managerial, economic, and technological perspectives.

Within this complex scenario, **surgery rooms represent one of the most critical and regulated environments**. Their design, construction, and operation are subject to rigorous standards, as they directly influence patient safety and clinical effectiveness. In the Italian context, these requirements were codified in the Presidential Decree of 1997 (President of Italian Republic, 1997), which established the **minimum standards for public and private healthcare facilities**. These regulations encompass structural, technological, and organizational aspects across a broad spectrum of hospital units: from specialized clinics and diagnostic laboratories to imaging departments, mental health centres, emergency triage areas, inpatient wards, and, most prominently, surgical units.

Specific environmental requirements for surgery units are listed by law as reported in **Table 6**.

Table 6. Minimum environmental requirements for operating theatres

Minimum environmental requirements for operating theatres	
Air temperature range: 20-24°C	Relative humidity range: 40-60%
Air changes 15v/h	Air filtering: 99,97%
Medical gas system and anaesthetic gas scavenging system directly connected to the anaesthesia equipment	Pressure difference stations, provided in duplicate for each medical/Technical gas and designed to ensure an adequate level of reliability
Presence of fire detection system	Alarm system for medical gases depletion

Understanding how a hospital functions requires not only an appreciation of its technological complexity but also a clear grasp of its spatial and organizational structure. In Italy, the ISPESL guideline (ISPESL, 2009) has examined the hospital requirements in detail, outlining optimal conditions for their design, construction, and management.

To support decision-making in such a complex context, performance assessment tools become essential. The use of Key Performance Indicators (KPIs) offers a practical way to simplify evaluation processes, providing management teams with measurable benchmarks that can guide strategic choices and ensure alignment with the hospital's mission. In this sense, KPIs act as instruments of external control for the dynamic organizational model of healthcare facilities.

This rationale led to the development of a new tool: the **Environmental Condition Index (ECI)** (Marmo et al., 2019). Conceived ex novo, the ECI is designed to evaluate and quantify the environmental quality of both individual surgery rooms (environmental units) and entire surgical departments (functional areas). The terminology used here, environmental quality, environmental unit, and related terms, derives from the national standard UNI 10838 (UNI 10838:1999), which provides a classification system and defines the key concepts for performance assessment and building processes.

According to UNI 10838, the **building system** is the union of spatial and technological elements. Environmental quality represents the overall outcome of environmental performances, which themselves are defined as the capacity of spatial elements to satisfy a given environmental requirement. These requirements express user needs in terms of physical, technological, and spatial factors, allowing compliance conditions to be verified. The environmental system is therefore a structured set of environmental units and spatial elements, defined by their performances and interrelations. An **environmental unit** is conceived as a space dedicated to a set of homogeneous and compatible activities (e.g., a surgery room).

Complementing this view, UNI 8290–1 (UNI 8290-1:1981) further specifies the **technological system** of buildings, breaking it down into classes of technological units, technological units, and classes of technical elements. This hierarchical scheme can be extended: at finer levels, technological elements may be described in terms of their materials and resources, while environmental units may be aggregated into broader categories. Building on this logic, Terranova (2005) proposed a more articulated framework that situates environmental units within **functional areas** and **functional sectors**. Functional areas are groups of environmental units required to perform complex activities in an autonomous way (e.g., the surgery unit or the emergency department), while functional sectors aggregate multiple functional areas sharing homogeneous characteristics and macro-functions (e.g., the Diagnosis and Therapy sector, which includes both the surgery unit and emergency services).

The hierarchical decomposition of the hospital environmental system is illustrated in **Figure 17** and further detailed in **Table 7** (with regard to surgery units only). This structure provided the conceptual foundation for the definition of the Environmental Condition Index, ensuring that the evaluation of hospital spaces is firmly anchored to both their spatial-technical organization and their functional role within the wider healthcare system.

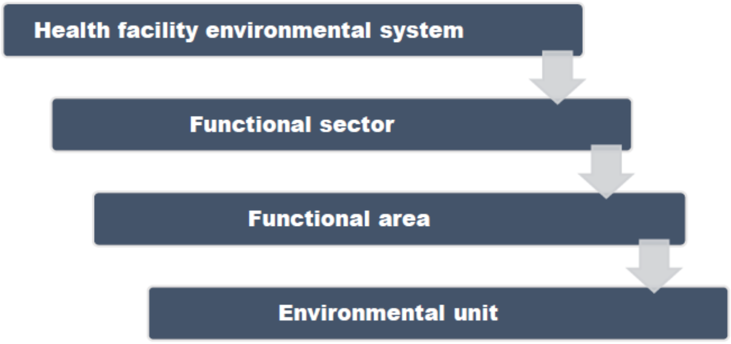


Figure 17. Hierarchically breakdown of a hospital environmental system

Table 7. Detailed surgery unit breakdown structure

Functional sector	Functional area	Functional sub-area	Environmental unit
Diagnosis & therapy	Surgery unit	Reception	
		Surgery	Clean corridors
			Dirty corridors
			Surgery room
			Changing rooms
			Preparation and reviving of patients
			Filter Zones
			Sub-sterilization
			Surgery room slop sink
		Staff services	Staff room
			Staff rest room
			Staff toilets
		Support	Dirty storage area
			Clean storage area
			Storage area for sterilized material

Stakeholder information requirements definition

When no BIM exists yet, it is crucial to analyse stakeholders' information requirements in advance, in order to optimise both geometric modelling and information handling. For this purpose, the specifications of local health authorities regarding surgery rooms, particularly concerning maintenance, risk management, and work organisation, are to be examined.

Two Italian hospitals (a public hospital in the South of Italy and a public hospital in the North of Italy) provided documents and data to set hospital information requirements needed to test the Performance Information Model concept.

Reviewed documents include tender specifications for facilities management and surgery unit environmental conditions, monitoring databases, adjustment plans, organisational documents on risk assessment, and technical drawings of the buildings.

In addition, interviews and focus groups were carried out with FM personnel, maintenance teams, and safety staff, which enabled a deeper understanding of the information needed to monitor performances, conditions, and communication flows.

Maintenance contractors also contributed by providing CMMS databases, work order registers, and further details on maintenance processes. This information enrichment allowed the definition of stakeholders' information requirements, which represent crucial knowledge for developing an efficient PIM model. The list of monitored parameters is presented in **Table 8**, while the recorded data on preventive and corrective maintenance tasks is reported in **Table 9**.

Table 8. Monitored parameters in surgery theatres

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

Table 9. List of preventive and corrective maintenance information that can fill the model as objects properties

Work Orders History	
WorkOrderID	Description
BuildingID	DateOfRegistration
DateOfCompletion	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	DateOfCompletion
Notes	StatusID

Environmental Condition Index definition and formulation

In order to define the Environmental Condition Index (ECI), the **Analytic Hierarchy Process (AHP)** and the **Delphi method** were deployed.

AHP (Saaty, 1980) is a widely recognised methodology based on pairwise comparisons that derive criticality weights from expert judgement.

The Delphi method, applied with a panel of 17 experts (engineers, architects, medical doctors, nurses, and a chemist) from the Salerno and Verona organisations, structured iterative rounds of comparison to achieve consensus on environmental quality parameters to me measured and relevant functional sub-areas and units.

Through a Delphi, the control parameters to me measured to monitor operating theatre environmental quality were identified as follows:

- Contamination at rest;
- Contamination during operation;
- Microclimatic conditions at rest;
- Microclimatic conditions during operation;
- Air volumes/Recovery time;
- Anaesthetic gases concentration;
- Noise level.

The pair comparison matrix concerning the functional sub-areas (Consistency Ratio equal to 0,03) and related vector of weights are reported in **Table 10**.

The pair comparison matrix concerning the environmental quality factors (Consistency Ratio equal to 0,07) and its related vector of weights are reported in **Table 11**.

Table 10. Pairwise comparison matrix and criticality weights of functional sub-area forming a surgery unit

Functional sub-area	Reception	Surgery	Staff services	Support	**Weight (%)**
Reception	1.00	0.15	0.25	0.37	**7**
Surgery	6.69	1.00	1.83	1.37	**42**
Staff services	3.97	0.55	1.00	0.59	**22**
Support	2.70	0.73	1.69	1.00	**29**

Table 11. Pair comparison matrix and criticality weights of environmental quality parameters

Environmental Quality Parameter		1	2	3	4	5	6	7	**Weight (%)**
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, Recovery time	5	3.90	2.27	5.39	3.78	1.00	0.27	2.47	**21**
Anaesthetic gases concentration	6	6.65	3.71	6.65	4.72	3.66	1.00	5.62	**40**
Noise level	7	1.08	0.21	1.98	0.38	0.40	0,18	1.00	**5**

On this basis, the **Environmental Condition Index (ECI)** was developed as a weighted average of control parameter values, where weights correspond to the criticality of each factor in relation to environmental quality.

ECI is a **Key Performance Indicator (KPI)** that **quantifies the environmental quality/compliance** of a healthcare environmental unit (e.g., operating theatre, staff room, filter zone, etc.) or, by aggregation, a functional area, such as a surgery unit. It aggregates **control parameters** (e.g., contamination at rest, microclimatic conditions, noise level), each expressed as a **performance state** p_i and weighted by its **criticality** w_i.

For an environmental unit k, with the applicable set of control S_k the **ECI** is expressed by the formula:

$$ECI_{Uk} = \frac{\sum_i^k p_i \; x \; w_i}{\sum_i^k w_i}$$

Where:

- ECI_{Uk} is Environmental Condition Index referred to the environmental unit *k*. It varies from 0 (best scenario) to 1 (worst scenario);
- $p_i \in [0,1]$ (typically binary: 0=compliant, 1= non-compliant);
- $w_i > 0$ reflects the parameter's criticality for environmental quality. The sum of all the weights is 1 (100%).

For a functional area *j* composed of environmental units *k* with unit criticalities a_k>0 the ECI can be calculated as follows:

$$ECI_{Aj} = \frac{\sum_k^j ECI_{Uk} \ x \ a_k}{\sum_k^j a_k}$$

Where:

- ECI_{Aj} = Environmental Condition Index referred to the functional area *j*. It varies from 0 (best scenario) to 1 (worst scenario).
- ECI_{Uk} = Environmental Condition Index referred to the environmental unit *k*.
- a_k = criticality weights of each environmental unit (i.e., operating room) with respect to the environmental quality of the functional area (i.e., the operating unit).

The ECI has the following features:

- It eliminates overlapping and redundant information, as some parameters are grouped when they depend on the same equipment element. This simplifies the identification of the required intervention.
- It expresses each relevant aspect of the system assessed. The list presented in **Table 8** was discussed in two focus groups to select seven parameters necessary and sufficient to evaluate the environmental quality of a surgery room.
- It provides wide applicability across the authority FM systems, as it is based on their requirements. The developed ECI is related to surgery rooms only, but further studies may expand the results to new environmental units and sub-functional areas of the surgery unit, as well as to other hospital functional areas.

- It is expressed as a numerical value ranging from 0 to 1. This results from two factors: the formula used to express the KPI and the evaluation mechanisms applied.
- Having a single index for each functional area helps facility managers rank the facilities under their responsibility, thereby simplifying decision-making. If more than one index is considered, comparisons can be made between the condition of the assessed building and an optimal one, for instance by using a radar graph (**Figure 18**).

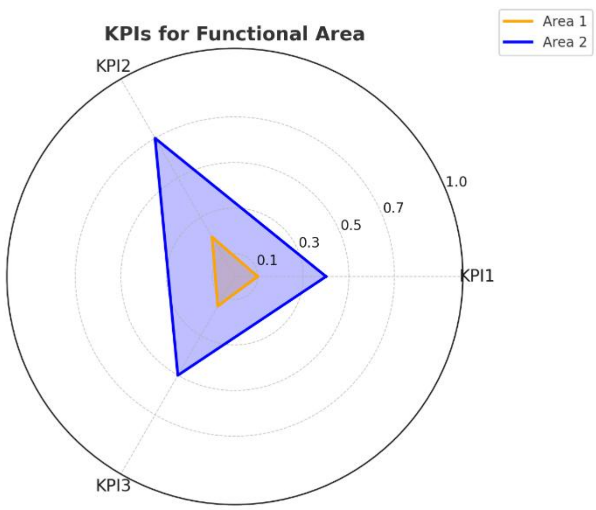


Figure 18. Instance KPIs visualisation for a functional area of interest

Correlation between environmental and technical performances

To integrate performance assessment with maintenance planning and to enhance the effectiveness of the Environmental Control Index, a systematic link was established between the values of control parameters and the corresponding maintenance interventions.
These interventions consist of inspections and checks designed to detect potential failures or inadequate operating conditions within the technological and functional systems.
The correlations between environmental parameters and the required technical actions are presented in **Table 12**. These links were defined in collaboration with experts in mechanical systems and indoor air quality, ensuring that both the monitoring approach for environmental quality and the characteristics of the installed systems were adequately considered.

For example, contamination at rest is associated with inspections of HEPA filters and HVAC pipes, while contamination in operational conditions requires verification of behavioural protocols.
Microclimatic conditions, both at rest and during operations, are linked to project condition checks and power control of Air Treatment Units (ATU). Air exchanges and recovery time involve a broader set of tasks, including filter inspections, load loss verification, forced air volume calculation, and control of mixing and ventilation efficiency.
Similarly, maintaining appropriate anaesthetic gas concentrations requires inspection of pipe fittings in both high- and low-pressure systems, as well as checks of gas evacuation systems. Finally, noise levels are managed through inspections of air-cooled systems, HVAC ducts, and ATUs.
This structured correlation ensures that environmental performance indicators are directly tied to actionable maintenance activities, thereby strengthening the operational reliability of the systems and improving the overall quality of the controlled environment.

Table 12. Links between environmental and technological performances

N°	Parameter	Task N°	Task Description
1	Contamination at rest	1.1	HEPA filters inspection
		1.2	HVAC pipes inspection
2	Contamination in operational	2.1	Behavioural protocols check
3–4	Microclimatic conditions (at rest & 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	Anaesthetic gases concentration	6.1	Pipes fitting controls (High- and Low-pressure systems)
		6.2	Gas evacuation system controls
7	Noise	7.1	Air-cooled system inspection
		7.2	HVAC ducts inspection
		7.3	ATU inspection

6.2 PIM testing on real surgery units

The methodology presented in the Chapter 4 has been implemented first on a public hospital in the South of Italy.
The Local Health Authority under study has provided new contractors for FM and Prevention and Safety activities for hospitals under its responsibility. No existing BIM models are held by the authority or the FM contractors, and the processes currently in use among them are not BIM-oriented. This is a common situation within the Italian built environment. In such context this case-study constitutes the first step taken to a BIM-aided FM.
In this case study BIM is used to gather information related to the environmental control, to communicate the monitoring results, and to analyse the condition assessment in terms of maintenance interventions required.
The controls discussed in this study concern the risk management associated with surgery rooms activities. Database containing the surgery units' environmental controls, which regard air quality, served as a first data source. 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) 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.
The case study is focused on the environmental quality management, so it was enriched by the definition of rooms and related properties (i.e., environmental condition index). The examined hospital performs environmental quality control according to a planned schedule of activities.
The analysed database regard the monitoring results related to one semester of activities carried out in three operating rooms. In this database the results were not grouped by operating room, but they were reported for each type of test separately. They were translated in a summarized Excel sheet to make them easier to read by Dynamo (**Table 13**). The monitoring results were translated to Boolean values to define the failure (1) or the fulfilment (0) of each control in each room.

Table 13. Control parameters values for each surgery room presented as Boolean values

Surgery Room	1	2	3	4	5	6	7
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 can be easily updated when monitoring activities are conducted. The data concerns 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). 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 19**).

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 20** 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).

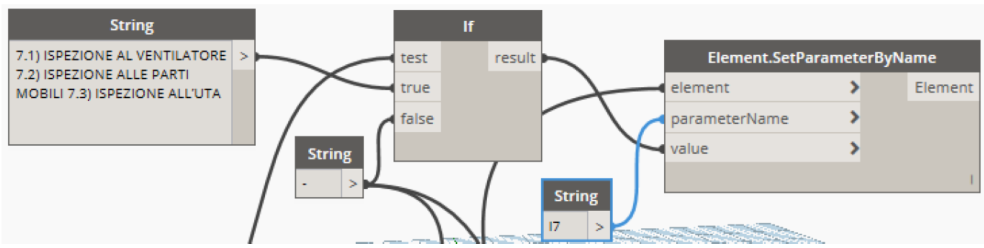


Figure 19. Dynamo conditional logic

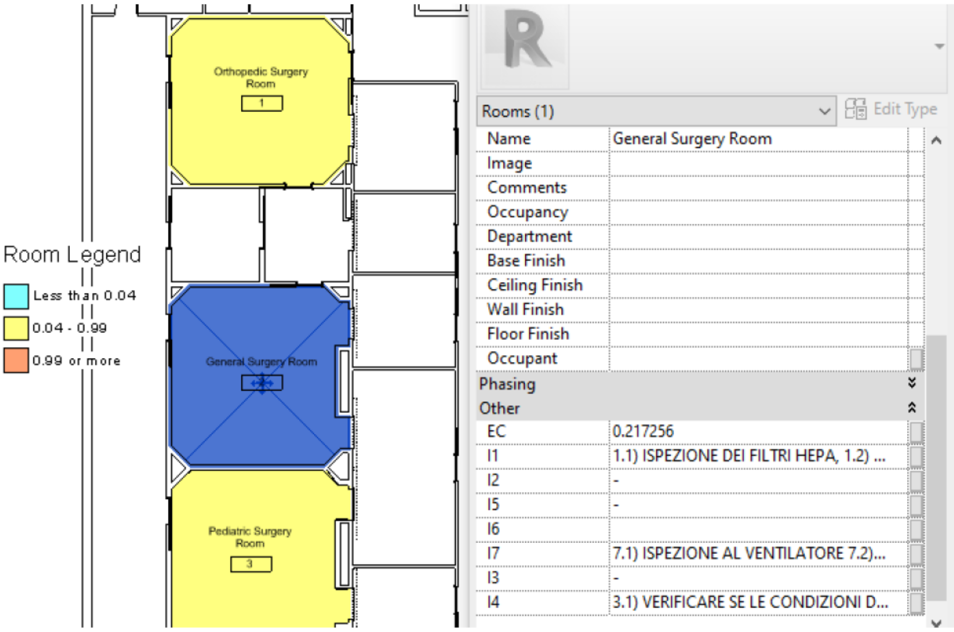


Figure 20. Thematic view of rooms and properties

6.3 OpenPIM testing on real surgery units

The implementation of the openPIM approach presented in the Chapter 5 is discussed here. Three case studies have been developed, and they concern:

- One hospital located in the South of Italy (case study A);
- One hospital located in the North of Italy (case study B);
- One hospital located in Slovenia (case study C).

The openPIM database has been filled with information retrieved from those organisations. In particular the following sources were used:

- Tenders' specifications about monitoring activities and O&M management for identifying contractors and managers involved in those processes. In this way the tables *RoleEnum, Person, Organization, PersonAndOrganization, ActorRole, Actor* were filled;
- Maintenance plans, reports of corrective maintenance activities and project orders records were examined to fill *WorkPlan, WorkPlanTypeEnum, WorkSchedule, WorkScheduleTypeEnum, Task, TaskTimeRecurring, TaskTypeEnum, ProjectOrder, ProjectorderTypeEnum, Product* tables;

- Results of environmental condition and evaluation of the Environmental Condition Index were used for *Measurement, KeyPerformanceIndicator, KeyPerformanceIndicatorResult* tables.

The implementation of the openPIM regards surgery units. An Environmental Condition Index (ECI) has been used to quantify and evaluate the environmental quality of surgery rooms of A and B case studies. The case study A was used also to validate the openPIM framework related to corrective and preventive maintenance management, while the case study C aimed at testing the openPIM framework for the planned maintenance management.
Filling the database implies following its structure. As an example, to define an instance of an actor it is necessary to fill *RoleEnum, ActorRole, Person, Organization, PersonAndOrganization* tables first. Each actor instance is identified by a unique id. The **Figure 21** reports the example of the environmental monitoring supplier, to whom the id=6 in the *Actor* table is associated.

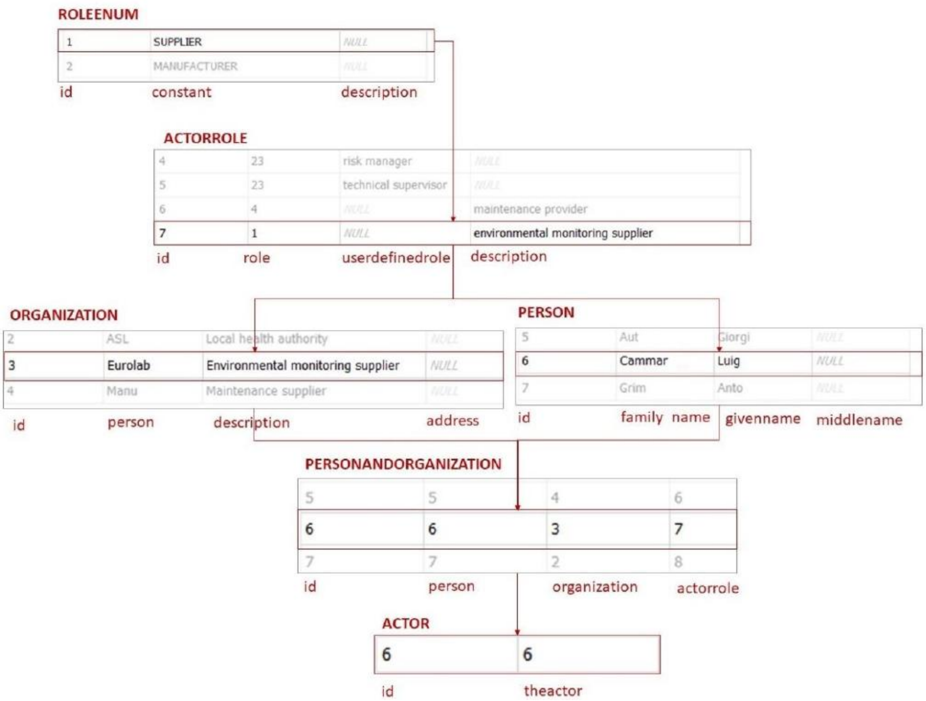


Figure 21.Example of database filling process

Autodesk Revit 2019 was used to create native models. This modelling software allows to export IFC models in different versions, including IFC4 Reference View and IFC4 Design Transfer View. The re-importation of such IFC models in the modelling platform (Revit 2019) was affected by a certain grade of loss of information. For this reason, the IFC 2x3 Coordination View version, correctly and comprehensively exported and re-imported, was chosen to implement the BIM-FM-BPA integration (**Figure 22**). During the exportation the IFC GUID was stored as element parameter, the level of detail for element geometry was settled as low.

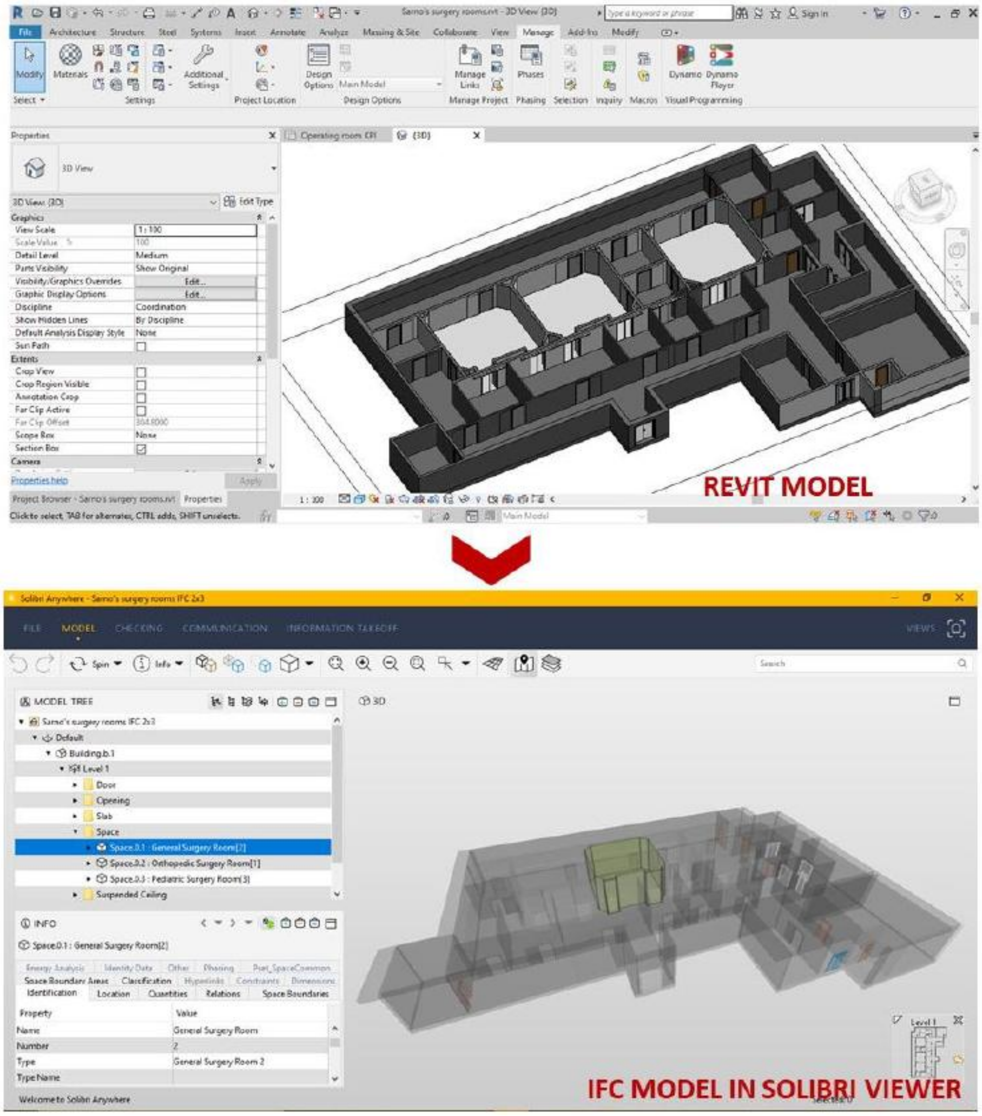


Figure 22. The BIM model was created using Autodesk Revit 2019. The IFC model has been exported and visualized on Solibri viewer

After the exportation, the IFC was opened in Revit and managed by Dynamo. In order to establish a connection between the model and the database, the *Slingshot!* Dynamo package was used. It contains a group of nodes for utilizing relational database management system.
The SQLite engine database was chosen among others (i.e. PostgreSQL and MySQL) as it is commonly used all over the world and above all, it is

file-based, so that possible connection issues can be avoided (**Figure 23**). The database was created and edited in DB Browser for SQLite.

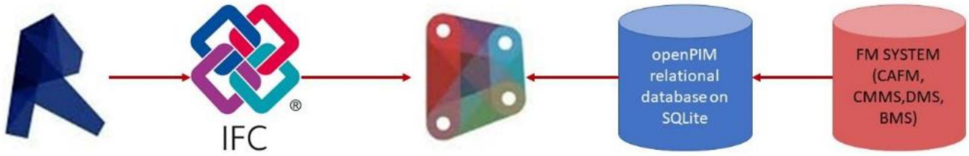


Figure 23. Integration process between FM systems and BIM model. Revit has been used for creating native models and exporting them in the IFC data format, the relational database integrates the IFC model through a Dynamo application

Case study A

The **case study A** regards a public hospital containing three surgery rooms. In this case study BIM is used to **gather information related to the environmental control, to communicate the monitoring results, and to analyse the condition assessment in terms of maintenance interventions required**.

The *SelectModelElement* node has been used to identify id elements directly from the view in use on Revit. This is the starting point for querying the database about further information related to that element. As an example, it is possible to extract the environmental performance assessment results for the general surgery room. Retrieving the *localId* and the associated *globalId* from the element model it is possible to deduct the measurements related to it. These measurements are linked to one or more KPI results through the *RelAssignsToMeasurement* relationship.

From the *KeyPerformanceIndicatorResult* table it is possible to retrieve the KPI value and other attributes (interpretation, comment, etc.). Furthermore, the *Element.SetParameterByName* node can be used to update the IFC model with data from the database (**Figure 24**).

The results can be also visualised in a thematic plan (**Figure 25**). It must be noticed that user-defined parameters are not exported in IFC model by default. To store customised parameters, such as ‘EC’ that stands for Environmental Condition Index value, the Revit property set has been exported too.

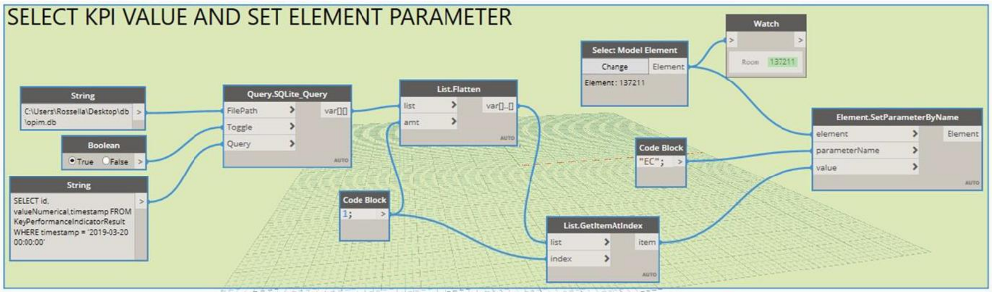


Figure 24. database query performed on Dynamo and the element parameter setting

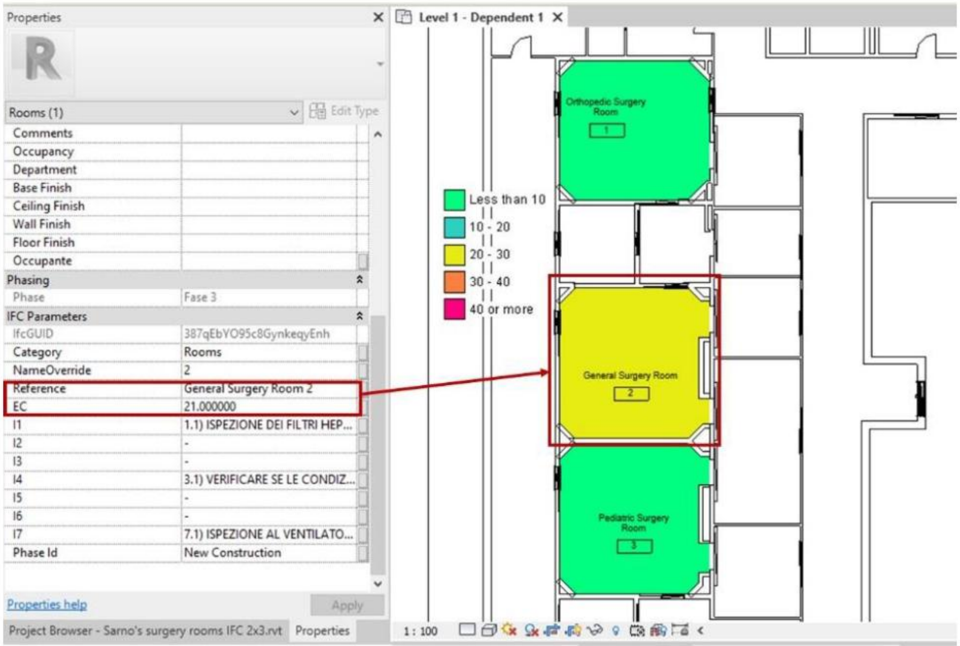


Figure 25. Thematic plan for surgery rooms. The value 21 stands for 21%

The same information can be obtained from the DBMS itself. An SQL *JOIN* clause can query columns from several tables to obtain combined results. A *JOIN* combines columns from one or more tables by using common values.

Some condition can be used to identify the specific required KPI value. As an example, to differ one KPI from another when they are about the same product, the *timestamp* attribute can be used as specifier.

The SQL statement used to retrieve the KPI value associated to a determined element *localID* is reported below:

SELECT globalId, localID,
RelAssignsToMeasurement.relatedMeasurement, valueNumerical
FROM Product
INNER JOIN RelAssignsProductToMeasurement
ON RelAssignsProductToMeasurement.relatingProduct =
Product.globalId
INNER JOIN RelAssignsToMeasurement
ON RelAssignsToMeasurement.relatedMeasurement=
RelAssignsProductToMeasurement.relatedMeasurement
INNER JOIN KeyPerformanceIndicatorResult
ON KeyPerformanceIndicatorResult.id =
RelAssignsToMeasurement.relatingResult
WHERE timestamp='2019-03-20 00:00:00' **AND** localId= '137211'.

Through the database it is possible to get information about planned or corrective maintenance activities associated to an object, both done or waiting to be performed.
For example, from the *ActionRequest* table it is possible to retrieve the request for corrective intervention regarding a door. The *localId* and/or the *globalId* permits to identify univocally the object, the *RelAssignsActionRequestToProduct* relationship gives the request for intervention related to that object, the *ActionRequest* table contains information about such a request.
The SQL statement in this case is:

SELECT globalId, name, identification, longDescription
FROM Product
INNER JOIN RelAssignsActionRequestToProduct
ON RelAssignsActionRequestToProduct.relatedProduct =
Product.globalId
INNER JOIN ActionRequest
ON ActionRequest.id =
RelAssignsActionRequestToProduct.relatingActionRequest
WHERE globalId = '3EZqFqD0T2y9ctbXGTnNRR'

The results of this query are showed in the **Figure 26**. The *identification* attribute of the *ActionRequest* table has been defined considering the **Uniclass** classification system. Uniclass is a consistent classification structure for all disciplines in the construction industry. It is based on a set of tables which allow information about a project to be defined from the broadest view to the most detailed view (Uniclass, 2015). The *Ac* table of the Uniclass system contains a list of activities. The Ac_10_70 code is related to a group of remediation, repair and renovation activities.

```
SELECT globalId, name, identification, longDescription FROM Product
INNER JOIN RelAssignsActionRequestToProduct
ON RelAssignsActionRequestToProduct.relatedProduct = Product.globalId
INNER JOIN ActionRequest
ON ActionRequest.id = RelAssignsActionRequestToProduct.relatingActionRequest
WHERE globalId = '3EZqFqD0T2y9ctbXGTnNRR'
```

	globalId	name	identification	longDescription
1	3EZqFqD0T2y9ctbXGTnNRR	Fire Doors	Ac_10_70_70	Replace panic bar

Figure 26. Results showed on the Database Management System. The task concerns replacing a panic bar of a fire door

Finally, it is possible to keep track of planned preventive maintenance activities. The example reported below is related to the visual inspection of the ceiling (**Figure 27**).

```
SELECT globalId, name, task.identification, Task.longDescription, workMethod, taskTimeRecurring
FROM Product
INNER JOIN RelAssignsTaskToProduct
ON RelAssignsTaskToProduct.relatedProduct = Product.globalId
INNER JOIN Task
ON Task.id = RelAssignsTaskToProduct.relatingTask
WHERE globalId = '2K3bdZyIn3hO0kLyOnmvo0'
```

	globalId	name	identification	longDescription	workMethod	taskTimeRecurring
1	2K3bdZyIn3hO0kLyOnmvo0	Compound Ceiling	Ac_15_55	checking the ceiling complanarity and degradation	visual inspection	1

Figure 27. Results showed on the Database Management System. The task concerns preventive maintenance of ceilings

Such a task is contained in the *Task* table, the *RelAssignsTaskToProduct* relationship link the *Task* table to the *Product* table. Further information about the task, such as the frequency and the related work schedule, can be retrieved from other task-related tables. The SQL statement to get product global id, product name, task identification, task work method, task description and task time is:

SELECT globalId, name, task.identification, Task.longDescription, workMethod, taskTimeRecurring
FROM Product

```
INNER JOIN RelAssignsTaskToProduct
ON RelAssignsTaskToProduct.relatedProduct = Product.globalId
INNER JOIN Task
ON Task.id = RelAssignsTaskToProduct.relatingTask
WHERE globalId = '2K3bdZyIn3hO0kLyOnmvo0'
```

The identification code in this case is Ac_15_55 which stands for ‘Performance surveying’ according to the Uniclass classification system.

Case study B

Case study B regards a big surgery unit containing 33 operating rooms. The healthcare facilities management is not BIM-oriented and no BIM models were available. For this reason, the openPIM model was developed entirely from scratch, using the architectural and mechanical plans as the main references for building the native BIM model. This model was then employed **to gather data on environmental controls and to visualize the corresponding results**.
The sources for developing the case study were provided by the hospital’s maintenance department, which supplied information concerning three key parameters: anaesthetic gases concentration, air particle concentration, and microclimatic conditions. Other environmental quality factors were excluded, as their assessment is performed periodically in accordance with the health and safety department and the healthcare director’s requirements.
Monitoring of anaesthetic gases concentration and air particle contamination covered 31 out of the 33 operating rooms, while microclimatic conditions were reported only for 2 rooms. These factors were continuously monitored through dedicated sensors. Air contamination data were collected every two minutes, and for each surgery room, the maximum daily value was compared against the threshold limit adopted by ISPESL guidelines (ISPESL, 2009), which serve as the regulatory reference for the healthcare organization.
Anaesthetic gases concentration was evaluated on the basis of monthly reports for 31 surgery rooms, including both measured values and compliance assessments (fulfilled or failed).
Microclimatic conditions were examined to verify compliance of temperature and relative humidity levels. Temperature data were collected every minute, while relative humidity was measured every 15

minutes. As in the case of air particles, the maximum daily value was compared with the reference limits, which are established by the ISPESL guidelines (ISPESL, 2009).
All these data were used to populate and update the openPIM database. Following the same logic as in Case Study A, the measurement results were inserted into the *Measurement* table, calculated KPI values were stored in the *KeyPerformanceIndicatorsResult* table, and relationships between these data were managed in the *RelAssignsToMeasurement* table.
To enhance data integration, a **Python application** was developed and tested to automatically update the IFC model with information drawn from the database. The advantage of using Python lies in its ability to create a unique node that enables direct querying of the database. Moreover, Python nodes can handle long and complex queries (such as *inner join* statements), thereby improving the efficiency of both the database and the Dynamo application.
As part of the implementation, an application was built to retrieve KPI results for a specific product (for example, a cardiac surgery room). This application connects to the database and queries the ECI values of elements, starting from their *localId* (**Figure 28**).
These results are then used to set ECI parameter values directly within the IFC model through the *Element.SetParameterByName* node.
Due to the complexity of the BIM model, only the common IFC property set has been exported from the Revit model. Nevertheless, the IFC exportation retrieved the 'EC' parameter as IfcSpace attribute, among the IfcPropertySet of the product.

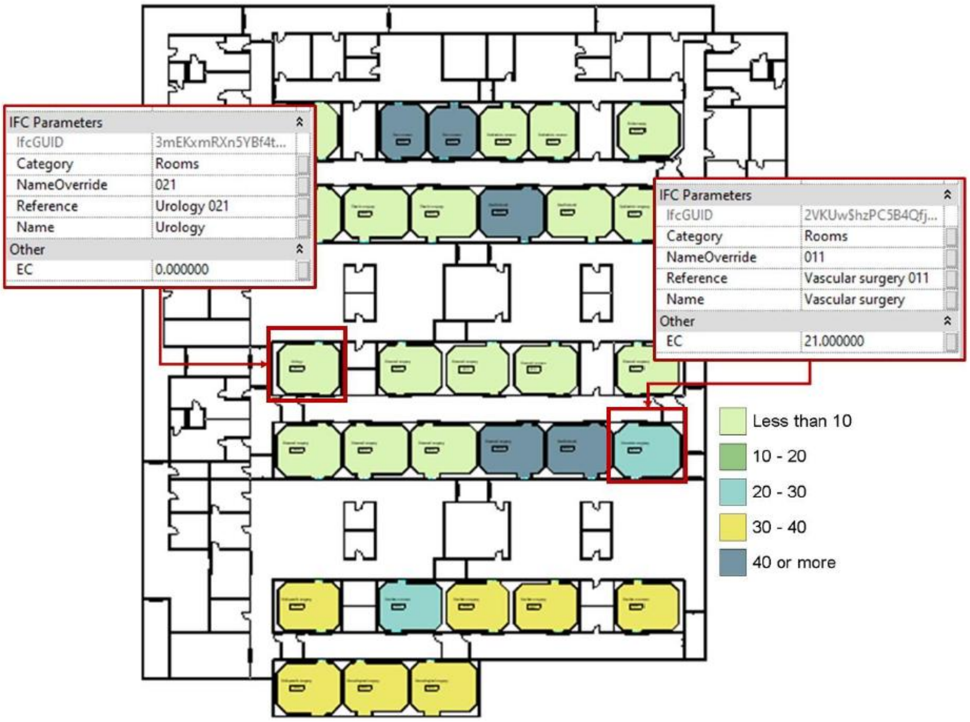


Figure 28. Thematic view reporting ECI for 31 surgery rooms

Case study C

Case study C includes a surgical unit, located in Slovenia, concerning five oncological surgery rooms.

This case study was developed **to test the capability of the openPIM database in supporting planned maintenance management within a surgical unit**. Unlike previous implementations, no environmental monitoring reports were available for this case. Nevertheless, the healthcare authority carries out both monitoring and ordinary maintenance of the surgical unit once a year, providing a framework of activities that could be used for the pilot implementation.

The maintenance plan adopted for this case included all inspection, repair, and cleaning tasks scheduled for 2019. These activities were systematically translated into the openPIM structure: the *WorkPlan, WorkSchedule, Task, TaskTimeRecurring, Product*, and related tables were populated with the data extracted from the maintenance documentation. To ensure consistency and standardization, the identification attributes of the *Task* table were defined according to the Uniclass classification system.

The database allows detailed task information, such as time resources, start and end dates, task descriptions, and the elements involved, to be stored and retrieved. An IFC model of the surgical unit was also created, based on the original CAD architectural plans. This model serves as the link between the geometric representation of building elements and the associated maintenance data.

By querying the database through the *globalId* of any IFC product, the planned maintenance information related to that element can be obtained.

A sample SQL query performed on the database, together with its results, is presented in **Figure 29**. However, since this information is not directly geometry-related, it cannot be displayed within the IFC model itself. Instead, the IFC model acts as the structural backbone, while the database provides the operational intelligence needed for managing maintenance activities in a systematic and standardized way.

SQL query

```
SELECT globalId, Task.identification, task.longDescription, task.workMethod FROM Product
INNER JOIN RelAssignsTaskToProduct
ON RelAssignsTaskToProduct.relatedProduct=Product.globalId
INNER JOIN Task
ON Task.id=RelAssignsTaskToProduct.relatingTask
WHERE globalId='23yv66nlP8wA5vCN9xEVBe'
```

Results

globalId	identification	longDescription	workMethod
23yv66nlP8wA5vCN9xEVBe	Ac_15_55	General inspection and reparation of wood and steel furnitures	visual inspection and manual work

Figure 29. SQL statement for retrieving data about planned maintenance tasks

Lessons learnt from the case studies

The case studies here presented differ in scale, in the type of data collected, and in the analyses performed (**Figure 30**).

	Case study A 3 rooms	Case study B 31 rooms	Case study C 5 rooms
Model workflow	.dwg / .rvt / .ifc LOD 200 / IfcSpace Pset (EC)	.dwg / .rvt / .ifc LOD 200 / IfcSpace Pset (EC)	.dwg / .rvt / .ifc LOD 200
Monitoring strategy	Six months based, not automated	Mostly continous and automated	Annual based, not automated
Evaluation frequency	Six-monthly	Montlhy	Annually
Planned Maintenance DB	Provided	Provided	Provided
Corrective Maintenance DB	Provided	Provided	Not provided
Monitoring DB	Provided	Provided	Not provided
Evaluation report	Provided	Provided	Not provided

Figure 30. Case study comparative analysis

Despite these differences, they share a common methodological foundation for model development, structured in three main steps:

1. **Analysing the organization's information requirements**;
2. **Developing the model in response to those needs**;
3. **Integrating Facility Management (FM) systems with BIM models**.

Within this framework, the Performance Information Model (PIM) implementation proved to be particularly effective, as it enabled:

- the definition of a workflow for PIM implementation through a **BPMN model**;
- the identification of **maintenance-related information** that can be embedded in the BIM model as element properties;
- the development of a new **Key Performance Indicator (KPI)** for surgery rooms, combining environmental and functional performance;
- the correlation between **measured performances** and the corresponding **maintenance interventions**, including inspections and controls;

- the introduction of **conditional logic** and the **integration of information systems**.

The outcomes highlight the positive impact that BIM can have on FM. A Performance Information Model does not merely store data, on the contrary, it facilitates performance analysis and streamlines information exchange across stakeholders.

A central contribution of this work is the **integration of a relational database with the BIM model**, a combination that has demonstrated strong potential. This integration allows users to efficiently store, query, and analyse building data for multiple purposes, particularly facility management. Because the data are stored in a standardized BIM-compatible form, they can be easily accessed and manipulated using SQL statements.

It is important to note, however, that alternative strategies for linking data sources exist. For example, research has explored the **use of Semantic Web technologies** for construction data management within BIM environments. This approach, capable of linking heterogeneous knowledge bases, enables complex searches and advanced data integration. As demonstrated by Shen and Chua (2011), Aziz et al. (2006), and Pauwels et al. (2015), Semantic Web approaches improve information exchange and allow machines to process building data more effectively, thereby increasing efficiency and accuracy. Niknam et al. (2019) showed how Semantic Web methods could support maintenance by linking BIM knowledge with manufacturers' product data.

Nonetheless, the openPIM approach offers distinct advantages, especially when relying on an external database. Such a system can connect multiple users to a shared information environment; store life-cycle data in a structured and user-friendly way; integrate diverse datasets to enable comparative analyses over time.

Moreover, openPIM can manage historical data, including maintenance records, assessment activities, and performance evaluation results, that are seldom captured in conventional BIM models.

The results of the openPIM case studies provide further evidence that:

- the openPIM database is structured around entities that go beyond geometry (e.g., tasks, actors, project orders). These might not be visible in IFC viewers currently available yet are essential for FM processes;

- the existing IFC 4.2 schema is already capable of supporting FM workflows in a comprehensive way, providing a broad set of entities for maintenance and performance assessment;
- the proposed openPIM can be seen as an expansion of the FM Handover MVD, introducing additional entities such as *IfcActionRequest, IfcProjectOrders, IfcTask, IfcWorkPlan, IfcWorkSchedule, IfcApproval, IfcKeyPerformanceIndicator, IfcKeyPerformanceIndicatorsResult,* and *IfcMeasurement*. These entities are crucial to support maintenance management, monitoring, planning, and performance evaluation.

In summary, the openPIM approach demonstrates how BIM, when integrated with structured databases, can evolve from a static information container into a dynamic system for performance-driven maintenance and facility management.

6.4 Patterns of BIM use for resilience and risk management

Traditional approaches to infrastructure management have long depended on visual inspections and manual measurements, which, although effective to some extent, are often time-consuming and limited in their capacity to capture complex interactions within a facility. In contrast, emerging digital technologies offer the potential for far more efficient and timely evaluations of a facility's resilience. For instance, the combination of a digital representation of physical infrastructure with artificial intelligence allows for dynamic and adaptive modelling of how various hazards may impact the built environment (Argyroudis et al., 2022). Among these technologies, Building Information Modeling has emerged as a particularly powerful tool. Yet, despite its potential, the adoption of digital technologies like BIM specifically for enhancing infrastructure resilience remains limited (Baarimah et al., 2022).
Existing literature on BIM applications in disaster management indicates that its primary use has been in evacuation route planning during fires and in anticipating damages from earthquakes or floods (Khanmohammadia et al., 2020). Nevertheless, there is still a pressing need to investigate the full spectrum of BIM's capabilities, particularly in terms of real-time monitoring and integrating it with complementary technologies such as the Internet of Things (IoT) and sensors, to prevent hazards and mitigate their effects more effectively (Sergi et al., 2020).

Risk management in the built environment generally involves identifying, assessing, mitigating, and monitoring potential threats to infrastructure and operations (Sawalha, 2020). While separating these stages aids in analysis, they are interdependent, often overlapping in practice. A practical approach involves classifying specific risk-related activities according to temporal periods of “planning, monitoring, and response” (Neal, 1997).

The increasing interest in BIM for risk management is reflected in recent literature: of 165 identified documents, 119 were published after 2017 (Marmo et al., 2023). A review of 44 selected studies categorized them into key themes: fire safety and evacuation, maintenance and operational risk management, structural integrity, sustainable construction, and other applications, including literature reviews and digital frameworks for post-event recovery.

BIM for Fire Safety

Researchers have extensively explored how building information models can be used to extract geometry and material properties, providing a foundation for advanced analyses in fire scenarios. For example, BIM was used to analyse the elements of a rail station that can affect the evacuation time to reach the shelter in place (Kim et al., 2021). Similarly, the geometry of structural and non-structural elements has been retrieved from the digital model to store them in a spatial database used to calculate the most feasible evacuation route inside a building (Castillo & Ever, 2019). Also, geometry and material properties have been used to predict temperature and CO concentration in specific spaces to find a safe path (Zhang et al., 2014). BIM and Internet of things have been integrated for enhancing fire prevention and emergency management (Chen et al., 2021). The visualisation capabilities of BIM have been used to plan optimal paths in real time, integrating Bluetooth sensors and visual guidance (Chou et al., 2019).

BIM for supporting operational risk management

When configured as an as-built, system-centric model, BIM enables facility owners to quickly identify components within building systems that may contribute to, or be affected by, specific emergencies, thereby supporting timely and well-informed decision-making.

Beyond its information management capacity, BIM's visualization capabilities have also been combined with probabilistic methods, such as Bayesian networks, to evaluate the potential consequences of adverse events and to assess the effectiveness of alternative decisions (TohidiFar et al., 2021)
The relevance of BIM to resilience assessment has been demonstrated in critical settings such as hospitals, where it has been used to create structured databases linking requirements and functions to tangible building objects, including spaces, construction elements, furniture, and equipment (Ransolin et al., 2020). Extending this approach, researchers have proposed resilience rating systems that integrate BIM with KPIs to support asset and portfolio management (F. Re Cecconi et al., 2018).
In terms of bridge performance assessment, BIM was employed to develop a visualization tool that organizes sensor data and structural health information, thereby enabling systematic and more intuitive condition assessment (Boddupalli et al., 2019).

BIM for improving seismic safety

In the context of seismic risk, BIM has been applied for site-specific planning, monitoring potential hazards, and guiding repair or retrofit interventions (Liu et al., 2016). It provides critical information for operational planning and risk mitigation, including predictive modelling for structural failures and prioritization of interventions. It must be considered that predicting the seismic loss of a building is critical for improving its resilience. In this regard, an office building in Beijing served as a pilot test for a BIM-based framework aimed at visualising and understanding the seismic damage and loss, thus for planning mitigation interventions of such a disaster (Xu et al., 2019).

BIM for more sustainable construction

BIM's potential for supporting energy management is widely acknowledged (Gao et al., 2019). By recording building data from the earliest design stages, BIM enables energy simulations that can inform performance optimization throughout the life cycle. More recent studies have extended its application to life cycle cost analysis, allowing designers to evaluate alternatives and select options that balance cost efficiency with resilience (Rad et al., 2021).

Beyond cost, BIM has also been used to assess environmental impacts. For example, customized frameworks within BIM authoring software have been developed to evaluate the implications of different material and component choices (Angeles et al., 2021). Similarly, existing tools have been integrated with BIM models to perform life cycle assessments, capturing resource use and emissions associated with each material or process (Phillips et al., 2020).

Mapping BIM uses in risk management phases

The analysis of the scientific findings shows that BIM has been applied primarily in the pre-disaster phase, particularly for mitigation and preparedness activities such as performance prediction, extraction of building geometry for further analysis, and generation of bills of material. Nevertheless, several studies also demonstrate its application during and after hazardous events, where BIM has been used to analyse and visualize building components and systems, supporting timely decision-making and guiding retrofitting interventions.

Across all phases, the most common purposes of BIM use are the gathering and communication of data. Typical examples include retrieving the current status of facilities, quantifying building elements, collecting performance information, visualizing geometry, and facilitating the transfer of information to other processes. In some cases, BIM is also used to forecast performance and locate specific facility elements.

With respect to model characteristics, no significant differences emerge between studies conducted in the design phase and those in the operational phase. The facility elements most frequently addressed are architectural and structural systems, though mechanical, plumbing, and electrical installations, particularly fire safety systems, are also well represented in studies focused on emergency management.

In most cases, resilience assessments are performed outside the BIM environment; however, BIM consistently serves as a central tool for gathering and communicating the data required for further analysis.

The potential of BIM for resilience assessment becomes particularly evident when evaluation criteria and key performance indicators are defined in advance. In such cases, BIM can provide a structured framework to measure resilience systematically. Looking ahead, BIM could play an important role for example by embedding evaluation criteria related to robustness, redundancy, or flexibility of facilities and their systems. Integrating such criteria within BIM platforms would support the identification of adaptive interventions, enhancing the resilience of buildings against diverse hazards, whether epidemics, climate-related challenges such as rising temperatures, or seismic events.

References

Angeles, K., Patsialis, D., Taflanidis, A. A., et al. (2021). Advancing the design of resilient and sustainable buildings: An integrated life-cycle analysis. *Journal of Structural Engineering, 147*(3), 04020341. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002939

Argyroudis, S. A., Mitoulis, S. A., Chantzi, E., et al. (2022). Digital technologies can enhance climate resilience of critical infrastructure. *Climate Risk Management, 35,* 100387. https://doi.org/10.1016/j.crm.2021.100387

Aziz, N. D., Nawawi, A. H., & Ariff, N. R. M. (2016). ICT evolution in facilities management (FM): Building Information Modelling (BIM) as the latest technology. *Procedia – Social and Behavioral Sciences, 234,* 363–371. https://doi.org/10.1016/j.sbspro.2016.10.253

Baarimah, A. O., Alaloul, W. S., Liew, M. S., et al. (2022). A bibliometric analysis and review of building information modelling for post-disaster reconstruction. *Sustainability, 14*(1), 393. https://doi.org/10.3390/su14010393

Boddupalli, C., Sadhu, A., Rezazadeh, E., & Pattyson, S. (2019). Improved visualization of infrastructure monitoring data using building information modeling. *Structure and Infrastructure Engineering, 15*(9), 1247–1263. https://doi.org/10.1080/15732479.2019.1602150

Castillo, O., & Ever, E. (2019). Simulation of evacuation route scenarios through multicriteria analysis for rescue activities. *Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 37*(5), 303–313.

Chen, C., Lee, Y., & Chen, A. (2021). A building information model enabled multiple traveling salesman problem for building interior patrols. *Advanced Engineering Informatics, 47,* 101237. https://doi.org/10.1016/j.aei.2020.101237

Chou, J., Cheng, M., Hsieh, Y., Yang, I., & Hsu, H. (2019). Optimal path planning in real time for dynamic building fire rescue operations using wireless sensors and visual guidance. *Automation in Construction, 99,* 1–17. https://doi.org/10.1016/j.autcon.2018.11.007

Gao, X., & Pishdad-Bozorgi, P. (2019). BIM-enabled facilities operation and maintenance: A review. *Advanced Engineering Informatics, 39,* 227–247. https://doi.org/10.1016/j.aei.2019.01.005

ISPESL – Istituto Superiore per la Prevenzione e la Sicurezza del Lavoro. (2009). *Linee guida sugli standard di sicurezza e di igiene del lavoro nel reparto operatorio.* INAIL. https://www.inail.it/cs/internet/docs/linee-guida-igiene-reparto-operatorio.pdf?section=attivita

Khanmohammadi, S., Arashpour, M., & Bai, Y. (2020). Applications of building information modeling (BIM) in disaster resilience: Present status and future trends. In K. Tateyama, K. Ishii, &

Kim, Y.-H., Choi, J.-S., Yuan, T.-F., & Yoon, Y.-S. (2021). Building-information-modeling based approach to simulate strategic location of shelter in place and its strengthening method. *Materials, 14*(13), 3456. https://doi.org/10.3390/ma14133456

Lavy, S., Garcia, J. A., & Dixit, M. K. (2014). KPIs for facility's performance assessment, Part I: Identification and categorization of core indicators. *Facilities, 32*(5), 256–274. https://doi.org/10.1108/F-09-2012-0066

Lavy, S., & Shohet, I. M. (2007). A strategic integrated healthcare facility management model. *International Journal of Strategic Property Management, 11,* 125–142. https://doi.org/10.1080/1648715X.2007.9637565

Liu, Z., & Zhang, F. (2016). A BIM-based preliminary database framework for structural hazard prevention analysis. *Open Civil Engineering Journal, 10,* 695–705. https://doi.org/10.2174/1874149501610010695

Marmo, R., Adey, B. T., & Celentano, G. (2025). Stress testing hospitals using service measures and resilience indicators. *International Journal of Disaster Risk Reduction, 123,* 105492. https://doi.org/10.1016/j.ijdrr.2025.105492

Marmo, R., Pascale, F., & Sicignano, E. (2023). A review of Building Information Modelling applications for disaster resilience assessment. In F. Gaspar & A. Mateus (Eds.), *Sustainable and digital building.* Springer. https://doi.org/10.1007/978-3-031-25795-7_21

Marmo, R., Nicolella, M., Polverino, F., & Tibaut, A. (2019). A methodology for a performance information model to support facility management. *Sustainability, 11,* 7007. https://doi.org/10.3390/su11247007

Neal, D. M. (1997). Reconsidering the phases of disaster. *International Journal of Mass Emergencies and Disasters, 15*(2), 239–264.

Niknam, M., Jalaei, F., & Karshenas, S. (2019). Integrating BIM and product manufacturer data using semantic web technologies. *Journal of Information Technology in Construction (ITcon), 24,* 424–439. http://www.itcon.org/2019/22

Pauwels, P., Terkaj, W., Krijnes, T., & Beetz, J. (2015). Coping with lists in the ifcOWL ontology. *22nd EG-ICE International Workshop Proceedings,* 113–122. http://hdl.handle.net/1854/LU-6890532

Phillips, R., Troup, L., Fannon, D., & Eckelman, M. J. (2020). Triple bottom line sustainability assessment of window-to-wall ratio in US office buildings. *Building and Environment, 182,* 107057. https://doi.org/10.1016/j.buildenv.2020.107057

President of the Italian Republic. (1997). *Presidential Decree 14/01/1997.* Gazzetta Ufficiale della Repubblica Italiana, n. 42, 20 February 1997.

Rad, M., Jalaei, F., Golpour, A., et al. (2021). BIM-based approach to conduct life cycle cost analysis of resilient buildings at the conceptual stage. *Automation in Construction, 123,* 103480. https://doi.org/10.1016/j.autcon.2020.103480

Ransolin, N., Saurin, T. A., & Formoso, C. T. (2020). Integrated modelling of built environment and functional requirements: Implications for resilience. *Applied Ergonomics, 88,* 103154. https://doi.org/10.1016/j.apergo.2020.103154

Re Cecconi, F., Moretti, N., Maltese, S., et al. (2018). A rating system for building resilience. *TECHNE, 15,* 358–365. https://doi.org/10.13128/Techne-22119

Saaty, T. (1980). *The analytic hierarchy process: Planning, priority setting, resource allocation*. McGraw-Hill.

Sawalha, I. H. (2020). A contemporary perspective on the disaster management cycle. *Foresight, 22*(5), 469–482. https://doi.org/10.1108/FS-11-2019-0097

Sergi, I., Malagnino, A., Rosito, R. C., et al. (2020). Integrating BIM and IoT technologies in innovative fire management systems. In *2020 5th International Conference on Smart and Sustainable Technologies (SpliTech)* (pp. 1–5). IEEE. https://doi.org/10.23919/SpliTech49282.2020.9243706

Shen, L., & Chua, D. (2011). Application of Building Information Modeling (BIM) and Information Technology (IT) for project collaboration. In *Proceedings of the International Conference on Engineering, Project and Production Management (EPPM)* (pp. 67–76).

Shohet, I. M., & Lavy, S. (2017). Facility maintenance and management: A health care case study. *International Journal of Strategic Property Management, 21*(2), 170–182. https://doi.org/10.3846/1648715X.2016.1258374

Terranova, F. (2005). *Edilizia per la sanità*. UTET.

TohidiFar, A., Mousavi, M., & Alvanchi, A. (2021). A hybrid BIM and BN-based model to improve the resiliency of hospitals' utility systems in disasters. *International Journal of Disaster Risk Reduction, 57,* 102176. https://doi.org/10.1016/j.ijdrr.2021.102176

UNI. (1981/1983). *UNI 8290-1:1981 + A122:1983. Residential building. Building elements. Classification and terminology.*

UNI. (1999). *UNI 10838:1999. Building – Terminology for users, performances, quality and building process.*

Uniclass. (2015). *Uniclass 2015*. https://www.thenbs.com/our-tools/uniclass-2015

Xu, Z., Zhang, H., Lu, X., et al. (2019). A prediction method of building seismic loss based on BIM and FEMA P-58. *Automation in Construction, 102,* 245–257. https://doi.org/10.1016/j.autcon.2019.02.016

Zhang, C., Xu, H., Liu, Z., & Cui, J. (2018). BIM-based safe path finding for building evacuation. In M. Anderson (Ed.), *Proceedings of the 6th Annual International Conference on Architecture and Civil Engineering (ACE 2018).* Global Science and Technology Forum.

7. Looking forward

Current research trends reveal that there is a continuously growing interest in facilities information management using BIM, which offers a good opportunity for integrating various data sources needed for daily O&M activities. 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 has been tested.
Current BIM applications in the operational phase regard mostly the opportunity to release a comprehensive inventory about the asset to be managed. Visualisation is the key benefit. Nevertheless, a seamless information process between BIM and FM systems is hard to obtain. For this purpose, open standard data models improve data mapping and data integration between BIM models and FM systems.
Surveys aiming at developing the common BIM data requirements for O&M are limited and more focused surveys for specific building types and for specific O&M tasks must be conducted.
Literature findings demonstrate that digital models hardly become digital twins of real assets, that is to say these models unlikely are updated during the asset lifecycle.
Within this context, this book argues for developing a methodological approach to integrate BIM, BPA and FM systems, supporting organisational, environmental and technical requirements achievement during the asset lifecycle. To do so a novel Performance Information Model is presented. It is meant to be a decision- making support tool, based on the use of KPIs as relevant summarized knowledge vehicles which keep the model beneficial to FM and maintenance scopes.
A comprehensive Performance Information Model has at least the following application benefits:

- Integrated and updated visualization of the operating condition of building and its elements;
- Inventory management of building components, spaces, furniture and documents;
- Automation of the quantity take-off;
- Supported maintenance history management;
- Supported scheduling of future maintenance interventions;
- Integrated sources of knowledge.

The PIM framework allows the creation of a client-oriented model which will be kept updated more likely than a non-performance based model.
Stakeholders' information requirements lead the model and related database design; an IFC model is created according to this set of information; many applications and technologies (through visual programming language, python programming language, structured query language, semantic web, etc.) can be developed to integrate sources of data. The openPIM directly supports performances reports, and, as a consequence, several analyses (as financial, technical, environmental, sustainability, etc.) which can target future interventions.
It is evident that different application areas lead to Performance Information Models depicting new system and addressing new information requirements and performance assessment procedures.
Following the methodological approach here used (analysis of organization's information requirements; development of Performance Information Models; integration of sources useful for the operational phase), new case studies will require the identification and/or the definition of new KPIs and related measurable control parameters and they will result into new asset information requirements, that is to say different PIMs. Those case studies will implement the openPIM database in a way that its structure will be respected but the measurements and related KPI results will differ for scopes.
Further research serves to test on more comprehensive as-built models the PIM and openPIM applicability and related benefits. Technical and economic aspect of facilities management must be considered to obtain a fully integrated Performance Information Model supporting FM ad BPA activities.
More complex analysis (e.g., related to system affordability, reliability, vulnerability, sustainability, obsolescence, components actual service life, etc.) are to be explored through the PIM development. These analyses can be conducted at the component and at the asset scale. The use of KPIs (financial, technical, organisational) will address different scales of decision making and will enable benchmarking activities.

List of Figures

List of Tables

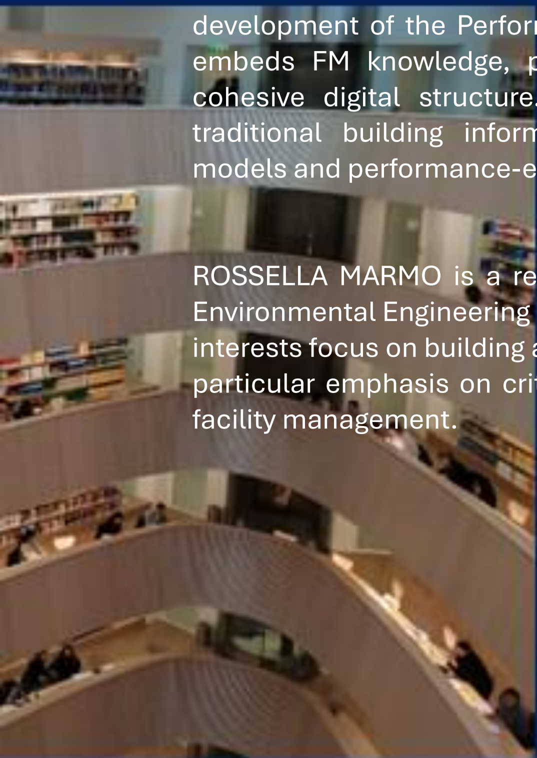
Acronyms

AEC	Architecture, Engineering and Construction
AHP	Analytical Hierarchy Process
BAS	Building Automation Systems
BEMS	Building Energy Management Systems
BIM	Building Information Modeling
BPA	Building Performance Assessment
BPE	Building Performance Evaluation
BPMN	Business Process Modelling Notation
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-Aided Design
CAFM	Computer Aided Facility Management
CDE	Common Data Environment
CMMS	Computerized Maintenance Management System
COBie	Construction Operations Building Information Exchange
CSFs	Critical Success Factors
DDL	Data Definition language
DML	Data Manipulation Language
DMS	Document Management System
ECI	Environmental Condition Index
ER model	Entity-Relationship model
FM	Facility Management
HSE	Health and Safety Environment
ICT	Information Communication Technologies
IFC	Industry Foundation Classes
KPI	Key Performance Indicator
LEED	Leadership in Energy and Environmental Design
LOD	Level Of Development
LOG	Level of Geometry
LOI	Level of Information
MVD	Model View Definition
O&M	Operation and Maintenance
PDCA	Plan-Do-Check-Act
PIM	Performance Information Model
POE	Post Occupancy Evaluation
SLA	Service Level Agreement
SQL	Structured Query Language
VPL	Visual Programming Language

This monograph presents a comprehensive exploration of the intersection between Building Information Modelling (BIM) and Facility Management (FM), offering a collection of research activities aimed at enhancing the management of buildings and complex systems. In recent years, the advent of advanced information technologies has created new opportunities to optimize Facility Management, with BIM emerging as a particularly powerful tool for integrating multiple disciplines within a single digital environment. Despite its potential, achieving a fully integrated model that connects BIM and FM systems remains a challenge.

The research activities discussed in this monograph advocate for the development of the Performance Information Model (PIM), a framework that embeds FM knowledge, performance monitoring, and assessment into a cohesive digital structure. The monograph highlights the transition from traditional building information models to facility management–oriented models and performance-enriched digital twins.

ROSSELLA MARMO is a researcher in the Department of Civil, Building and Environmental Engineering at the University of Naples Federico II. Her research interests focus on building asset management and resilience assessment, with particular emphasis on critical facilities such as hospitals and on BIM-aided facility management.



ISBN: 978-88-6887-369-1
DOI: 10.6093/978-88-6887-369-1