Design for Smart Maintenance enabled by BIM and IoT

Beatriz Campos Fialho

University of São Paulo
Institute of Architecture and Urbanism of São Carlos (IAU/USP)

(Corrected version)

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Projeto para manutenção inteligente assistido por BIM e IoT

Beatriz Campos Fialho

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Abstract

FIALHO, Beatriz Campos. **Design for smart maintenance enabled by BIM and IoT.** 2021. 319 p. Thesis (Doctor of Science) - Institute of Architecture and Urbanism, University of São Paulo, São Carlos, 2021.

Building Design Process management plays a strategic role in the Architecture, Engineering and Construction (AEC) industry concerned with business performance, users' comfort and satisfaction, and sustainable use of natural resources over buildings' lifecycles. Of particular importance are the Reactive Maintenance (RM) services performed within the longest and costly phase of Operation and Maintenance (O&M). RM is characterized by delays, waste, and difficulties in service prioritization and identification of root causes of failures, impacting on critical problems attendance and users' experience. Such inefficiencies are mainly related to the management of asset information and communication and hamper the generation and access to accurate information over a lifecycle. Recently, Information and Communication Technologies (ICTs), such as Building Information Modelling (BIM) and Internet of Things (IoT) have been applied to Facilities Management (FM) activities, showing potential for predictive and sustainable practices. However, the literature lacks scientific and empirical evidence regarding process requirements and impacts involved in their implementation in FM. In this respect, this research aimed at the development of a framework for BIM and IoT implementation in reactive maintenance services oriented to a predictive approach from the definition of three key objectives: (i) to characterize critical reactive maintenance problems and scenarios and opportunities for BIM and IoT implementation; (ii) to analyse and classify BIM and IoT solutions recently applied to FM and reactive maintenance services according to their benefits, gains, enablers, and barriers; and (iii) to characterize strategies and decisions involved in the planning, development, implementation, testing, and assessment of a BIM and IoT-based smart maintenance system and its impacts on the maintenance services and potential contributions to the design phase. The research was based on a pragmatic philosophy and a qualitative and quantitative mixed method design. Multiple Case Study and Prototyping were the research strategies, adopting university campuses as objects of investigation. Literature Review and Systematic Literature Review (SLR) supported the generation of theoretical data for the multiple case study and prototyping and discussion of the findings. Documental Analysis, Semi-structured Interviews, Focus Group, and Prototype development assisted the generation of empirical data on universities' FM sector and RM services. Qualitative and Content Analyses were applied to qualitative data, whereas Statistical Analysis involved quantitative ones. Both research process and methodology contributed to knowledge gain. The study has provided a holistic approach of the topic through the clarification of circumstances in which maintenance services and FM sectors can benefit from BIM and IoT and identification of technological, procedural, and policy issues involved in their implementation. The research findings have evidenced a necessity for the identification of critical services and activities within organizations and standards, guidelines, and upskilling actions for an efficient data management between BIM and IoT systems and over a building's lifecycle. They have also demonstrated the role of building performance information as an input for improvements in O&M and the initial design process stages. The thesis has addressed an agenda towards an innovative, sustainable, and efficient management of buildings, mitigating the environmental impacts of AEC industry and its contributions to climate change.

Keywords: Facilities Management. Reactive Maintenance. Predictive Maintenance. Building Information Modelling. Internet of Things. Digital Twin. University Campus.

Resumo

FIALHO, Beatriz Campos. **Projeto para manutenção inteligente assistido por BIM e IoT.** 2021. 319 p. Tese (Doutorado em Ciências) – Instituto de Arquitetura e Urbanismo, Universidade de São Paulo, São Carlos, 2021.

A gestão do Processo de Projeto de edifícios desempenha um papel estratégico na indústria da Arquitetura, Engenharia e Construção (AEC) voltada para o desempenho dos negócios, conforto e satisfação dos usuários e uso sustentável de recursos naturais no ciclo de vida dos edifícios. De particular importância são os serviços de Manutenção Reativa (MR) executados durante a longa e onerosa fase de Operação e Manutenção (O&M). A MR é caracterizada por atrasos, desperdícios e dificuldades na priorização de serviços e identificação da causa de falhas, impactando o atendimento de problemas críticos e experiência dos usuários. Tais ineficiências estão principalmente relacionadas à gestão da informação e comunicação, dificultando a geração e acesso a informações precisas durante o ciclo de vida. Tecnologias da Informação e Comunicação (TICs), como Modelagem da Informação da Construção (BIM) e Internet das Coisas (IoT), têm sido aplicadas às atividades de Gerenciamento de *Facilities* (FM), demonstrando potencial para práticas preditivas e sustentáveis. Entretanto, há uma falta de evidências científicas e empíricas sobre requisitos processuais na implementação dessas tecnologias e seus impactos sobre FM. Esta pesquisa teve como objetivo desenvolver um framework para implementação de BIM e IoT em serviços de MR orientados a uma abordagem preditiva a partir de três objetivos específicos: (i) caracterizar problemas e cenários críticos de MR e oportunidades para a implementação de BIM e IoT; (ii) analisar e classificar soluções BIM e IoT recentemente aplicadas aos serviços de FM e MR conforme seus benefícios, ganhos, facilitadores e barreiras; (iii) caracterizar estratégias e decisões envolvidas no planejamento, desenvolvimento, implementação, teste e avaliação de sistema de manutenção inteligente baseado em BIM e IoT, seus impactos nos serviços de manutenção e contribuições potenciais para a fase de projeto. Baseada em uma filosofia pragmática e no método misto, Estudo de Casos Múltiplos e Prototipagem foram adotados como estratégias de pesquisa e os campi universitários como objetos de investigação. Revisão da Literatura e Revisão Sistemática da Literatura geraram dados teóricos para o desenvolvimento dos casos e prototipagem e discussão dos resultados. Análise documental, entrevistas semiestruturadas, grupo focal e prototipagem geraram dados empíricos sobre o setor de FM e serviços de MR das universidades. Os dados foram analisados por meio de Análises Qualitativa, de Conteúdo e Estatística. O processo de pesquisa e a metodologia contribuíram para o conhecimento. A pesquisa forneceu uma abordagem holística do tópico, esclarecendo circunstâncias em que serviços de manutenção e setores de FM podem se beneficiar de BIM e IoT e identificando questões tecnológicas, processuais e políticas envolvidas em sua implementação. Os resultados demonstraram a necessidade de mapear serviços e atividades críticas nas organizações e desenvolver padrões, diretrizes e ações de aprimoramento para o gerenciamento eficiente de dados entre sistemas BIM e IoT e durante o ciclo de vida. Além disso, evidenciam a importância de informações de desempenho para melhorias nas atividades O&M e nos estágios iniciais do processo de projeto. Esta tese abordou uma agenda para a gestão inovadora, sustentável e eficiente de edifícios, mitigando impactos ambientais da AEC e suas contribuições para as mudanças climáticas.

Palavras-chave: Gerenciamento de *Facilities*. Manutenção Reativa. Manutenção Preditiva. Modelagem da Informação da Construção. Internet das Coisas. Campus Universitário.

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ABNT	Associação Brasileira de Normas Técnicas (Brazilian Association of Technical Standards)
AEC	Architecture, Engineering and Construction industry
BAS	Building Automation System
BIM	Building Information Modelling
BMS	Building Management System
BSI	The British Standards Institution
CAD	Computer Aided Design
CAFM	Computer Assisted Facilities Management system
CMMS	Computerized Maintenance Management System
CDE	Common Data Environment
COBie	Construction Operation Building Information Exchange
FM	Facilities Management
HVAC	Heating Ventilation and Air Conditioning system
ICT	Information and Communication Technology
IFC	Industry Foundation Classes
IoT	Internet of Things
ISO	International Organization for Standardization
IT	Information Technology
LED	Light-Emitting Diode
LPL	Luminaire Priority Level
O&M	Operation and Maintenance
RM	Reactive Maintenance
SLR	Systematic Literature Review
WO	Work Order
WR	Work Request

Contents

1. Introduction

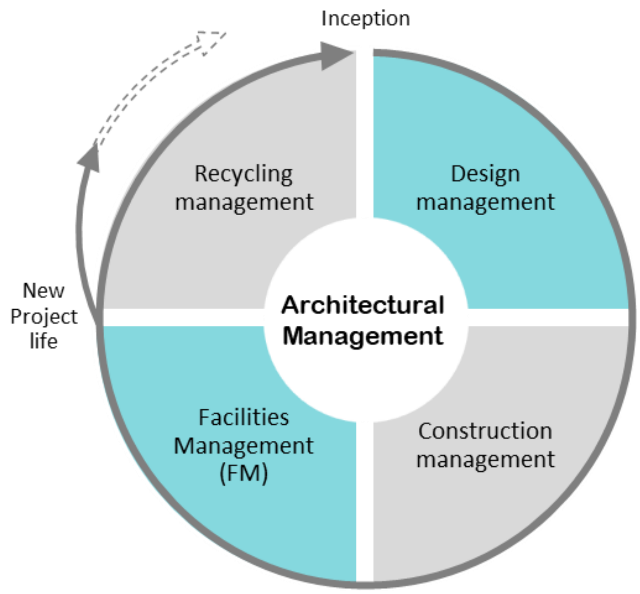
1.1. Background

Building Design Process management plays a key role in the Architecture, Engineering and Construction (AEC) industry due to its strategic importance for business performance, users' comfort and satisfaction, and sustainable use of natural resources over a building's lifecycle. Also known as Architectural Management (EMMITT, 2002), the Design process management involves people and communications in the management of the complex activities of Design, Construction, Operation and Maintenance (O&M), and recycling of buildings (Figure 1).

O&M is the longest and costly phase within the asset lifecycle, consuming roughly 80% of the whole costs and resources (ROYAL INSTITUTION OF CHARTERED SURVEYORS, 2015). The environmental impacts of buildings and the AEC industry are significant and responsible for approximately one third of energy consumption and around 40% of indirect and direct global carbon emissions among all sectors (INTERNATIONAL ENERGY AGENCY, 2021) (Figure 2). In general, the O&M phase is inefficient and negatively impacts both the development of professional and social activities in a comfortable, functional, and safe environment and the performance of businesses (SULLIVAN et al., 2010).

Facilities Management (FM)[1] is the core sector within organizations responsible for improving the performance of assets over time, user's satisfaction and quality of life, and resources consumption (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017; BOOTY, 2009). Among the typical areas described by Barrett and Finch (2014), O&M comprises FM central activities such as running and maintenance of buildings and monitoring of performance and energy management (Figure 3).

Figure 1: Architectural management

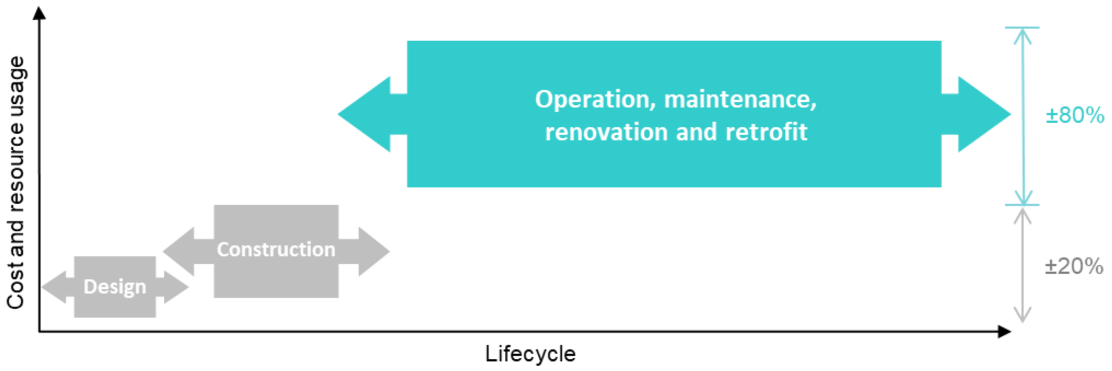


Source: Author based on Emmitt (2016)

[1] Facilities Management (FM) is defined as an "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).

The performance of Reactive Maintenance (RM) services, also known as Corrective maintenance, is the most predominant in comparison with preventive and predictive maintenance (SULLIVAN et al., 2010). Reactive Maintenance refers to items restoration after fault recognition towards ensuring the functionality of the building, electric, and mechanical systems (THE BRITISH STANDARDS INSTITUTION, 2017); if not adequately dealt with, it can directly impact on the experience and safety of building users, the organization service provision, and the business value.

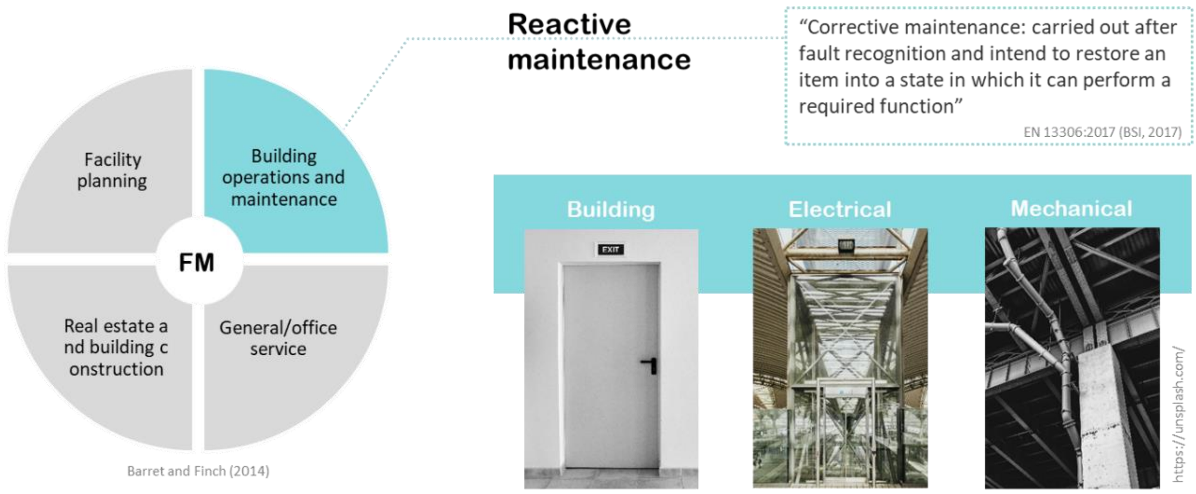
Figure 2: Cost and resource use over the life cycle of an asset



Source: Author based on the Royal Institution of Chartered Surveyors (2015)

Despite their relevance, Reactive Maintenance processes are characterized by delays and waste and difficulties in the identification of root causes of failures (ABDUL-LATEEF, 2010; AKCAMETE; AKINCI; GARRETT JR, 2010; SALLEH et al., 2016) and service prioritization (GOBER, 2008; JASPERS; TEICHOLZ, 2012; OLANREWAJU; ABDUL-AZIZ, 2015), impacting on the attendance of critical problems. Among the several aspects that contribute to this scenario are unsatisfactory performance of craftsmen, unexpected variances in work coordination, and unavailability of supplies (HIGGINS; MOBLEY, 2001).

Figure 3: FM areas and Reactive Maintenance services.



Source: Author (2021)

Nevertheless, one of the main causes of inefficiencies is related to the management of asset information and communication (LEE; AKIN, 2009; PISHDAD-BOZORGI, 2017; SULLIVAN et al., 2010), which involves not only the "collection, classification, storage and redistribution of information in digital, audio-visual or paper form", but also the ability of production and extraction of value from available information (INFORMATION MANAGEMENT, 2021).

Such difficulties in asset information and communication be explained by the complex and heterogeneous set of information generated during the building design process (SACKS et al., 2018; TALAMO; BONANOMI, 2016). FM information is characterized by a high volume and variety of information (AKCAMETE et al., 2011; PARN; EDWARDS; DRAPER, 2016) and its different formats and sources produced by multiple stakeholders (e.g., manual or digital drawings, specifications, cost spreadsheet, and list of equipment) (KIVINIEMI; CODINHOTO, 2014; PATACAS; DAWOOD; KASSEM, 2016). In most cases, requirements related to operation and maintenance are disregarded in the design phase and ineffectively provided in information handover (BECERIK-GERBER et al., 2012; MCARTHUR, 2015; PINTI et al., 2018).

Information management is typically supported by information technology systems, such as Computer Assisted Facilities Management (CAFM), Computerized Maintenance Management System (CMMS), and Building Management System (BMS) or Building Automation System (BAS) (GHOSH; CHASEY, 2013; HIGGINS; MOBLEY, 2001; PARK, 1994; SULLIVAN et al., 2010), but hampered by technical, procedural, and policy limitations (e.g., fragmentation of data among systems, need for manual input of data after building handover, and lack of standards for data structure) (BECERIK-GERBER et al., 2012; CODINHOTO et al., 2013; TALAMO; BONANOMI, 2016).

Consequently, staff time and effort are wasted in non-value adding (KOSKELA, 1992) or nonproductive activities for generating and finding accurate information when required (ABDUL-LATEEF, 2010; ARASZKIEWICZ, 2017; CODINHOTO; KIVINIEMI; KEMMER, 2013). In fact, the cost of inadequate interoperability in the O&M phase was estimated at approximately 10 billion dollars in the U.S. in 2004, reaching two-thirds of the total costs estimated for owners and operators (TALAMO; BONANOMI, 2016).

The resources used in such activities reduces the performance of FM processes (BECERIK-GERBER et al., 2012; LEWIS, 2012; PINTI et al., 2018) and reactive maintenance services, resulting in poor service delivery, dissatisfied customers, and loss of value for the organization. Besides, the lack of an integrated, structured and accessible set of information reinforces the "firefighting" culture based on uninformed decisions and reactions (BOOTY, 2009; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018).

Such limitations must be overcome for the conversion of "building's in-use data and information into tangible business knowledge to augment FM performance" (HOSSEINI et al., 2018, p. 2), moving FM and maintenance towards a more predictive approach. It is also an opportunity for an effective communication with the early stages of the design process, providing feedback on O&M for more informed design decisions.

1.2. Research problem

Information and Communication Technologies (ICTs) are key elements for remote communication and collaboration among stakeholders, expanding the capacity of technological development and the exchange of information (FABRICIO, 2002; MELHADO et al., 2006). Recently, the use of Building Information Modelling (BIM) has demonstrated potential for improving the efficiency of the AEC industry (ROYAL INSTITUTION OF CHARTERED SURVEYORS, 2015)[2], and particularly of FM (PISHDAD-BOZORGI, 2017). Defined as "the 'current

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[2] In fact, there is a global consensus regarding the potential benefits of BIM for improving environmental and social performance (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019). Consequently, organizations and governments have >>

expression of digital innovation' across the construction industry" (BUILDING INFORMATION MODELLING (BIM), 2021), BIM is comprehended in this study as an approach that integrates information on a building and its objects in a centralized digital database, thus enabling collaboration among stakeholders throughout the whole lifecycle (CORRY et al., 2014; EASTMAN et al., 2014; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019) and improvements in both quality and performance of buildings (EMMITT, 2016; SACKS et al., 2018).

Although its adoption is more representative in design and construction (KASSEM; AMORIM, 2015; MOREIRA; RUSCHEL, 2015; VOLK; STENGEL; SCHULTMANN, 2014), BIM substantially contributes in the O&M stage, where most resources and costs are consumed (AKCAMETE; AKINCI; GARRETT JR, 2010; ROYAL INSTITUTION OF CHARTERED SURVEYORS, 2015; TALAMO; BONANOMI, 2016). BIM models provide rich information on systems and spaces, improving the quality, access, and update of information over a building's lifecycle (AKCAMETE; AKINCI; GARRETT JR, 2010; BRITISH INSTITUTE OF FACILITIES MANAGEMENT, 2015). Besides, BIM enables the integration and automation of FM processes (EASTMAN et al., 2014; ROYAL INSTITUTION OF CHARTERED SURVEYORS, 2015), assisting FM sectors in more sustainable practices.

Internet of Things (IoT), a term primarily used by Kevin Ashton in 1999 (ASHTON, 2010) to designate the network connecting physical things or objects to the Internet, is another ICT that has been transforming FM activities. Centred in the idea of data generated by things (i.e., sensors, Radio-frequency Identification (RFID) tags), IoT overcomes human limitations to capture data, thus increasing the accuracy and availability of information (ASHTON, 2010). In this sense, IoT is not a new technology, but a new approach that uses existing technologies and explores communication capabilities enabled by the Internet (LOVE; MATTHEWS, 2019).

Along with a new generation of ICTs, IoT supports more flexible, interactive, sustainable, and efficient operations of buildings (FROUFE et al., 2020). It offers FM the possibility for understanding what occurs with each aspect and component of a building and their operation in real-time, increasing both quality of information and efficiency of services (AL-FUQAHA et al., 2015; GUNDUZ; ISIKDAG; BASARANER, 2017; PISHDAD-BOZORGI, 2017; WONG; GE; HE, 2018). In this scenario, the concepts of "Smart Facilities Management" (FAIRCHILD, 2019) and "Smart Maintenance" (BOKRANTZ et al., 2020; BREUKER; ROSSI; BRAUN, 2000; COLEMEN et al., 2017; KATONA; PANFILOV, 2018) emerge from manufactory to the AEC industry, guiding the sector towards predictive, autonomous and sustainable decisions.

Given the individual benefits of each digital technology, the BIM and IoT integration enables the production of smart cities and a digital economy (HM GOVERNMENT, 2015; TEICHOLZ, 2012; THE BRITISH STANDARD INSTITUTION, 2014), since they "offer new ways of creating and capturing value throughout the life-cycle of an asset and can facilitate pervasive changes to practice" (LOVE; MATTHEWS, 2019, p. 11). Besides, they enable the cost-effective creation of Digital Twins[3] for FM, supporting the capture of changes in real buildings, monitoring of the performance of their components and systems, and generation of data for the prediction of performance behaviour and failures (FINK; MATA, 2020; GRIEVES; VICKERS, 2017).

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been adopting BIM, particularly in public works, through mandates such as Denmark, Hong Kong, the United States, the United Kingdom (CADENAS, 2016; CBIC, 2016; KASSEM; AMORIM, 2015), and Brazil (BRASIL, 2020).

[3] Digital Twin is defined by Grieves and Vickers (2017) as "a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level".

Previous research has discussed potential benefits, application areas and activities, challenges, and gaps associated with the implementation of BIM for FM (BECERIK-GERBER et al., 2012; CODINHOTO; KIVINIEMI; KEMMER, 2013; EDIRISINGHE et al., 2017; HOSSEINI et al., 2018; KASSEM et al., 2015; PÄRN; EDWARDS; SING, 2017; PIN; MEDINA; MCARTHUR, 2018; PINTI et al., 2018). However, few studies have addressed the application of BIM and IoT for FM (CHAN et al., 2016; KENSEK; KAHN, 2013; PÄRN; EDWARDS, 2017), in special for Reactive Maintenance (CHUNG et al., 2018; LIN; SU; CHEN, 2014; MIRARCHI et al., 2018). Moreover, investigations on the implementation of such technologies are mostly disconnected to business goals (KELLER, 2012; MUNIR; KIVINIEMI; JONES, 2019) and focused on the acquisition and installation of technological components, rather than on the process issues required for their operation and maintenance over time (COLEMEN et al., 2017; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; LEWIS, 2012; VALKS et al., 2021).

Consequently, scientific and empirical evidence involved in the implementation of FM systems based on BIM and IoT has been demanded, such as the identification of priority areas and steps and information requirements. Besides, gaps on the clarity of impacts BIM and IoT on supporting reactive maintenance services towards a proactive decision-making (CODINHOTO et al., 2021; LEWIS, 2012) and the potential benefits of such information for design decisions have been identified. As stated by Valks et al. (2021, p. 7) “it is not always apparent how the information from IoT applications are, could or should be used”. This lacuna was also reported by Love and Matthews (2019), who highlighted the role of digital transformation for AEC industry:

> “While there has been considerable focus on ‘why’ organizations operating in the construction industry need to adopt digital technologies to enable Building Information Modelling, Internet of Things and Industry 4.0 and thus deliver assets more effectively and efficiently, there has been limited attention given to ‘how’ they can realize their expected benefits and simultaneously generate value. Seldom have studies within the construction industry placed emphasis on planning, monitoring and managing the benefits that digital technologies can bring. There has been a natural assumption that the adoption of digital technologies will result in productivity improvements, but the change needed to unlock their benefits has been over-looked or misunderstood.” (LOVE; MATTHEWS, 2019)

Given the practical problems faced by the FM sectors for providing efficient services and the lacuna in the literature about the topic, the formulated research problem aims to address such a knowledge gap.

1.2.1. Research Question

In view of the stated problems, the research question formulated in this study is:

How can the integration of BIM and IoT support more efficient decision-making driving maintenance services from a reactive approach to a predictive one?

1.2.2. Aim and objectives

This research aims at the development of a framework for BIM and IoT implementation in reactive maintenance services oriented to a predictive approach. To do so, the following three key objectives have been defined:

i. To characterize critical reactive maintenance problems and scenarios and opportunities for BIM and IoT implementation.
ii. To analyse and classify BIM and IoT solutions recently applied to Facilities Management and reactive maintenance services according to their benefits, gains, enablers, and barriers.
iii. To characterize strategies and decisions involved in the planning, development, implementation, testing, and assessment of a BIM and IoT-based smart maintenance system and its impacts on the maintenance services and potential contributions to the design phase.

1.3. Focus and Scope of the Research

This research approaches the efficiency gains of maintenance services through improvements in information management by BIM and IoT solutions. The focus is on the process issues involved in the application of such solutions to critical reactive maintenance services. BIM and IoT are understood here as ICTs and managerial tools that support reactive maintenance processes. Therefore, regulations and standards for their implementation in Reactive Maintenance and the technical operational specification of devices and systems involved are out of the scope.

University campuses were selected as the object of investigation of this phenomenon due to the complexity and variety of their building functions (e.g., catering, accommodation, education, administration, healthcare, science, etc.), meaning they can be compared to small cities. Besides, universities are dynamic and innovative environments, that support and encourage technological and scientific advances within the society. The adequate management of built environment is essential, since the performance of buildings is positively correlated with the quality of academic activities (ABDUL-LATEEF, 2010) and with the environment (INTERNATIONAL ENERGY AGENCY, 2021).

1.4. Relevance and Contributions to Knowledge

The relevance of this research lies in the topic and the object of investigation, as well as in the contribution of the expected findings. It addresses BIM5.0 or AI BIM, one of the trends for BIM in the construction sector expected for the 2030s, according to which BIM is extended to urban, city, aerospace and other large-scale projects. According to the Building Informatics Group of the Yonsei University, technologies such as big data, IoT, GIS, and Artificial Intelligence (AI) will enable smart cities and connected BIM (Digital Twin), and informed decision-making over the lifecycle of a project (SACKS et al., 2018).

The study bears international scientific relevance, since it discusses the role of ICTs in the efficiency of FM and Reactive Maintenance services, a subject still in development, according to the literature. Its novelty and relevance have been validated by experts from BIM Academy, Northumbria University, and the Building Research Establishment (BRE) group, and its main contribution to knowledge is the proposal of a framework for BIM and IoT implementation in reactive maintenance services oriented to a predictive approach and based on empirical evidence. It explores the potential contributions of information provided by BIM and IoT to the early stages of the building design process, supporting the development of Digital Twins. To do so, this investigation involved a deep understanding of Reactive Maintenance processes, the FM sectors' structure and competences for using BIM and IoT and, BIM and IoT capabilities and limitations, still not clear for researchers and facilities managers. The collaborative work with professionals from the Computation and AEC fields and the participation of the FM end-users in many stages of the investigation contributed to the validity of the findings.

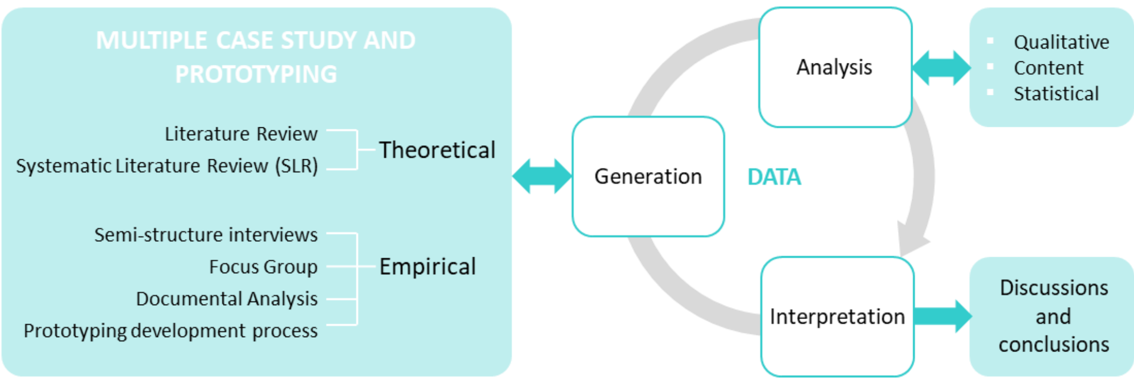
The study addresses both knowledge and practice of FM and Reactive Maintenance by generating theoretical background and empirical evidence on opportunities and strategies for BIM and IoT implementation. Given the financial, physical, and organizational transformations imposed by any managerial and technological implementation, such contributions can support researchers and organisations in identifying cases and activities in which BIM and IoT are worth it and must be implemented. It also provides references of steps and decisions required for the planning, development, implementation, testing, and assessment of a BIM and IoT-based smart maintenance system, as well as information to be considered in the early design phase.

Due to the large number of public universities in Brazil and in other countries and the restrictions of governmental funding for universities in general (VALKS et al., 2021), studies on an efficient and responsible use of public funds are imperative. In this sense, this research provides guidance for a smart maintenance management in universities as part of the smart city context (AMARATUNGA; BALDRY, 2000), addressing the agenda for sustainable building management solutions and contributing to the development of the built environment of university campuses and other organisations.

1.5. Outline Research Methodology

This research is based on a pragmatic philosophy and uses qualitative and quantitative methods within a mixed method design. Multiple Case Study and Prototyping are the strategies for the achievement of the aim through the adoption of University Campuses as the object of investigation. A set of methods for data generation and analysis were defined for addressing the research objectives. Theoretical and empirical sources of evidence were triangulated towards increasing both significance and validity of the findings (Figure 4).

Figure 4: Research data management



Source: Author (2021)

The theoretical data generation was based on Literature Review and Systematic Literature Review (SLR), which provided a common understanding of the topic of investigation and the literature gaps, supporting the development of the multiple case study, the prototyping, and the discussion of the research findings. On the other hand, empirical data were generated through Documental Analysis, Semi-structured Interviews, Focus Group, and Prototype development, involving the universities' FM sector and reactive maintenance services. Qualitative Analysis and Content Analysis were applied to qualitative data, whereas Statistical Analysis involved quantitative ones. A detailed description of the methodology developed is provided in Chapter 2.

1.6. Structure of the thesis

This thesis is organized into six chapters and reflects the process for building the knowledge. Chapter 1 presents the work background, research problem, question, aim and objectives, focus and scope, contributions to knowledge and an outline of the research methodology.

Chapter 2 describes the research methodology, detailing the research philosophy, design, strategies, and methods for data generation and analysis. It also describes the procedures for data gathering, analysis, interpretation, and the decisions made for addressing the research problem.

Chapter 3 presents the theoretical background on the building design process, Facilities Management (FM), maintenance services, and FM digital transformation through BIM, IoT and Digital Twin implementation. Addressing Objective ii, it provides the findings of a Systematic Literature Review (SLR) based on the analysis and classification of BIM and IoT solutions recently applied to FM and reactive maintenance services, thus summarized in a conceptual framework.

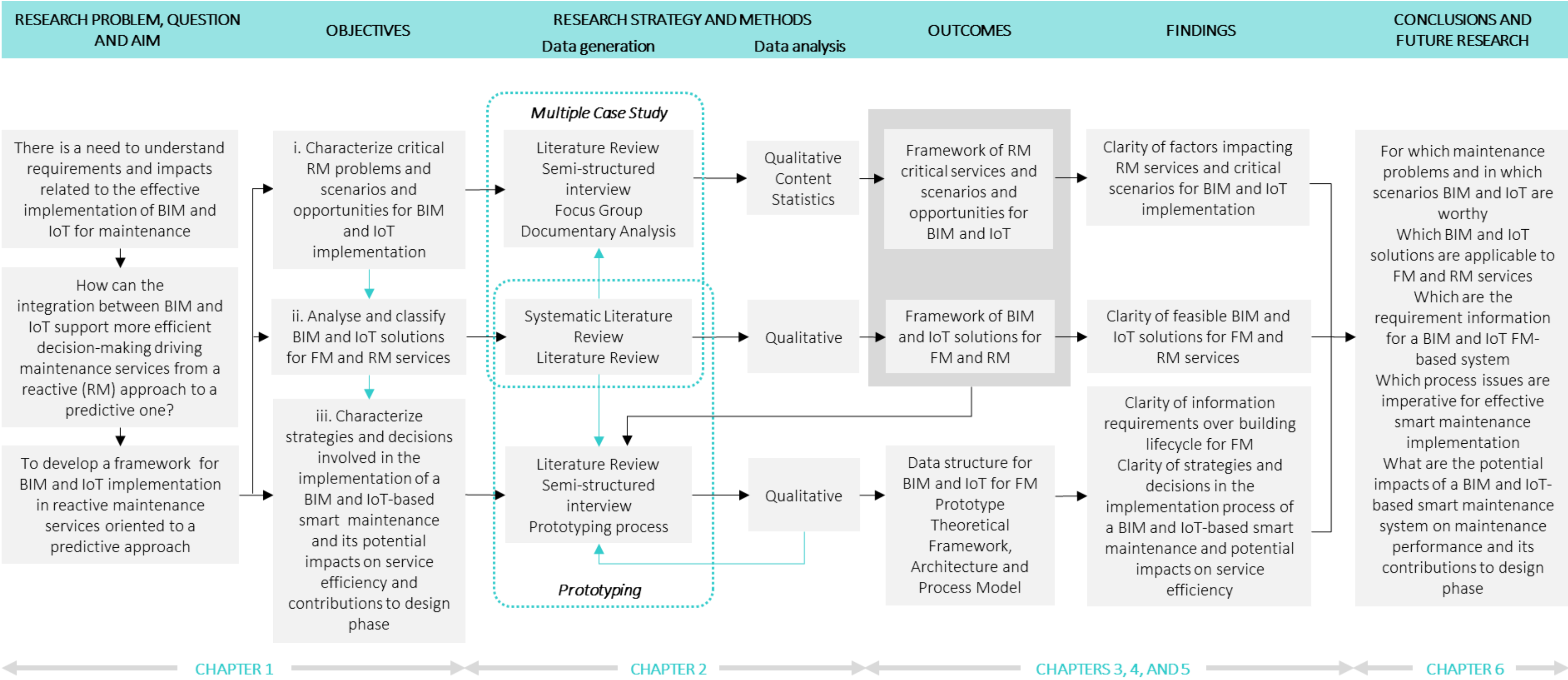
Chapter 4 is devoted to the Multiple Case Study conducted with the selected universities from the United Kingdom and Brazil. Concerning Objective i, it encompasses the generation, analysis, and discussion of empirical evidence towards characterizing critical reactive maintenance problems and scenarios, as well as opportunities for BIM and IoT implementation. From this investigation, a representative scenario was identified to support the prototyping process described in the following chapter.

Chapter 5 addresses the development of a Smart lighting maintenance system prototype focusing on Objective iii. It covers the generation, analysis, and discussion of empirical evidence towards identifying strategies and decisions involved in the planning, development, implementation, testing, and assessment of a BIM and IoT-based smart maintenance system. Besides, it characterizes the potential impacts of the system on the maintenance services and its contributions to the design phase.

Finally, Chapter 6 provides the conclusions, highlighting the achievement of the research aim and objectives, contributions, limitations, and the recommendations for further studies. References, Appendices and Annexes are placed in the final sections of the document.

The research framework depicted in Figure 5 summarizes the iterative research process over the chapters. Primarily, it presents the research problem, question, and aim (left side). Three main layers of procedures were established towards addressing each research objective and covering the outcomes and findings (horizontal flow). Since the objectives are complementary, additional procedures were proposed for their integration (vertical flow). Conclusions and suggestions for future studies are displaced in the right side of the figure.

Figure 5: Research Framework

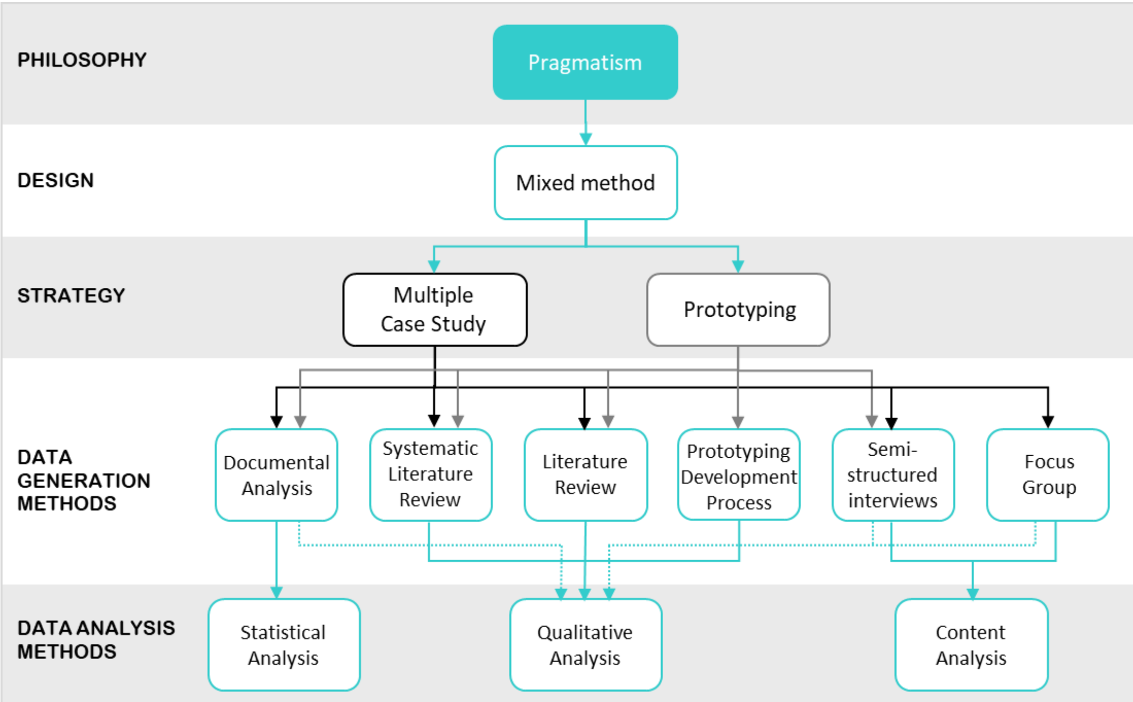


Source: Author (2021)

2. Methodology

The definition of the most appropriate research methodology was essential for ensuring the reliability and validity of this study, hence, the fulfilment of its aim. This chapter describes the procedures for data gathering, analysis, interpretation, and the decisions made to address the research problem. The methodology framework was developed from a broad-to-narrow perspective proposed by Creswell (2014). As depicted in Figure 6, it comprehends the research philosophy, design, strategies, and methods for data generation and analysis.

Figure 6: Methodology Framework



Source: Author (2021)

The chapter is divided into four sections. Section 2.1. presents the structure of the research, its philosophy, design, and strategies. Section 2.2. describes the methods for data generation, analysis, and interpretation. Finally, Section 2.3. summarizes the chapter and the overall research framework.

2.1. Research structure

The comprehension of the research aim, objectives, and expected contributions guided the definition of the research structure. This section describes the philosophy, design, and strategies of the research addressing its complexity.

2.1.1. Research philosophy and design

The adoption of the research design, strategy and methods was influenced by the author's position upon how new knowledge is created, i.e., by the research philosophy (SAUNDERS; LEWIS; THORNHILL, 2009) or philosophical worldview (CRESWELL, 2014). Defined by Creswell (2014, p. 42) as “a general philosophical orientation about the world and the nature of research that a researcher brings to a study”, philosophical worldviews influence the adoption of qualitative, quantitative, or mixed method designs.

Three research philosophies, namely positivism, interpretivism, and pragmatism have been extensively discussed (CRESWELL, 2014; FELLOWS; LIU, 2015; SAUNDERS; LEWIS; THORNHILL, 2009) and has revealed a clear opposition between positivism and interpretivism. Whereas positivism is based on the rational and objective observation of phenomena for the determination of cause-effect relations and generalisations by quantitative methods, interpretivism understands reality as a social construction and investigates social phenomena and their subjective meanings mainly through qualitative methods. Alternatively, pragmatism focuses on real-world practical research, analysing observable phenomena and subjective meanings through mixed methods (i.e., combining qualitative and quantitative methods).

Pragmatism based on mixed method design was considered appropriate to this research, since it provides a pluralistic approach for the generation and analysis of a variety of evidence. The mixed method design offered a comprehensive view of the area investigated, overcoming the individual weaknesses and bias inherent to both quantitative and qualitative methods (BRYMAN, 2012). The convergent parallel mixed method design was selected from the six mixed method design models proposed by Creswell (2014) for social sciences (i.e., convergent parallel, explanatory sequential, exploratory sequential, transformative, embedded, and multiphase). This design merges qualitative and quantitative methods for the collection (roughly simultaneously), analysis, and interpretation of data (CRESWELL, 2014; SAUNDERS; LEWIS; THORNHILL, 2009), addressing this research needs.

2.1.2. Research strategies

Multiple Case Study and Prototyping were the two complementary research strategies adopted. The rationale for the selection of each strategy and their general procedures and stages are described in the following sections.

a. Multiple Case Study

Case Study was the first strategy adopted for this research from the five most relevant strategies for social sciences, namely longitudinal, comparative, experimental, cross-sectional, and case study (BRYMAN, 2012). Its adoption was due to its capability to deal with a contemporary and complex phenomenon in its real context. As an empirical method, it embraces both qualitative and quantitative methods, ensuring an in-depth and extensive investigation of data for the understanding of a problem (YIN, 2018).

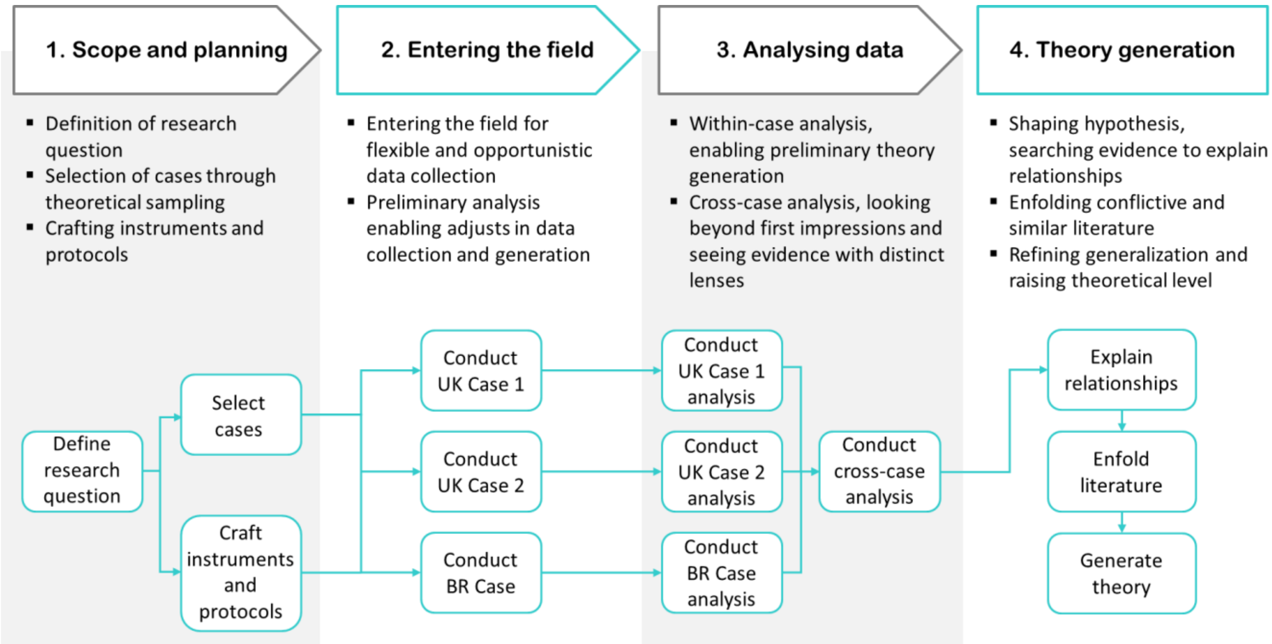
This research aims at the construction of a theory from the generalization of findings (BRYMAN, 2012; CRESWELL, 2014), which is one of the three common aims of a case study described by Eisenhardt (1989), i.e., the supply of description, test theory, and theory generation. The latter is particularly relevant for new research areas (as the one investigated in this study), since it addresses novelty, testability, and empirical validity (EISENHARDT, 1989).

Multiple cases were selected through the logic of replication, which checks whether findings of a case are observed in others. Therefore, a better comprehension of the social phenomenon was provided, supporting generalization. In this study, university campuses were the objects of investigation, and the reactive maintenance process undertaken by FM sectors was the core observed phenomenon. Multiple sources of evidence (described in Section 2.2) were adopted and mutually corroborated through triangulation, strengthening the validity of findings (BRYMAN, 2012; SAUNDERS; LEWIS; THORNHILL, 2009).

Symbol of scientific and technological progress in the 1960s, the spatial organisation of university campus was based on principles of the modern architecture and urban planning, namely rationality and functionality, and is still the dominant style among the contemporary universities (BUFFA; PINTO, 2017; FIALHO, 2012). The university campus is commonly featured by a high complexity and variety of building functions (e.g., teaching, research, administration, catering, accommodations, sport and leisure, and healthcare), and can be compared to small cities. Challenges are faced in the management of campus-built environment due to the budgetary, administrative and technological constraints and legal requirements for designing and operating the building infrastructure (CAMPOS, 2011; CAPELLO; LEITE; FABRICIO, 2007; ESTEVES; FALCOSKI, 2013; MARTINS, 2014). In this scenario, significant demands for FM services - particularly maintenance and operations – must be fulfilled to ensure the development of academic and scientific activities. Such characteristics address the research problem, justifying the university campus adoption.

The Multiple Case Study was organized into four stages, namely, Scope and planning, Entering the field, Analysing data, and Theory generation (Figure 7), according to the propositions of Eisenhardt (1989). Initially, the Scope and planning stage involved the definition of the research question, the selection of cases through theoretical sampling, and the crafting of multi-methods instruments and protocols for field work. The question addressed by the Multiple Case Study was “what are the critical reactive maintenance problems and the scenarios and opportunities for BIM and IoT implementation?”

Figure 7: Multiple Case Study Process



Source: Author based on Eisenhardt (1989)

Subsequently, the selection of universities searched for representative cases of a broader category, providing an appropriate context for investigation (BRYMAN, 2012). Two groups of criteria, namely, Intermediate and Low were defined according to the level of BIM and IoT implementation for FM activities, as shown in Table 1. According to such criteria, three universities were selected - two from the United Kingdom, representing Group 1, and one from Brazil, representing Group 2. Instruments and protocols were developed towards generating empirical data through multiple data generation methods. Questionnaires and protocols supported the Semi-structured Interviews, Documentary Analysis, and Focus Group[4]. Section 2.2. and Chapter 4 provide a detailed description of the case study data generation.

The second stage, called Entering the field, is related to the flexible and opportunistic generation of data and their preliminary analysis (EISENHARDT, 1989). A thorough investigation of British organizations was enabled by the author's six-month internship as visiting student at the University of Bath in the UK, from September 2018 to February 2019, as part of the CAPES Foundation Sandwich Doctorate Program Abroad. Due to the proximity with the selected organizations, face-to-face communication with the participants and visits to the campuses were undertaken. Adjustments were made in data generation instruments and protocols, which supported the Brazilian Case Study conducted between October and December 2019. Together, the three cases generated approximately eight hours of interviews and 300.000 Work Requests, thus providing relevant evidence for investigation, as detailed in Chapter 5.

Table 1: Criteria for universities selection

Group	Criteria
1. Intermediate level of BIM and IoT implementation for FM activities	Availability of a CAFM system; Availability of online tools for users reporting faults; Availability of digitalised asset information (drawings, spreadsheets, standards, etc.); Availability of BIM models of buildings/ university campus; Use of BIM model as one, but not the only, reliable source of information for FM purposes; Partial integration of BIM models and CAFM system; Change management triggered by BIM implementation; Availability of IoT devices to support building management OR intention to integrate IoT devices into BIM model.
2. Low level of BIM and IoT implementation for FM activities	Availability of a CAFM system; Availability of online tools for users reporting faults; Availability of digitalised asset information (drawings, spreadsheets, standards, etc.)

Source: Author (2021)

In the third stage, the analysis of data involved within and cross-case analyses, looking beyond the first impressions and seeing evidence with distinct lenses (EISENHARDT, 1989). Qualitative Analysis, Content Analysis, and Statistical Analysis were applied, and Theory generation was based on hypothesis shaping and literature enfolding. The research internal validity was built, enabling refinements in the generalization and raising the theoretical level (EISENHARDT, 1989). Section 2.3. and Chapter 5 detail case study data analysis and theory generation.

b. Prototyping

Prototyping was the second strategy selected to investigate the phenomena. Defined as "the process of developing such an approximation of the product" (ULRICH; EPPINGER, 2012, p. 291), prototyping is commonly employed in business and engineering industries as part of the design process. Supporting the

[4] This research project was approved by the Brazilian Research Ethics Committee - Plataforma Brasil (code n. 3.566.474). Interviews and questionnaires applied to professionals from the UK universities complied with the ethical standards of that country and guidance from the University of Bath.

development of products according to the users' needs, prototypes are applied for many purposes, such as expansion of design concepts, gathering of users' feedback on physical and functional aspects, and assistance to cost analysis and tests (CAMBURN et al., 2017; CHRISTIE et al., 2012).

Prototyping was adopted here as a research method to validate findings and generate knowledge. Its understanding as a method has been discussed in the academia, which has emphasized its capability for investigating knowledge building processes and developing "ideas into concrete manifestations" (BERGLUND; LEIFER, 2013, p. 2). Particularly relevant for Design Research, prototypes are comprehended "as vehicles for research about, for and through design" (WENSVEEN; MATTHEWS, 2014, p. 262). Developed in a social context and suitable for innovative solutions and complex phenomena (CAMBURN et al., 2017), prototypes

> "unlock cognitive association mechanisms related to visualisation, prior experience, and interpersonal communication in ways that favour iterative learning between peers in the product development community." (BERGLUND; LEIFER, 2013, p. 2)

Although an overlay of prototype as a design tool and a research method is inevitable, Wensveen and Matthews (2014) established four distinct roles of prototype in research, namely, "experimental component", "means of inquiry", "research archetype", and "vehicle for inquiry". Table 2 shows the major elements of each role.

Table 2: Major elements of prototype roles in design research

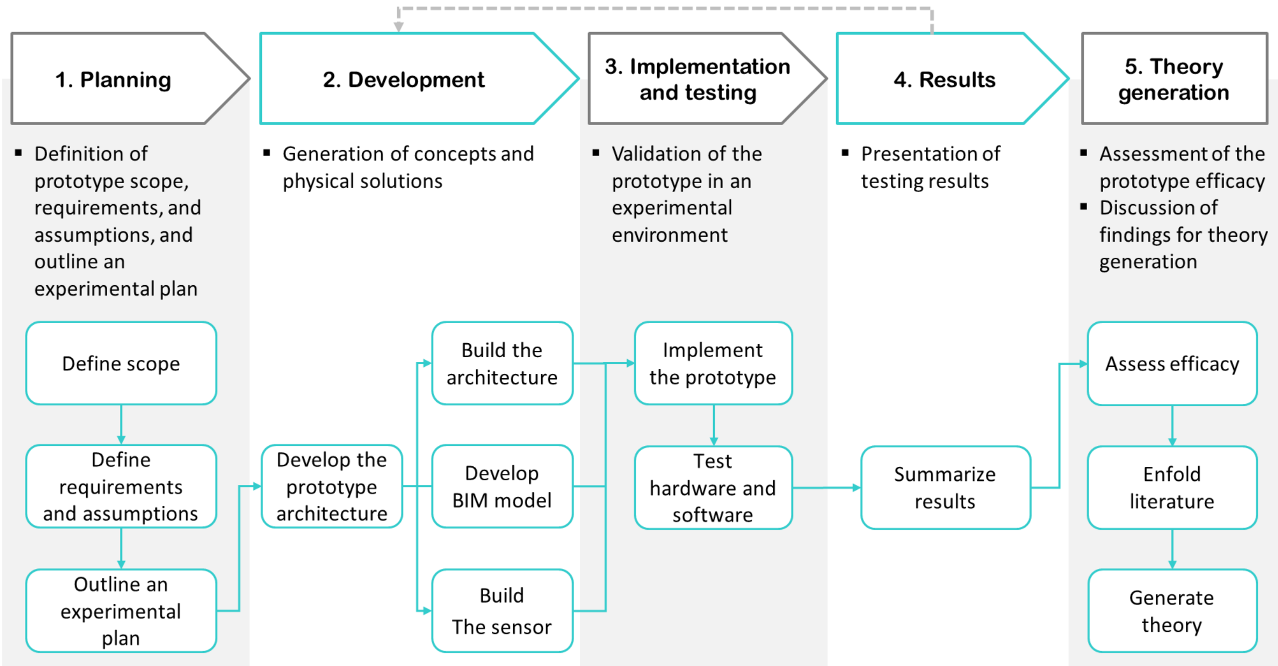
Element	Experimental component	Means of inquiry	Research archetype	Vehicle for inquiry
Purpose and role	Test of specific hypotheses	Open-ended exploration	Illustration or demonstration	Driver for the research direction
	Systematic prototype variations of context of use	Instrument for the collection, recording and measurement of phenomena	Physical embodiment of research concept, understanding or design research space	Research contribution is tied to the crafting of artifacts
Special issues	Design of the experiment is equally crucial	Often combined with interviews	Critical perspective is equally crucial	Process is documented, analyzed and critically assessed
Data	Primarily quantitative data (e.g. data logging, questionnaire)	Qualitative (e.g. interviews) and/or quantitative (e.g. data logging)	Designed artifacts that form the basis of critical analysis	Qualitative case study
Method of analysis	Statistical analysis	Ethnographic analysis	Expository analysis	Case analysis
Type of research contribution	Empirical, Theoretical Ethnographic	Empirical	Conceptual, Methodological	Methodological

Source: Author based on Wensveen and Matthews (2014)

In this study, prototype was considered a research archetype, which is a physical embodiment of literature and multiple case study findings used to demonstrate their potential and contributions to the field (WENSVEEN; MATTHEWS, 2014). Based on an empirical investigation, prototyping explored approaches for integrating BIM, IoT, and CAFM tools and generating intelligence from raw building data, providing new insights on smart maintenance process. It also raised limitations involved in the development and implementation of a BIM and IoT system for assisting maintenance management. The contributions to knowledge were both conceptual and methodological, related to the scope and stages of the prototyping process. A five-stage systematic process based on the statements of Ulrich and Eppinger (2012) and Wensveen and Matthews (2014) was proposed to develop a BIM and IoT prototype system, involving Planning, Development, Implementation and testing, Results and assessment, and Theory generation, as shown in Figure 8.

Planning activities were conducted for the definition of the prototype scope, requirements, and assumptions, and the outline of an experimental plan, defined according to the research objectives and resources available. A critical scenario identified in the Multiple Case Study (e.g., the lighting system of students' accommodations) was the object of prototyping. The functional and technical requirements and strategies were established with support of university maintenance experts, AEC and IT professionals, consulted through online questionnaires and interviews. The experimental plan involved the identification of variables to be tested, development of test settings and protocol, and definition of performance measurements and a data analysis strategy.

Figure 8: Prototype Development Process



Source: Author based on Ulrich and Eppinger (2012) and Wensveen and Matthews (2014)

In the Development stage, activities were conducted for the generation of conceptual, processual, and technological solutions. First, the Architecture of the prototype was developed, and described the prototype from a computational point of view. Subsequently, the architecture, the sensor, and the BIM model were built, integrating hardware and software components for data generation, transmission, processing, visualization, and management.

The prototype was developed, implemented and tested (Stage 3) in an experimental environment between July 2020 and April 2021. The test protocol assessed the prototype capability for effectively managing data and providing accurate information. As functional tests, they supported the identification of defects and failures on the prototype components (HEVNER et al., 2004). A qualitative analysis of the results supported the assessment of prototype performance (Stage 4). A descriptive evaluation of the prototype was also carried out to demonstrate its potential impacts on the university maintenance processes. The discussion of the findings led to theory generation, identifying limitations and contributions of the process (Stage 5). Sections 2.3. and 2.4. and Chapter 5 provide a detailed description of prototyping data generation, analysis, and interpretation.

2.2. Research data methods

This section presents the methods selected for the generation and analysis of Multiple Case Study and Prototyping data. As proposed by Mason (2002, p. 52), traditional term “data collection” was replaced by “data generation”, since the research involved not only “data which already exist in a collectable state”, but also data generated from the selected sources. The theoretical data generation was based on Literature Review and Systematic Literature Review, whereas empirical data generation was conducted through Documental Analysis, Semi-structured Interviews, Focus Group and Prototype development. Qualitative Analysis and Content Analysis were applied to qualitative data, while Statistical Analysis was employed for quantitative ones. Chapters 4 and 5 detail the procedures and activities for data generation and analysis.

2.2.1. Data generation methods

a. Literature Review

The literature review played distinct roles over the research process. Primarily, it provided a common understanding of the topic of investigation (i.e., relevant concepts, theories, methods, strategies) and a critical analysis of previous findings, supporting the identification of a lacuna in the literature to be addressed (BRYMAN, 2012). In this study, key topics involved aspects of Facilities Management (FM) and maintenance (i.e., sector and services, performance and information management, maintenance types, reactive maintenance process, buildings characteristics the influence problem occurrence and time response, criteria for priority service classification), and concepts e technologies on FM digital transformation, for instance, BIM, IoT, Smart Cities, Smart Maintenance, and Digital Twin.

The literature also reports methodological decisions for the achievement of the research objective (SAUNDERS; LEWIS; THORNHILL, 2009). Theoretical aspects related to the observed phenomena were further explored towards supporting the development of the multiple case study and prototyping as well as the discussion of findings (i.e., identification of building characteristics that impact problem occurrence). Relevant books, standards (i.e., ISO, ABNT, etc.), conference papers, and scientific journal articles were the literature sources of evidence.

b. Systematic Literature Review (SLR)

The Systematic Literature Review explored distinct nuances of BIM and IoT solutions for Facilities Management and reactive maintenance purposes. Since it refers to an innovative field of investigation, the literature lacks the understanding of not only technological solutions and application areas, but also the pros and cons of such an implementation. Based on systematic, explicit, and accountable procedures, this method provided a context of the investigated subject from previous and reliable studies methodically identified, analysed, and synthesized (GOUGH; OLIVER; THOMAS, 2012; PETERSEN et al., 2008). Often adopted in medicine research to support evidence-based decisions, it has been diffused in other areas of knowledge (e.g. social policy) due to its rigorous concerns over the summarization of evidence of a knowledge field (BRYMAN, 2012). Accordingly, it aims at assuring bias exemption and possibility of replication and update of results (MORANDI; CAMARGO, 2015).

Journal articles and conference papers published between 2013 and 2018 available in international databases (i.e., Scopus, Technology Collection, Science Direct, Directory of Open Access Journals, ASCE Library, Compendex, and Web of Science) were the selected sources of evidence. The systematic review was summarized into a conference paper, published in the proceeding of the 36th CIB W78 2019 (Annex 1), and briefly presented in Chapter 3. The findings contributed to the interpretation of case study results and development of the prototype.

c. Semi-structured interviews and Focus Group

Semi-structured interviews were conducted for the obtaining of primary evidence over the research process. Also called qualitative interviews, this method is vastly applied in qualitative research, particularly in case studies, since it raises relevant contexts through less formal-style conversations (MASON, 2002; YIN, 2018). Besides, it provides flexibility for interaction with interviewees in different ways (e.g., one-to-one, larger groups, focus group), through various interfaces (e.g., face-to-face, telephone, e-mail, online meetings), and based on distinct approaches (e.g., narrative, thematic, topic-centred), thus enabling the development of unforeseen themes (MASON, 2002).

Initially, such interviews were conducted with professionals of the selected universities towards the comprehension of organizational, processual, and technological aspects involved in FM services. The selection of the interviewees considered their availability for participation, knowledge of the internal practices of the maintenance sector, and work in the FM sector for a year or more. At least one member of each University FM sector (e.g., Facilities Manager, BIM Manager, Maintenance supervisor) was interviewed.

In the three cases, face-to-face interviews based on predesigned open questionnaires were conducted, and a face-to-face focus group was prepared with members of an organization in which this approach was feasible. By establishing an interactive environment for participants to share and compare experiences, the focus group provided a deeper comprehension of the phenomenon and generation of ideas within a social context (BREEN, 2006; BRYMAN, 2012). The interviews were audio recorded and transcribed for further analyses.

A second stage of semi-structured interviews supported the validation of research findings and identification of requirements for the prototype development through an Expert Assessment. The focus was on the capability of implementation in real organisations, usefulness for maintaining managers performing their roles, and potential for generalisation to other contexts. Such interviews were conducted with university professionals involved with maintenance services through online meetings and questionnaire forms. Chapters 4 and 5 provide detailed information on the interview’s protocol, conduction, analysis, and interpretation.

d. Documental analysis

A Documental Analysis gathered empirical evidence of the multiple case study. Considered a key method of social research (MASON, 2002), the analysis of documents might include primary data, collected by the researcher for a specific goal, or secondary data, already collected and stored by organizations towards assisting operational procedures (SAUNDERS; LEWIS; THORNHILL, 2009). Among its capabilities, documental analysis identifies social aspects, evidences the occurrence of phenomena, and contextualizes other forms of data (e.g., interviews) (MASON, 2002).

The main role of documentary analysis in this study was to characterize the FM sectors and services in each organization (in particular, aspects of reactive maintenance problems and time response) and to identify patterns and critical scenarios across the cases. The sources of evidence included primary data on previous FM work requests, and secondary data related to both FM sector and activities (e.g., organization flowchart, website, protocols, guidelines). Chapters 4 and 5 provide detailed information on the generation, analysis, and interpretation of documentary data sources.

e. Prototyping process

The prototyping process was also considered a method for data generation (WENSVEEN; MATTHEWS, 2014). The empirical activities of planning, building, implementing, testing, and assessing results provided evidence of the challenges and potentiality of BIM and IoT tool propositions for maintenance management. Records of team meetings, notes of field work, frameworks of the proposed solution, and photos of the artifact were the sources of evidence generated over the process, as described in Chapter 5.

2.2.2. Data Analysis methods

a. Qualitative analysis

A Qualitative analysis was applied to all sources of evidence. Differently from quantitative analysis, no predetermined formulas or rules are available to guide researchers in the analysis (GIL, 2008). Nevertheless, three steps established by Miles, Huberman, and Saldaña (2013) were adopted in this study for the analysis procedures, namely, data condensation, data display, and data conclusion drawing and verification. The steps and the related sources of evidence are described in the following sections.

- **Data condensation**

Data condensation is related to the selection, emphasis, simplification, organization, and transformation of raw data for supporting further analyses (MILES; HUBERMAN; SALDAÑA, 2013). In this study, distinct procedures were taken for each source of evidence. Data from articles selected in the Systematic Literature Review were filtered according to the enquiry requirements and summarized into a digital spreadsheet (i.e., Microsoft Excel). The focus was on bibliometric (i.e., journal, publication year, country, etc) and research aspects (i.e., method, aim and objectives, findings), defined as categories of analysis.

The set of semi-structured interviews and focus group transcriptions recorded in Microsoft Word files was simplified, and materials with no relation with the investigation were discarded. Since the transcriptions were performed by several professionals, both structure and terminology (e.g., identification of interviewer and interviewee) of the documents were standardized. The responses of online questionnaire forms were recorded in digital reports. Condensation procedures facilitated individual and cross analysis of both transcriptions and reports.

The condensation of documentary primary data (i.e., universities work requests) was the most complex and time-consuming one, due to their volume and variety. Approximately data on 300.000 work requests provided by the organizations in individual files were summarized into a single Excel spreadsheet. Since each organization adopts a distinct standard for work request classification (i.e., service category, room type, floor identification, etc), the homogenization of categories was necessary for comparisons among cases. Work requests with missing data were also discarded for avoiding file overload. The records of prototyping activities were condensed in project reports which describe procedures, decisions, results, and findings of the process.

- **Data Display**

The display of data involved the organization of condensed data into a compact and objective form (e.g., tables, graphs, diagrams, and matrices) that supports analyses and decision-making (MILES; HUBERMAN; SALDAÑA, 2013). Systematic Literature Review protocol, results, and findings were organized into tables, graphs, charts, and diagrams; they inform on the procedures undertaken and provide a clear understanding of the bibliometric and research aspects raised. The semi-structured interview and focus group transcriptions were organized in a standard format in Word files, thus facilitating the reading and interpretation of data.

Data on reactive maintenance processes in each case were displayed in process models. Applied by organizations to understand and communicate internal procedures (OBJECT MANAGEMENT GROUP, 2011), the process modelling technique was adopted in this study to generate process flow diagrams with the core activities, stages, stakeholders, decisions points, and flows. Business Process Model and Notation (BPMN)[5] was selected among other languages and standards, since it provides graphical and user-friendly interfaces for modelling (KO; LEE; LEE, 2009; NESPOR, 2012). Concise tables showed data on universities work requests, highlighting variables for analyses, an in a range of graphs and charts[6], and their relationship. Data from the Prototyping process were displayed in project reports (i.e., Word file) and presentations (i.e., Microsoft Power Point).

- **Data conclusion drawing and verification**

The last stage of qualitative analysis is related to drawing and verifying conclusions (MILES; HUBERMAN; SALDAÑA, 2013), for supporting the researcher in theoretically contributing to the literature (BRYMAN, 2012; CRESWELL, 2014). The conclusion was generated from the interpretation of explanations, patterns and trends, and the development of inferences, and verifications were performed revisiting raw data, discussing findings with peers, and iteratively reassessing the validity of conclusion.

Each source of evidence provided distinct contributions. For example, systematic literature review findings identified predominant BIM and IoT aspects for implementation in FM and reactive maintenance

[5] Created and managed by the Object Management Group. Available at: <https://www.bpmn.org/> Accessed in 02 Mar. 2021.
[6] Line graphs, area chart, bar chart, stacked column charts, line and stacked column chart, pie chart, donut chart, scatter chart, Sankey chart.

scenarios. Results from the interviews enabled a comprehension of the FM sector and services, the reactive maintenance services process, and the applications of BIM and IoT-based solutions for FM services. Process models were essential for the understanding of the processual dynamics and identification of non-value added activities and opportunities for improvements through BIM and IoT implementation. The analysis of tables, graphs, and charts of universities work requests revealed the most critical problems in the universities' infrastructure over the studied period. Finally, a prototyping report analysis endorsed the case findings and explored new concepts and methods on the topic.

b. Content analysis

Complementary to the broad qualitative analysis, Content analysis examined semi-structured interviews and focus group transcriptions generated by the three cases. Considered a central technique for social research (KRIPPENDORFF, 2004), it is an investigative approach that describes communication contents through objective, systematic and reliable procedures, avoiding personal bias (BRYMAN, 2012). As an inductive instrument, it enables the raising of underlying meanings for supporting interpretations and inferences about an observed phenomenon occurred in semiotic, oral, and written communication formats (e.g., interviews, messages, discussions, books) (BARDIN, 2011).

In this study, content analysis characterized the scenario for current and potential applications of BIM and IoT-based solutions for FM services, particularly for maintenance services. An information-based qualitative approach was adopted, as recommended for short documents (BARDIN, 2011). The analytical process was organized into three steps, according to Bardin (2011), namely, Pre-analysis, Exploration of the corpus, and Treatment and interpretation of results. The pre-analysis step involved the summarization of initial ideas and definition of an analytical plan. Through a free-floating reading of the material, it comprised the selection and preparation of documents for analysis, formulation of hypotheses and objectives to be answered, and establishment of indexes for content interpretation.

Subsequently, the exploration of the corpus corresponded to the analysis of the selected material through codification, a systematic process that transforms raw data into a representation of the content or its expression (BARDIN, 2011). Coding process involves the labelling and organization of content according to categories or themes related to the research focus, which can be predefined by the literature or identified through the data (CRESWELL, 2014). Codification was undertaken through the clipping (i.e., selection of record and context unities), enumeration (i.e., definition of rules for counting), and classification (i.e., choice of categories) of content. Principles such as mutual exclusion, homogeneity, relevance, objectivity, and fidelity were observed towards the establishment of appropriate categories for analyses (BARDIN, 2011).

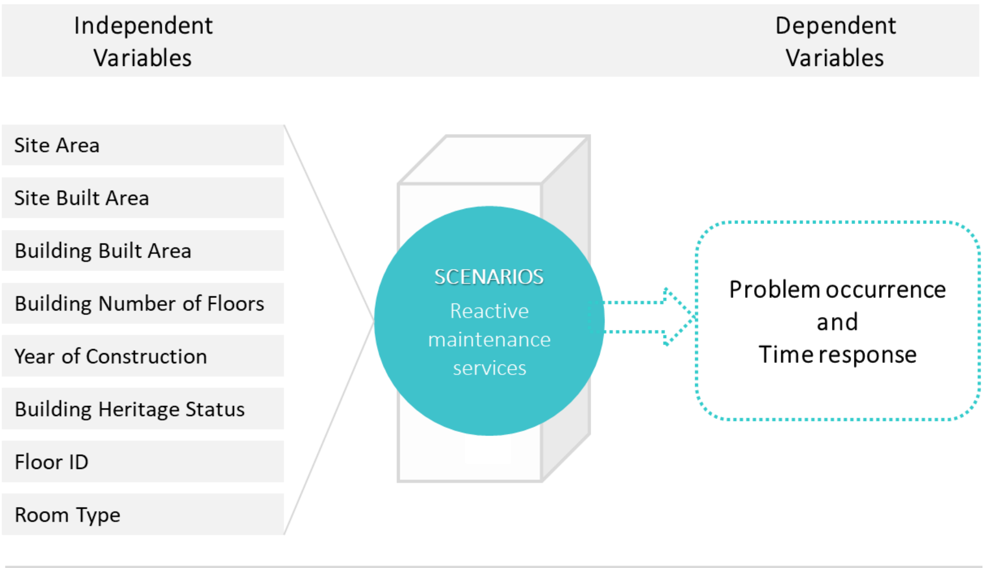
Finally, the treatment and interpretation of results involved the identification of latent factors in the descriptions and categories (e.g., ideologies, representations, discourses, intentions, contexts, relationships, valuations) (BARDIN, 2011), supporting the theoretical contribution to the literature (BRYMAN, 2012; CRESWELL, 2014). Chapter 4 presents the procedures and findings of content analysis.

c. Statistical analysis

Statistical techniques analysed and interpretated the reactive maintenance work requests generated by the UK organizations. In the context of social research, statistical analysis supports a precise characterization, description, and summarization of quantitative data. However, the most important contribution was the exam of relations among variables, thus enabling the identification of trends and, potentially, the generalization of conclusions out of the sample analysed (GIL, 2008; SAUNDERS; LEWIS; THORNHILL, 2009).

In this study, statistical analysis revealed the influence of building characteristics (related to size, age, type, and heritage status) on both reactive problem occurrence (number of requests in the period) and time response (number of days between the problem report and solution) (Figure 9). Since the data involved a set of variables to be simultaneously analysed, multivariate techniques were applied (BRYMAN, 2012). According to Hair et al. (2014), the use of such techniques among organisations is frequent, due to their capability for generating knowledge and improving decision-making. Descriptive and inferential statistical approaches (DANCEY; REIDY, 2006; SCHUENEMEYER; DREW, 2011) were adopted and applied with the support of SAS University Edition software.

Figure 9: Contribution of independent variables on Reactive Maintenance problem occurrence and time response



Source: Author (2021)

Initially, work requests data were prepared for analysis. Although a previous organization had been made for qualitative analysis purposes, a second summarization was necessary for filtering and structuring relevant data. A descriptive statistics described and compared the sample metric variables, focusing on their central tendency (e.g. mode, median, mean) and dispersion (e.g. standard deviation, variance, range, coefficient of variation) (SAUNDERS; LEWIS; THORNHILL, 2009). The normality distribution of variables was tested by the goodness of fit Kolmogorov-Smirnov test and a graphical inspection on histograms and box plots. A Pearson's correlation analysis evaluated the strength of relationship among all variables, called multicollinearity (HAIR et al., 2014). The descriptive stage enabled the assessment of the data validity and definition of techniques for inferential analyses (SCHUENEMEYER; DREW, 2011).

The Inferential statistics measured both degree and character of the relationship among the independent variables and their individual relationship with a single dependent variable. Partial Least Squares regression (PLS) (GELADI; KOWALSKI, 1986) was selected among other applicable analysis methods (e.g., Multiple regression, Canonical correlation, Multiple Discriminant Analysis (HAIR et al., 2014)). Primarily developed for the econometric area, PLS is currently employed for the development of predictive models related to linear relationships among multivariate measurements (NGUYEN; ROCKE, 2002), addressing this research needs. The results of descriptive and inferential statistics were depicted in tables and charts, thus facilitating visualization and supporting discussion and interpretation. Chapter 5 presents the procedures and findings of the statistical analysis.

2.3. Summary

This chapter presented the methodology adopted in this study, detailing the research philosophy, design, strategies, and methods. The complexity of the research question and the perspective chosen for observation of the phenomena required a pluralistic approach that explored the benefits and potentialities of Multiple Case Study and Prototyping strategies. The adoption of multiple sources of evidence, the bespoke integration of qualitative and quantitative methods for data generation and analyses, and the systematic procedures aimed to strengthen the validity, reliability, and replicability of the research. Therefore, the cases and the literature provided evidence of maintenance problems, critical scenarios, solutions, and requirements for BIM and IoT implementation, while the prototyping process validated such findings through an empirical demonstration, raising conceptual and methodological levels.

3. Background

This chapter presents a literature review on building design process, Facilities Management (FM), maintenance services, and FM digital transformation through BIM, IoT and Digital Twin implementation towards a common understanding of the key topics and a critical analysis of previous findings. It highlights lacunas in such knowledge and supports the development of the multiple case study and prototyping as well as the discussion of results.

First, the building design process was characterized according to related concepts, definitions and frameworks. Next, the focus was on the characterization of the FM and maintenance scenario (i.e., scope, activities, information management tools), identifying bottlenecks in FM maintenance information and in reactive maintenance service provision. BIM, IoT, and Digital Twin definitions and enabled technologies were explored, and opportunities for moving FM and maintenance towards a predictive approach were emphasized. Relevant books, standards, conference articles, and scientific journal articles as sources of evidence raised gaps in the knowledge on the role of BIM and IoT in such transformations. Lastly, an investigation on BIM and IoT for FM and reactive maintenance service is provided, highlighting trends in the research field, solutions, devices, areas, activities, and outcomes involved in such implementation through a Systematic Literature Review (SLR) of scientific journal and conference articles.

The chapter is divided into four sections. Section 3.1. describes the building design process features; Section 3.2. presents the core aspects of the Facilities Management (FM) and maintenance services; Section 3.3. presents the context of BIM, IoT, and Digital Twin for FM and reactive maintenance; finally, Section 3.4. summarizes the chapter, highlighting its contributions to the overall research.

3.1. Building design process

The production of buildings has become more complex over the past decades due to the increasing number of design disciplines and stakeholders involved, and financial, legal, technical, and environmental requirements. More than meeting the users' functional demands, the project must include a set of information for the execution and operation of the building throughout the lifecycle. In this scenario, design process management faces new challenges to increase its efficiency and productivity for developing buildings with higher quality. This section explores the building design process through concepts, definitions, and frameworks, and discusses the importance of its management for the asset value.

3.1.1. Design as a product and design as a process

Distinct connotations can be attributed to design in the building production context as either a product, or a process. In a narrower view, it can be considered a product, aggregating information required for the execution, operation, and maintenance of a building. Marques (1979) [7] apud Melhado (1994, p. 175)

[7] MARQUES, G.A.C. O projeto na engenharia civil. São Paulo, 1979. Dissertação (Mestrado) - Escola Politécnica, Universidade de São Paulo.

conceptualizes it a "static" design "composed of graphic and descriptive elements, ordered and elaborated according to an appropriate language, aiming to meet the needs of the construction stage”.

Melhado (1994, p. 169) claimed design should not be limited to the geometric and constructive characterization of a product but gather information on the production process that guides the sequence of activities and defines the "strategic, physical and technological means necessary to execute its construction process". The development of the "product-design" must address a set of normative, legal, technical, and environmental requirements, certifying its quality and enabling its approval by competent authorities (SALGADO, 2005).

Beyond the requirements for design conception and construction, design as a product can provide enough information for the meeting of needs of the contractor, the end-user and the team involved in building maintenance (SALGADO, 2005). Therefore, it can be understood as the process of developing solutions addressing stakeholders’ demands.

The “dynamic concept” of design refers to “a process wherewith solutions are developed for the problems that triggered the real estate and legitimate the investment” (Marques, 1979 apud Melhado, 1994, p. 175), reinforcing its comprehension as a service or activity inherent to the real estate process production (MELHADO, 1994). Fabricio (2002) conceptualizes the design process as a coordinated set of actions towards the quality of the design and its products, also including the As-built and the design evaluation in the use stage.

As discussed by Melhado (2001), Rozenfeld et al. (2006) and Silva and Souza (2003), the design development is based on two aspects, namely concept of process, related to a logical and sequential organisation of activities towards the production of goods or services, and flow of input (parameters) and output (design) information, developed by internal and external stakeholders. Consequently the product of a process will be used as input to the following processes, feeding the design development (SILVA; SOUZA, 2003) (Figure 10).

Figure 10: Process concept

Source: Author based on Silva and Souza (2003)

Rozenfeld et al. (2006) organised the Process of Development of Products (PDP) into three macro phases, namely Pre-development, Development and Post-Development. The first is based on the competitive strategy of the organisation towards investigations on alternatives and definition of the project to be developed. In the second macro phase, the multidisciplinary team establishes the product specifications and the functions to be addressed, delivering both development and improvement of the solution through the iterative cycle of “Design – Build – Test – Optimize”. Finally, the Post-Development assess the product life cycle through technical performance monitoring and client’s satisfaction evaluation, recording lessons learned and the feedback to the process (ROZENFELD et al., 2006).

The results of each phase are evaluated in the gate stage for certifying tasks, objectives, quality of the results, and value of the project have been achieved (ROZENFELD et al., 2006). Melhado (2001) reinforced the importance of validating the results at the end of each stage for ensuring the accuracy of the information for feeding the following stages or being sent to the building construction. As a process, design plays a strategic role in organisations and its development must consider the market demands, the technological potentials and limitations, and the product monitoring throughout the life cycle (ROZENFELD et al., 2006).

In this context, the concept of quality in the design process relates to the development of products and services addressing the requirements for contracting, building and using the building (MELHADO, 1994; SILVA; SOUZA, 2003). As shown in Table 3, a set of intrinsic and extrinsic factors to the process must be considered for the achievement of design quality. Besides the professionals' individual skills, the design quality depends on the coordination and management of activities in each stage of the process, thus supporting communication among stakeholders and achievement of the expected results (SILVA; SOUZA, 2003).

Table 3: Factors of quality in design

Intrinsic factors	Skills of the design team reflected in the quality of the solutions; Presence of experts (e.g., consultants) for specific problems; Standardization of design information; Observation of entrepreneur´s needs and expectations; Consideration of production needs and quality control of services; Coordination of activities and control of interfaces among designers.
Extrinsic factors	Quality of departments or companies associated with the entrepreneur; Adequate standardization of design criteria, content, and presentation; Availability of technical information for design development; Clear and efficient guidance on the legal requirements for the design defined by approval bodies.

Source: Author based on Melhado (1994)

3.1.2. Characteristics of the building design process

The building design process involves a series of aspects that influence the selection of stakeholders and the strategies for the process management (e.g., activities and results with high degree of uncertainty and risks, necessity of important decision-making in the early stages of the process, difficulty in changing primary decisions during the process, management and generation of high volumes of information from various sources, and multiple requirements to be addressed to the clients in all phases of the product lifecycle (ROZENFELD et al., 2006).

Some aspects distinguish the design process of buildings from other products and must be considered in its planning and control. The first is the singularity of the product. Despite the expertise of organisations in producing buildings, each design has functional, environmental, or financial particularities, which precludes a simple reproduction of previous productive processes. Amorim[8] (1996) apud Fabricio (2002, p. 46) understand civil construction as a prototype industry "organizing the real estate development according to relatively unique cycles of production related to a specific site where the building product will be generated".

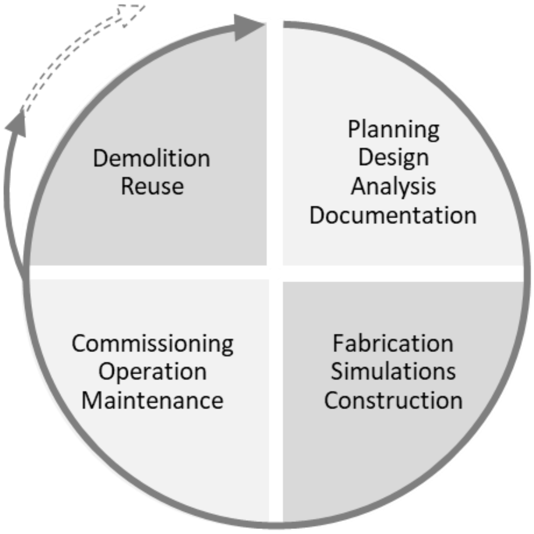
Regarding a second aspect, the building production involves large variety and quantity of stakeholders assuming different roles and responsibilities throughout the building life cycle (FABRICIO, 2002; SILVA; SOUZA, 2003). Multidisciplinary teams for design, construction, operation, and maintenance of buildings vary for each project, and, in many cases, the selection of suppliers prioritizes the low cost of services rather than the technical qualifications of the professionals. Such stakeholders follow their own and often conflicting procedures (SILVA; SOUZA, 2003), leading to a low level of collaboration among designers (MELHADO, 2001). Besides, they and their needs and expectations in relation to the built environment are often replaced. The

[8] AMORIM, S.L. Inovações tecnológicas nas edificações: papéis diferenciados para construtores e fornecedores. Gestão & Produção, São Carlos, v.3, n.3, p.262-73. 1996.

interaction among users and suppliers challenges the management and coordination of the design process, which must mediate individual and transitory interests and provide solutions for product development.

Third, a building lifecycle tends to be long, i.e., from decades to hundreds of years. It starts with the planning and design of the building, goes through several stages, reaches the operational phase, and, finally, the demolition or reuse of the asset (Figure 11). Towards ensuring the quality and sustainability of the building, the design process must consider the building adaptability to new demands, the natural resources consumed, the lifespan of the materials and the requirements for maintenance and operation (FABRICIO, 2002).

Figure 11: Typical building lifecycle activities



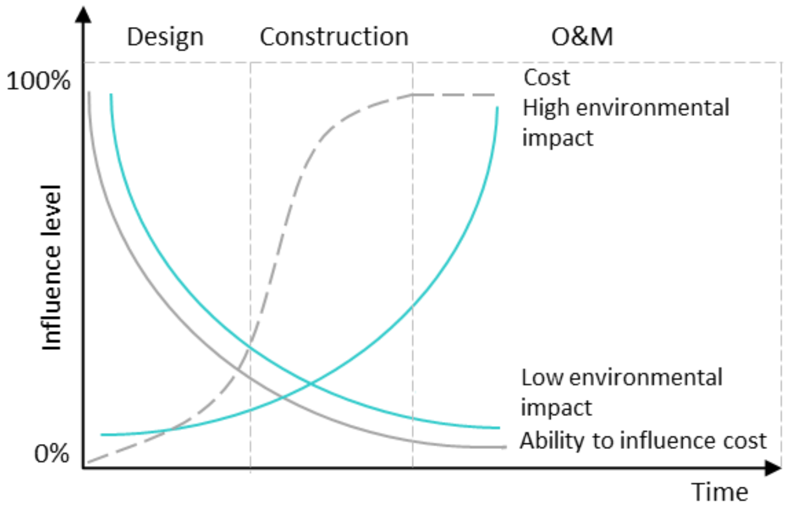
Source: Author based on Agência Brasileira de Desenvolvimento Industrial (2017) and Emmitt (2016)

Although design and construction are responsible for only around one fifth of the costs and resources (ROYAL INSTITUTION OF CHARTERED SURVEYORS, 2015), they concentrate the most important decisions in the process impacting on the global costs of the product. Melhado et al. (2006) claimed the time necessary for design and planning activities represents 15 to 20% of the global time of traditional projects, reaching 25% in complex ones.

Possible interferences in previous decisions is reduced during building design and construction, whereas the costs of changes increase exponentially (BØLVIKEN; GULLBREKKEN; NYSETH, 2010; FABRICIO, 2002; KNOTTEN et al., 2015; MELHADO, 1994; SACKS et al., 2018; SILVA; SOUZA, 2003). As shown in Figure 12, decisions made in early stages also interfere in the performance of the building and the environmental impacts of its use (BRASIL, 2010; CEOTTO, 2008). Therefore, improvements in the design phase are imperative for reductions in the costs of the asset and higher building quality over time, optimizing O&M activities and increasing user's satisfaction.

Lastly, buildings production has become more complex over time due to a set of factors, such as advances in systems and constructive processes, changes in user's habits, increase of environmental and competitive requirements, and changes in resources that support development and communication in the design process (BØLVIKEN; GULLBREKKEN; NYSETH, 2010). The building and its surrounding have incorporated new equipment and systems, such as telecom, sensors and meters, and sophisticated electrical equipment. Moreover, the complexity of legal, organizational, and financial structures for the delivery of buildings has grown, requiring more specialized services and professionals and expanding the volume and variety of information (FABRICIO, 2002; SACKS et al., 2018). This scenario demands considerable efforts related to coordination and managerial activities (BØLVIKEN; GULLBREKKEN; NYSETH, 2010), particularly regarding quality of information over building lifecycle.

Figure 12: Level of influence of decisions on the costs and environmental impacts



Source: Author based on Brasil (2010), Melhado (1994), and Sacks et al. (2018)

3.1.3. Relevance of the building design process management

Design Process Management plays a key role in the AEC industry, due to its strategic importance for business performance and building life cycle sustainability. According to Tzortzopoulos and Cooper (2007), design management has emerged as a discipline based on two schools of thought - one concerned with the organisation of design companies, and another focused on improvements in communication and coordination tools, leading to discussions on its application and comprehensiveness by several authors. Melhado et al. (2011) understand design management as an activity that ensures design quality and assertiveness of its solutions to users:

> "a single function that starts with the understanding of design as a process, identifying the needs of at least the three main interested players (the client, the contractor and the user) and goes through models and tools to improve the design quality, thus having a comprehensive view of design with the aim of ensuring that appropriate design information is delivered within the project schedule to meet those needs". (MELHADO et al., 2011, p. 2)

In a simplified perspective, design management deals with managing interactions between people and information over the stages and disciplines of the process (EMMITT; RUIKAR, 2013; FABRICIO, 2011). The Brazilian Architecture and Urbanism Council (CAU/BR) considers management one of the competencies of architects, encompassing design, construction, assessment, and maintenance of buildings and services (CONSELHO DE ARQUITETURA E URBANISMO, 2012). Considering the whole lifecycle in the building management, Emmitt (2002) presented the "Architectural Management" concept, which involves people and communications in the management of design, construction, maintenance, and recycling of the building.

Design management and coordination must consider the constant transformations in the productive building process caused by the increasing in functional, technical, normative, and sustainable requirements. Silva and Souza (2003) emphasized the importance of design management for mitigating recurrent problems in building production (e.g., low productivity and rework of professionals, and dissatisfaction of clients and end users).

Despite its relevance, the traditional design management approach is based on a “static planning” of production focused on the control of costs and deadlines, thus neglecting interactions among activities, essential for the quality of solutions (SILVA; SOUZA, 2003). The sequential processes and the hierarchical structure of organisations limit the interaction and communication among stakeholders, reducing the possibilities of collaboration (FABRICIO, 2008). Such a fragmented structure is characterized by unsystematic practices and lack of protocols for collaboration among disciplines, generating deficiencies in design management (TAURIAINEN et al., 2016). As depicted in Table 4, several problems in the design process (e.g., errors and reworks) are caused by managerial failures.

Table 4: Managerial failures in the design process

Author	Managerial failures
Tauriainen et al. (2016)	Lack of clarity in sharing responsibilities among designers Design manager with insufficient knowledge and experience Lack of communication among members of the design team
Fabricio (2002)	Lack of decisions integration in outsourced designs Insufficient time for decisions Responsibility for planning design activities delegated to designers Quality neglected in early stages of design Lack of standards for team integration and design compatibilization
Vargas (2000)	Lack of comprehension on the complexity of the design Failures in scheduling activities Design developed with no adequate managerial supervision Lack of knowledge of required personnel, equipment, and supplies Lack of standards for the development of the design

Source: Author (2021)

Unlike most production processes, building design management is characterized by a range of interactions for the achievement of the expected solution, rarely following a sequential logic (KNOTTEN et al., 2015). According to Knotten et al. (2015), the greater the interaction among team members, the higher the complexity of tasks and necessity of synchronous communication among them. Therefore, the challenge is to manage the design process on the one hand as a continuous and reciprocal process, and on the other hand as a productive process rigorously sequential.

Given the impact of managerial practices on the design process, some initiatives, principles, and theories are discussed towards a more efficient design management based on collaboration and coherent with the quality and competitiveness requirements of the AEC industry. Melhado (2001) identified improvements in the design management of organisations in the civil construction sector, focused on new strategies for hiring and coordinating designers, establishing criteria for design assessment, and sharing information with the construction team.

Knotten et al. (2015) and Bølviken, Gullbrekken and Nyseth (2010) proposed the use of Collaborative Design Management, an approach centred in design development and decision-making processes rather than in the creative design process. It aims to address contractual requirements, such as cost, quality, constructive feasibility, and handover on time, and applies principles of *Lean Construction and The Last Planner System* – the latter used for planning and building complex and collaborative designs (KNOTTEN et al., 2015).

Fabricio and Melhado (2001) used the Concurrent Engineering principles to develop the philosophy of Concurrent Design, focusing on the integration of activities and stakeholders in the early stages of the design process for delivering quality to the building over the life cycle (FABRICIO, 2002). Knotten et al. (2015) described two important aspects for improving building design management, namely definition of indicators for process control, considering time, cost, and participation, and increase in the integration among design stakeholders based on synchronous (e.g., meeting or telephone call) and asynchronous (e.g., e-mail, drawing, model) communication towards information exchange and development of new ideas and design solutions.

In fact, there is a consensus on communication as a central factor for improvements in the design process of modern and increasingly complex buildings and facilities (SACKS et al., 2018). Fabricio (2002) and Melhado et al. (2006) emphasized the importance of Information and Communication Technologies (ICTs) for the remote communication and collaboration among stakeholders, expanding the capacity of technological development and exchange of information. BIM, IoT, and Digital Twin play a key role in design process management, triggering positive transformations in the design, construction, and maintenance of buildings.

3.2. Facilities Management (FM) and maintenance services

This section describes the core aspects of Facilities Management (FM) and maintenance services, including FM areas and value, maintenance categories, and reactive maintenance process and challenges.

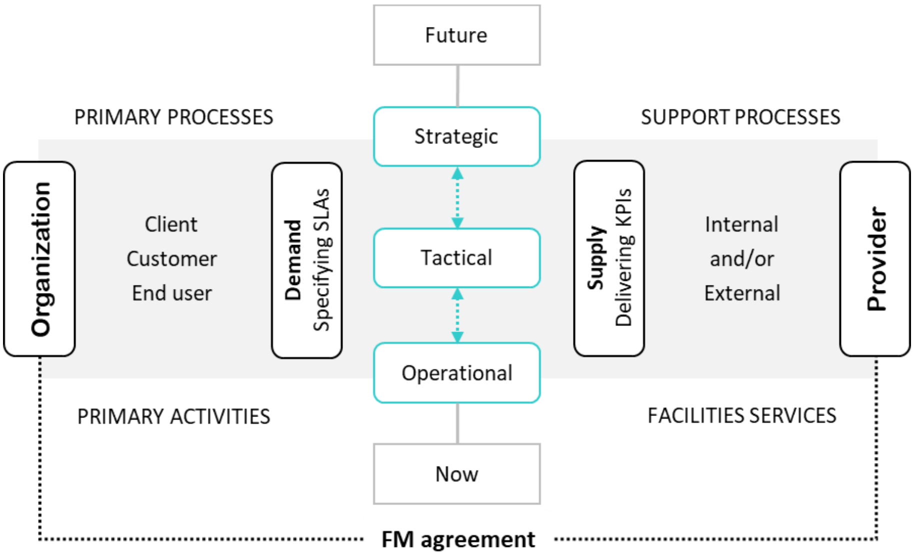
3.2.1. Facilities Management (FM) areas and value

Facilities Management (FM) plays a key role within the building lifecycle, optimizing resources consumption, increasing user's satisfaction, and providing feedback with integrated building information to the early stages of the design process. As discussed by (CODINHOTO et al., 2013), distinct definitions and concepts have been provided to FM over time, thus addressing transformations in the field. The standard BS EN 15221-1:2006 defines FM as the "integration of processes within an organisation to maintain and develop the agreed services which support and improve the effectiveness of its primary activities" (THE BRITISH STANDARDS INSTITUTION, 2006).

On the other hand, ISO 41011:2017 defines FM as an "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). A deeper comprehension of FM is extracted from this definition. The importance of people in the structure as both providers and users of FM services is emphasized. Also, the notion of place indicates the necessity to consider the individuality of each organization for effective service provision. Finally, the mention to the built environment denotes the scope and the context of FM activities, which involves, but is not limited to, the management of buildings, infrastructure, and other physical assets.

Despite the distinct practices over the organizations (BARRETT; FINCH, 2014), in general, the support of FM to the core activities covers the strategic, tactical, and operational levels, aiming at optimizing costs and improve the performance of services and assets (THE BRITISH STANDARDS INSTITUTION, 2006). A framework with the main components within FM was proposed by BS EN 15221-1:2006 comprising the primary and support processes and tools (i.e., Service Level Agreements, Key Performance Indicators), the service demandant (i.e., client, customer, end user) and providers (i.e., internal, external, both) and the levels of interactions (i.e., strategic, tactical, operational). A second model was presented by Barrett and Finch (2014), also establishing the interactions among strategic and operational FM, future and current situations, and external and internal environments. Figure 13 depicts the main components of both frameworks.

Figure 13: FM Framework



Source: Author based on Barrett and Finch (2014) and The British Standards Institution (2006)

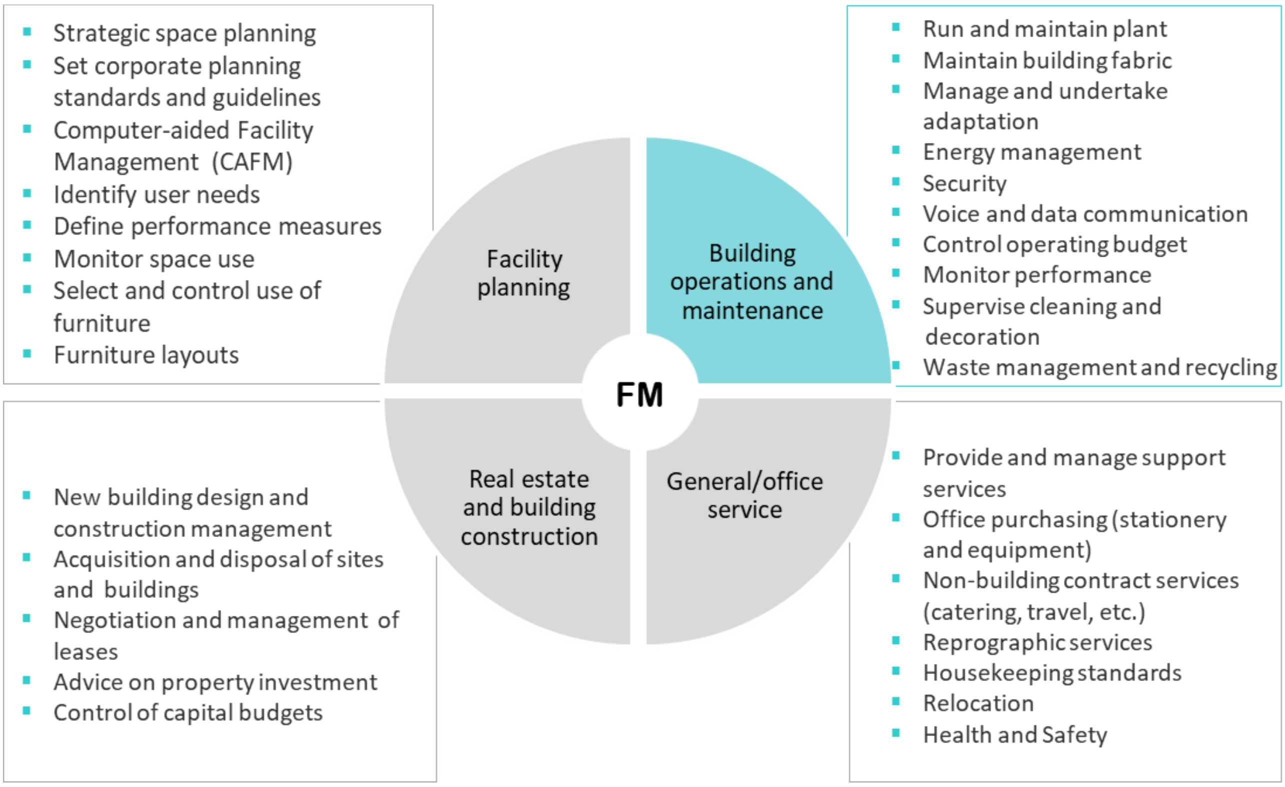
A series of organization factors might influence the structure of the FM sector and the modality of service execution (i.e. in-house, outsourced), such as the typology (i.e., educational, health care, industrial, etc.), size and location of the organization (i.e., single-site, multi-site) (ABDUL-LATEEF, 2010; BARRETT; FINCH, 2014; CHANTER; SWALLOW, 2007) as well as the skills of staff (CODINHOTO et al., 2013). In general, some among the four typical FM areas (i.e., Building operations and maintenance, General/office service, Real estate and building construction, and Facility planning) and related activities described by Barrett and Finch (2014) are performed by any FM sector, as depicted in Figure 14..

FM operational services are essential to support the business activities, health and safe of users, and the preservation of physical assets. However, the value of FM is also in the strategic decisions for optimizing resources and improving the performance of assets over time (ABDUL-LATEEF, 2010; BOOTY, 2009). The phase of use, Operation and Maintenance (O&M) is considered the longest and costly within the asset lifecycle (ROYAL INSTITUTION OF CHARTERED SURVEYORS, 2015) and presents significant environmental impacts in comparison with other sectors (INTERNATIONAL ENERGY AGENCY, 2021). Beyond the operational and maintenance services, such resources are driven to renovation and retrofit necessary for adjusting the current space to new functions (ROYAL INSTITUTION OF CHARTERED SURVEYORS, 2015; SILVA; SOUZA, 2003).

Despite its importance, O&M phase is, in general, inefficient and negatively impacts business performance regardless of the sector (SULLIVAN et al., 2010). Part of such inefficiencies are influenced by decisions taken in the Design (PINTI et al., 2018)and Construction phases that impact the global costs of the asset. For instance, problems in the briefing phase involving the definition of needs, parameters and requirements respond for approximately 30% of the reworks in the following phases of the design process (KNOTTEN et al., 2015).

Nevertheless, most of such inefficiencies are associated with the management of FM activities, often considered a firefighting service (BOOTY, 2009). The predominance of a reactive approach misaligned with the business objectives and needs in long-term contributes to "poor service delivery, dissatisfied customers and loss of value to the organisation" (CODINHOTO; KIVINIEMI, 2014). Budget restrictions, unsatisfactory performance of craftsmen, unexpected variances in work coordination, unavailability of supplies (HIGGINS; MOBLEY, 2001) figure among the sources of unplanned actions. However, one of the main causes is related to management of asset information and communication to adequately fulfil users' needs according to cost, time and quality requirements of organisations (LEE; AKIN, 2009; PISHDAD-BOZORGI, 2017; SULLIVAN et al., 2010). Due its relevance, the strategic role of FM information management is thoroughly discussed in Section 3.3.2.

Figure 14: FM typical areas and activities



Source: Author based on Barrett and Finch (2014)

3.2.2. Maintenance categories

Building operation and maintenance are among the core FM areas performed by organizations. In this section, the main categories of maintenance programs applied to organizations' assets are characterized, namely, Reactive, Preventive, and Predictive or Condition-Based Maintenance (CBM), highlighting their impacts on service provision and building end-users. A prior comprehension of maintenance scope is therefore necessary for such differentiation. The standard "BS EN 13306:2017 Maintenance - Maintenance terminology" defines 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" (THE BRITISH STANDARDS INSTITUTION, 2017, p. 8). Important aspects raised from this definition supports this research approach.

First, that maintenance is an interdisciplinary area, requiring not only technical expertise but also coordinated administrative and managerial support for service provision. Second, that maintenance is an essential and permanent area within FM organizational structure due to the extended lifetime of facility assets. Ensuring the safe and efficient performance of asset components is essential to assist core activities and protect the value of assets (THE BRITISH STANDARDS INSTITUTION, 2012). Third, that distinct maintenance programs can be provided depending on the strategies adopted by the organization and on the performance state of an item. Among such maintenance programs is the Reactive maintenance, also known as Corrective maintenance, which is defined as the maintenance undertaken after fault recognition with the purpose to restore an item to its performable function (THE BRITISH STANDARDS INSTITUTION, 2017). The unpredictable occurrence is the main characteristic of faults addressed by this maintenance program. As a result, actions towards fault repair are commonly triggered when the breakdown is already impacting on building users' routine.

Such conditions position reactive maintenance among the critical areas within FM structure, concentrating resources and efforts in service provision. In fact, reactive maintenance is the most predominant program (MOBLEY; HIGGINS; WIKOFF, 2008), representing more than 55% of the overall breakdowns in the United States of America (SULLIVAN et al., 2010). Despite the reduced staff and capital costs, some of its disadvantages involve the increased costs of material and labour involved in unplanned repairs, the possible damage of secondary process or equipment, and the likelihood of unexpected disruption in organizations activities (COLEMEN et al., 2017; KATONA; PANFILOV, 2018; SULLIVAN et al., 2010).

In opposition, preventive and predictive maintenance actions involve the assessment of performance, mitigation of degradation, and reduction of likelihood of faults in items (THE BRITISH STANDARDS INSTITUTION, 2017). Preventive maintenance is based on predetermined timespan or number of uses of a component, aiming at controlling degradation to sustain or extend its useful life. By increasing the reliability of components, preventive maintenance mitigates fault occurrence, thus improving its performance and extending its lifetime. Although generating energy and cost savings if compared to reactive maintenance, preventive programs might drive efforts in unnecessary activities, increase spare part inventory, and do not anticipate random failures (COLEMEN et al., 2017; KATONA; PANFILOV, 2018; SULLIVAN et al., 2010).

Predictive or CBM is based on the current condition of an item, performing maintenance actions only if required (KATONA; PANFILOV, 2018; NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, 2008; VELMURUGAN; DHINGRA, 2015). The aim is to detect deterioration in advance and forecast failure, enabling planned response, and minimizing unpredictable failures and disruptions. To do so, the condition of components must be periodically monitored and analysed, representing "a new shift in the way pro-active maintenance has formerly been prescribed in the sector" (PÄRN; EDWARDS, 2017, p. 13). The benefits of predictive maintenance includes the improvement of the performance of components over lifetime, generating efficiency gains in maintenance service provision between 30 to 40% (SULLIVAN et al., 2010). In the manufacturing industry, predictive maintenance is expected to reduce the time for planning maintenance between 20 and 50% and increase the equipment lifetime by 10 to 20% (COLEMEN et al., 2017). On the other hand, robust investments in technologies, staff training and organizational changes are required for condition monitoring (COLEMEN et al., 2017; NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, 2008; SULLIVAN et al., 2010).

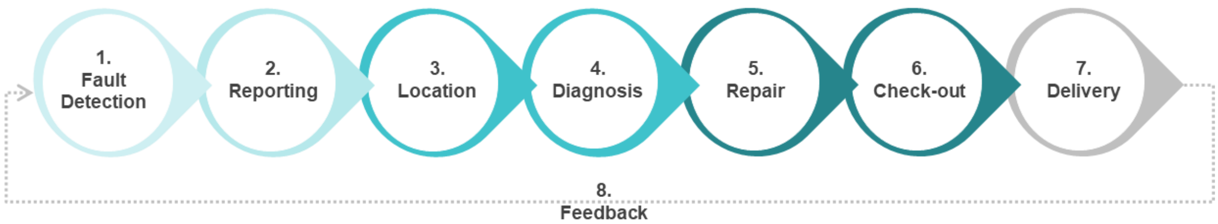
In fact, the decision on which maintenance strategy must be adopted involve various aspects associated with the organization needs and goals, the building characteristics and the impacts and risks of breakdown to the end-users. A poor strategy could affect the safety of users and commercial development of the organization (AKCAMETE; AKINCI; GARRETT JR, 2010; THE BRITISH STANDARDS INSTITUTION, 2012). According to Lewis (2012, p. 234), moving maintenance towards a proactive approach would require the development of a maintenance plan and the assessment of "what systems and equipment could cost effectively use condition-based (predictive) maintenance". Also, periodic reviews of maintenance performance and strategy are recommended to ensure the effective implementation of a maintenance strategy (VELMURUGAN; DHINGRA, 2015). Addressing such requirements, the role of BIM and IoT solutions in predictive approaches and the identification of critical scenarios for predictive maintenance implementation are furthered discussed in Chapter 4.

3.2.3. Reactive Maintenance process and challenges

As previously presented, reactive maintenance is the most predominant and critical maintenance category in organizations, requiring special attention from FM sectors. A thorough understanding of reactive maintenance process and challenges is essential to improve the performance of corrective actions and support the implementation of predictive approaches in decision-making.

As an interdisciplinary area, the reactive maintenance process involves many steps, activities, and stakeholders to accomplish with the end-user needs and expectations. A conceptual framework of a traditional reactive maintenance process was here proposed based on the standard BS EN 13306 (THE BRITISH STANDARDS INSTITUTION, 2017), as depicted in Figure 15. The process is comprised by eight stages, namely, 1. Fault Detection, 2. Reporting, 2. Location, 4. Diagnosis, 5. Repair, 6. Check-out, 7. Delivery, and 8. Feedback.

Figure 15: Conceptual Framework of the traditional Reactive Maintenance Process



Source: Author (2021)

The stage *1. Fault Detection* relates to the identification of a failure in any building of infrastructure system, equipment, or fabric by an end-user of staff member (GUNAY et al., 2018; OUBODUN, 1996). The *stage 2. Reporting* involves the communication of the fault or issue by an end-user or staff member to the FM sector. The Work Request is the physical or digital document used to inform the work required, thus identifying, for instance, the faulty item, the job number, the work requested and the priority level (GOBER, 2008; GUNAY et al., 2018; MÁRQUEZ, 2007). Once the request is approved by the FM staff, the service is scheduled and allocated to the maintenance staff. To do so, the Work Order (or job ticket) is generated, providing to the maintenance staff the necessary information to carry out the service (i.e., material, tools, critical times) (CHANTER; SWALLOW, 2007; GOBER, 2008).

The *stage 3* refers to the *Location* of the problem in the building or infrastructure environment. It commonly involves surveys in statutory and asset documents and field inspections to examine the characteristics of the faulty item (BECERIK-GERBER et al., 2012). The stage *4* relates to the *Diagnosis* of the problem, recognizing the faulty items and the related causes with support of statutory and asset documents. Activities for planning the repair are usually triggered in this stage, involving an interface of the FM sector with the financial sector and the external suppliers.

The stage *5. Repair* refers to the fault correction, comprising physical actions to restore the function of a faulty item. The stage 6 comprises the *Check-out* of the service, ensuring that the repaired item is performing as required and authorizing related payments (CHANTER; SWALLOW, 2007). The stage 7. Involves the *Delivery* of the service to the end-user or staff member, registering the attendance of the request. Finally, the stage *8.* comprises the *Feedback* from the requestor to the FM sector, informing the level of satisfaction with the service provided, an important metric for service improvements (PIN; MEDINA; MCARTHUR, 2018; ROYAL INSTITUTION OF CHARTERED SURVEYORS; INTERNATIONAL FACILITY MANAGEMENT ASSOCIATION, 2018). Once approved, the request is closed and recorded into FM databases.

The complexity of the reactive maintenance process imposes challenges to the FM sector in service provision. One challenge refers to the identification of root causes of failures, thus impacting on planning service response and maintenance costs. According to Park (1994, p. 35), the main causes of breakdowns might be associated with "component failure within projected lifespan, vandalism, maintenance failure, human error, damage". In fact, some of these causes are random, such as vandalism and human error, necessarily requiring unplanned actions. However, causes related to the performance of components might be associated with the characteristics of the design, construction, and use of the building stock (i.e., age, size, typology, material, number of users, etc.). In this scenario, defects in components can be anticipated through the monitoring of real-time performance and analysis of historical data, thus enabling the identification of a pattern of breakdowns (AKCAMETE; AKINCI; GARRETT JR, 2010; COLEMEN et al., 2017; VELMURUGAN; DHINGRA, 2015).

Previous studies have discussed such root causes for failure in buildings and their effects on maintenance costs (BORTOLINI; FORCADA, 2020; KRSTIĆ; MARENIAK, 2012; OFORI; DUODU; BONNEY, 2015). The age of buildings is one of the most important variables associated with the degradation of components and the increase of maintenance cost (ABDUL-LATEEF, 2010; PERERA; ILLANKOON; PERERA, 2016; SALLEH et al., 2016; TALIB et al., 2014). As discussed by Chanter and Swallow (2007), failures related to design and construction are expected after building completion, but tend to increase over its lifecycle.

The size of buildings measured in terms of building area and height is also described as a variable impacting on maintenance costs (ALI et al., 2010; KRSTIĆ; MARENIAK, 2012; OLANREWAJU; ABDUL-AZIZ, 2015; PERERA; ILLANKOON; PERERA, 2016; SALLEH et al., 2016). In fact, maintenance works in old and high rise buildings tend to involve complex interventions to retrofit and access systems and equipment, thus requiring a large allocation of resources (ALI et al., 2010). The investigation of the root cause of a breakdown rather than its symptoms is essential to effectively solve maintenance problems, improving planning activities and reducing maintenance frequency and cost (AKCAMETE; AKINCI; GARRETT JR, 2010; MÁRQUEZ, 2007; MOBLEY; HIGGINS; WIKOFF, 2008).

A second challenge relates to the prioritization of reactive maintenance services, ensuring that the most important problems will be promptly solved (BARRETT; FINCH, 2014; CHANTER; SWALLOW, 2007; JASPERS; TEICHOLZ, 2012; MÁRQUEZ, 2007). In general, a first prioritization is informed in the Work Request by the service solicitor (GOBER, 2008) or defined by the FM sector after receiving it. This classification is based on predefined priority code, usually developed by the FM sector as part of the Service Level Agreement (a document which defines the conditions for service provision) (CHANTER; SWALLOW, 2007). The severity of the fault is the main element of this classification, considering its current or potential consequences for end-users and the organization assets, according to aspects such as safety, cost, environment (THE BRITISH STANDARDS INSTITUTION, 2017). The number of levels and their time response vary among organisations and might depend on the typology of building stock, the volume of requests, and availability of maintenance staff.

Chanter and Swallow (2007) exemplifies a priority classification code comprised by four levels, namely, i. emergency work, attended within 24 hours; ii. urgent work to be addressed within a week; iii. Normal work attended in medium-term, which might represent most of the unplanned requests; and iv. Stand-by work, which could be addressed as part of the planned programme. Although a predefined code is provided, the lack of technical knowledge or enough description of the problem for assessing the fault severity might influence the reliability of the prioritization.

A second prioritization is carried out by the FM staff to plan the order of service attendance. The decision on service assignment order is challenging due to the dependence of a series of variables, such as the complexity of the repair, the availability of history record (AKCAMETE; AKINCI; GARRETT JR, 2010), budget, labour, and material resources (AHLUWALIA, 2008; JASPERS; TEICHOLZ, 2012; OLANREWAJU; ABDUL-AZIZ, 2015), the accessibility to the faulty item, the geographic location of shops (DABBS, 2008), and the impact on organizations activities. As discussed by Gober (2008), the lack of a systematic approach to support prioritization leads to subjective judgment from the FM staff, thus impacting on the attendance of critical problems.

The third and most significant challenge refers to the efficient management of FM and maintenance information management. Despite the technological potential of FM tools to improve the performance of FM services, technical limitations contribute to inefficiencies in the information management process (CODINHOTO et al., 2013; TALAMO; BONANOMI, 2016), hampering the execution of FM activities (AKCAMETE; AKINCI; GARRETT JR, 2010; AZIZ; NAWAWI; ARIFF, 2016; MISIC; GILANI; MCARTHUR, 2020). For instance, the fragmentation of data among systems and the need for manual data input after building handover hamper the management of information, hence, the efficiency of the process (BECERIK-GERBER et al., 2012; BOOTY, 2009; LEWIS, 2012; PINTI et al., 2018). As a result, the FM staff waste time and efforts for generating and obtaining accurate information when required (ABDUL-LATEEF, 2010; ARASZKIEWICZ, 2017; CODINHOTO; KIVINIEMI; KEMMER, 2013; MIRARCHI et al., 2018).

Procedural issues also impact information management over the reactive maintenance process. According to Akcamete, Akinci, and Garrett Jr (2011), keeping facility documents updated over the lifecycle of a building is a challenge for the FM sector, which rarely register facility changes after a maintenance completion. Lee and Akin (2009, p. 546) observed “the tradespeople tend to rely on their and/or colleagues recall rather than computerized O&M systems when they collect information on the specific equipment and the facility”.

The lack of reliable and centralized information on the current and historical conditions of building facilities hampers decision-making on maintenance and repair, leading to significant time waste in maintenance activities (GUNAY et al., 2018; LEE; AKIN, 2009). For instance, the imprecise description of a defective item and its location in the work request impacts further stages and time response (MIRARCHI et al., 2018), and the lack of information on recurrent defects hampers the identification of root causes and the adoption of proactive actions.

In general, data produced by FM systems are underutilized by organizations (BARRET; BALDRY, 2003) and the technical capabilities to manage information are unexploited, as exemplified by Lewis (2012, p. 236):

> "For example, trend data collected by a BAS is often only stored for a few days before being overridden with new data. CMMSs are mainly used for work order management, when they are also capable of being used to manage proactive maintenance and inventory control." (LEWIS, 2012, p. 236)

As a result, inefficiencies in information management impact on strategic decisions and exploration of new business opportunities. In 2004, the cost of inadequate interoperability in O&M phase was estimated at approximately 10 billion dollars in the U.S., reaching two-thirds of the total estimated costs for owners and operators (TALAMO; BONANOMI, 2016). Such limitations must be overcome sot that "building's in-use data and information can be converted into tangible business knowledge for augmenting FM performance" (HOSSEINI et al., 2018, p. 2), moving FM to a strategic position. BIM and IoT are important allies in this process, as discussed in Section 3.3.

3.3. BIM and IoT fostering Facilities Management (FM) digital transformation

This section presents Building Information Modelling (BIM) and Internet of Things (IoT) as the most disruptive approaches and Information and Communication Technologies (ICT) and enablers of Digital Twins, fostering FM and maintenance towards a more efficient, proactive, and sustainable scenario. Primarily, definitions of BIM, IoT, and Digital Twin are explored. Then, FM information management and tools are discussed within this innovative environment, considering the interface between O&M with other phases of the building lifecycle. Finally, previous studies and applications of BIM and IoT in FM areas are addressed with a focus on gaps and trends in the research field, and solutions, devices, areas, activities, and outcomes involved in the implementation.

3.3.1. Definitions

a. Building Information Modelling (BIM)

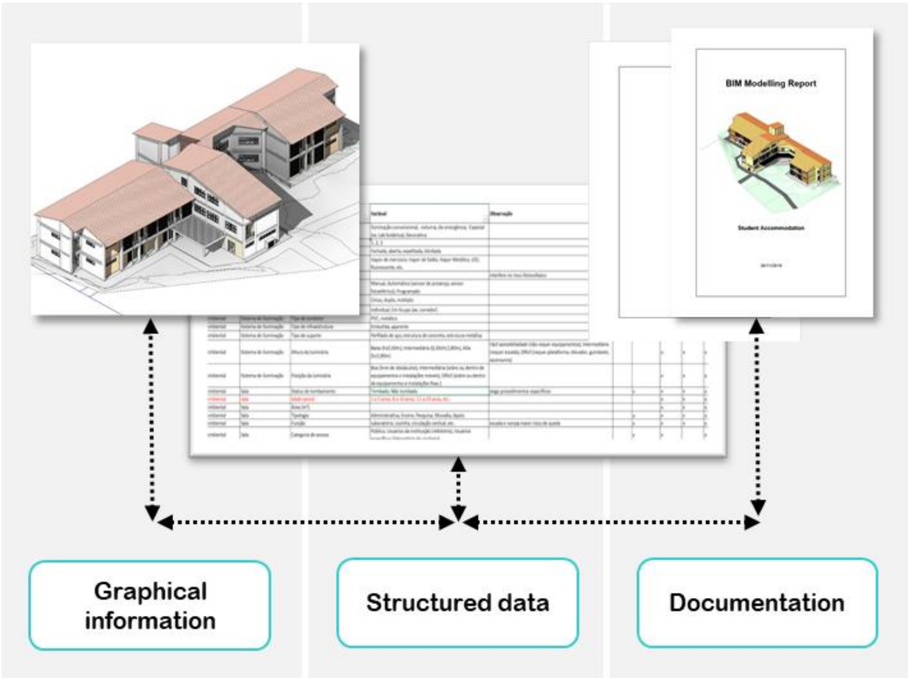
Building Information Modelling (BIM) is considered one of the key disruptive ICTs that improve the efficiency of Architecture, Engineering and Construction (AEC) industry (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; ROYAL INSTITUTION OF CHARTERED SURVEYOR, 2015). Defined as "the 'current expression of digital innovation' across the construction industry" (BUILDING INFORMATION MODELLING (BIM), 2021), BIM is a "methodology to manage the essential building design and project data" (PENTTILÄ, 2006) enabled by "a set of interacting policies, processes, and technologies" (SUCCAR, 2009).

In this study, BIM is comprehended as the integration of data and information about a building and its objects in a centralized digital database, thus enabling collaboration among stakeholders throughout the whole lifecycle (CORRY et al., 2014; EASTMAN et al., 2014; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019). It represents an opportunity for changes in the design process development and management (EMMITT, 2016), increasing accuracy and availability of information and the final building quality:

> "In a collaborative environment BIM should encompass both the modelling aspects and the information management aspects. BIM should be an enabler and an agent for change, and the potential for buildings to be delivered in a more collaborative way is, quite literally, at our fingertips." (EMMITT, 2016, p. 123)

The adoption of BIM in the Design and Construction phases has been extensively discussed regarding its benefits for improving the quality of drawings, the coordination of building systems, and the engineering productivity (SACKS et al., 2018). However, BIM is still an emergent area of investigation in the O&M phase and FM activities (EDIRISINGHE et al., 2017; KASSEM; AMORIM, 2015; MOREIRA; RUSCHEL, 2015; VOLK; STENGEL; SCHULTMANN, 2014) and whose greatest contributions are risk reduction and optimization of resources and costs (AKCAMETE; AKINCI; GARRETT JR, 2010; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; ROYAL INSTITUTION OF CHARTERED SURVEYOR, 2015; TALAMO; BONANOMI, 2016). BIM provides a consistent and rich repository of building operational performance information for FM (CORRY et al., 2014; MCARTHUR, 2015), integrated by graphical information, structured data, and documentation on systems and spaces, as depicted in Figure 16.

Figure 16: BIM graphical information, structured data, and documentation



Source: Author based on UK Government (2018)

The parametric modelling of geometric and nongeometric features and the management and visualization of information is assisted by core technologies within a BIM environment, such as BIM tools (e.g., AutoCAD-based applications, cost estimation, scheduling, simulation, and FM and Excel-based engineering tools) and BIM platforms (e.g., ArchiCAD, Revit, Vectorworks, Tekla Structures, Bentley AECOSim, DESTINI

Profiler) (SACKS et al., 2018). The value of information within BIM for FM teams is beyond the visualization of geometry, and includes access to maintenance records and real-time performance data:

> "Although the geometry can provide information to help locate items within the building, the information from the model often will be most valuable to the facility management team. The vision is that information within the BIM can include anything from maintenance manuals and warranty information to real-time linking to sources of building performance information, such as energy data." (LEWIS, 2012, p. 235)

BIM improves the quality of documentation, facilitating the access, update, and analysis of information over a building lifecycle (AKCAMETE; AKINCI; GARRETT JR, 2010; BRITISH INSTITUTE OF FACILITIES MANAGEMENT, 2015). According to Sacks et al. (2018), BIM models can be strategically used for improving building handover, providing documents that satisfy operational needs, and assessing the impact of failures in building systems. In this sense, BIM-based FM systems can facilitate the visualization of information by the maintenance team, enabling the simulation of maintenance procedures and the identification of the best solution to a problem (SACKS et al., 2018). As a result, BIM can assist FM sectors in a more sustainable and efficient management and operation of buildings, integrating and automating FM processes and anticipating and planning costs (EASTMAN et al., 2014; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018; ROYAL INSTITUTION OF CHARTERED SURVEYORS, 2015).

b. Internet of Things (IoT)

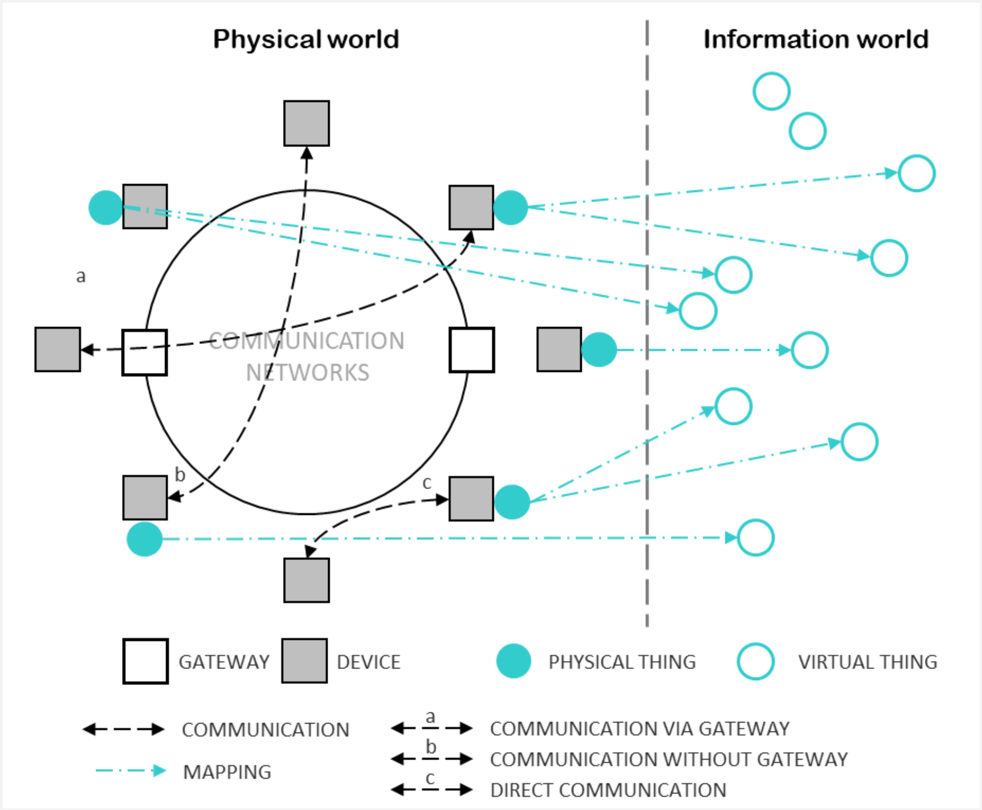
Internet of Things (IoT) is another digital innovation that has been transforming the AEC industry. The term was primarily used by Kevin Ashton in 1999 (ASHTON, 2010) to designate the network connecting physical things or objects to the Internet. Numerous definitions have been provided by organizations and researchers in the field:

> "Interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications." (GUBBI et al., 2013, p. 4)
>
> "A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies." (INTERNATIONAL TELECOMMUNICATION UNION, 2012, p. 1)

According to Madakan, Ramaswamy, and Tripathi (2015), the definitions of IoT share the idea the first version of the Internet concerned data created by people, whereas the next referred to data created by things. Therefore, IoT overcomes human limitations (e.g., lack of attention, accuracy, and time) to capture data, increasing the available information (ASHTON, 2010). In this sense, it is not a new technology, but a new approach that uses existing technologies and explores communication capabilities enabled by the Internet (LOVE; MATTHEWS, 2019).

The International Telecommunication Union (2012) provided a technical overview of the IoT (see Figure 17), emphasizing the interactions between physical and virtual worlds through communication networks. In the physical world, physical things, such as environment, goods, and electrical equipment can be identified, sensed, actuated, and connected supported by devices and gateways. The information collected by devices is processed by information and communication networks and provided to the virtual things. In the information world, virtual things (i.e., application software, multimedia content) can be processed, stored, and accessed.

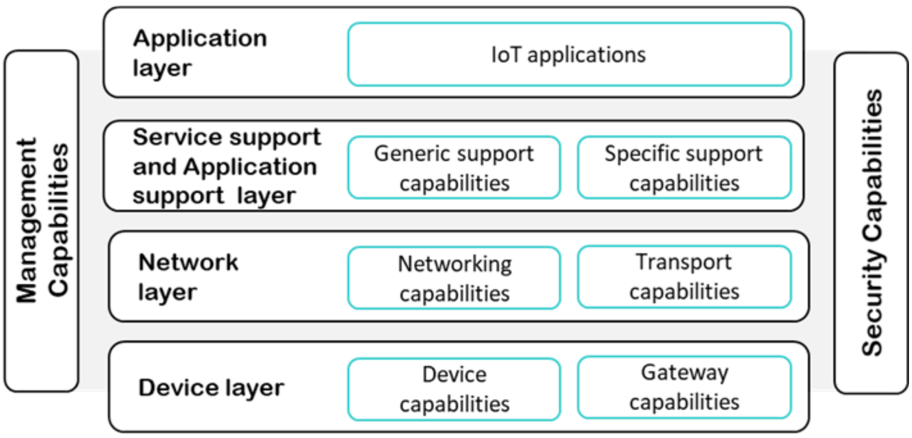
Figure 17: IoT technical overview



Source: Author based on the International Telecommunication Union (2012)

Several IoT ecosystems, architectures, and reference models have organized such components according to functional layers (LI; TRYFONAS; LI, 2016; MADAKAN; RAMASWAMY; TRIPATHI, 2015). For instance, The International Telecommunication Union (2012) developed an IoT reference model comprised of four layers, namely device, network, service support and application support, and IoT application, and two capabilities (i.e. management and security), as shown in Figure 18.

Figure 18: IoT reference model



Source: Author based on ITU (2012)

The Device layer is integrated by the device and gateways capabilities, enabling direct or indirect communication between devices and with communication network via multiple interface support and protocol conversion (INTERNATIONAL TELECOMMUNICATION UNION, 2012). In the Network layer, the networking and transport capabilities regard control functions and connectivity for access, management, and transport of information. The Service support and Application support layer is related to capabilities such as data storage and data processing, and the Applications layer contains the IoT applications based on proprietary or common application support platforms, thus establishing an interface with the end user. Finally, the Management and Security capabilities involve remote device activation, detection of network overflow conditions, authorization, authentication, and access control (INTERNATIONAL TELECOMMUNICATION UNION, 2012).

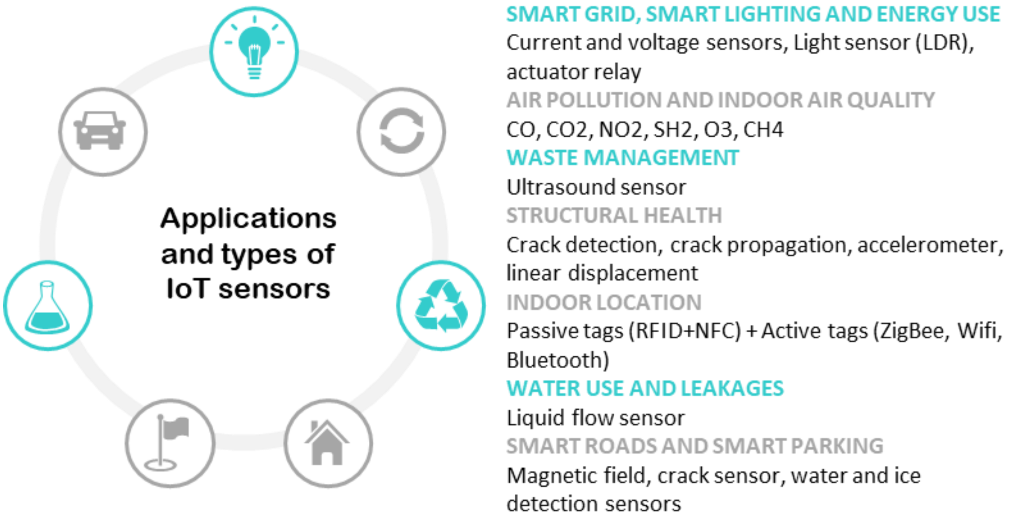
A group of technologies might directly contribute or add value to the development of IoT (EUROPEAN COMISSION, 2010), as shown in Table 5. Among such enabling technologies is a range of sensors (e.g., Smart Grid, Smart Lighting, and Energy use) developed for distinct applications (ASIN; GASCÓN, 2020), as depicted in Figure 19.

Table 5: IoT technologies

Enabling technologies	Adding-value technologies
▪ Machine-to-machine interfaces and protocols of electronic communication	▪ Geo-tagging/geo-caching
	▪ Biometrics
	▪ Machine vision
▪ Microcontrollers	▪ Robotics
▪ Wireless communication	▪ Augmented reality
▪ Radio-frequency Identification (RFID)	▪ Mirror worlds
	▪ Telepresence and adjustable autonomy
▪ Energy harvesting	▪ Life recorders and personal black boxes
▪ Sensors	▪ Tangible user interfaces
▪ Actuators	▪ Clean technologies
▪ Location	▪ Artificial Intelligence
▪ Software	▪ Machine Learning

Source: Author based on the European Comission (2010)

Figure 19: Examples of applications and types of IoT sensor



Source: Author based on Asin and Gascón (2015)

Since IoT overcomes people's lack of time and accuracy to capture data, it can "track and count everything, and greatly reduce waste, loss and cost" (ASHTON, 2010). Within the context of smart cities [9], IoT applications show a great potential over the sectors of society, such as manufacturing, retail, logistics, pharmaceutical, healthcare, transportation, telecommunications, and agriculture (ASIN, GASCÓN, 2015;

[9] Smart city is defined as the "effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens" (THE BRITISH STANDARDS INSTITUTION, 2014).

EUROPEAN COMISSION 2010, EUROPEAN COMISSION, 2008; INTERNATIONAL TELECOMMUNICATION UNION, 2005). In the building environment domain, IoT has enabled the development of smart buildings, a key component of the smart city ecosystem, concerned with a more flexible, interactive, sustainable, and efficient operation of buildings (FROUFE et al., 2020).

IoT technologies embedded in Building Automation System (BAS) and Building Management System (BMS) have supported the monitoring of buildings performance and the control and optimization of infrastructure systems (JASPERS; TEICHOLZ, 2012). Moreover, IoT has contributed to advances in smart homes, offices, and industrial plants, supporting the control and automation of functions for increasing the comfort and security of users and the productivity of industry (ATZORI; IERA; MORABITO, 2010). For instance, a series of commercial solutions for smart home have been disseminated in the market, (e.g., Philips Hue, Samsung Smart Home, Google Home, Alexa Amazon), providing computing and network intelligence to building systems (e.g., lighting, Heating Ventilation and Air Conditioning system (HVAC), components (e.g., windows and doors), and appliances (e.g., fridge and vacuum cleaner) (INTERNATIONAL TELECOMMUNICATION UNION, 2005).

The main contribution of IoT to the building and city environment is the reduction in resources consumption in the asset's lifecycle, particularly in the O&M stage IoT offers Facilities Management (FM) the possibility of understanding, in real-time, what occurs with every aspect and component of a building and its operation, increasing the accuracy and availability of information and the efficiency of the services (AL-FUQAHA et al., 2015; GUNDUZ; ISIKDAG; BASARANER, 2017; PISHDAD-BOZORGI, 2017; WONG; GE; HE, 2018). In this scenario, the concepts of "Smart Facilities Management" (FAIRCHILD, 2019) and "Smart Maintenance" (BOKRANTZ et al., 2020; BREUKER; ROSSI; BRAUN, 2000; COLEMEN et al., 2017; KATONA; PANFILOV, 2018) emerge from manufactory to the AEC industry, guiding the sector towards predictive, autonomous and sustainable decisions.

c. Digital Twin

Digital Twins have been vastly applied for years to the manufacturing industry for simulations and performance assessments. Recently, technological advances such as BIM and IoT have been fostering the introduction of Digital Twins in AEC (FINK; MATA, 2020), thus addressing the digitization gap within the built environment sector (BRILAKIS; FISCHER; FELLOW, 2019; ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020). The term Digital Twin was first defined in 2002 by Grieves and Vickers (2017) as "a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level".

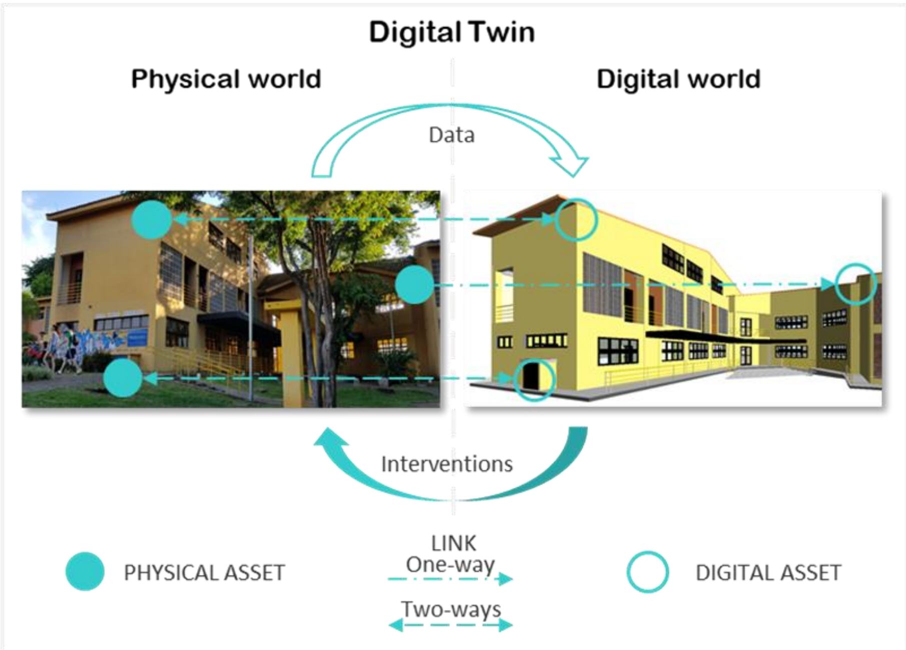
Other definitions have been proposed from different sectors and preserve the idea of linking information between physical and virtual worlds through the lifecycle of a system – similarly to the IoT definition. For instance, Digital Twin is defined within the built environment as "a digital replica of a building or part of a building, that can mirror the way the actual building performs" (ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020, p. 107) and as "a realistic digital representation of assets, processes or systems in the built or natural environment" (BOLTON et al., 2018, p. 26). Figure 20 shows the concept of Digital Twin within the built environment.

Misunderstandings over the concepts of Digital Twin and BIM have been identified in the literature – e.g., "the outcome of BIM is a 'digital twin' of the asset to be constructed" (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019, p. 11). According to Brilakis, Fischer, and Fellow (2019), differently from BIM, the concept of Digital Twin covers large facilities and information exchange among different sectors and systems. Besides, a BIM model can be considered a basis for digital twinning that, associated with IoT technologies, provides a dynamic representation of building information:

> "(...) some researchers suggest that a digital building twin must be based on integrating BIM with IoT technology to allow a seamless integration of various devices and the data they produce. In summary, digital twins for buildings can be seen as BIM models extended by means for capturing the real-world data and feeding it back into the model, thus closing the information loop as demanded by the digital twin concept." (BRILAKIS; FISCHER; FELLOW, 2019, p. 8)

In fact, the value of Digital Twins stems from the stored information, especially for large-scale private and public operators and owners, which are their main clients (BRILAKIS; FISCHER; FELLOW, 2019). Digital Twins enable the monitoring, registration, and assessment of the current performance of physical assets against their predicted performance and can be used for different purposes towards supporting decision-making within a building lifecycle. For instance, Digital Twins can improve BMS management, intervention into the physical asset through real-time control, and diagnosis and prognosis for optimizing the performance and safety of assets. It can also support planning and simulation of future scenarios, the preventive and predictive maintenance regimes, and the improvement of future projects using historical records (BOLTON et al., 2018; ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020).

Figure 20: Concept of Digital Twin within the built environment

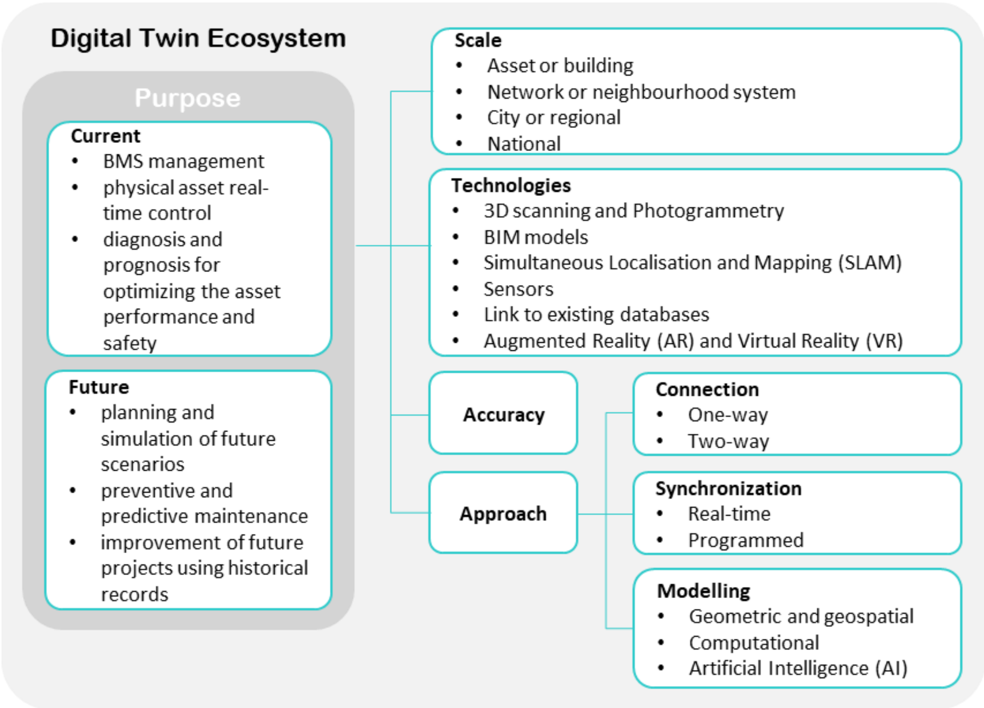


Source: Author (2021)

Defining the purpose of the Digital Twin within FM processes will determinate its scale (i.e. asset or building, network or neighbourhood, system, city or regional, national), level of accuracy (or asset coupling) (i.e., digital asset matched the physical one), related technologies for data acquisition and visualization (i.e., 3D scanning, BIM models, Simultaneous Localisation and Mapping (SLAM), sensors, link to existing databases, Augmented Reality (AR), Virtual Reality (VR), etc.), and approach for representing physical assets.

The latter might involve, for instance, the connection between physical and digital assets (i.e., one-way or two-way), the synchronization of data (i.e., real-time, programmed), and the approach for data modelling (i.e., geometric and geospatial, computational, Artificial Intelligence (AI), etc.) (BOLTON et al., 2018; BRILAKIS; FISCHER; FELLOW, 2019; DIGITAL TWIN, 2021). Figure 21 shows typical elements within a Digital Twin ecosystem.

Figure 21: Digital Twin ecosystem



Source: Author (2021)

The uses of Digital Twins in FM are broad, covering "from essential aspects of building management such as building fabric integrity, energy consumption and air-quality to optional ones such as patterns of movement" (CODINHOTO et al., 2021, p. 212). As a result, they assist the capture of changes in real building, the monitoring and control of systems and environmental performance, and the generation of data for the prediction of performance behaviour and failures prior to disruptions in organizations' businesses (CODINHOTO et al., 2021; DIGITAL TWIN, 2021; FINK; MATA, 2020; GRIEVES; VICKERS, 2017). Besides, data provided by Digital Twins foster new ways of using assets (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019) and are essential inputs for improving design solutions in future projects:

> "These real time feeds allow those using the building to understand where a building's performance is deviating from what was planned, permitting adjustments to be made. In addition, this feedback loop allows designers to gain a clearer understanding of how their buildings are working in practice, and to hone the design process accordingly. Crucial building maintenance, aligned to predictive analytics, can be undertaken proactively rather than allowing a sub-par item of building plant to underperform until failure." (ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020)

The adoption of a Digital Twin in the built environment is a complex and embryonic task (BRILAKIS; FISCHER; FELLOW, 2019), since it involves a common agreement among stakeholders on how to how to capture, model, update, exchange, and extract value from building data over a lifecycle. In design activities, the lack of standards for data generation impacts the reuse of relevant information (BRILAKIS; FISCHER;

FELLOW, 2019). For FM and maintenance, difficulties such as lack of access to maintenance problems data and use of unsuitable methods for data analytics hamper the development of knowledge on digital twinning (CODINHOTO et al., 2021) and the feedback to the early stages of the process. Combined efforts between industry and academia are necessary to increase the application of BIM and IoT in FM and make Digital Twin beneficial for the AEC industry.

3.3.2. FM BIM information management

As a core sector within organisations, FM handles relevant information of assets for operational, tactical, and strategic decisions (BARRETT; FINCH, 2014; CLAYTON, 2012). The set of FM and maintenance information is typically comprised of As-built information such as drawings, specifications, and schedules generated before the facility handover, and "as subsequently altered" information (THE BRITISH STANDARDS INSTITUTION, 2012, p. 17) produced over O&M phase (KASSEM et al., 2015; PARN; EDWARDS; DRAPER, 2016). Such information container[10] (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018) is provided by multiple stakeholders in distinct formats and standards and stored in physical and digital repositories (KIVINIEMI; CODINHOTO, 2014; PATACAS; DAWOOD; KASSEM, 2016). The result is a high-volume (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018), complex, and heterogeneous set of information (TALAMO; BONANOMI, 2016), which is gradually increased with the implementation of new technologies (LEWIS, 2012).

Information management involves not only the "collection, classification, storage and redistribution of information in digital, audio-visual or paper form", but also the ability to produce, re-use, and extract value from available information (INFORMATION MANAGEMENT, 2021). BIM, IoT, and Digital Twins are important allies in the optimization of FM information management, supporting more informed decision-making. Addressing this issue, the following subsections approach the generation and management of BIM information over a building lifecycle, the technologies and tools for FM BIM information, and the approaches for the creation of a BIM and IoT-based FM model.

a. BIM information management over a building lifecycle

The management of BIM information over a building lifecycle is a complex and extensive process directly associated with the complexity and scale of the asset itself (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018). The establishment of clear activities, requirements, and responsibilities in each phase is crucial for an efficient management of information. Therefore, international standards (i.e., ISO 19650 series)[11] and documents (i.e., CIC BIM Protocol, RIBA Plan of Work, Employers Information Requirements (EIR), Building Execution Plan (BEP), etc.) have been developed to support all stakeholders involved in the BIM

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[10] Information container is defined by the International Organization for Standardization (2018, P. 4) as the "named persistent set of information retrievable from within a file, system or application storage hierarchy." Examples of set of information include "sub-directory, information file (including model, document, table, schedule), or distinct sub-set of an information file such as a chapter or section, layer or symbol." (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019, p. 15)

[11] The standard "ISO 19650 - Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling" is comprised by four published parts, namely: ISO 19650-1:2018 - Part 1: Concepts and principles; ISO 19650-2:2018 - Part 2: Delivery phase of the assets; ISO 19650-3:2020 - Part 3: Operational phase of the assets; ISO 19650-5:2020 - Part 5: Security-minded approach to information management

information management. BEP is among the most important managerial tools, since it provides a detailed specification of what, how, why, and by whom information will be produced and delivered, ensuring the attendance of the owners' needs, the quality of information, and its efficient use in the lifecycle phases (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; SACKS et al., 2018; THE COMPUTER INTEGRATED CONSTRUCTION RESEARCH GROUP, 2010).

Figure 22 depicts a framework of BIM information management, comprised of typical activities, deliverables, functions, and uses of BIM over a building lifecycle. BIM integration and Design management and approval are conducted in the early phase of Design, generating the Overall federated BIM model and the Review reports and Visualization materials as main deliverables (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019). In the Procurement phase, Tender preparation for construction is undertaken, delivering Takeoff with visualization, BIM 4D (i.e., BIM model for schedule planning and management), and BIM 5D (i.e., BIM model for cost estimation) simulations, as well as Procurement Orders (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019). Lifecycle optimization is the core function of BIM for design and procurement, enabled by several uses such as Programming, Site Analysis, Design Authoring, and Lighting Analysis (SACKS et al., 2018; THE COMPUTER INTEGRATED CONSTRUCTION RESEARCH GROUP, 2010).

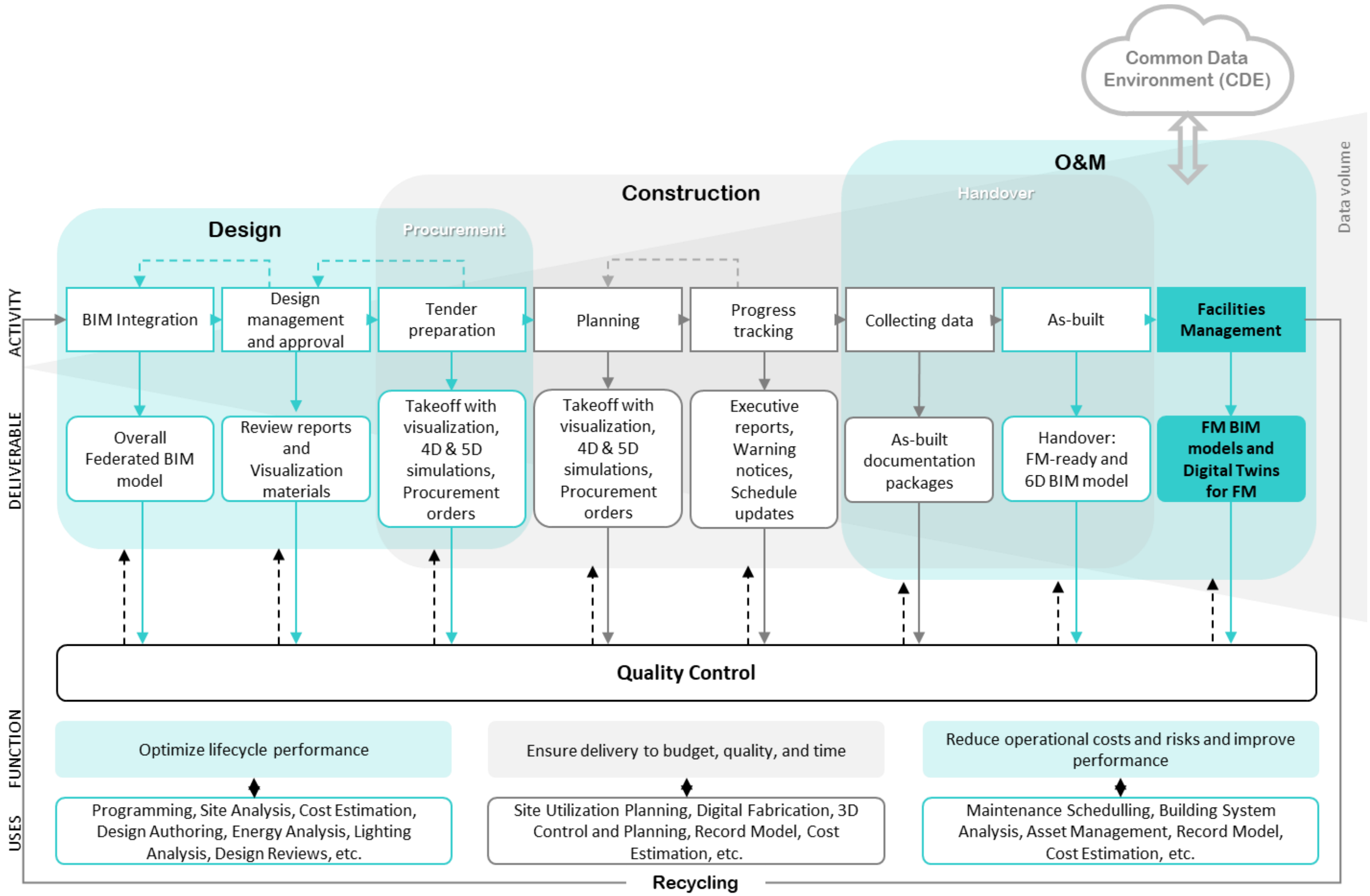
The Construction phase is characterized by activities of Planning and Process Tracking, involving the delivery of Takeoff, BIM 4D and 5D simulations, Procurement Orders, Executive reports, Warning notices, and Schedule updates (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019). Through diverse BIM uses such as Site Utilization Planning, Digital Fabrication, and Record model, the function of BIM for Construction function ensures the delivery of the building according to the planned budget, quality, and time (SACKS et al., 2018; THE COMPUTER INTEGRATED CONSTRUCTION RESEARCH GROUP, 2010).

The Handover phase establishes the bridge between Construction and O&M and is considered a critical step in the information provision for FM activities (BECERIK-GERBER et al., 2012; MCARTHUR, 2015; PINTI et al., 2018). Activities of data collection and As-built register are undertaken towards reflecting the changes in the design solutions made during construction (SACKS et al., 2018), generating As-built documentation packages and "FM-ready" and 6D[12] BIM models (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019). Besides, the effective transference of such knowledge to the owner and FM team involves the training of users and the provision of a user-friendly building manual for supporting FM activities (ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020).

FM BIM models and Digital Twins are then created with useful assets and space information for owners and FM managers. The main functions of BIM for FM are reduction of risks and operational costs and improvement of building performance (SACKS et al., 2018), which require several BIM uses (e.g., Maintenance Scheduling, Building System Analysis, Asset Management, Record model, and Cost estimation) (THE COMPUTER INTEGRATED CONSTRUCTION RESEARCH GROUP, 2010).

[12] "6D: Model developed by the addition of sustainability information to a 5D (3D or 4D) model. In some parts of the world, term 6D is also used to describe a model for facility management." (ROYAL INSTITUTION OF CHARTERED SURVEYORS, 2015).

Figure 22: BIM activities, information deliverables, and BIM model functions and uses over building lifecycle phases



Source: Author based on the European Federation of Engineering Consultancy Associations (2019), Sacks et al. (2018), and The Computer Integrated Construction Research Group (2010)

Regular aftercare meetings with the FM team, contractors, and design team are crucial in this phase for reviewing the progress of maintenance and energy monitoring and the rectification of defects (ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020). Finally, the recycling of the building (i.e., refurbishment or renovation project) triggers a new lifecycle from the Design phase, as previously characterized.

As shown in Figure 22, the volume of data gradually increases towards the O&M phase. A global quality control is required for ensuring only accurate and relevant information is shared among stakeholders and made available between phases whenever necessary (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018). A Common Data Environment (CDE) is adopted as an “agreed source of information” comprised of processes and technologies to assist the collection, management, and transference of information containers (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018, p. 5), providing an integrated dataset for the creation of BIM models and digital twins (BRILAKIS; FISCHER; FELLOW, 2019):

> “[CDE] reduces the need for hard copies of deliverables, it re-uses information and it prevents the use of unreliable or obsolete information thereby reducing financial losses. All the information, data and metadata can be verified in real time.” (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019, p. 16)

Open standards and data formats are prioritized in CDEs towards a consistent information management process in a collaborative context and legacy of data over time (BRILAKIS; FISCHER; FELLOW, 2019; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018). In fact, an efficient management of information avoids waste, overload, or lack of information (BRILAKIS; FISCHER; FELLOW, 2019; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019). One of the principles of BIM is the re-use of information by distinct users and purposes over a building lifecycle. In general, drawing-based processes are characterized by “duplicate, tedious, and error-prone data entry” (SACKS et al., 2018, p. 132) providing more opportunities for information loss:

> “At present, considerable resources are spent on making corrections to unstructured information or incorrect management of information by untrained personnel, on solving problems arising from uncoordinated efforts of delivery teams, and on solving problems related to information reuse and reproduction.” (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018, p. vi)

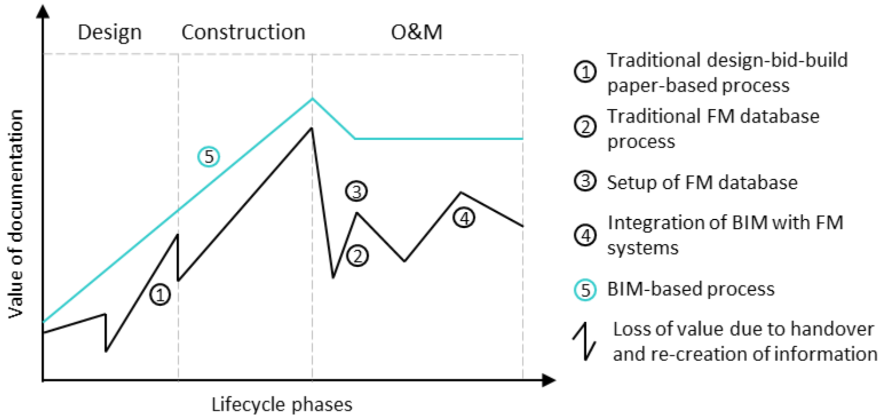
On the other hand, BIM is centred in a CDE (BRILAKIS; FISCHER; FELLOW, 2019), reducing the efforts for information management and increasing the value of information for owners, as depicted in Figure 23. However, deliverables can be re-used only if the potential of BIM and the information requirements of each phase are considered through a “start-with-the-end-in-mind approach” (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019, p. 27), ensuring the most efficient generation, provision, and access of information over time (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018):

> “(…) the project team should first consider the later phases of a project to understand what information will be valuable to have during that phase. Then, they can move back through all of the project phases in reverse order (Operations, Construction, Design, and then Planning).” (THE COMPUTER INTEGRATED CONSTRUCTION RESEARCH GROUP, 2010, p. 11)

> “Deliverables should be able to be used and re-used throughout the project lifecycle, avoiding the need for re-entering (essentially waste in lean terminology) information that was already present in a way but is unusable due to technical (software, format etc.) or legal (rights, availability) restrictions. Each deliverable should be structured in line with existing project management processes, with clear quality control and assurance procedures, and workflow

instructions on where it will be reused later in the lifecycle and what will be the necessary information handover and requirements for it." (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019, p. 28)

Figure 23: Information quality over building lifecycle phases in drawing-based vs BIM-based processes



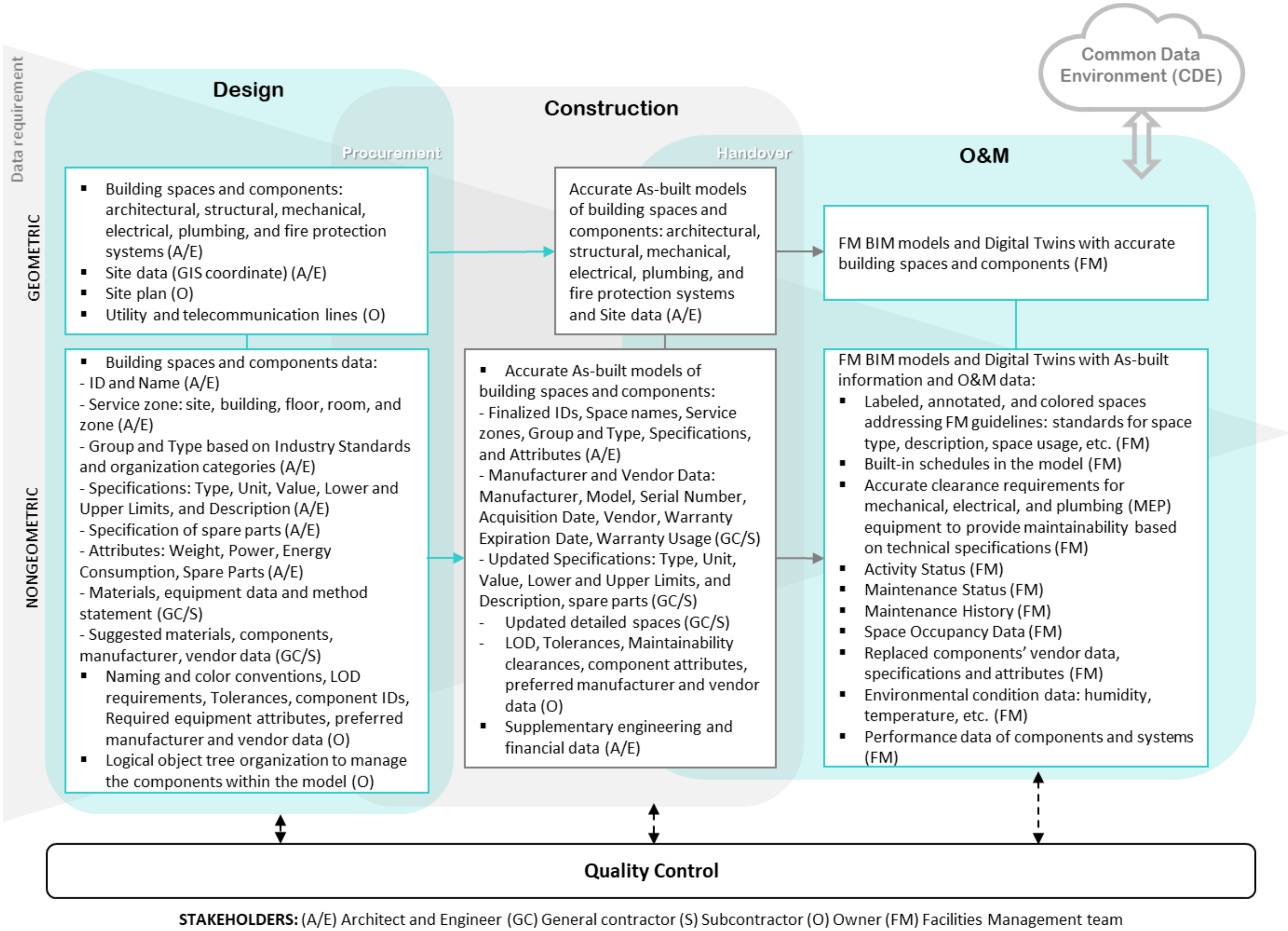
Source: Author based on Sacks et al. (2018)

The development of FM activities in O&M depends on the adequacy of the information incrementally generated in the previous phases. Most FM BIM data are produced in the Design phase, in which key decisions influencing both costs and performance of the building are made (ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020). According to Knotten et al. (2015), problems in the briefing phase, in which needs, parameters and requirements of design are defined, respond for approximately 30% of the reworks in the following stages. In most cases, requirements related to O&M are disregarded in the building conception (PINTI et al., 2018) and ineffectively provided in the information handover (CAVKA; STAUB-FRENCH; POTTINGER, 2015; MCARTHUR, 2015).

The creation of FM BIM models and Digital Twins is based on a series of geometric and nongeometric data requirements addressed by the stakeholders of the process and that can vary according to the end-users' needs and the proposed BIM use (e.g., maintenance scheduling, cost estimation, etc.) (BECERIK-GERBER et al., 2012; CAVKA; STAUB-FRENCH; POTTINGER, 2015; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019). The level of information to be delivered must also be defined and involve level of geometry (i.e., precision of the representation of objects), level of information (i.e., semantics attached to objects), and level of documentation (i.e., type of documents related to the object) (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019). Figure 24 shows the general FM BIM data requirements to be addressed over building lifecycle phases for a more effective information delivery and management.

In the Design and Procurement phases, the geometric requirements refer to the building space and components, site data, site plan, and utility and telecommunication lines and are addressed by Architects, Engineers, and Owners. The set of nongeometric data for FM needs includes identification and classification of spaces and components (e.g., ID, name, service zone, group, and type), specification and attributes of components and parts (e.g., type, weight, energy consumption, etc.), and suggested materials, components, manufacturer, and vendor data, addressed by Architects, Engineers, General Contractors, and Subcontractors (BECERIK-GERBER et al., 2012; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019).

Figure 24: FM BIM geometric and nongeometric data requirements over building lifecycle phases



Source: Author based on Becerik-Gerber et al. (2012) and the European Federation of Engineering Consultancy Associations (2019)

In fact, the individuation of elements is essential to guide operation and maintenance services (MIRARCHI et al., 2018). Owner's requirements regarding the desired features of the building (e.g., equipment attributes) and the BIM model for future uses (e.g., Level of Development (LOD), preferred manufacturer and vendor data, organization logic) are also defined in this phase (BECERIK-GERBER et al., 2012; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019).

In the Construction and Handover phases, geometric and nongeometric data on the final building spaces and components (e.g., ID, service zone, weight, energy consumption, etc.) are generated by Architects and Engineers through the As-built models. Particularly important for FM, additional specifications and data on manufacturer and vendor (e.g., model, serial number, warranty, etc.) are provided by General Contractors and Subcontractors. Once again, the Owner's requirements related to the model integrity are essential to ensure the quality of information for FM activities (BECERIK-GERBER et al., 2012; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019).

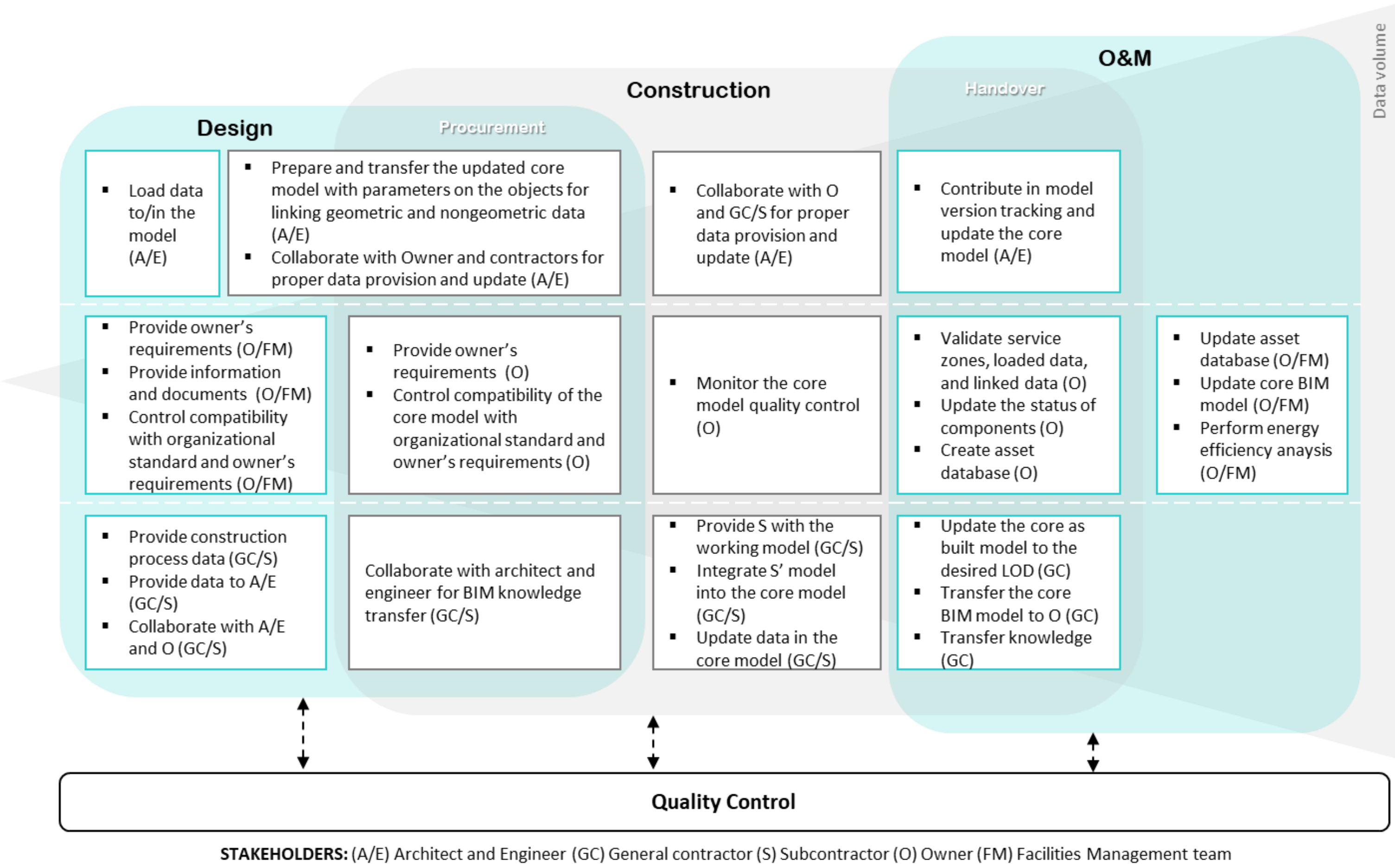
Finally, FM BIM models and Digital Twins are developed in the O&M phase, according to the As-built information. Apart from the final geometric data on spaces and components, a set of data is provided by the FM team to support O&M activities (e.g., classification of spaces according to FM guidelines, such as standards for space type, usage, occupancy, etc., schedules in the model, clearance requirements for maintaining Mechanical, Electrical, and Plumbing (MEP) equipment, FM activity status, Maintenance Status and History, replaced components' vendor data, specifications, and attributes (BECERIK-GERBER et al., 2012; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020), environmental condition data, and performance data of components and systems. Kensek (2015) and The British Standards Institution (2012) provided two examples of information necessary for maintaining lighting fixtures:

> "Repair and preventive maintenance require a database of what exists and when equipment ought to be fixed, upgraded, or replaced. This is exactly what an accurate and information FM database is. For example, an energy upgrade to a building might entail replacing low efficiency bulbs with LEDs; the location of the bulbs, characteristics of the fixture, and links to manufacturer sites can be in the model." (KENSEK, 2015, p. 902)

> "Electrical installations Records: schedule of lighting fittings installed stating location, manufacturer and type or catalogue number together with the type or manufacturer's reference, voltage and wattage of the lamp installed; incoming supply details including the type of system, voltage, phases, frequency, rated current and short circuit level, with the details of the supply protection and time of operation as appropriate." (THE BRITISH STANDARDS INSTITUTION, 2012, p. 17)

The complexity and increased volume of information produced over the process imposes distinct responsibilities to the stakeholders involved in the management of FM BIM data, as depicted in Figure 25. A clear definition of functions is essential, since a succession of individuals and organizations might be assigned within such a long-term process (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018). In the Design phase, Architects and Engineers load data in the BIM model considering the information and documents and the requirements provided by the Owner and FM team, who are also responsible for controlling the solution's compatibility with organizational standards and needs. General Contractors and Subcontractors provide construction process data and collaborate with Architects, Engineers, and Owners (BECERIK-GERBER et al., 2012; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019).

Figure 25: Stakeholders' responsibilities for FM BIM data provision over building lifecycle phases



Source: Author based on Becerik-Gerber et al. (2012) and the European Federation of Engineering Consultancy Associations (2019)

In the Procurement phase, Architects and Engineers prepare and transfer the updated core models for construction in collaboration with General Contractors, Subcontractors and Owners, ensuring a link between geometric and nongeometric data. The Owner must also provide data requirements for procurement and keep the control of the model´s compatibility. In the Construction phase, Architects, Engineers, and Owners assume a similar responsibility, supplying precise and compatible data. Additional responsibilities are given to General Contractors and Subcontractors, and involve the coordination and integration of models and the update of data in the core BIM model (BECERIK-GERBER et al., 2012; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019).

In the building Handover phase, Architects and Engineers contribute to the model version tracking and updating the core model. General Contractors update it to the desired LOD and transfer models and knowledge to the Owner, who performs validation, loading, and connection of data, updates components status, and creates an asset database. Over the O&M phase, both Owner and FM team update the asset database and the core BIM model, thus supporting operational and strategic FM activities (BECERIK-GERBER et al., 2012; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019):

> "This phase is getting more and more about enriching the BIM model with additional information and using this information for innovative approaches (Internet of Things, Smart Buildings, Smart Cities, etc.) and maintenance or for operational purposes." (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019, p. 24)

For instance, information can be regularly gathered and recorded for maintenance through surveys that register defects and adopt actions for repair, as well as investigate the root causes of recurrent defects (THE BRITISH STANDARDS INSTITUTION, 2012). Although BIM models and Digital Twins can be generated from scratch in any phase of the building lifecycle, the most efficient approach for their creation considers data requirements in the early stages of the process: "the effort for compiling a digital twin is concentrated at the start of their life (whether from existing infrastructure or at the handover from a project built with BIM)" (BRILAKIS; FISCHER; FELLOW, 2019, p. 25). Owners play a key role in the process, since they are the only part directly involved with its all phases. In this sense, they must clearly identify, understand, document, and transmit the level of detail of BIM models and the requirements to all stakeholders (SACKS et al., 2018; THE COMPUTER INTEGRATED CONSTRUCTION RESEARCH GROUP, 2010) and control the quality of delivered information. Collaboration with Architects, Engineers, and FM team is essential for the definition and update of core requirements over the process and assessment of their compliance (SACKS et al., 2018)

b. Approaches for the creation of a BIM and IoT-based Digital Twin for FM

The creation of a BIM and IoT-based Digital Twin for FM depends on a series of factors, such as availability of As-built and real-time records, type of existing technologies, and methods adopted for integrating tools and exchanging information. As discussed in Section 3.3.2.a, the As-built models generated in the Construction phase are usually the point for the creation of a FM BIM model. However, procedures are needed for their adequacy to the FM data requirements, due to the lack, excess, or inaccuracy of data:

> "[…] there is still a gap between the building information models created by the architect and contractors and the information desired by the facility managers" (KENSEK, 2015, p. 913)

> "The architectural model lacks adequate detail and information about building systems and equipment data, many facility elements are not modeled due to either complexity of the

modeling process, or they are considered nonessential to design drawings and visualization. The construction model normally contains too much information about construction details that have no relevance to FM, lacks proper definitions for space management, and lacks systems connectivity information and equipment data needed for FM." (SACKS et al., 2018, p. 154-155)

Modifications in As-built models for the creation of FM BIM models were proposed by BIM FM Consortium (SCHLEY et al., 2016) and can be structured into four macro steps, namely, i. Clean, ii. Merge, iii. Identify, and iv. Link, as shown in Table 6. The cleaning of unnecessary data for FM operations is the first macro step for the generation of a more dynamic, lighter, and accessible model, thus avoiding overload and personnel efforts related to data management (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; MCARTHUR, 2015; SACKS et al., 2018; VANDECASTEELE; MERCI; VERSTOCKT, 2017). The use of approaches that query and visualize only the essential part of such data is recommended (AKCAMETE; AKINCI; GARRETT JR, 2010).

Table 6: Macro steps for the creation of FM BIM models based on As-built models

1. Clean	"Extraneous information is removed, including construction details and working drawing sheets. This information can be obtained from the as-built model if needed, but otherwise encumbers the BIM FM Model." (SCHLEY et al., 2016, p. 9)
2. Merge	"Where linked models have been used to distinctly represent building core, building shell, and tenant improvements, these are merged into a single model. If practical, linked models representing architectural, mechanical, electrical, fire protection, and specialized equipment are merged. For large buildings this may not be practical with current technology, so there may be the need to maintain multiple models that are linked." (SCHLEY et al., 2016, p. 9)
3. Identify	"Occupancy room numbers are derived from construction room numbers with numbers matching building signage. For office space, workstations and offices are defined separately from rooms and are numbered with an occupancy numbering system. This is key to matching office occupants to desks, cubicles, and offices and is also essential for management of work orders. Building equipment items are numbered with unique asset IDs" (SCHLEY et al., 2016, p. 9)
4. Link	"The BIM FM model is linked to the facility management system that tracks ongoing work orders, maintenance operations, occupancy information, equipment and material replacement costs, and other data related to building operations" (SCHLEY et al., 2016, p. 9)

Source: Author based on Schley et al. (2016)

The second macro step merges the linked models from distinct disciplines and is recommended mainly for small buildings (SCHLEY et al., 2016) in which the elements of each system are appropriately represented into a single model. The third macro step refers to the identification of building spaces and components with unique ID codes, thus enabling the access, input and review of maintenance and operation information related to the architectural, structural, and MEP systems (SACKS et al., 2018). As addressed in Section 3.3.2.a, the accuracy of nongeometric data, such as individuation and location of building elements, is more relevant for FM and maintenance purposes than the high level detail of the geometric parameters (BECERIK-GERBER et al., 2012; CAVKA; STAUB-FRENCH; POTTINGER, 2015; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; MIRARCHI et al., 2018).

The last and most complex macro step links BIM models to FM data and technologies within a BIM environment, thus providing relevant and accessible information to the FM systems used over a building lifecycle (BECERIK-GERBER et al., 2012; SACKS et al., 2018). The typical FM tools include Computer Assisted Facilities Management (CAFM), the Computerized Maintenance Management System (CMMS), and Building Management System (BMS) or Building Automation System (BAS). Previous studies have described their both relevance and evolution over time towards addressing FM needs (BARRETT; FINCH, 2014; CODINHOTO; KIVINIEMI; KEMMER, 2013; HOFFMANN, 2012; KELLER, 2012; MISIC; GILANI; MCARTHUR, 2020; PARK, 1994;

PARN; EDWARDS; DRAPER, 2016; SULLIVAN et al., 2010; TALAMO; BONANOMI, 2016). Table 7 shows the main functionality and abilities of the FM tools and examples of commercial software.

Table 7: FM tools' functionalities, abilities, and examples of commercial software

System	Functionality and abilities	Commercial software
CAFM	Automatization of functions and support to an effective coordination of information required in FM operations (CODINHOTO; KIVINIEMI; KEMMER, 2013; THE BRITISH STANDARDS INSTITUTION, 2012). CAFM abilities include: ▪ "helpdesk administration; ▪ maintenance scheduling; ▪ administration of contracts; ▪ health and safety management and risk assessment; ▪ space management and room booking; ▪ procurement and management of stock; ▪ energy and environmental management; ▪ real estate portfolio management" (BARRETT; FINCH, 2014, p. 204)	ARCHIBUS CAFM system, Oracle Unifier, IBM TIRIGA Planon, Manhattan
CMMS	CMMS is designed to support maintenance management needs, enabling the planning, organization, and control of activities, and management of asset data performance (THE BRITISH STANDARDS INSTITUTION, 2012). CMMS abilities include: ▪ "work order generation, prioritization, and tracking by equipment/component; ▪ historical tracking of all work orders generated which become sortable by equipment, date, person responding, etc.; ▪ tracking of scheduled and unscheduled maintenance activities; ▪ storing of maintenance procedures as well as all warranty information by component; ▪ storing of all technical documentation or procedures by component; ▪ real-time reports of ongoing work activity; ▪ calendar- or run-time-based preventive maintenance work order generation; ▪ capital and labor cost tracking by component as well as shortest, median, and longest times to close a work order by component; ▪ complete parts and materials inventory control with automated reorder capability; ▪ outside service call/dispatch capabilities." (SULLIVAN et al., 2010, p. 45).	Facility maintenance management; IBM Maximo; FAMIS Accruent; eMaint; AssetWorks; Corrigo
BAS/ BMS	BAS or BMS tools are integrated by sensors, actuators, and controllers, enabling the monitoring of building infrastructure systems, with emphasis on energy management and asset control (JASPERS; TEICHOLZ, 2012). BAS abilities include: ▪ monitoring of building performance variables (i.e., energy consumption, room temperature and humidity); ▪ control and optimization of infrastructure systems, such as HVAC, lighting, safety (fire alarms) (JASPERS; TEICHOLZ, 2012; MISIC; GILANI; MCARTHUR, 2020; ROYAL INSTITUTION OF CHARTERED SURVEYOR; INTERNATIONAL FACILITY MANAGEMENT ASSOCIATION, 2018)	Honeywell EBI, Siemens Apogee, Schneider Electric StruxureWar, OPC, BACnet, Johnson Controls

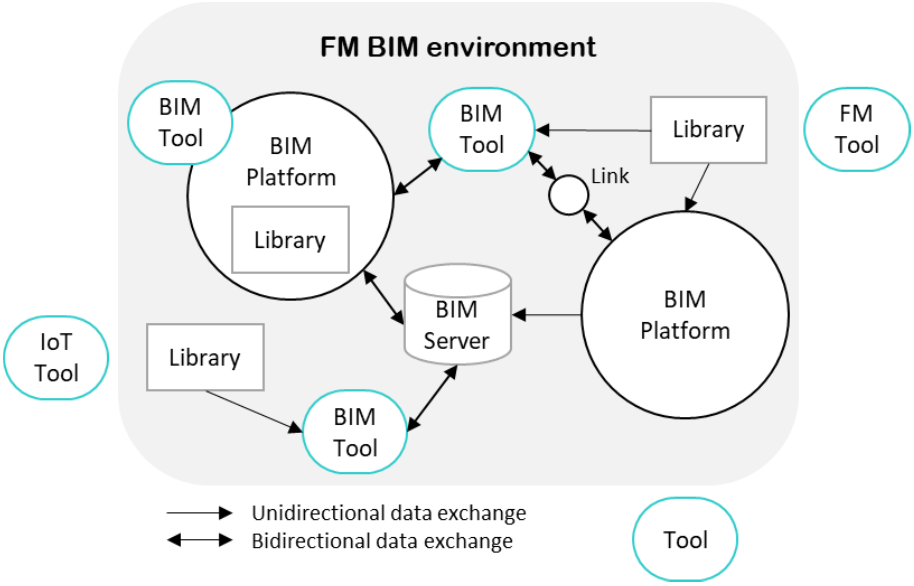
Source: Author (2021)

Within a BIM environment, such systems are used as BIM tools and integrated with other geometric and text-based tools and platforms to assist FM information management (Figure 26). Tools for drawing and processing information (e.g., AutoCAD-based applications and Excel-based tools (SACKS et al., 2018)) can update As-built records and assist O&M activities. Also, parametric and object-based modelling platforms, such as Revit and ArchiCAD (SACKS et al., 2018) can support the management of FM information in a centralized and integrated environment, facilitating its access and visualization. Moreover, IoT tools (e.g., BIM Watson IoT for FM (SACKS et al., 2018)), can analyse information captured by sensors and support more informed decision-making.

As depicted in Figure 26, a BIM environment is also encompassed by workflows, libraries, and servers, thus enabling either unidirectional or bidirectional data exchange (SACKS et al., 2018). Such tools and platforms are integrated by Common Data Environment (CDE) tools, such as Ecodomus and Oracle Aconex, supporting the development of Digital Twins for FM (BRILAKIS; FISCHER; FELLOW, 2019; ECODOMUS, 2021).

Four main approaches can be used to integrate FM BIM components aiming at the generation of a BIM and IoT-based Digital Twin for FM, namely, 1. Manual entry, 2. Transference via exchange format, 3. Direct Integration, and 4. Middleware (IBRAHIM et al., 2016; SACKS et al., 2018), as shown in Figure 27. The manual input of models, documents, and other BIM files into FM tools is the first approach for such integration, particularly for less complex and small size buildings. Despite the benefit of not requiring changes in the work process of FM teams, this approach imposes a high consume of time and financial resources and risk of errors in information input and update (IBRAHIM et al., 2016; SACKS et al., 2018).

Figure 26: FM BIM environment components



Source: Author based on Sacks et al. (2018)

The second approach involves the transference of data from a BIM model to a FM tool via exchange formats and standards, such as Industry Foundation Classes (IFC)[13] and Construction Operation Building Information Exchange (COBie)[14]. A variety of BIM and FM software interfaces enables importing and exporting data in such formats, facilitating the integration between tools, and addressing interoperability issues. However, attention must be paid in the importation process to interpret, transform, and validate data in order to ensure its usefulness and accuracy for FM purposes (IBRAHIM et al., 2016; SACKS et al., 2018).

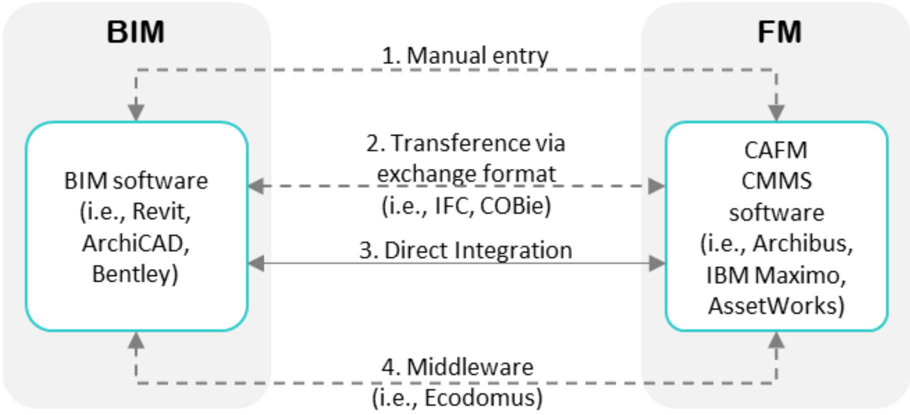
The third approach is related to the direct integration between BIM and FM tools. CAFM systems available on the market, such as Archibus, provides an extension for Revit using web services, thus enabling the synchronized and bi-directional data exchange and the visualization of the BIM model on the FM interfaces with a web browser (ARCHIBUS, 2021). As a result, data is automatically uploaded and validated, improving its visualization, accuracy and access by FM team members and owners (SACKS et al., 2018).

The fourth approach involves the use of middleware systems for integrating BIM and FM authoring systems. Different from the direct link, this approach uses Application Programming Interfaces (APIs), neutral

[13] IFC is defined by the BIM Dictionary as "a neutral/open specification (schema) and a non-proprietary 'BIM file format' developed by buildingSMART. Major BIM Software Tools support the import and export of IFC files." (INDUSTRY FOUNDATION CLASS, 2021)
[14] COBie is defined by the BIM Dictionary as "a specification for the capture and delivery of design/ construction information to Facility Managers. COBie Specifications can be collated using a spreadsheet template or a COBie-enabled software solution." (COBie, 2021)

file formats, web services, and design patters to integrate systems and platforms of distinct vendors, providing more flexibility to owners and FM team members in implementing BIM and FM tools. The provision of a centralized database dynamically updated also reduces human errors, improving the quality of information (IBRAHIM et al., 2016). Ecodomus is an example of such commercial middleware system, integrating through hyperlink BIM tools (i.e., Bentley, Revit) with CAFM and CMMS tools (i.e., IBM Maximo, Archibus, AssetWorks) (IBRAHIM et al., 2016; SACKS et al., 2018).

Figure 27: Four approaches for integrating BIM platforms and FM tools



Source: Author based on Ibrahim et al. (2016) and Sacks et al. (2018)

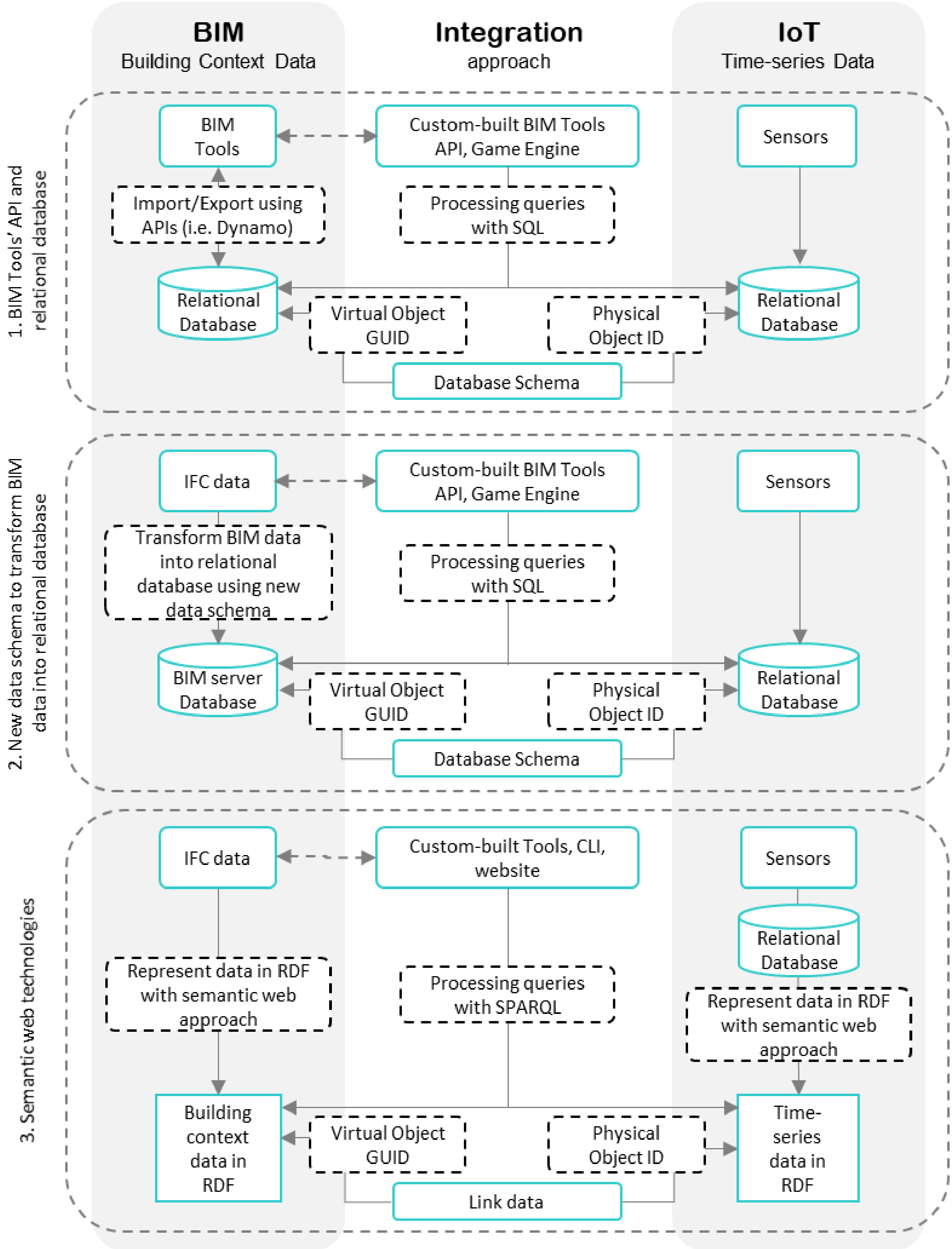
After BIM and FM tools are fully integrated, entering IoT information is necessary to create a Digital Twin for FM. A range of approaches is applicable for integrating BIM and IoT tools and devices, thus bringing BIM models to life. Among those, three approaches identified by Tang et al. (2019) can support the integration of BIM context data and time-series sensors data using, for instance, 1. BIM Tools' API and relational database, 2. New data schema to transform BIM data into relational database, and 3. Semantic web technologies, as shown in Figure 28.

The first approach applies existing BIM tool's APIs and relational database, and it is vastly adopted for integrating BIM and IoT tools (e.g., sensors, BMS, etc.) (FINK; MATA, 2020; KENSEK, 2015; TANG et al., 2019). In the IoT side of the process, sensor's data is collected, stored, and updated in relational databases (e.g., Microsoft Access, SQL server database). In the BIM side, APIs such as Dynamo, Revit DB Link, and Grasshopper are applied to both export data from the BIM model to a relational database and import it from a relational database to the BIM model. Once BIM and IoT are stored in the relational database and associated with virtual and physical objects, a database schema establishes the relationship between objects, using custom-built BIM Tools API (e.g., Revit graphic user interface (GUI)), game engine (e.g., Unity engine), and querying over SQL database (TANG et al., 2019).

Working like the middleware for integrating BIM and FM tools, this approach has the advantages of applying existing APIs, facilitating the link between BIM and sensor's data, and automatically updating sensor's data in BIM models. On the other hand, it requires the manual development of virtual objects to represent the physical sensors, which would be a time-consuming activity for complex BIM models with a big number of sensors (TANG et al., 2019).

The second approach involves the transformation of BIM data in IFC format into a queryable relational database through new data schema, such as the BIM Rule Language (BIMRL). The purpose is to enable the extraction of BIM model data for its integration with sensors' data according to the user's perspective, using custom-built BIM Tools API, game engine, and querying over SQL database to link virtual and physical objects (TANG et al., 2019). By using new data schema, this approach uses existing SQL and retains sensors' data in its original database, providing more flexibility for complex buildings with a large number of sensors. However, if compared to the first approach, it requires more skills in programming knowledge, IFC, and language design (TANG et al., 2019).

Figure 28: Three approaches for integrating BIM and IoT tools



Source: Author based on Tang et al. (2019)

The third approach applies semantic web technologies for integrating BIM and IoT data and is also extendable to other heterogeneous sets of AEC industry's data, such as behaviour data and geospatial information data (TANG et al., 2019). Both BIM and sensors' data are represented in the Resource Description Format (RDF) using a semantic web approach. The link between data silos is established using virtual and physical objects, SPARQL Protocol and RDF Query Language and the query results shown on Custom-built tools, Command Line Interface (CLI), websites, and other tools. (TANG et al., 2019). This approach has the advantage of linking data from distinct sources, thus addressing projects with various data sources in a single framework. Nevertheless, it might require the transformation of original data formats, the duplication of data and the availability of large storage capacity, hampering the efficiency of systems dependent on real-time data (TANG et al., 2019).

According to Tang et al. (2019), the development of a hybrid approach combining Service Oriented Architecture (SOA), relational database, and semantic web technologies is a trend in the field for integrating BIM and IoT tools, overcoming limitations of the individual approaches. The topic is still a lacuna in the AEC industry and standards must be developed to address cloud computing and interoperability issues, fostering the realization of BIM, IoT and Digital Twin concepts.

3.4. Research on BIM and IoT for FM

Along with a new generation of ICTs, BIM and IoT are enablers of Digital Twins and key components of smart cities through an efficient management of building operation and maintenance. The integration of BIM and IoT solutions into FM is an emerging area of investigation (TANG et al., 2019). Previous theoretical and empirical studies have discussed potential benefits, application areas and activities, challenges, and research lacunas associated with the implementation of BIM for FM, as shown in Table 8. In general, such benefits involve the automatization of functions, the efficiency gains in information management and FM services, and the increase in users' satisfaction.

The application activities in which BIM could contribute to FM practices were classified based into the four FM typical areas described by Barrett and Finch (2014), namely Building operations and maintenance, Facility planning, General and office services, and Real estate and building construction. Most studies have approached the use of BIM in Building operations and maintenance activities, such as location of rooms and building components, space management, energy monitoring and control, building performance assessment, and fault reporting. Other activities, also described, include creation, update, and access of digital assets and support to maintenance planning.

However, several challenges faced by organizations in the implementation of BIM in FM have been identified, and encompass technology, process, and policy issues. Among other challenges, special attention has been devoted to difficulties in information management, thus involving the access and update of real-time information in BIM and FM databases. Moreover, studies have showed lacunas in knowledge due to the lack of clarity on BIM benefits for FM and the related impacts of its implementation on processes and regulations.

The integration of IoT solutions into this environment can potentially overcome difficulties related to information management, as described in Section 3.2.1.b. Nevertheless, only few studies have investigated the combined application of BIM and IoT to support FM activities, as well as their impact on service provision. The following Systematic Literature Review (SLR) was conducted towards addressing this gap.

Table 8: BIM for FM: potential benefits, application areas and activities, challenges, and research lacunas

Benefits	▪ Automatization of functions and efficient management of building information over lifecycle (i.e., gather, access, accuracy, update) (BECERIK-GERBER et al., 2012; CODINHOTO; KIVINIEMI; KEMMER, 2013; PINTI et al., 2018); ▪ increased efficiency of maintenance response (KASSEM et al., 2015; PIN; MEDINA; MCARTHUR, 2018); increased users' satisfaction (PIN; MEDINA; MCARTHUR, 2018)
Application areas and activities	Building operations and maintenance activities: ▪ location of rooms and building components (BECERIK-GERBER et al., 2012; KENSEK, 2015; MCARTHUR, 2015; PIN; MEDINA; MCARTHUR, 2018); ▪ checking of maintainability (BECERIK-GERBER et al., 2012); ▪ space management (BECERIK-GERBER et al., 2012; KENSEK, 2015; PIN; MEDINA; MCARTHUR, 2018); ▪ monitoring and control of energy (BECERIK-GERBER et al., 2012; MCARTHUR, 2015); ▪ preventative maintenance (KENSEK, 2015); ▪ report of faults (KASSEM et al., 2015); ▪ assessment of building performance (KASSEM et al., 2015; PIN; MEDINA; MCARTHUR, 2018).
	Facility planning activities: ▪ creation, update, and access to digital assets (AKCAMETE; AKINCI; GARRETT JR, 2010; BECERIK-GERBER et al., 2012; CODINHOTO; KIVINIEMI; KEMMER, 2013; KASSEM et al., 2015; KENSEK, 2015; MCARTHUR, 2015; PARN; EDWARDS; DRAPER, 2016; PINTI et al., 2018); ▪ generation of space reports (MCARTHUR, 2015); ▪ Post-Occupancy Evaluations (POEs) (PIN; MEDINA; MCARTHUR, 2018)
	General and office service: ▪ emergency management (BECERIK-GERBER et al., 2012); ▪ inventory tracking and hazard mapping (MCARTHUR, 2015); ▪ maintenance planning (AKCAMETE; AKINCI; GARRETT JR, 2010)
	Real estate and building construction: ▪ "planning and feasibility studies for noncapital construction" (BECERIK-GERBER et al., 2012; KASSEM et al., 2015).
Challenges	Technology: ▪ interoperability among BIM and FM tools (BECERIK-GERBER et al., 2012; CODINHOTO et al., 2013; EDIRISINGHE et al., 2017; IBRAHIM et al., 2016; PARN; EDWARDS; DRAPER, 2016; PINTI et al., 2018); ▪ lack of open systems (IBRAHIM et al., 2016; KASSEM et al., 2015); ▪ lack of understanding on data capturing techniques (EDIRISINGHE et al., 2017)
	Process: ▪ lack of collaboration between stakeholders for managing the BIM model (BECERIK-GERBER et al., 2012; PINTI et al., 2018); ▪ difficulties in engaging software providers and cultural resistance to changes (BECERIK-GERBER et al., 2012; CODINHOTO; KIVINIEMI; KEMMER, 2013); ▪ need for investments in infrastructure and training for the generation and management of BIM models (AKCAMETE; AKINCI; GARRETT JR, 2010; BECERIK-GERBER et al., 2012; CODINHOTO; KIVINIEMI; KEMMER, 2013; MCARTHUR, 2015; VOLK; STENGEL; SCHULTMANN, 2014)
	Policy: ▪ lack of processes and standards (i.e., data requirements, libraries) and clear responsibilities and roles for managing information in BIM model and FM databases (BECERIK-GERBER et al., 2012; CODINHOTO; KIVINIEMI; KEMMER, 2013; HOSSEINI et al., 2018; KASSEM et al., 2015; MCARTHUR, 2015; VOLK; STENGEL; SCHULTMANN, 2014; ZADEH; STAUB-FRENCH; POTTINGER, 2015)
Research lacunas	▪ Lack of methodologies, real-world cases and proof of positive return of investment (BECERIK-GERBER et al., 2012; CODINHOTO; KIVINIEMI; KEMMER, 2013; KASSEM et al., 2015; PARN; EDWARDS; DRAPER, 2016; VOLK; STENGEL; SCHULTMANN, 2014); ▪ lack of research on BIM related changes of processes and regulations (VOLK; STENGEL; SCHULTMANN, 2014); ▪ lack of "well-developed practical strategies for the purposeful exchange, compatibility and integration of meaningful information among the BIM model components to the different FM information systems" (IBRAHIM et al., 2016); ▪ "the management influence of governmental or organisational policies on BIM-enabled FM" (EDIRISINGHE et al., 2017)

Source: Author (2021)

3.4.1. Systematic Literature Review (SLR) on BIM and IoT -based solutions for Facilities Management (FM) and Reactive Maintenance

The Systematic Literature Review (SLR) aimed at establishing a context of BIM and IoT for FM and reactive maintenance service, highlighting gaps and trends in the research field, as well as solutions, relates devices, areas, activities, and outcomes. To do so, it involved search, analysis, and classification of scientific journal and conference articles published in international databases between 2013 and 2018. A detailed description of its steps, research protocol, results, discussion, and findings is provided in our article entitled "Trends in BIM and IoT for Reactive Maintenance" (FIALHO; CODINHOTO; FABRICIO, 2019) and available in the Annex 1. Table 9 shows a summary of the investigated articles.

This section reports the main findings and contributions of this study. Primarily, the research status in the field was established based on a general bibliometric analysis. Then, a Conceptual framework of BIM IoT implementation for Facilities Management and reactive maintenance summarized the key aspects of the review related to the research approaches, FM and reactive maintenance areas and activities, BIM and IoT solutions and devices, and outcomes of BIM and implementation. Lastly, gaps in the field, contributions of the study and opportunities for future research are presented.

The establishment of the research status in BIM, IoT, FM, and reactive maintenance was supported by an analysis of general bibliometric aspects, i.e., distribution of publications per year, country, database, journal, and conference (FIALHO; CODINHOTO; FABRICIO, 2019). The scarcity of publications between 2013 and 2018 was evidenced by the sample size, since only 40 articles addressed the search criteria. Out of this sample, only two publications directly focused on reactive maintenance (LIN; SU; CHEN, 2014; MIRARCHI et al., 2018), highlighting the vast lacuna in the field. The gradual increase in the number of publications over the selected period showed a trend for new investigations in the area; however, the concentration of studies in specific environments (European countries, engineering source journals, and events on robotics and automation in construction) has evidenced the critical mass was still emerging.

The Conceptual framework depicted in Figure 29 synthesized the four key aspects for investigating BIM and IoT implementation in Facilities Management (FM) and reactive maintenance (FIALHO; CODINHOTO; FABRICIO, 2019). The first aspect was related to the research approach of the publications. A predominance of technological and process tools (e.g., software and models) for FM, mostly validated through prototype, illustrative, or pilot implementations, demonstrates the embryonic stage of the studies and the necessity for building data management solutions. In this sense, the importance of implementing BIM and IoT in real circumstances was emphasized due to the need for empirical evidence regarding their impact on FM performance.

The second aspect refers to BIM and IoT solutions and devices for FM and reactive maintenance activities. A prevalence of Autodesk software and sensors and actuators as core BIM and IoT components was observed in the publications. However, Fialho, Codinhoto, and Fabricio (2019) identified an additional range of technological components required for an effective implementation, such as system and networks, cloud and databases, mobile applications, smart devices, and associated technologies. Along with the technical limitations raised by Chung et al. (2018), Lin, Su, and Chen (2014), and Mirarchi et al. (2018), the study revealed the complexity of combined BIM and IoT implementation in FM activities.

Table 9: Summary of the selected articles

Year	Citation	Country	Database	Source	Title	FM Application
2018	(RAMPRASAD et al., 2018)	Canada	Scopus	2018 IEEE 4th World Forum on Internet of Things (WF-IoT)	Leveraging existing sensor networks as IoT devices for smart buildings	Building data management and synchronization
2018	(KIM, 2018)	China	Compendex (Engineering Village)	CAADRIA 2018 - 23rd International Conference on Computer-Aided Architectural Design Research in Asia: Learning, Prototyping and Adapting	Field survey system for facility management using BIM model: IoT management for facility management	Building data management and synchronization
2018	(CHANG; DZENG; WU, 2018)	Taiwan	Scopus	Applied Sciences (Switzerland)	An automated IoT visualization BIM platform for decision support in facilities management	Environmental monitoring and visualization
2018	(CHUNG et al., 2018)	Korea	Compendex (Engineering Village)	ISARC 2018 - 35th International Symposium on Automation and Robotics in Construction and International AEC/FM Hackathon: The Future of Building Things	Smart facility management systems utilizing open BIM and augmented/virtual reality	Maintenance Work process
2018	(KUČERA; PITNER, 2018)	Czech Republic	Science Direct	Advanced Engineering Informatics	Semantic BMS: Allowing usage of building automation data in facility benchmarking	Facility benchmarking and operation analysis
2018	(MIRARCHI et al., 2018)	Italy, Austria, China, Korea	Technology Collection (ProQuest)	2017 AEIT International Annual Conference	Supporting Facility Management Processes through End-Users' Integration and Coordinated BIM-GIS Technologies	Maintenance Work process (corrective)
2018	(ZHONG et al., 2018)	China	Scopus	Automation in Construction	Ontology-based framework for building environmental monitoring and compliance checking under BIM environment	Environmental monitoring and compliance checking
2018	(EDMONDSON et al., 2018)	UK	Scopus	Automation in Construction	A smart sewer asset information model to enable an 'Internet of Things' for operational wastewater management	Operational and maintenance management

Table 9: Summary of the selected articles (continued)

Year	Citation	Country	Database	Source	Title	FM Application
2018	(DI GIUDA et al., 2018)	Italy	Scopus	2018 AIP Conference Proceedings	Refurbishment and school buildings management in a smart building environment	Energy, environmental and occupant's behaviour monitoring
2018	(SAVA et al., 2018)	Romania	Scopus	2018 IEEE International Conference on Future IoT Technologies, Future IoT	Integration of BIM Solutions and IoT in Smart Houses	Energy and environmental monitoring and visualization
2018	(POUKE et al., 2018)	Finland	Scopus	2018 IEEE International Conference on Future IoT Technologies, Future IoT	Comparison of two workflows for Web-based 3D smart home visualizations	Environmental monitoring and visualization
2018	(NG et al., 2018)	Hong Kong, China	Compendex (Engineering Village)	2018 Construction Research Congress	A social networking enabled crowdsourcing system for integrated infrastructure asset management	Building data management and synchronization
2018	(PH.D; YE, 2018)	China	ASCE Library	2018 International Conference on Construction and Real Estate Management	A Novel IoT-Cloud-BIM Based Intelligent Information Management System in Building Industrialization	Building data management and synchronization
2018	(YE et al., 2018)	China	Scopus	ISARC 2018 - 35th International Symposium on Automation and Robotics in Construction and International AEC/FM Hackathon: The Future of Building Things	Cup-of-Water theory: A review on the interaction of BIM, IoT and blockchain during the whole building lifecycle	Building data management and synchronization
2018	(LOUIS; RASHID, 2018)	USA	Scopus	2018 Proceedings of the Human-Habitat for Health (H3): Human-Habitat Multimodal Interaction for Promoting Health and Well-Being in the Internet of Things era - 20th ACM International Conference on Multimodal Interaction, ICMI	Utilizing building information models as operating systems for smart homes	Building data management and synchronization
2018	(GERRISH et al., 2018)	UK	Scopus	2018 EG-ICE: Workshop of the European Group for Intelligent Computing in Engineering	Visual pattern recognition as a means to optimising building performance?	Energy and environmental management

Table 9: Summary of the selected articles (continued)

Year	Citation	Country	Database	Source	Title	FM Application
2018	(MARROQUIN; DUBOIS; NICOLLE, 2018)	France	Scopus	ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences	Ontology for a Panoptes building: Exploiting contextual information and a smart camera network	Environmental monitoring and visualization
2018	(DAVE et al., 2018)	Finland	Science Direct	IET Conference Publications	A framework for integrating BIM and IoT through open standards	Energy, environmental and occupancy monitoring
2017	(TEIZER et al., 2017)	Germany	Compendex (Engineering Village)	ISARC 2017 - Proceedings of the 34th International Symposium on Automation and Robotics in Construction	Internet of Things (IoT) for integrating environmental and localization data in Building Information Modeling (BIM)	Monitoring safety of a worker's location
2017	(NEGES et al., 2017)	Germany	Technology Collection (ProQuest)	ISARC 2017 - Proceedings of the 34th International Symposium on Automation and Robotics in Construction	Improving Indoor Location Tracking Quality for Construction and Facility Management	Location tracking
2017	(ARASZKIEWICZ, 2017)	Poland	Science Direct	Procedia Engineering	Digital Technologies in Facility Management – The state of Practice and Research Challenges	Operational and maintenance management
2017	(VANDECASTEELE; MERCI; VERSTOCKT, 2017)	Belgium	Science Direct	Fire Safety Journal	Fireground location understanding by semantic linking of visual objects and building information models	Firefighting and protection
2017	(GOKCELI et al., 2017)	Turkey	Technology Collection (ProQuest)	Journal of Computer Networks and Communications	IoT in Action: Design and Implementation of a Building Evacuation Service	Firefighting and protection
2017	(TERKAJ; SCHNEIDER; PAUWELS, 2017)	Italy	Scopus	2017 CEUR Workshop Proceedings	Reusing domain ontologies in linked building data: The case of building automation and control	Energy and environmental management

Table 9: Summary of the selected articles (continued)

Year	Citation	Country	Database	Source	Title	FM Application
2017	(CIRIBINI et al., 2017)	Italy	Science Direct	Procedia Engineering	Tracking Users’ Behaviors through Real-time Information in BIMs: Workflow for Interconnection in the Brescia Smart Campus Demonstrator	Operational and maintenance management
2017	(DESOGUS et al., 2017)	Italy	Scopus	2017 AEIT International Annual Conference	Preliminary performance monitoring plan for energy retrofit: A cognitive building: The 'Mandoles Pavillon' at the University of Cagliari	Operational and maintenance management
2017	(MCGLINN et al., 2017)	Ireland, UK, Germany, Indonesia	Science Direct	Journal of Information Technology in Construction	Usability evaluation of a web-based tool for supporting holistic building energy management	Environmental monitoring and compliance checking
2017	(ARSLAN; RIAZ; MUNAWAR, 2017)	France, Pakistan	Scopus	PICMET 2017 - Portland International Conference on Management of Engineering and Technology: Technology Management for the Interconnected World, Proceedings	Building Information Modeling (BIM) Enabled Facilities management using hadoop architecture	Environmental monitoring, visualization and notification
2017	(GUNDUZ; ISIKDAG; BASARANER, 2017)	Turkey	Technology Collection (ProQuest)	2017 ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences	Integration of BIM, web maps and IoT for supporting comfort analysis	Environmental monitoring and visualization
2016	(MOTAMEDI et al., 2016)	Canada	Science Direct	Advanced Engineering Informatics	Extending IFC to incorporate information of RFID tags attached to building elements	Building data management and synchronization
2016	(KUBLER et al., 2016)	Luxembourg	Scopus	IFIP 2016 - Advances in Information and Communication Technology	Building lifecycle management system for enhanced closed loop collaboration	Environmental monitoring and visualization
2016	(HANLEY; BRAKE, 2016)	UK	Scopus	2016 IET Conference Publications	Putting asset data at the heart of organisational decision-making using an Integrated Workplace Management System	Building data management and synchronization

Table 9: Summary of the selected articles (conclusion)

Year	Citation	Country	Database	Source	Title	FM Application
2015	(LIU et al., 2015)	Taiwan	Scopus	2015 IEEE International Conference on Data Science and Data Intensive Systems	A Building/Environment Data Based Indoor Positioning Service	Location tracking
2015	(CHEN et al., 2015)	Hong Kong	Scopus	International Journal of Project Management	Bridging BIM and building: From a literature review to an integrated conceptual framework	Lifecycle management
2015	(COSTA et al., 2015)	Portugal	Science Direct	Procedia Engineering	3I Buildings: Intelligent, Interactive and Immersive Buildings	Energy, environmental and occupant's behaviour monitoring
2015	(RONZINO et al., 2015)	Italy	Science Direct	Semantic Web	The Energy Efficiency Management at Urban Scale by Means of Integrated Modelling	Energy and environmental management
2014	(COSTIN; PRADHANANGA; TEIZER, 2014)	USA	Scopus	CRC 2014: Proceedings of the Construction Research Congress 2014: Construction in a Global Network	Passive RFID and BIM for real-time visualization and location tracking	Location tracking
2014	(LIN; SU; CHEN, 2014)	Taiwan	Directory of Open Access Journals	The Scientific World Journal	Developing Mobile BIM/2D Barcode-Based Automated Facility Management System	Maintenance Work process (inspection, repair)
2014	(ARSLAN et al., 2014)	Pakistan, USA	Scopus	Procedia Engineering	Real-time environmental monitoring, visualization and notification system for construction H&S management	Energy and environmental management
2013	(LEE et al., 2013)	Korea	Compendex (Engineering Village)	ISARC 2013 - 30th International Symposium on Automation and Robotics in Construction and Mining, Held in Conjunction with the 23rd World Mining Congress	Realtime facility management system framework based on Building Information Modeling and Web of Things	Building data management and synchronization

Source: Author (2021)

The third aspect involves the FM and reactive maintenance areas and activities. A prevalence of studies on building operations and maintenance, especially regarding building performance monitoring, energy consumption management, and voice and data communication was observed. According to Fialho, Codinhoto, and Fabricio (2019), such results evidenced the importance of BIM and IoT solutions and data within a building lifecycle, supporting improvements in Operation and Maintenance (O&M) and in initial stages of design process.

Finally, the fourth aspect is related to the outputs of BIM and IoT implementation for FM and reactive maintenance. The authors identified a prevalence of positive, rather than negative issues of such implementation. The main benefits involved provision of real-time information and a central repository for building information, and gains concerned improvements in information management and performance of building maintenance and operation over its lifecycle.

The core enablers and barriers regarded both technological issues. Although enabling the processing of real-time information, the complexity of interoperable data management and the costs involved in technological solutions were considered barriers for the BIM and IoT implementation (FIALHO; CODINHOTO; FABRICIO, 2019).

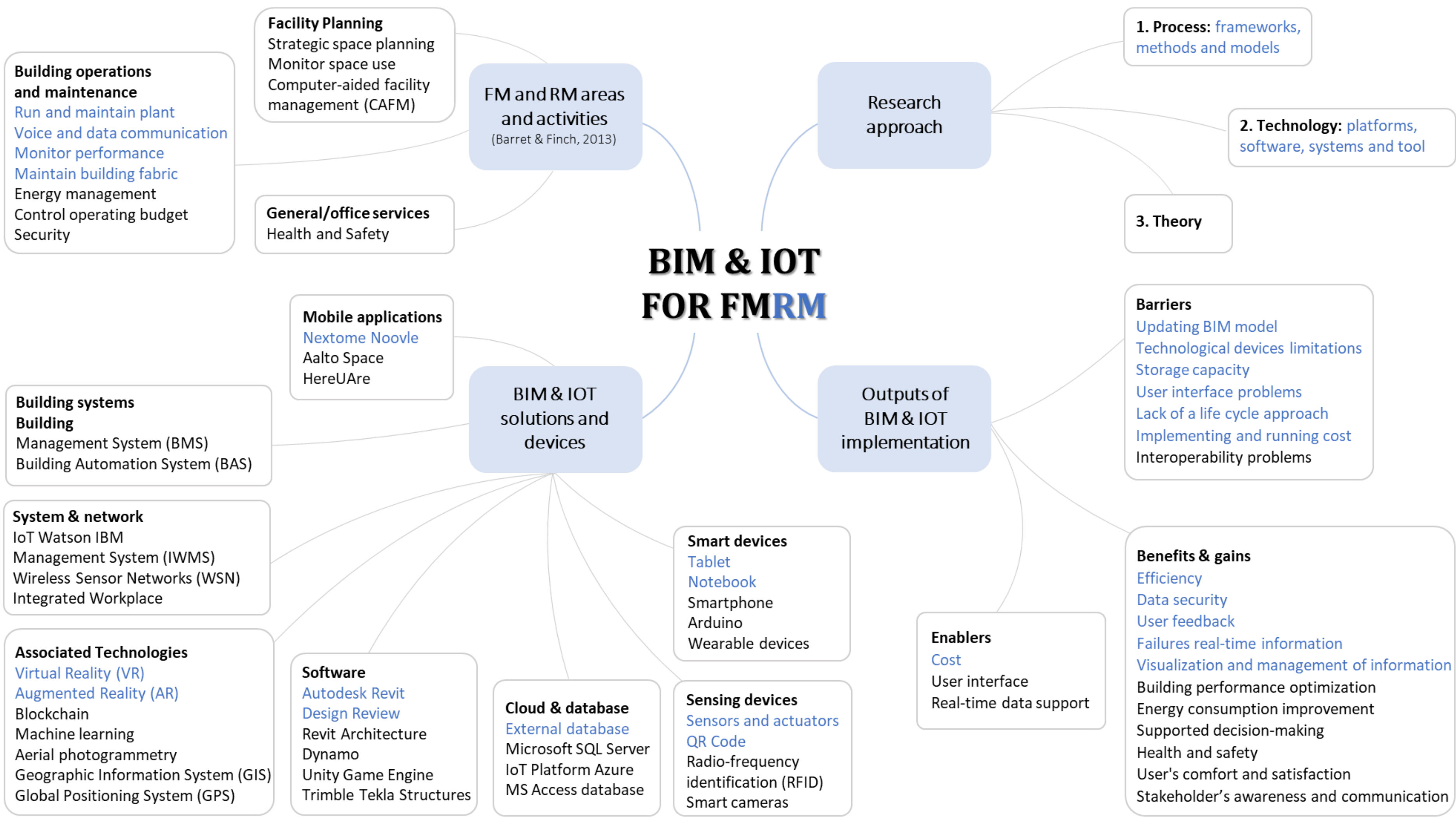
The SLR investigated significant publications in the field and provided an understanding on BIM and IoT implementation for FM and reactive maintenance service. Fialho, Codinhoto, and Fabricio (2019) highlighted the novelty and potential of the theme, as well as gaps in the literature and opportunities for future research, as shown in Table 10.

Table 10: Research gaps and opportunities in BIM and IoT for FM

Gaps	▪ Scarcity of studies on BIM and IoT combined implementation for FM, in particular for reactive maintenance ▪ Lack of clarity regarding the cost-benefit of BIM and IoT combined implementation ▪ Lack of clarity regarding barriers involved in BIM and IoT implementation for FM ▪ Lack of clarity regarding reactive maintenance services and activities to be potentially improved through BIM and IoT implementation ▪ Lack of holistic approaches covering technical challenges, people issues and organizational changes in FM process.
Opportunities	▪ Field investigations through case studies, surveys, and interviews for the generation of empirical evidence ▪ Investigation on reactive maintenance process towards the identification of bottlenecks and opportunities for improvements through BIM and IoT implementation ▪ Development of strategies for BIM and IoT implementation

Source: Author based on Fialho, Codinhoto, and Fabricio (2019)

Figure 29: Framework for BIM and IoT implementation for FMRM



Source: Fialho, Codinhoto and Fabricio (2019)

3.5. Summary

This chapter provided a review of literature on Facilities Management (FM), maintenance services, and digital transformation through BIM and IoT implementation. The FM and maintenance context was characterized, emphasizing the value of efficient information management and proactive actions towards more sustainable building operation and maintenance. BIM, IoT, and Digital Twin concepts and enabled technologies were explored as powerful allies in FM digital transformation, and a context of BIM and IoT for FM and reactive maintenance was provided through a Systematic Literature Review (SLR) and synthesized in a Framework for BIM and IoT implementation for FMRM. Research gaps and opportunities were identified, guiding the development of the multiple case study and the BIM and IoT-based system prototype for maintenance purposes following presented in Chapters 4 and 5.

4. Multiple Case Study

This chapter approaches the empirical research activities related to the Multiple Case Study, exploring data generation, analysis, and discussion. The process followed the four stages described in the methodology chapter (Figure 7), namely, 1. Scope and planning, 2. Entering the field, 3. Analysing data, and 4. Theory generation. Initially, the investigation was conducted with the two British universities (here named UK University 1 and UK University 2), as part of the Sandwich Doctorate in the United Kingdom between September 2018 and February 2019. Such universities were selected as examples of organizations with an intermediate level of facilities information management supported by digital systems (criteria described in Section 2.2.1.a), a key component for the understanding of critical issues of FM services and proposal of effective BIM and IoT solutions.

Through the adoption of an exploratory perspective, the case studies representing Group 1 have generated empirical evidence in the following distinct levels: characterization of FM sectors and reactive maintenance services and processes, identification of most critical reactive maintenance problems, assessment of building characteristics that impact on problem occurrence and time response, and investigation on current and potential applications of BIM and IoT-based solutions for FM services, specifically maintenance services.

The third case study was developed with the Brazilian University (here named BR University), an organisation with low level of digital supported FM, representative of Group 2. The definition of data to be collected was supported by the outputs of the UK case studies, e.g., accommodation building Work Requests. Given the specific organizational and service characteristics (i.e., public organization, restricted FM sector scope, small volume of available FM data), the following evidence was generated: characterization of FM sector and reactive maintenance services and processes, identification of critical scenarios for reactive maintenance problems, and characterization of the scenario for current and potential applications of BIM and IoT-based solutions for FM services, focusing on reactive maintenance.

Section 4.1 addresses the universities characterization, and Section 4.2 describes the data generation through interviews, focus group and document collection. Section 4.3 presents the Content Analysis, Descriptive Analysis and Statistics Analysis of the data extracted from the Interviews and Work Requests. Section 4.4 discusses the results, supported by the literature. Finally, Section 4.5 provides a summary of the chapter, highlighting the outputs and contributions of the cases for the overall research.

4.1. Universities characterization

4.1.1. UK University 1

The UK University 1 was created in 1965 in the Southwest England, with the construction of its main Campus. Currently it has 18.103 students (UK UNIVERSITY, 2018) and approximately 2.600 staff and it is ranked as one of the top universities in the UK, contributing to the local and national economic development (UK UNIVERSITY 1, 2014). The main Campus concentrates most of the university's activities, such as administrative services, teaching, research, sports, and students' accommodation, and covers an area of approximately 75 ha with 289.904 m^2 of building built area distributed in 118 buildings.

Other buildings around the city integrate the university asset, and include students' residences, a centre for innovation, and a sport centre. The FM Sector supports the planning, development and management of the university assets (UK University 1, 2019a), providing construction and facilities services, such as maintenance and repair, refurbishment, landscape, capital projects, portering, mail services, central stores, cleaning, administration, records management, telecommunications, energy, and recycling and waste.

4.1.2. UK University 2

UK University 2 was formally created in 1992 in Southwest England, when a previous technical school was awarded the status of university (UK UNIVERSITY 2, 2019). UK University 2 is one of the largest universities in the region, with approximately 30.000 undergraduate and postgraduate students and 3.700 staff. Since its creation in 1975, the main Campus (here named *FR Campus*) has centralized the university's activities, such as teaching, research, sports and leisure, and students' accommodations. It covers an area of approximately 63 ha with 324.000 m^2 of building built area.

The university has two other campuses in the main city, namely, *GL Campus*, which covers approximately 9,6 ha with 32.000 m^2 of building built area, and CC *Campus,* integrated by *three sites*, summing approximately 3 ha of site area and 16.000 m^2 of building built area. In addition, the HU *Campus* and GC *Campus* are located in another city in the region (UK UNIVERSITY 2, 2019), resulting in a built area of approximately 400.000 m^2 (UK UNIVERSITY 2, 2019a).

The FM Sector plans and manages the buildings and infrastructure of the campuses, including "planned and reactive maintenance, energy and environmental management, space management, cleaning, portering, post, transport, car parking, and security" (UK UNIVERSITY 2, 2019). Besides, it provides business (i.e., catering, conferencing, printing and stationery), accommodations, health and safety, and sport services (UK UNIVERSITY 2, 2019).

4.1.3. BR University

The BR University was created in 1934 in the Southeast Brazil, while the selected Campus (here named *Campus A*) was implemented in a distinct city in 1956. In 2005, a second campus (here named *Campus B*) was implemented in a new neighbourhood for supporting new demands for built environment. Currently, *Campus A* covers an area of approximately 32 ha with 135.433,81 m² of built environment, while *Campus B* has around 98 ha with 33.617,72 m² of built environment. Besides academic and research assets, the campus holds administrative, residential, sportive, cultural, catering, and health buildings.

In addition, the university owns a cultural and scientific centre, located in a 2.354,96 m² building at the city centre, and a research centre in a neighbour city, covering an area of approximately 25 ha and 4.350,39 m² of built environment. Together, the sites have 7.867 undergraduate and postgraduate students and 1.604 staff. The FM Sector provides infrastructure and services to the university activities of teaching, research, sports, and culture.

4.2. Data generation: Interviews, Focus Group and Data collection

4.2.1. UK University 1

Five face-to-face interviews were conducted with members of UK University 1 for the collection of relevant data on FM sector, RM services process, and the impact of BIM and IoT on FM activities. The interviewees were classified into two groups, namely professionals directly involved with the management and supervision of FM activities, and professionals working on Information Technologies to support asset and FM data management. A consent form (Appendix D) was applied to the participants, thus clarifying the research objectives, and obtaining their consent for participation.

Table 11 shows a synthesis of the interviews, including location, date, duration, and identification (ID), professional characterization (ID, job title and department/sector), type of interview and recording tools, emerging topics, and documents provided. The interviewees were identified by a code containing the acronym of the organisation, and professional and chronological numbers of the interview (e.g., UK University 1_Prof_1).

The first interview was conducted with a General Maintenance Manager from the FM Sector (UK University 1_Prof_1) on the 6th December 2018 and lasted approximately 30 minutes. It was a first approach towards the understanding of the typical FM sector, Reactive Maintenance activities and areas, and the ICT solutions involved in such services. The main topics discussed were the FM sector and budget, critical maintenance, RM service process, building database, CAFM system, and BIM model. The collected information was registered through written notes (UK UNIVERSITY 1, 2018a). The interviewee provided records of Workshop RM services between 2014 and 2017 and Work Orders between 2014 and January 2019 (UK UNIVERSITY 1, 2018a).

A preliminary analysis of UK University 1 Work Request characteristics was undertaken from the data provided in the first interview (UK UNIVERSITY 1, 2018a). The available data from 2014 and 2015 indicated an average of 10.869 reactive maintenance requests per year, including building, mechanical and electrical services, which enabled a comprehension of the scale and variety of problems in the FM sector. Focusing on building services between 2014 and 2017, Figure 30 shows the annual distribution of building request per month. A peak of services is observed in 2017, reaching 900 requests in September, thus reinforcing the critical period of the year.

The theoretical and practical background from the interview supported the characterization of RM services at UK University 1 and development of the questionnaire for the next interviews. It has also contributed to the development of the preliminary version of the Reactive Maintenance Service Process Model, as further described. The scale of the sector and the volume of services attended annually were determinant aspects for focusing the research investigation over the period of 2017 and 2018, as explained in Chapter 2.

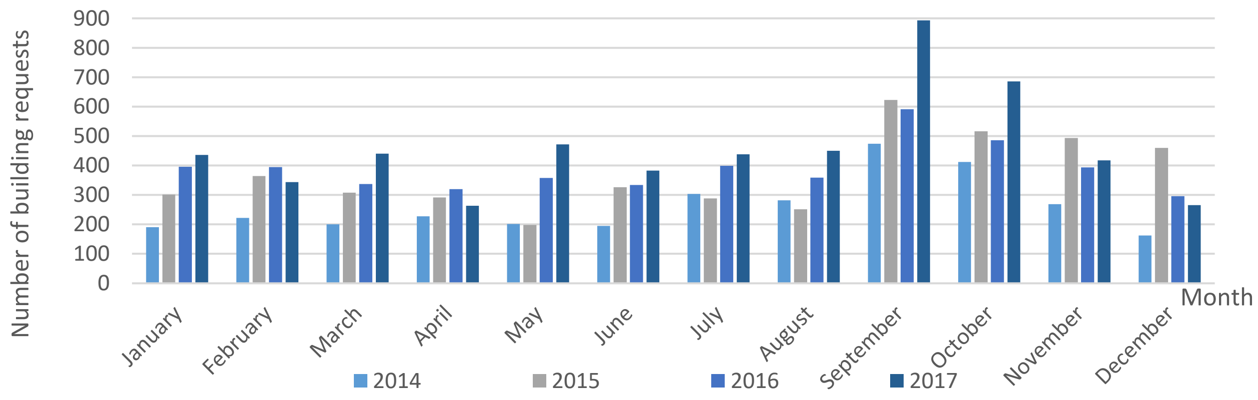
The second interview was conducted with two professionals - a Technical Lead from the Department of Computing Services (UK University 1_Prof_2) and a CAFM/CAD/BIM Technician from the FM Sector (UK University 1_Prof_3) - on 15th February 2019. The aim was to gather complementary information from both sectors, towards the construction of a common picture of both the FM sector and Reactive Maintenance services processes, and the technological support applied.

Table 11: Synthesis of Interviews with members of UK University 1

UK University 1 Interviews				
Date	**06/12/2018**	**15/02/2019**	**25/02/2019**	**27/02/2019**
Duration	00:30:00	01:28:00	01:00:29	00:12:54 (Part 1) 42:56:00 (Part 2)
Interview ID	UK University 1_Interview_1 (2018)	UK University 1_Interview_2 (2019)	UK University 1_Interview_3 (2019)	UK University 1_Interview_4 (2019)
Interviewee identification	UK University 1_Prof_1	UK University 1_Prof_2 UK University 1_Prof_3	UK University 1_Prof_4	UK University 1_Prof_5
Job Title	General Maintenance Manager	Technical Lead CAFM/CAD/BIM Technician	Director of Estates Operations	Network Engineer
Department/ Sector	FM Sector	Computing Services FM Sector	FM Sector	Computing Services
Type of interview	Not structured	Semi-structured (Appendix A)	Semi-structured (Appendix B)	Not structured
Recording tools	Written notes	Audio record and questionnaire	Audio record and questionnaire	Audio record
Transcription ID	(UK UNIVERSITY 1, 2018a)	(UK UNIVERSITY 1, 2019b)	(UK UNIVERSITY 1, 2019c)	(UK UNIVERSITY 1, 2019d)
Topics	FM sector FM budget Critical maintenance RMS process Building Database CAFM system BIM model	CAFM system BMS system Database BIM model Financial information RMS process model IoT uses App for monitoring FM craftsman	Characterization of FM sector and services (scope, hierarchy, professionals, budget) BIM and IoT implementation (solutions, costs, impact on RM efficiency, benefits, and barriers)	Current and potential applications of IoT to FM activities (e.g., emergency lighting system management)
Provided documents	Workshop RM services (2014-2017) Work Requests (2014-Jan2019) (UK UNIVERSITY 1, 2018b)	Work Requests (2017-February 2019) (UK UNIVERSITY 1, 2019c)	No	No

Source: Author (2021)

Figure 30: UK University 1 building services request per month



Source: UK University 1 (2018b)

The main topics discussed included the current capabilities of CAFM, BMS and databases, applications of BIM model to FM, financial information about Reactive Maintenance services, IoT uses by the university, development of a mobile application for monitoring FM craftsman work, and Reactive Maintenance process model (UK UNIVERSITY 1, 2019b). A questionnaire (Appendix A) and the consent form (Appendix D) were previously sent to the interviewees via e-mail towards explaining the research objectives and guiding the conversation.

The questionnaire was structured in five sections. The first was related to the profile information of the interviewee (e.g. gender, age, professional background, job position, time in the organisation); the second focused on the characterization of asset information for FM activities, including type and format of available data, databases, systems and software for FM; the third addressed the flow of information in RM services, stages, stakeholders, systems and software; the fourth referred to the BIM implementation in FM services; and the fifth regarded the adoption of IoT solutions and devices for FM and RM services.

Towards supporting the discussion, the interviewer presented a preliminary Reactive Maintenance Service Process Model based on information provided by UK University 1_Prof_1 and available on the FM Sector website. The interviewees were invited to analyse the coherence of the document with the real scenario steps and stakeholders. Some corrections and complementary information were provided, supporting the final version of the model (Figure 36). The interview lasted approximately 90 minutes, and was audio recorded and transcribed (UK UNIVERSITY 1, 2019b). Part of the questions not answered during the meeting due to unavailability of data or time was later replied via e-mail. Additionally, UK University 1_Prof_2 provided FM Work Requests from 2017 to 2019 for investigation (UK UNIVERSITY 1, 2019c).

On 25th February 2019, the third interview was conducted with a Director of Estates Operations (UK University 1_Prof_4), and lasted approximately one hour (UK UNIVERSITY 1, 2019c). The focus was on the understanding of managerial characteristics of the FM sector and complementing missing data on Reactive Maintenance processes. The consent form and the questionnaire (Appendix B) were sent in advance to the interviewee by e-mail. Among the topics, UK University 1_Prof_4 informed the scope, hierarchy, number of professionals, and budget of the FM sector related to Reactive Maintenance services; data on BIM and IoT implementation were discussed, pointing solutions, costs, impact on RM efficiency, benefits, and barriers. The RM process model was analysed by the interviewee, who provided supplementary information, supporting corrections in the final version of the map presented in Section 4.4.1. No additional documents were provided. The interview was audio recorded, and its transcription and analysis were conducted according to the procedures described in Section 2.3.1.

Finally, the fourth interview was undertaken with a Network Engineer from the Department of Computing Services (UK University 1_Prof_5) on 27th February 2019. The emphasis was on current and potential applications of IoT devices and solutions to FM activities. The meeting was audio recorded for further transcription and no documentation was provided (UK UNIVERSITY 1, 2019d).

4.2.2. UK University 2

The UK University 2 Case Study was developed with the contribution of a Digital/BIM Manager (UK UNIVERSITY 2_Prof_1), a key member of the staff. At that time, this professional was a member of the Digital Campus Innovations Team directly working on building data management for FM Sector, providing relevant data from both managerial and technological areas. A face-to-face semi-structured interview was undertaken in two parts - on 19th December 2018 which lasted approximately an hour and fifteen minutes (UK UNIVERSITY 2, 2018), and on 18th February 2019, with duration of approximately fifty minutes (UK UNIVERSITY 2, 2019b), as shown in Table 12. The meetings were conducted according to the questionnaire (Appendix C) and audio recorded with the agreement of the interviewee, who signed the consent form (Appendix D).

Table 12: Synthesis of Interviews with members of UK University 2

UK University 2 Interviews		
Date	19/12/2018	18/02/2019
Duration	01:15:35	00:48:04
Interview ID	UK UNIVERSITY 2_Interview_1_2018	UK UNIVERSITY 2_Interview_2_2019
Interviewee ID	UK UNIVERSITY 2_Prof_1	
Job Title	Digital/BIM Manager	
Department/Sector	Digital Campus Innovations Team Estates | FM Sector	
Type of interview	Semi-structured interview (Appendix C)	
Recording tools	Audio record and questionnaire	
Transcription ID	(UK UNIVERSITY 2, 2018)	(UK UNIVERSITY 2, 2019b)
Topics	CAFM system RMS process model BIM model	FM sector BIM benefits and barriers for RM IoT uses Financial information
Provided documents	No	Work Requests (2017-2018) Maintenance Budget Building areas Spaces codification (UK UNIVERSITY 2, 2019c)

Source: Author (2021)

As detailed in Appendix C, the interviews' purpose was to characterize the FM sector, the RM services processes, and the impact of BIM and IoT on the efficiency of the FM activities. The first part of the interview provided data on the main topics in Table 12, whereas the second provided documents related to the FM sector and the RM services operated in 2017 and 2018, including Work Orders, Maintenance budget, buildings areas, and spaces codification (UK UNIVERSITY 2, 2019c). The interviews were further transcribed and analysed according to the procedures described in Section 2.3.1.

4.2.3. BR University

The characterization of the BR University FM sector, its reactive maintenance services, as well as the identification of potential impacts of BIM and IoT on FM activities were performed through semi-structured interviews with members of the BR University FM sector, as depicted in Table 13. The communication was made in Portuguese, and further translated into English.

First, a 90-minute Focus Group was conducted with three interviewees (BR University_Prof_1, BR University_Prof_2 and BR University_Prof_3), on 15th October 2019 for clarifying the sector activities and discussing potential benefits of BIM for the performance of FM services. A consent form and a questionnaire (Appendix E) were applied to the participants, supporting the activity development. The interview was transcribed for further analysis (BR UNIVERSITY, 2019a). As expected, the group activity provided different points of view regarding the topic, thus, contributing to its comprehension.

A second interview was conducted with BR University_Prof_1 on 13th December 2019 for detailing the capabilities of the CAFM software for supporting maintenance services and obtaining of Work Requests data. The interview applied a questionnaire on the characterization of the FM sector, services, and systems (Appendix F) and lasted approximately 90 minutes. A consent form (Appendix H) was delivered, ensuring the research objectives comprehension. was further filled out. The interview was transcribed (BR UNIVERSITY, 2019b) and analysed according to the procedures defined in Section 2.3.1.

Table 13: Synthesis of Interviews with members of the BR University FM sector

BR University Interviews		
Date	15/10/2019	13/12/2019
Duration	00:07:49 (Part 1) 01:23:50 (Part 2)	00:55:41
Interview ID	BR University_FocusGroup (2019)	BR University_Interview (2019)
Interviewee ID	BR University_Prof_1 BR University_Prof_2 BR University_Prof_3	BR University_Prof_1
Job Title	General Maintenance Chief Architect CAD Technician	General Maintenance Chief
Department/ Sector	Division of Maintenance and Operation	Division of Maintenance and Operation
Type of interview	Semi-structured (Appendix E)	Semi-structured (Appendix F)
Recording tools	Audio record and questionnaire	Audio record and questionnaire
Transcription ID	(BR UNIVERSITY, 2019a)	(BR UNIVERSITY, 2019b)
Topics	Characterization of FM sector RMS process Maintenance support system Potential BIM advantages for FM Critical maintenance problems to be benefited from BIM adoption Steps for BIM adoption Project documentation for the campus management Main problems for the campus management related to cost, labour, risk, and disruption	Maintenance support system RMS process Database Characterization of FM sector and services (scope, hierarchy, professionals, budget) BIM and IoT implementation (solutions, costs, impact on RM efficiency, benefits, and barriers)
Provided documents	No	Work Requests (12/2018-12/2019) (BR UNIVERSITY, 2019c)

Source: Author (2021)

General Work Requests data the asset identification, type of service, time spent, material, and labour costs informing (BR UNIVERSITY, 2019c) from December 2018 to December 2019 were provided. The one-year period was established because it corresponded to the time required for the implementation of the current computer system for maintenance management. The purpose was to identify critical buildings and services to be potentially benefited from the implementation of BIM and IoT.

Work Requests related to the newest student accommodation (E) were collected, since this typology was considered one of the most critical for maintenance management, according to the UK University 1 and UK University 2 previous analysis. The building was selected due to the availability of design data, such as digital drawings of distinct disciplines (i.e., Architecture, Electrical, Plumbing), supporting the information modelling in software BIM and the pilot implementation of IoT solutions. Data collected through the interviews, questionnaire and documents were analysed, as described in the following sections.

4.3. Data Analysis

4.3.1. Descriptive Analysis of Interviews

The analysis of the interviews aims to support the comprehension of the FM sector and services, the reactive maintenance services process, and the applications of BIM and IoT-based solutions for FM services. Since the interviews were complementary, all data were organized according to the topics, as described in what follows.

a. UK University 1

- **Characterization of FM sector and services**

The scope of the FM sector covers the projects of new buildings and refurbishment, maintenance, and operation of buildings and infrastructure. The operational area manages both *Soft FM*, including cleaning, transports, grounds and post, and *Hard FM*, related to the preventive and corrective maintenance of buildings and infrastructure (i.e., electrical, mechanical, building) (UK UNIVERSITY 1, 2019c).

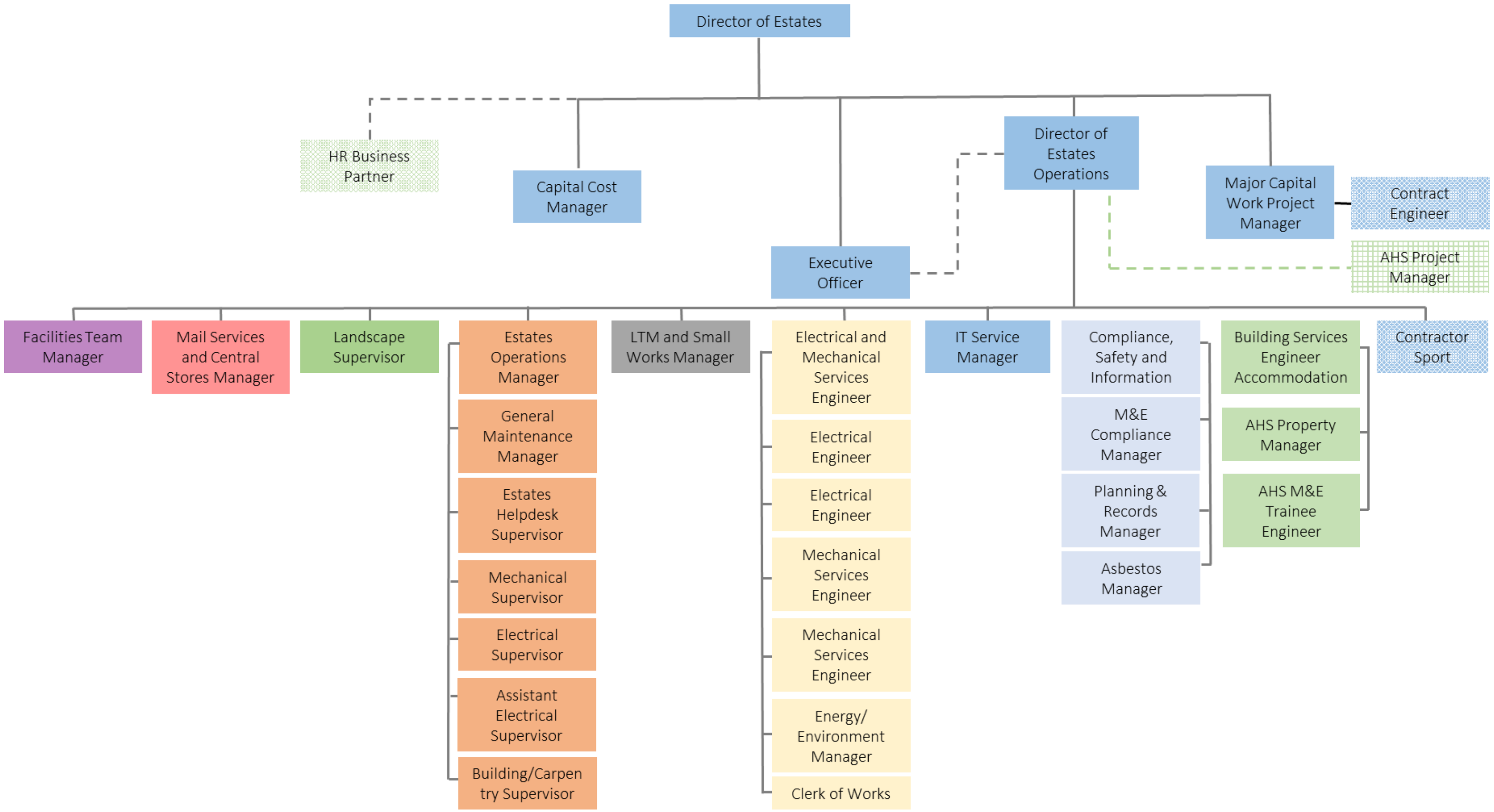
The FM Sector Organogram (Figure 31) shows the functional top-down structure of the sector, mainly driven to operational activities. In the first level is the head of the department, the Director of Estates, supported by seven main collaborators, namely HR (Human Resources) Business Partner, Capital Cost Manager, Executive Officer, Major Capital Work Project Manager, Contract Engineer, AHS (Accommodations, Hospitality, Events, Retail and Security) Project Manager, and the Director of Estates Operations. In the third level, the following ten professionals coordinate the workgroups, vertically organized: Facilities Team Manager, Mail Services and Central Stores Manager, Landscape Supervisor, Estates Operations Manager (responsible for General Maintenance, Estates Helpdesk, Mechanical, Electrical, Building, and Carpentry services), LTM and Small Works Manager, Electrical and Mechanical Services Engineer (coordinating Mechanical, Electrical Energy/Environment and Clerk of works), IT Service Manager, Compliance Safety and Information (related to asbestos, planning and records, and M&E compliance), Building Services Engineer Accommodation, and Contractor Sport.

According to one of the interviewees, most maintenance services are provided in-house and supported by Workshops. A team of approximately 212 professionals with various qualifications work in the department. Roughly 50 directly manage reactive maintenance requests, although they are also responsible for care maintenance and some projects, depending on the priority (UK UNIVERSITY 1, 2019c). The sport club centre and Accommodation and Catering hospitalities have administrative and financial independence to manage and operate their assets. The residences have their own work force, a Handy-mend team for small repairs.

Depending on the complexity of the issue, maintenance services can be provided by either external companies, or the Department of Estates, which must charge for it (UK UNIVERSITY 1, 2019c). Some data on budget allocation were provided by one of the interviewees. In 2019, the total (annual) budget of the FM Sector was £17.000.000 (seventeen million pounds), covering labour (for the whole FM sector), utilities, rents, and similar items. From that, £1.500.000 (one and a half million pounds) were spent on materials for reactive maintenance - the labour costs were computed in the overall budget (UK UNIVERSITY 1, 2019c).

According to one of the interviewees, setting the budget for the maintenance sector is challenging, due to the lack of a “scientific” approach for that. Traditionally, the setting of the budget for plan & preventive maintenance is based on a condition survey conducted every 5 years; however, it should also take into consideration the operational manuals of the buildings. The budget setting is more straightforward for some services (e.g., cleaning), which causes inflation to the last year costs. However, no reliable method can set the budget for reactive maintenance services, since the problems are unpredictable: “you never know what’s going to be like, because you never know what’s going to happen” (UK UNIVERSITY 1, 2019c).

Figure 31: UK University 1 FM Sector Organogram



Source: Author based on UK University 1 (2019)

To understand the most critical reactive maintenance problems for the organization was one of the interviews' purposes. Among the most recurrent problems, are electrical plugs or appliances, tripping electrics, leaks, and problems with locks, on a micro scale, and an "electrical substation forming out", which affects all university users (UK UNIVERSITY 1, 2019c), as pointed by one of the interviewees. Major floods and electrical issues are among the most disruptive problems, followed by the underground infrastructure. According to the same interviewee, long-term maintenance tends to be in comparison with reactive maintenance. In this group, the most expensive services might involve plumbing and all the electrical support for heating systems (UK UNIVERSITY 1, 2019c).

The following set of systems and databases supports FM activities: *Building Management Systems (BMS)* for energy management, *Archibus CAFM System*, *RapidACCESS,* and *Share Point* for managing general maintenance and operation services, *Space Management* for occupancy optimization, *Asbestos Register* for healthy and safety issues, and *Agresso Finance*, for supporting financial transactions. *Archibus Web Central* and *Topdesk* support the whole reactive maintenance process.

At the time of the interviews, all buildings had a Building Management System (BMS) at various stages connected to a set of sensors (e.g., air temperature, CO2 levels, energy consumption), with a larger number in the new buildings. Other aspects of building systems and components have been monitored for FM purposes (e.g., flow rates for pumps, temperature of water in the pumps, and electrical current in emergency lighting (UK UNIVERSITY 1, 2019c, 2019d).

Archibus, the main tool for FM activities, is managed by the FM Sector, which provides access to external users. According to one of the interviewees, in October 2018, the FM Sector acquired a more powerful licence of Archibus and migrated to a new structure of data management, including cost information on the FM services (UK UNIVERSITY 1, 2019b). The group of asset data available in *Archibus* includes As-built data, such as CAD plans of campus buildings, *Occupational* data, such as Space Details (i.e., type, usage, area), Space Utilisation by departments (i.e., % office, research, support), Building Assets and Equipment, Condition Survey, *Healthy and Safety* data, regarding Asbestos, and Hazards, *Reactive & Planned Maintenance* data, such as Work Orders and Work Requests, *Financial* data, including Internal Orders, Purchase Orders against maintenance, Parts, and Labour. *RapidACCESS* database was previously used for holding data on place, manual, and plans. Figures 32 and 33 show the visualization of asset data on *RapidACCESS* interface. As reported by one of the interviews, *RapidACCESS* was being replaced by SharePoint (UK UNIVERSITY 1, 2019b).

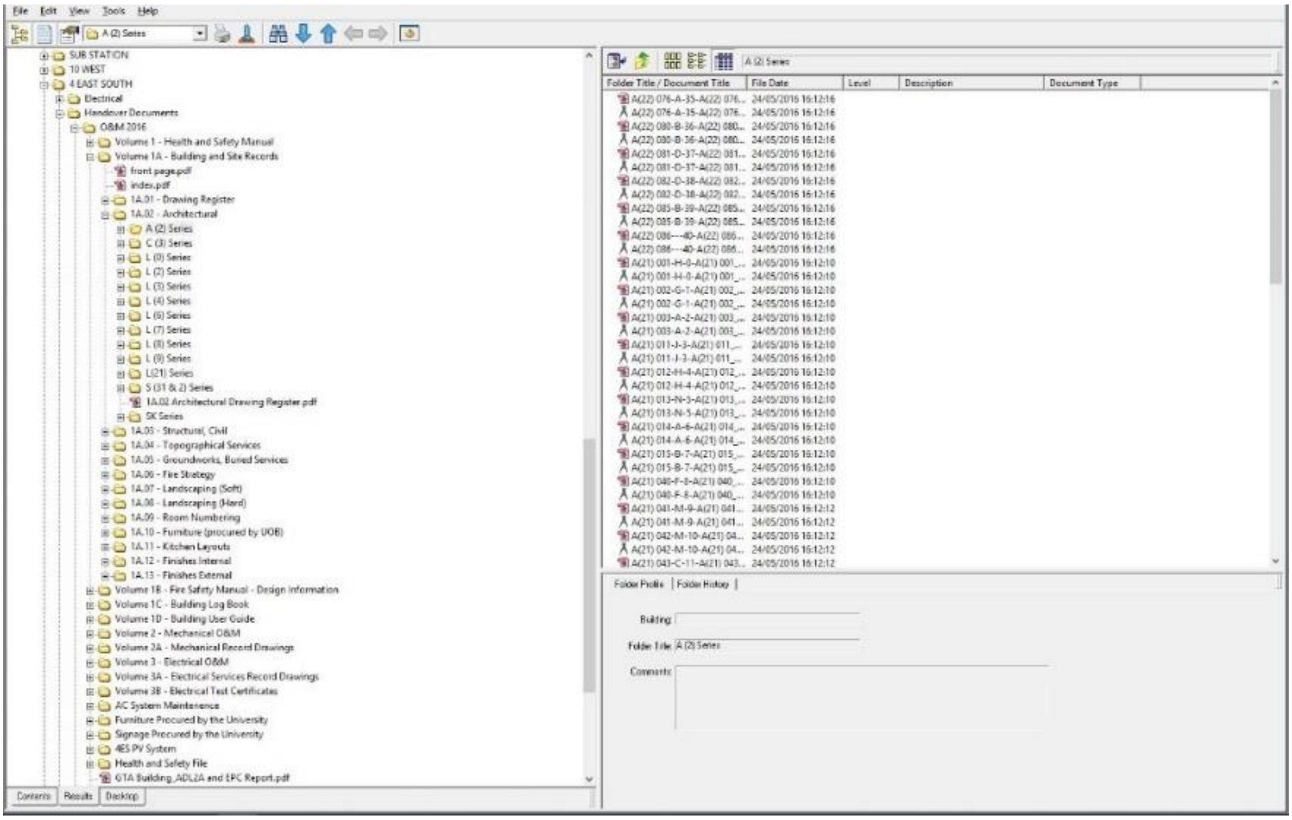
Building data is stored and shared in various ways, including Physical Repositories, Network Shared Drive, and digital Database, accessible by *Windows Smart Client* and Web application on the Mobile phone. The Staff of the FM Sector and the Accommodation, Hospitality and Security (AHS) finance team are responsible for managing data asset. The database is available to the University staff, contractors and some postgraduate research students (UK UNIVERSITY 1, 2019b).

The BIM and IoT technological support for FM activities was also approached in the interviews. Although the FM Sector had hired some projects of buildings to be delivered in BIM, the UK University 1 has not yet developed a plan for BIM implementation in the asset lifecycle. Similarly, according to UK University 1 (2019b), the university is in early stages regarding IoT adoption. Most IoT solutions are driven to students' comfort in accommodation assets and appliances, e.g., a fridge with a temperature sensor that informs the supplier on potential faults, catering vending machines with stock levels sensors, showing students the products available through a mobile app, and the Circuit Managed Laundry Systems, in which washing machines are connected to the Laundry View web system for use management, informing if the machines are being used and when they will be available. According to the interviewee, the UK University 1 staff cannot visualize their information, since the systems are managed by external companies.

Figure 32: RapidACCESS interface – University Campus visualisation

Source: UK University 1 (2018)

Figure 33: *RapidACCESS* interface – Visualisation of Building information



Source: UK University 1 (2018)

- **Characterization of Reactive Maintenance services**

The Reactive Maintenance Service Process Model of the UK University 1 (Figure 36) was developed according to the Swimming lines process model technique and the Operator Process Chart Analysis, using the Business Process Model and Notation (BPMN) and the software Microsoft Visio. The eight stages of the maintenance process (Figure 15) were established according to ISO EN 13306: 2017 Maintenance - Maintenance terminology and are sequentially placed over the columns: 1. Fault Detection, 2. Reporting (and Feasibility Analysis), 3. Location (and Inspection), 4. Diagnosis (and Planning), 5. Repair (Execution), 6. Check-out, 7. Delivery, and 8. Feedback (and closing the request). On the other hand, the stakeholders involved in the process are grouped into seven categories, namely Student and Visitor, Staff member (housekeeping, lecturer, sport centre team), Help Desk Team (Department of Estates), Work Team (Department of Estates), Procurement (D.E.), Finance Department, and Suppliers, displayed in horizontal lines named lanes. The maps were validated by the interviewees UK University 1_Prof_2 and UK University 1_Prof_4 (UK UNIVERSITY 1, 2019e, 2019b).

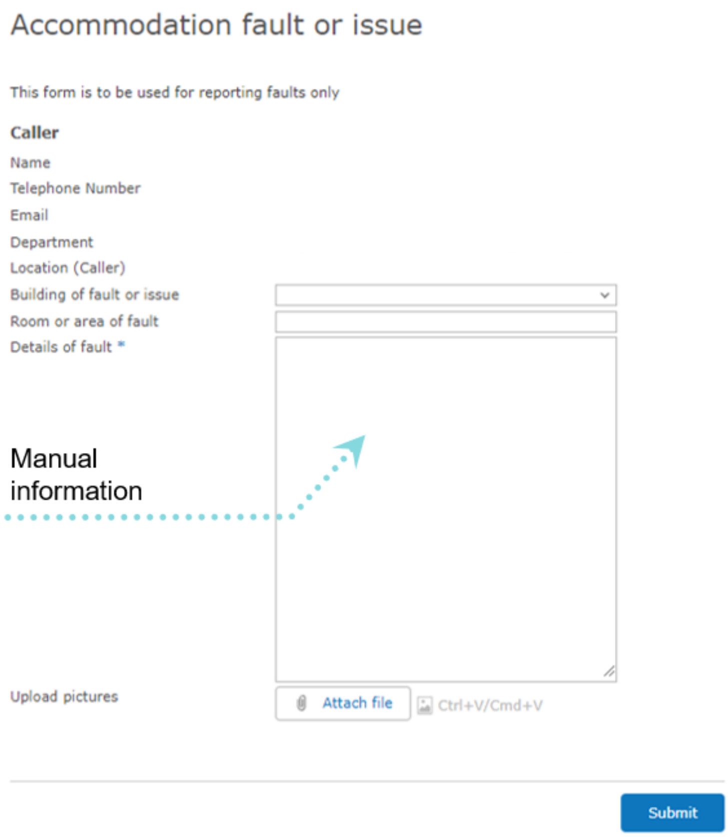
The process starts with a user recognizing a problem or issue in a university asset component or system (Stage 1). The Reporting Stage (2) is then observed. Distinct channels are provided for the reporting of a fault, depending on the type of user (UK UNIVERSITY 1, 2019b). *Estates Helpdesk* and *Security Team* offer an e-mail and phone number to the whole community. *Self-Service Portal* is driven to accommodation students, who can also inform on the problem to a building housekeeper. Figure 34 shows the *Self-Service Portal* interface, in which most information must be manually described.

Archibus Web Central is available for most members of staff (i.e., lecturers and administrators). As depicted in Figure 35, Archibus enables staff members to identify the fault location on a building floor plan and select a problem type category in a basic reference list (e.g., heating fault). Problems in catering hospitalities and sport club centre must be informed to the gatekeepers. Housekeepers and gatekeepers must ask the Estates for permission to access *Archibus Web Central,* if necessary. Such users have a twofold alternative to address the request, i.e., supported by either their internal staff, who contract the material and services to fix the problem, or the FM Sector, through a Work Request (WR). Faults reported to the Estates not through Archibus must be raised in the system by an Estates' member of staff.

A feasibility analysis is conducted WR approval or rejection by the Help Desk. Once approved, the service prioritization is set according to the Service Level Agreement (Table 14), structured in five levels, namely 1. Emergency, with response within 2 hours, 2. Urgent, with response in less than 24 hours, 3. Important, with response in less than 3 days, 4. Standard, with response in less than 7 days, and 5. Normal, responded in a date agreed with the client. The FM Sector target set of 100% response rate for Priority 1 services and 85% response rate for priorities 2, 3, 4 e 5. By default, all problems are automatically classified as a standard priority to be addressed in seven days, which can be endorsed or edited by the service supervisor. A second problem classification is performed for detailing the building systems or components (e.g., plumbing and electrical problems). At this point, additional information can be provided by, for example, attaching documents or informing the FM sector project codes (UK UNIVERSITY 1, 2019b).

After the service priority classification, a Work Order (WO) is generated by the Help Desk and forwarded to the Finance Department for addition in Agresso System and financial analysis. Once approved, the WO returns to the Help Desk for dispatching to one of the FM sections (i.e., Building, Electrical or Mechanical.), service scheduling and tradesman allocation. All information on assigned WO (i.e., contact details, problem location, service priority, target dates) is made available to the workman on the Archibus mobile application (UK UNIVERSITY 1, 2019b).

Figure 34: UK University 1 Self-Service Portal for accommodation fault or issue report

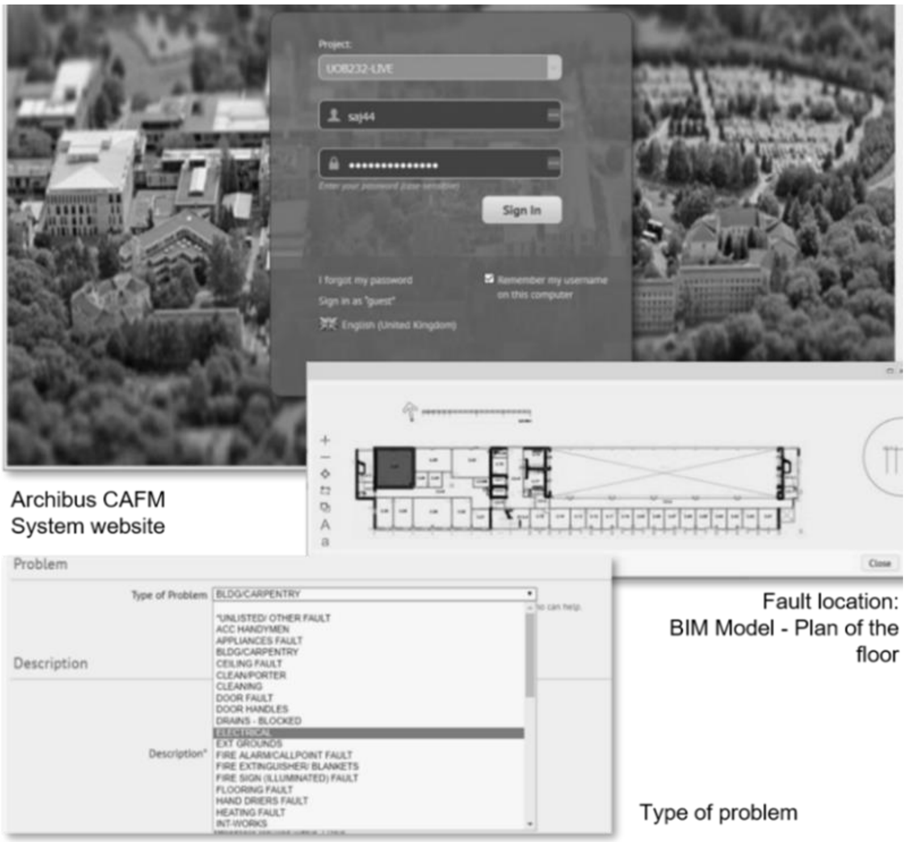


Source: Author (2021)

The service location (Stage 3) is conducted according to a Statutory and Building database, including Archibus, *RapidACCESS* and Share Point, followed by a site inspection. If necessary, damage containment is performed. The problem diagnosis (Stage 4) is also supported on such databases and on expert consulting, if required. Services with a high level of complexity or risks are forwarded to an external purchase. The same approach is taken in case of unavailability of material or staff for service execution. The Procurement Department then searches for three service/material proposals and raises a Purchase Request in the Agresso system. After approved by the Finance Department, the Purchase Order is forwarded to the selected supplier for delivery (UK UNIVERSITY 1, 2019b).

In the Repair stage (5), the service can be performed by either the FM Sector Work Team (in-house execution), or a supplier (contracted out execution). In the Check-out stage (6), the execution is inspected, registered, and analysed by the FM Sector. After approval, an Invoice is generated and submitted to the Finance Department for material/service payment. Simultaneously, an e-mail is sent to the service requester informing on the work completion. The last stages are Service Delivery (7) to the requester and Feedback (8) to the FM Sector, which can be conducted via phone call, e-mail or personally. The request is closed in the system and stored in the Archibus database (UK UNIVERSITY 1, 2019b).

Figure 35: Archibus Web Central interface for UK University 1 members of staff reporting faults



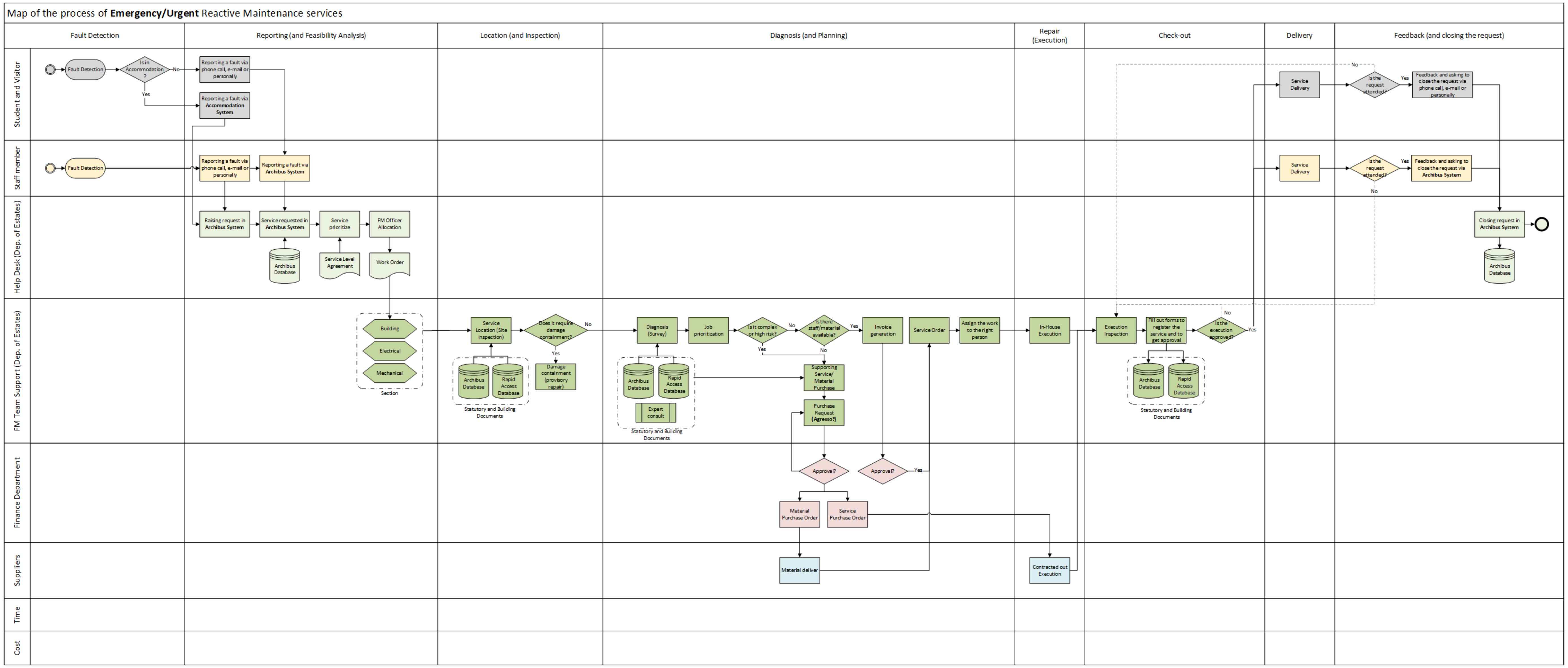
Source: UK University 1 (2018)

Table 14: Maintenance service priorities categories

Category	Response time	Example of problem
1. Emergency	Immediate response within 2 hours	▪ Fire or risk of explosion ▪ Gas leaks ▪ Water leaks from plumbing or heating services ▪ Loss of electrical supply to rooms ▪ Lift breakdown with passengers inside ▪ Any incident interrupting teaching or research
2. Urgent	Less than 24 hours	▪ Blocked drains or internal waste pipes ▪ Loss of ventilation and air conditioning ▪ Water leaks not causing damage to the building
3. Important	Less than 3 days	▪ Loss of heating or hot water in residential room ▪ Replacement or repairs to light fittings ▪ Loss of electrical power ▪ Damage to an internal door causing security problems
4. Standard	Less than 7 days	▪ Loose or missing floor tiles and paving in regions of minimal safety risk ▪ Replacement of cracked glass with no security or safety risk ▪ Replacement or repairs to sanitary ware fittings ▪ Adjustment of door closures or floor springs ▪ Repairs to joinery items in regions of no security risk
5. Normal	Date agreed with the client	▪ Repairing or purchasing of furniture

Source: Author (2021)

Figure 36: UK University 1 Reactive Maintenance Process Model



Source: Author (2021)

b. UK University 2

The scope of the FM sector covers provision and care of buildings and infrastructure. Besides planned and reactive maintenance, the department delivery services related to energy and environmental management, cleaning, transport, security, space management, catering, accommodation, sports, printing and stationery. Based on a functional organization, the FM Sector organogram (Figure 37) depicts the relationship among team members, led by the Assistant Director of Estates. From the maintenance point of view, the Lead Electrical Engineer plays an important role, coordinating activities related to electrical, mechanical, BMS and intelligent building services. The department of Estates has approximately 80 professionals over the sectors (i.e., Help Desk, Technology CAFM, BIM & CAD, Project, Inspections), of whom 36 are involved with maintenance (UK UNIVERSITY 2, 2019c). The FM service attendance is predominantly outsourced, provided by one main subcontracted company, and supported by other suppliers, depending on the service characteristics.

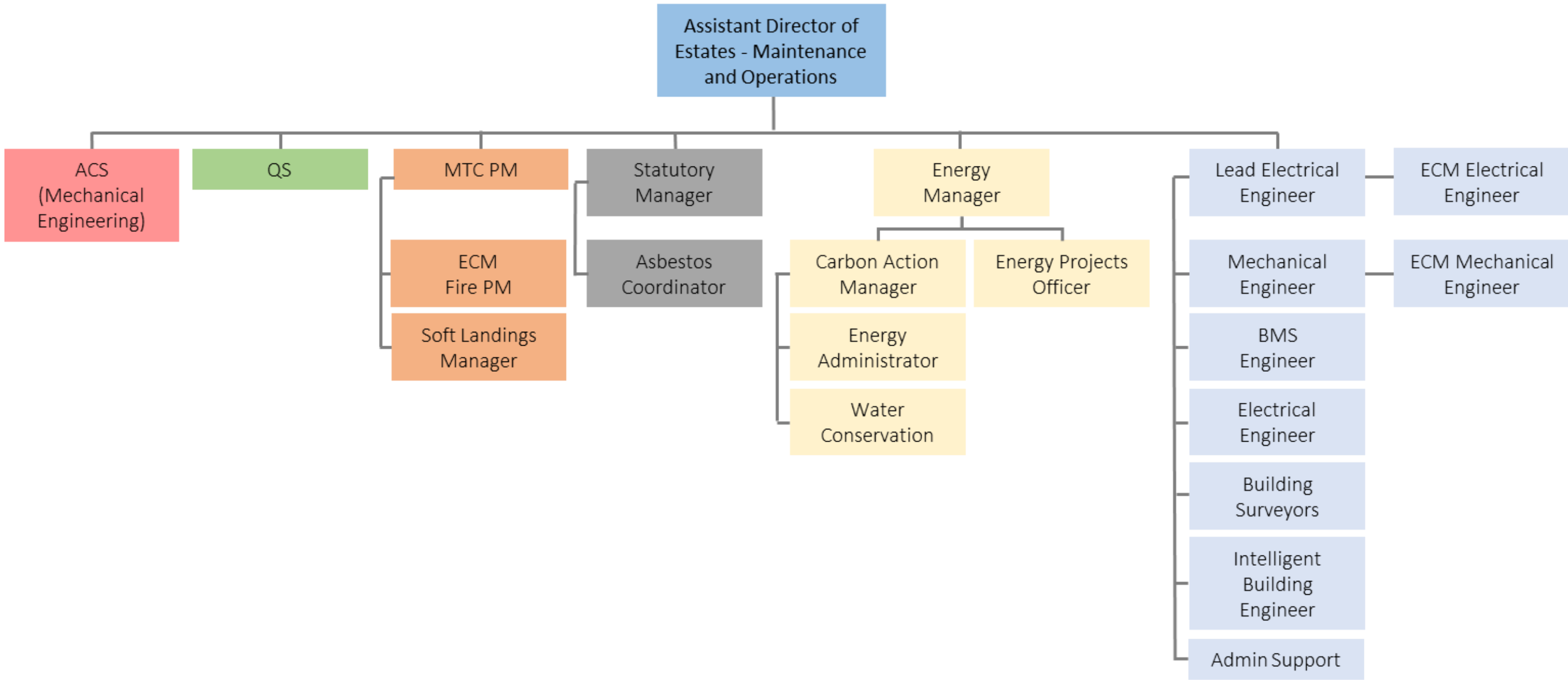
In 2019, the annual budget for reactive and preventive maintenance in all UK University 2 sites was approximately £5.000.000 (five million pounds) distributed among eleven service groups, as showed in Table 15. Approximately 60% of the budget was driven to the supplier contract, followed by Fabric (Building) and Mechanical services. Information regarding the most critical reactive maintenance problems for the organization was not provided by the interviewee, but identified through the Work Request analysis, as described in Section 4.3.3.

The ICT support for FM activities was approached in the interviews. The management of asset information is centralised in Archibus CAFM system. According to the interviewee, due to Archibus limitations, other databases are used for timetabling, hoteling, students' accommodations. Agresso system is used for financial management (UK UNIVERSITY 2, 2018). BMS is also installed in the whole Campus A, but without feeding back any relevant information to Archibus.

BIM implementation was triggered by the UK Government Mandate and, at that time, had been used by the sector for approximately 3 years, particularly for managing contractor's handover information. According to the interviewee, the costs of implementation are difficult to be determined, but has included, at least, two staff members dedicated to gathering information and working on some projects in BIM (UK UNIVERSITY 2, 2018).

At the time the interview was carried out, the whole Campus A with a total of 10.000 squares meters was being modelled for asset management information, with the prevision of conclusion for mid-2019. The software *Autodesk Revit has* been used for separately modelling architecture, structure and MEP, while the software *Vizerra Revizto* for federating them together. As explained the interviewee, through Revizto, the building model could be visualized and managed on a tablet, enabling the FM team to load relevant data for a specific activity during the field work. BIM models have been connected to the *Archibus CAFM* system through its plugin into *Revit*, synchronizing updated information in both platforms. Addressing a work request, the maintenance team is guided to check the BIM model before going to the site, also looking for actions performed in the past (UK UNIVERSITY 2, 2018). The use of IoT in FM activities is in an embryonic stage in the UK University 2. Despite the university is focused on the students' experience, the implementation of the IoT has been led by the department of Estates, so concentrating efforts on maintenance needs.

Figure 37: UK University 2 FM Sector Organogram



Source: Author based on UK University 2 (2019)

Table 15: UK University 2 Estates Maintenance Budget

Group	Budget (£)
Lift Maintenance	65.709
Pest Control	19.924
Asbestos removal	103.500
Mechanical	454.763
Electrical	236.122
Fabric	465.723
General Contingency	62.100
Supplier Contract	3.128.182
Arnolfini	298.080
Fire Alarm Systems	103.544
Building Access Control & CCTV	209.205
Total	**5.146.852**

Source: (UK UNIVERSITY 2, 2019c)

Some applications have been done for waste and cleaning management. For example, sensors have been installed into the toilets to monitor the use of bins, enabling to optimize the allocation of the cleaner and the removal of the garbage. Also, there are plans for installing sensors in critical assets, such as a boiler or an air handling system, to take a half check in unexpected conditions and inform the FM team about the necessity for some maintenance, which can benefit reactive maintenance services (UK UNIVERSITY 2, 2018). Since the implementation of BIM and IoT in maintenance services is in early stages, their use and impacts are still being measured. Therefore, the interviewee considers BIM and IoT key components for digitalization in the AEC industry, triggering the monumental change necessary in the industry, thus eliminating duplication, and ensuring up to date information (UK UNIVERSITY 2, 2018).

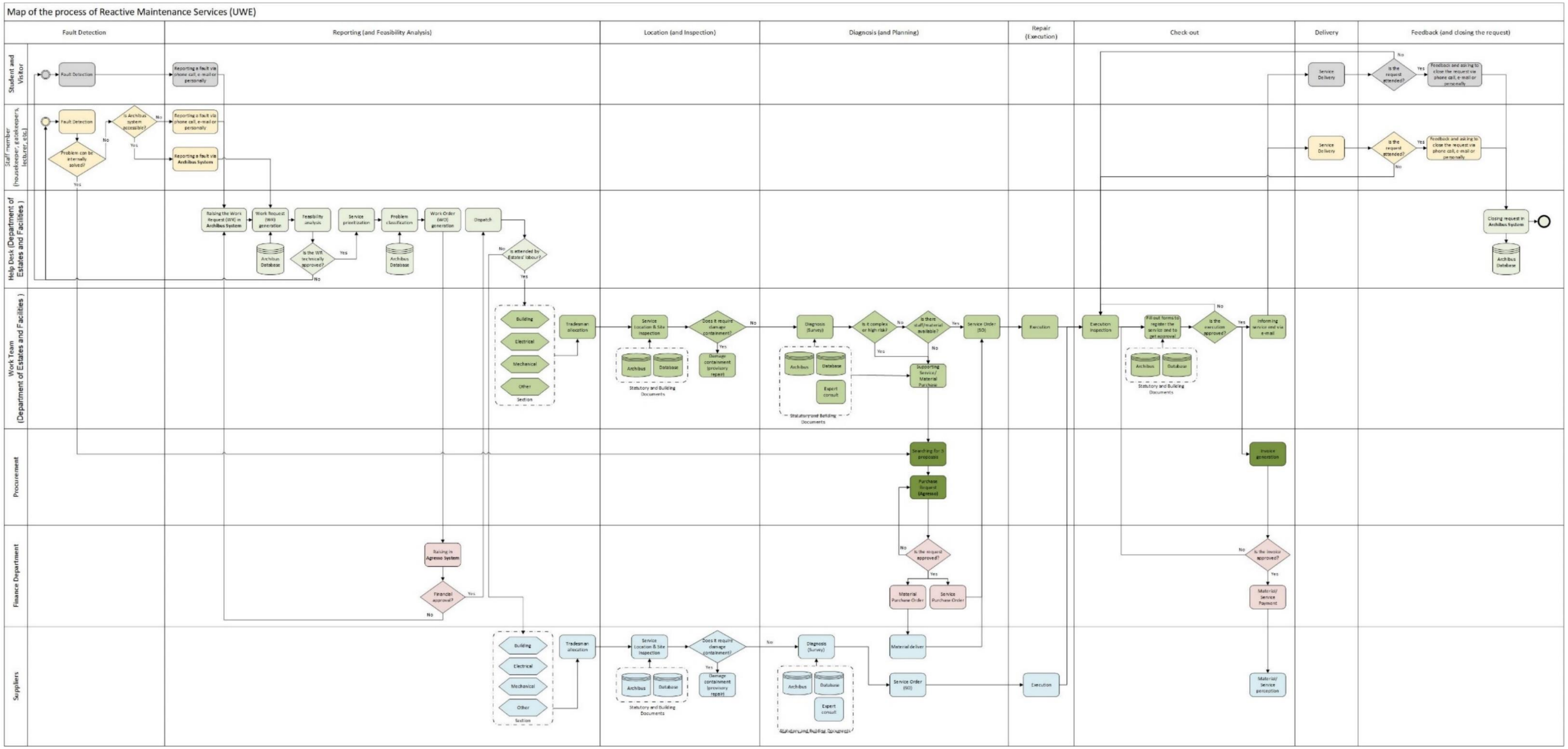
- **Characterization of RM services**

Following the same approach of UK University 1 case study, the Reactive Maintenance Service Process Model of the UK University 2 was developed (Figure 38). The columns concentrate the eight stages of the process: 1. Fault Detection, 2. Reporting (and Feasibility Analysis), 3. Location (and Inspection), 4. Diagnosis (and Planning), 5. Repair (Execution), 6. Check-out, 7. Delivery and 8. Feedback (and closing the request). Complementary, the horizontal lines place the seven category stakeholders: Student and Visitor, Staff member (housekeeping, lecturer, lecturer), Help Desk Team (Department of Estates and Facilities), Work Team (Department of Estates and Facilities), Procurement, Finance Department, and Suppliers

The first stage of the process is the detection of a problem or issue by a user. In the second stage, faults are reported via phone call, e-mail or personally by general users, and via Archibus systems by members of staff. After the Work Request is raised and approved in Archibus System, the problem is classified, and the service prioritized. The criteria for prioritization were not clarified by the interviewee. In the sequence, a Work Order (WO) is forwarded to the Finance Department and, after approval, returns to the Help Desk dispatching for service attendance. Depending on the complexity, a labour force or a maintenance contractor is assigned to attend it.

The service location (Stage 3) is carried out based on a Statutory and Building database, visualized on Archibus platform or on BIM model in Revizto. Before going to the field, the FM team can make a virtual site inspection in the BIM model, supporting the diagnosis and planning stage (Stage 4). After service execution (Stage 5), a member of the FM team may approve the service (Stage 6) and deliver to solicitor (Stage 7). The last stage is getting feedback from the solicitor and closing the request into the Archibus system (Stage 8).

Figure 38: UK University 2 Reactive Maintenance Process Model



Source: Author (2021)

c. BR University

- **Characterization of FM sector and services**

The scope of the University FM Sector covers from administrative to physical support for university activities development. The provided services include maintenance and construction, safety and security, transport, catering, library, communication, social support, nursery, informatics, and waste management. Figure 39 shows the of University FM Sector organogram, organized in a functional top-down structure of divisions, services, sectors, and sections.

The first level corresponds to the core administration, integrated by the Mayor, the Vice-Mayor, the Secretary, and the Technical Assistants. Four divisions occupy the second level, including the Administrative Division, the Community Service Division, the Physical Space Division, and the Maintenance and Operation Division. Beyond a series of services, sectors and sections integrating the mentioned divisions, some units are directly related to the main administration (e.g., Technical informatics Section, Institutional Support Service, Campus B Library Section, and Chemical Waste Laboratory Section). To do so, a team of approximately 210 professionals is available (BR UNIVERSITY, 2020).

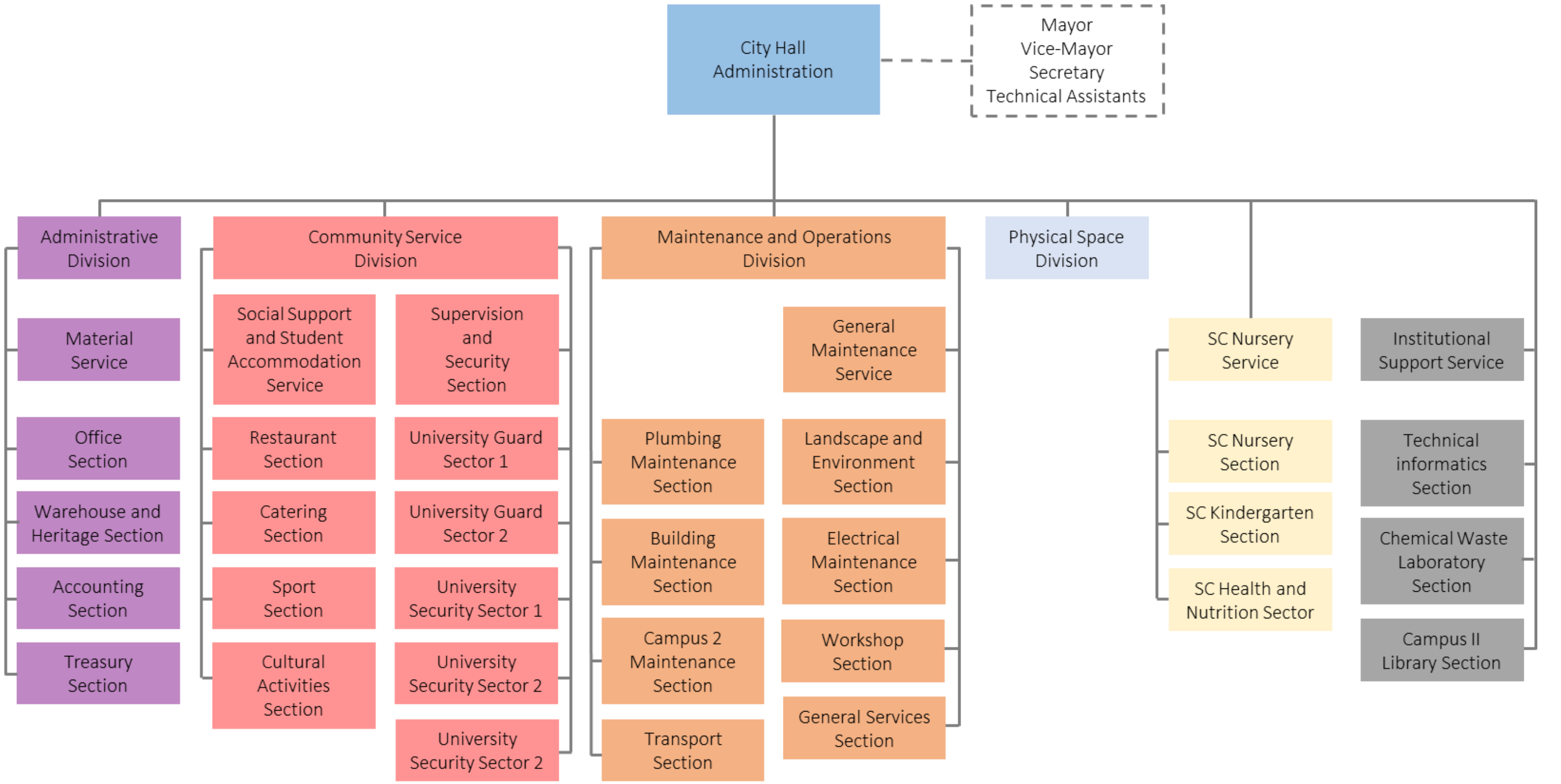
The Maintenance and Operation Division has 55 professionals distributed in sections and services, mostly directly involved with predictive, preventive and reactive maintenance of buildings and infrastructure systems (BR UNIVERSITY, 2014): General Maintenance Service, Campus B Maintenance Section, Landscape and Environment Section, Building Maintenance Section, Plumbing Maintenance Section, Workshop Section, Electrical Maintenance Section, Transport Section, General Services Section (Table 16).

According to the interviewees (BR UNIVERSITY, 2019a), the Maintenance and Operation Division mainly performs the maintenance, operations, design, bidding and construction inspection of common areas, infrastructure buildings and areas of the Campuses. Occasionally, some specifics services in teaching and research buildings are provided to the institutes, according to the necessity and the availability of resources. In these cases, the University FM Sector charges the services as an external contractor.

The built environment management of the remaining buildings is autonomously done by the university institutes, responsible for the refurbishment, expansion, operation, and maintenance services. These institutes have their own FM team and financial resources. According to the interviewees (BR UNIVERSITY, 2019a), mostly interventions are done without communication to the University FM Sector, which lacks information about the built development in the whole campuses.

The annual budget allocation to the university sectors and other financial decisions are taken by the University Council supported by the Coordination of General Administration) according to the annual Budget Guidelines. Annual Budget Reports are available for consultancy on a public website. According to financial data from 2019, approximately R$17.000.000 (seventeen million reais) was paid by FM sector in general services and about R$1.600.000 (one million six hundred thousand reais) in services related to building maintenance, road system maintenance, external areas maintenance, and construction.

Figure 39: BR University FM Sector Organogram



Source: Author based on BR University (2017)

Table 16: BR University Division of Maintenance and Operation Team

Section/Service	N. professionals
Maintenance and Operation Division	8
General Maintenance Service	1
Campus B Maintenance Section	8
Landscape and Environment Section	4
Building Maintenance Section	11
Plumbing Maintenance Section	2
Workshop Section	1
Electrical Maintenance Section	7
Transport Section	10
General Services Section	3
Total	**55**

Source: Author (2021)

The budget allocation for building maintenance services in Teaching and Research Unities (i.e., Institutes and Schools) is proportional to the building built area and follows a set of criteria according to the characteristics of the building (BR University, 2019), such as building age, building type, intensity of building usage and location in particular areas. Table 17 shows the indexes for classifying buildings according to the age and type. This set of criteria supports the administration in budget allocation and the FM sector in planning the future activities related to Academic & Research assets. The financial and operational management of other building typologies, such as Residential and Sport & Leisure, follows distinct approaches.

Table 17: Classification of building age and type for maintenance budget allocation

Category	Description	Index
Building Age	age < 5 years	1,00
	5 ≤ age < 10 years	1,05
	10 ≤ age < 15 years	1,10
	15 ≤ age < 20 years	1,15
	20 ≤ age < 25 years	1,20
	25 ≤ age < 30 years	1,25
	30 ≤ age < 35 years	1,30
	35 ≤ age < 45 years	1,40
	45 ≤ age < 55 years	1,50
	55 ≤ age < 65 years	1,60
	65 ≤ age < 75 years	1,70
	75 ≤ age < 85 years	1,80
	Age ≥ 85	2,00
Building Type	Laboratories, Bioterium, Historical Centres, Listed buildings	1,20
	Classrooms and Libraries	1,00
	Teacher's Offices	0,80
	Other functions	0,80

Source: Adapted from BR University (2019)

Addressing one of the focus group's purposes, the interviewees describe the most critical problems in managing the campuses. In terms of *Cost & Safety*, critical problems include urban and building refurbishments addressing accessibility issues and hiring technical report on tree conditions and tree cutting, aiming to ensure users safety and avoid interferences with electrical and water supply systems. Regarding the availability of *Labour force*, building maintenance services are considered the most difficult to be carried out, requiring big teams and long period of time to be attended; currently, most building services are outsourced due to the lack of inner labour in FM sector staff. They also emphasize the demand for maintenance in the student accommodation facilities proper use (BR UNIVERSITY, 2019a).

The three most disruptive problems in reactive maintenance and their impacts on the university routine are described: first, failures in the campus electrical distribution network, causing interruption of power supply in the whole campus and, consequently, in research and teaching activities developed in rooms devoid of power generators; second, failures in the Campus Water Supply System (pumping system), disrupting research and teaching activities in places without individual water tanks; thirds, tree branch falls, blocking paths and increasing the risks of injuries to the community and damagers to the assets. With respect to the services to be primarily benefited from BIM implementation, the interviewees describe the repair of the electric supply infrastructure, involving the maintenance of electrical cabins, the infrastructure mapping (electricity, water) and the location of buildings in Campus A, characterized by an unplanned urban development (BR UNIVERSITY, 2019a).

The FM activities were traditionally done with the support of physical request forms and Excel spreadsheets. Since September 2018, an integrated system for informatics and telecommunication services (here named *BR University CAFM system*) has been adopted for managing O&M requests, besides the BR University System for purchase requests, and e-mail and print forms for general communication (BR UNIVERSITY, 2019b). *Autodesk AutoCad* is the software for designing and managing built environment information (BR UNIVERSITY, 2019a).

Gradually, the Information Technological Team of FM sector has been adjusting BR University CAFM system to the maintenance sector needs. The system is only available for specific members of the University FM Sector, providing distinct abilities depending on the user status in the system (e.g., chief; supervisor; etc). The abilities include the work request protocol; a communication channel for distinct stakeholders and sectors (e.g. suppliers, purchasing sector); the extraction of physical documents for field work; the generation of service reports about a specific request or a selected time-frame, informing, for instance, the work request number, the service location (e.g. building, external area), the division and sector responsible for, the type of service (e.g. electrical, plumbing), date of service end, the cost of services, etc..

The implementation of BIM and IoT technological to support FM activities was also discussed in the focus group. At that time, BIM was not yet implemented by the organization. According to the interviewees, a planning for a BIM software adoption (i.e., Autodesk Revit) Design and Construction areas [15] was being developed in response to a governmental mandate [16], which proposes a national strategy for BIM implementation in AEC industry (BR UNIVERSITY, 2019a, 2019b). The initial deadline set by the government for BIM implementation in the design stage is 2021, while the adoption in operational and maintenance stage is planned for 2028. With respect to IoT, the university was in an embryonic stage of implementation. According to the interviewees, an initiative of implementing an IoT-based lighting system was taken years early, but unsuccessfully progressed, as discussed in Section 5.3.2.

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[15] Available at: https://www.caubr.gov.br/governo-estabelece-metas-e-prazos-para-implementacao-do-bim/
[16] Decree nº 9.377, from 17th May 2018.

- **Characterization of RM services**

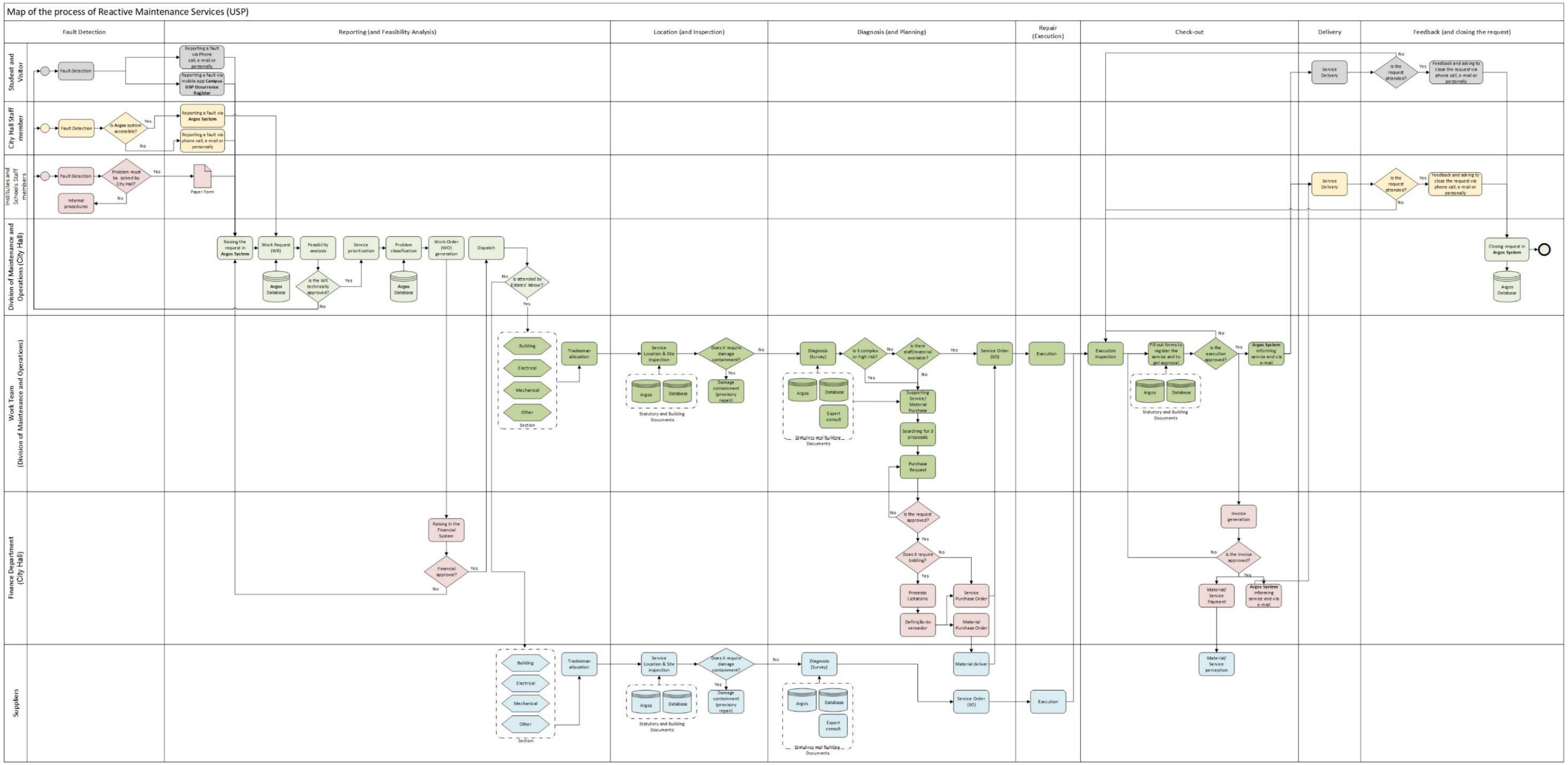
The Reactive Maintenance Service Process Model of the BR University (Figure 40) was developed according to the same approach of UK University 1 and UK University 2 case studies and validated by BR UNIVERSITY_Prof_1. The eight stages of the process are distributed over the columns: 1. Fault Detection, 2. Reporting and Feasibility Analysis, 3. Location and Inspection, 4. Diagnosis and Planning, 5. Repair, 6. Check-out, 7. Delivery, and 8. Feedback and closing the request. On the other hand, the stakeholders involved into the process are grouped in seven categories, displayed in the horizontal lines: Student and Visitor, FM Sector staff members, Institutes and Schools staff members, Division of Maintenance and Operations (FM Sector), Work Team (Division of Maintenance and Operations), Finance Department (FM Sector), and Suppliers.

The detection of faults by any university user corresponds to the first stage of the process (Stage 1). After that, the reporting stage takes place supported by distinct communication channels (Stage 2). General users have access to a mobile application for registering maintenance problems (i.e., water leaking, holes on the road pavement and lighting issues) in the Campuses A and B. This application is linked to an internal system of online occurrence reports of University FM Sectors, which captures the user's location from the smartphone GPS sensor, generating a notification e-mail to the maintenance staff responsible for solving the issue. Besides, telephone calls, e-mail, and personal communication are available, especially for urgent requests.

In addition to the mentioned channels, FM Sector staff members can report the fault through the BR University CAFM system, while institutes and schools staff members must fill a paper-based form. According to the BR UNIVERSITY_Prof_1 (2019), around 90% of the work requests currently comes from the internal sectors, while 10% from the institutes and schools (BR UNIVERSITY, 2019b). Due to the lack of integration among systems, in all cases the information must be manually raised into BR University CAFM system for generating the Work Request (WR). After approval, the service is prioritized, and the problems classified for attendance. The criteria for prioritization were not clarified by the interviewee. Since BR University CAFM system does not offer to the user a fault priority level classification, this activity is manually carried out by the Chief of the General Maintenance Service to support the Work Order (WO) generation (BR UNIVERSITY, 2019b). In the sequence, the WO is forwarded to the Finance Department and, after approval, returns to the Work Team dispatching for service attendance. The service might be assigned to a FM Sector labour force or to an external supplier. In some cases, a printed copy of the WO is provided to professional in work field or without access to the computer (BR UNIVERSITY, 2019b).

The service location (Stage 3) is carried out based on a Statutory and Building database, followed by the site inspection. In the problem diagnosis and planning (Stage 4), a deeper understanding of the issue is undertaken, supporting the acquisition of material or service, if necessary. Depending on the characteristics of the purchase, a bidding process is conducted, defining the service or material provider. Then, a Service Order (SO) is generated as a permission to the next stage, the in-house or out-sourced problem repair (Stage 5). In the Check-out stage (6), the execution is inspected, registered, and analysed by the Work Team. After approval, an Invoice is generated and submitted to the Finance Department for payment. An e-mail is sent to the service requester informing the service delivery (Stage 7). In the final stage (8) the user can feedback the FM Sector via phone call, e-mail or personally about the service satisfaction, leading to closing and storing the request in BR University CAFM system.

Figure 40: BR University Reactive Maintenance Process Model



Source: Author (2021)

4.3.2. Content Analysis of Interviews and Focus Group transcriptions

Table 18 shows the interviews and focus group transcriptions carried out with UK University 1, UK University 2, and BR University team members selected for analysis. A pre-analysis was initially carried out through the "free-floating reading" of the interview transcriptions, the selection of the key documents for analysis named "corpus", and the definition of the analysis aims (BARDIN, 2011).

Table 18: Interviews data for Content Analysis

University	Interview ID	Interviewee ID	Transcription ID
UK University 1	UK University 1_Interview_2_2019	UK University 1_Prof_2 UK University 1_Prof_3	(UK UNIVERSITY 1, 2019b)
	UK University 1_Interview_3_2019	UK University 1_Prof_4	(UK UNIVERSITY 1, 2019c)
	UK University 1_Interview_4_2019	UK University 1_Prof_5	(UK UNIVERSITY 1, 2019d)
UK University 2	UK UNIVERSITY 2_Interview_1_2018	UK UNIVERSITY 2_Prof_1	(UK UNIVERSITY 2, 2018)
	UK UNIVERSITY 2_Interview_2_2019	UK UNIVERSITY 2_Prof_1	(UK UNIVERSITY 2, 2019b)
BR University	BR UNIVERSITY_FocusGroup_2019	BR UNIVERSITY_Prof_1 BR UNIVERSITY_Prof_2 BR UNIVERSITY_Prof_3	(BR UNIVERSITY, 2019a)
	BR UNIVERSITY_Interview_2019	BR UNIVERSITY_Prof_1	(BR UNIVERSITY, 2019b)

Source: Author (2021)

The purpose of this analysis was to characterize the scenario for current and potential applications of BIM and IoT-based solutions for FM services, in particular for maintenance services. Questions to be addressed included: What is the capability of FM team members in asset data and information management? What are the technological abilities and requirements necessary to support FM digital transformation? What is the role played by standards and mandates in FM digital transformation? What is the level of engagement with digital transformation among the distinct stakeholders?

In sequence, the exploration of the corpus has been carried out in three steps according to proposed by Bardin (2011). First, the interviewees' answers for each question have been defined as the recording units, while the university FM sectors environment as the context units. Second, the presence of sets of words has been set as the index for the enumeration stage. The third step was the classification of the corpus according to semantic categories and themes. Table 19 depicts the Themes, Category Groups, Categories, and Codes examples.

The classification process was progressively developed through the differentiation and clustering of elements. *BIM Competency Sets* proposed by Succar (2010) and *BS EN 15221-1:2006 Facility management - Terms and definitions* (THE BRITISH STANDARDS INSTITUTION, 2006) supported the categorization, according to three themes, namely, Technology, Process, and Policy. Finally, the treatment and interpretation of results were undertaken according to the proposed categories and supported by the interviewees' statements. The inference generation is presented in Section 5.4.2.

Table 19: Content Analysis classification

Theme	Category Group	Category	Code examples
Technology	Software, Hardware and Network	Ability	functionalities; “the system can do”; “it was designed for”; “able to”; “poor structure”; synchronizes; visualise; “to take measurements”; “não tá funcionando” (“it is not working”); quantificar (to quantify); “half checks”
		User-friendliness	“easy to use”; “user friendly”; awful
		Interoperability	“easily go straight to”; “talk together”; fragmentado (fragmented); “não conversam” (“they do not talk”); “talk to each other”; integrated
	Data and Information	Accessibility and Availability	access; acesso (access); available; “looking for information”; perdeu (lost); permissão (permission); “it’s difficult to get the information”; “limited view”
		Accuracy and Reliability	precise; preciso (precise); accurate; “wrong data”; “knew exactly what was inside”; certeza (certain); confia (trusts); fiel (reliable); “it never matches”
Process	People issues	Awareness	understanding; “A lot of people don’t understand”; “understanding their own requirements”; “pegou a gente de surpresa essa informação” (“we got surprised with that information”)
		Capability	capability; skilled; specialists; “guys here struggle”; “baixa escolaridade” (“low literacy”); “we’ve got a little bit of education to do here”; treinamento (training); “a gente não consegue atender” (“we cannot address it”)
		Engagement	“I’m not convinced yet”; resistant; vontade (will); “to make everything a lot better”; cooperação (cooperation); “I’d like to move in that direction”
		Satisfaction	satisfaction; “I don’t like this”; reclamação (complaint); infelizmente (unfortunately); “that’s unfortunate about it”
	Strategic, Tactical and Operational FM	Value	“essential services”; important; “treated as commercial because they make income”
		Leadership	“Estates haven’t really asked for that”; “Estates don’t really drive for this kind of change”; “led by the Estates Department”; planejamento (planning)
		Feasibility	risk; change; cost; expensive; budget; context; time; savings; “a lot more difficult”; “do it for real”; “volume de trabalho alto” (“high workload”)
Policy	Regulatory	Classification	classify; categorization; priority; “ordem de prioridade” (“priority order”); prioritization
		Guidelines	“general report”; “plano director” (“masterplan”); “standard code”; “generic list”; “a plan”
		Standard and Regulations	standard; Uniclass, COBIE; UK government mandate
	Contractual	Responsibility and Compliance	“responsible for”; responsável (responsible); designada (assigned); poder (power); allocation; manage; contract; subcontractor; handover; delivery

Source: Author (2021)

a. Technology

Technology Theme clusters the *Software, Hardware and Network* and *Data Information Category Groups*, supporting FM processes.

○ Software, Hardware and Network

The first Category Group describes the aspects of the software, systems, hardware, devices, and network involved in the current and potential FM processes. Initially, the *Ability* category discusses the functionalities of the technological tools in the FM context, including CAFM, BIM, and IoT software and devices. According to some of the interviewees, the default abilities are usually insufficient or inappropriate to the FM sector needs, due to the complexity of the processes or the individual characteristics of each organization. On some occasions, the FM sector opt for developing or adapting in-house solutions to address specific activities. For example, the UK University 1 IT team has developed an app for tracking craftsman work, recording the time and cost spent in the services, an alternative to the traditional paper time sheet. The steps of the application use are described by one of its developers:

> "I developed a mobile application for our work men's, so, when they get the job it comes on the mobile and they're supposed to: go to the job, hit start, and when they finish the job hit stop, and it records the time, and if they go and have a break then they hit stop, the go and have a break, come back, hit start; and this way you get a lots of time being recorded." (UK UNIVERSITY 1, 2019b)

Similarly, the FM sector IT team has adapted an existing system to address the FM sector needs. To do so, an iterative process involving FM and IT professional was carried out, as described by one of the interviewees:

> "So, I would go back to the IT people and [say] "look, this isn't working, here I need a form for me to sign, to forward, because that person doesn't access the computer", or "because it needs a way to forward to purchase [sector] to buy something that is missing, when material is missing, or else he needs to be able to return to me." (BR UNIVERSITY, 2019a)[17]

Difficulties in updating versions and obtaining technical support to address FM needs are described by one of the interviewees as a barrier for adopting customized systems (UK UNIVERSITY 1, 2019b, 2019d; UK UNIVERSITY 2, 2018). Based on that and on the necessity of new system abilities (i.e., related to Plan maintenance), two organizations have decided to acquire a more powerful version of the Archibus CAFM system. One of the interviewees describes the abilities of the CAFM system integrated to BIM software, focusing on the visualization of building components characteristics in the BIM models to support the diagnosis and repair:

> "[…] what I've been asking the maintenance service to do is to start looking at the models to get the information before they get to site based on the actions that have been performed in the past […] For example, if they get a request that says a light fitting needs to be changed, or this light isn't working in this room, they can go to the model on the tablet and check what type of fitting it is, and, OK, it needs this type of replacement part, and go to the stores and get that before. […] it helps with the coordination and all the information come from the notes and things." (UK UNIVERSITY 2, 2018)

The participants describe potential abilities of software and systems which might benefit the FM sector. The visualization and operation of BIM models integrated to the CAFM software is seen as an important ability for FM team members and external stakeholders managing building information:

> "[...] all of that data being accessible and plus even you can take live sections of the building at this time for the connectivity [agencies] with different components and things like that. […] I think there is quite a lot we can do, the extra [view] through the ceilings. Yeah, asset data, to take measurements ... [...] Look at this model. If I click on this 2D bottom we've also got all of the [tons] from Revit in the background [...] So, all of these comments feeding back through into the 2D environment as well, you look at any of plan just in the relevant comments. One of the really cool things is if you press on this bottom, it cuts the model in the right place, orientates and overlays." (UK UNIVERSITY 2, 2018)

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[17] Free translation of: "Então eu voltava pro pessoal da TI e [dizia] "Ó, aqui não tá funcionando, aqui preciso de uma ficha pra eu poder assinar, pra encaminhar, porque essa pessoa não acessa o computador", ou então "porque precisa ter um caminho pra encaminhar pra compras pra fazer a compra de uma coisa que falta, quando fica faltando material, ou então ele precisa poder retornar pra mim." (BR UNIVERSITY, 2019a)

Also, the use of Construction Design and Management (CDM) walkthrough into the BIM model supports a multidisciplinary professional group (maintenance team, design team, contractor team) to visualise "soft clashes" and to plan maintenance and operational services. Besides, along with Augmented Reality, BIM enablers to access relevant information in place, making it easy to find it and navigate in the right asset.

Nevertheless, technical limitations are observed in these versions (e.g., lack of abilities and flexibility), impacting the performance of activities, and raising doubts about their suitability for digital transformation, as discussed by the interviewees:

> "I don't think Archibus was doing what it needed to." (UK UNIVERSITY 2, 2019b)
>
> "[...] last year they [Department of Estates] wanted to buy the full Archibus package and that came with its own mobile app. So, in October they [the craftsman] started using this one, they don't like this one, they keep saying "bring back the old one" [...] and they were complaining because they didn't like it, didn't worked very well for them." (UK UNIVERSITY 1, 2019b)
>
> "So, we are using Archibus to link Archibus to Revit. And my experience with CAFM software, in general, hasn't been great. I think they, for more I've seen, there are kinds of systems that were created in the 80' that haven't really moved a lot of sense. So, I think for the [kind of ...] digital campus I don't know if any system will really kind of living up to the [...]. They have very rigid data structures. Archibus, for example, uses inside the room number as a primary key which means if you want to change room number and [...] room add again, and you will lose all of the data of this. So, is a really poor structure, I think." (UK UNIVERSITY 2, 2018)

In addition, the replacement of databases is also described by one of the interviewees, since the previous one has not been efficient:

> "So *RapidACCESS* is something that was a database with a little bit development work that it was done on it, so it holds copy of plans, places, manuals, everything like that, it is not rapid, is not accessible, there is no such pictures on it worth talking about, so we're getting rid of it and we're moving on to SharePoint." (UK UNIVERSITY 1, 2019c)

In general, few IoT solutions have been implemented for FM purposes. One example is the system for monitoring external luminaire, able to detect and report failed lamps and to manage the nearby lamps to provide correctly lighting.

> "The idea of this LED was very good at the beginning, that it had a remote management system that theoretically still works, but the idea was to have a monitoring, someone to monitor the system, he/she would know when a lamp was failed, he/she would be responsible, the system could send information, the adjacent lamps could increase the brightness to compensate for that, or else you could generate energy savings, if it is a sector that at some point is being little used you could decrease a quadrant of the campus, so that it dims the starting at such an hour, I don't know, from midnight or from three to six in the morning, which doesn't have so many people, the whole idea was like that, right?" (BR UNIVERSITY, 2019a)[18]

Potential applications of IoT solutions in FM activities are described by the participants. The prediction of problems before occurrence is highlighted as a key IoT application, particularly in places without visibility and occasions without human presence (UK UNIVERSITY 1, 2019c). For example, inaccuracies in components of the heating system could be easily detected:

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[18] Free translation of: "A ideia desse LED era muito boa no começo, que ela tinha um sistema de telegestão que teoricamente ainda funciona, mas a ideia era ter um monitoramento, alguém monitorasse o sistema, ia saber quando queimou uma lâmpada, ia ficar responsável, o sistema podia mandar uma informação, as lâmpadas vizinhas podiam aumentar a luminosidade pra compensar aquela, ou então você podia gerar uma economia de energia, se é um setor que em algum momento usa pouco você podia diminuir um quadrante do campus, pra ele dimerizar a partir de tal hora, sei lá, da meia noite ou das três às seis da manhã, que não tem tanta gente, a ideia era toda essa, né." (BR UNIVERSITY, 2019a)

> "[...] let's say, maybe the boiler is not running in the temperature correctly, and they could actually send like a fault to an engineer and the engineer can come and fix it, but it might not be a fault, it's running analysis or looking how it's working, and if it doesn't look like is working correctly. (...) come and fix it before it breaks." (UK UNIVERSITY 1, 2019b)

Space management is another are to be potentially benefited from IoT implementation. Based on real time data regarding the number of users in a room, the Estates could control the environmental conditions (i.e., lighting, heating) and obtain information about the rational use of the space. Other applications might include a fire system, providing to the university staff the users' location through the wi-fi accessed point; and a computer location system, informing the position of free devices (UK UNIVERSITY 1, 2019d).

One of the interviewees describes a new perspective for maintenance services, in which the predominance of a condition-based approach driven to critical assets over the traditional plan and predictive maintenance might improve the efficiency of services, generating savings to the organization:

> "The potential for what we call condition-based maintenance is we can have half checks in key pieces of equipment. This is going to tell us what may go wrong before they fail. For instance, you are driving alone your car, and you have all this background data, you've got lots of the experience of driving a car. Then, you notice it's jittering, and there are all those noises that you don't know about, are not familiar with, and you know it's time to take your car to a mechanic. Your visual system, your hearing system, your nervous system has recorded some data and compared to a set of background information and then come up with a decision, which is exactly the same as things that we're trying to do with IoT, right? To put sensors on things to measure how they're working, recording some data on them, when something different is happening, raise a flag. And, what it kind of does is, this piece of equipment we need to plan the preventive maintenance, and with condition maintenance we need to go and inspect it regularly to make sure that the key is the asset critical, so we need to do those checks. So, we won't waste people's time on maintenance to check things that are working perfectly fine, rather we are looking for something that is about to fail. So that would be where the saving comes, our calls will be well informed. That will be quite a change." (UK UNIVERSITY 2, 2018)

Describing an unsuccessful application of sensors for monitoring environmental conditions in a previous job, one of the interviewees demonstrate uncertainty about the abilities of IoT systems in supporting FM:

> "I don't actually know whether the technology is sufficiently advanced to cope with certain things in universities, might be fine in office blocks, but whether it can cope with universities' and moving student every hour I don't know, I'm not convinced yet." (UK UNIVERSITY 1, 2019c)

The *User-friendliness Category* relates to the quality of the FM driven systems, software and devices being simple for people use. Difficulties in using a CAFM software due to its interface are reported by one of the participants:

> "Archibus itself it's not very easy to use, I'll show you. It's not very pretty, it's very much like a spreadsheet, it's simple. It does the job, but it's not very user friendly." (UK UNIVERSITY 1, 2019b)

One of the interviewees report obstacles in interacting with a software for construction field management, thus considered "a bit clunky" (UK UNIVERSITY 2, 2018). On the other hand, the same participant describes the facility of using Revizto BIM software for visualizing building components, enabling live interventions in the model either on the computer or iPad: "having access to all of the relevant information in a place that is easy to find it and navigate in the right asset" (UK UNIVERSITY 2, 2018).

The *Interoperability Category* discusses one of the core challenges faced by the AEC industry ICT users: seamlessly managing the data integrity over diverse systems and stakeholders (INTEROPERABILITY, 2019); in other words, "getting the systems to talk to each other" (UK UNIVERSITY 1, 2019c). In the context of the selected organization, the interoperability issues are mainly related to the integration among CAFM software and other supportive systems, such as financial system, occurrence reporting system, BMS system, IoT system and BIM software. The participants discussed applications, opportunities and barriers related to interoperability in FM practices.

Describing the maintenance process, some interviewees highlight the existence of independent systems for distinct stakeholders, such as accommodation and sport club centre, generating a fragmented structure: "I don't like this, I'd like to see everything come together", said one of the interviewees (UK UNIVERSITY 1, 2019c). A similar scenario is observed in relation to the *financial* system, hampering the FM team access to cost information. In some cases, the information automatically flows from CAFM to finance system, but the opposite is not observed:

> "[...] we're trying to see if we can bring the cost back over so the costumer can go to Archibus and see all the parts of the labour, at the minute all the financial stuff is at the Agresso and just the work request information is in Archibus. It been said by people "we rather go to Archibus on one place to see all the information" so most people don't know how to get the information out of the Agresso." (UK UNIVERSITY 1, 2019b)

One of the interviewees report the lack of interaction between CAFM and the occurrence reporting system, demanding manual actions for managing information. Providing the example of an external area problem reported via mobile application, the participant describes the manual process of transmitting the information from one system to another:

> "So, for example, someone went over there and said" look, there is a branch that will fall, that may fall on someone, it is dangerous to pass here by the building ", then the person did it by cell phone, by the application. Then it came to me. [...] this, it arrives by e-mail warning me that I have to access the system and that the call is there, then I access the system. [...] Then, I log into the system and I reply it. [...] And then what I put there, when I finish the request, then I will have had opened the WO and such, I open a call here on the system, then the person will receive this message. [...] Yeah, then I do it here, they don't talk, the app doesn't talk to this one". (BR UNIVERSITY, 2019b)[19]

Another example regards the interaction between the Archibus and Helvar, a centralized system to control the lighting infrastructure of a group of university's buildings with the purpose to reduce carbon emissions and energy consumption. According to one of the interviewees, the IT team is working on the integration of the two systems aiming to automatically generate a work request in case of failures:

> "So, he [the software developer] could run an emergency light test on the lighting system and if any of the lights fail then it could send request to Archibus and then get pulled straight to the electrical team and then they are aware of the fault." (UK UNIVERSITY 1, 2019d)

Although Building Management Systems (BMS) are a powerful source of real time information, their use for maintenance purposes is not fully explored by most organizations. As described by a participant, since

[19] Free translation of: "Então, por exemplo, alguém passou lá e falou "ó, tem um galho que vai cair, que pode cair em cima de alguém, tá perigoso passar aqui no prédio", aí a pessoa fez pelo celular, pelo aplicativo. Aí chegou pra mim. [...] isso, chega por e-mail me avisando que eu tenho que acessar o sistema e lá tem a chamada, aí eu acesso o sistema. [...] Aí eu entro no sistema e dou uma resposta. [...] E aí o que eu coloco ali, quando eu dou encerrado, aí vou ter aberto a OS e tal, abro uma chamada aqui no sistema, aí a pessoa vai receber essa mensagem. [...] é, aí eu pego e faço aqui, eles não conversam não, o aplicativo não conversa com esse". (BR UNIVERSITY, 2019b)

BMS "runs lots of analysis on faults" (UK UNIVERSITY 1, 2019b) in building facilities, its integration with the CAFM system could generate work requests in the system, communicating the FM team about potential problems. Sharing the same perspective, a second interviewee highlights a challenge to be overcome - getting data from BMS system:

> "I've got heating sensors in the buildings, but they do not feedback to anything. Like, you can in this room the lights come on, so something [here is over there] [...] but there is nothing feeding back to anything that says "this room is occupied between these hours" or anything like that, you know. Similar, we've got BMS System across the whole site, that kind of system that is a black box, they don't want data to come out of that, you know." (UK UNIVERSITY 2, 2018)

The integration between CAFM and BIM tools is a big concern among the participants. In one of the organizations, the issue is partially solved by adopting the Archibus CAFM system version with an extension for Revit, connecting BIM model with Archibus database. Integration is not yet bidirectional, as maintenance information is not automatically fed into the model: "No, it doesn't push back in that way. So, again, that needs integration between two systems that don't have integration at the moment" (UK UNIVERSITY 2, 2018).

However, from the network perspective, one of the interviewees emphasize the limitations imposed by proprietary protocols and vendor lock-in for operating and integrating systems and devices. Among the limitations are the unavailability of technical support, difficulties in getting information out of the systems, and lack of integration with other manufactures' products (e.g., switches), reducing the potential applications of the systems:

> "And what some companies do is, once you are bought into their system, you can't integrate into other manufactures' products. So, basically, you "buy their stuff" [...] or you don't have their system. [...] there are certain protocols that are only supported and maintained by one vendor and their proprietary, so we take the decision of just not using them, because if we later buy from another it won't work and we will have to buy all from that one company and that in my opinion is really risky. Because they can double the prices, or rack prices up [...] So, we avoid that. [...] So, that is the biggest thing that annoys me. But I know why companies do it. They do it because they want more money, basically. I might be wrong, but I am pretty sure [...] that's business." (UK UNIVERSITY 1, 2019d)

For one of the interviewees, this issue might be addressed by the development of open platforms, particularly trigged by IoT solutions: "hopefully, IoT is gonna be the disruptor that the industry needs, getting things talking to a common platform" (UK UNIVERSITY 2, 2018). In fact, the potential interoperability among diverse systems supporting FM is considered essential for making better decisions, automating processes, and generating savings to the organization, as described by some interviewees:

> "But if we could get information from all other systems, and tune them together, it would draw a better picture of what's going on." (UK UNIVERSITY 1, 2019d)
>
> "If you can link it through everything, if you got timetabling, CAFM system, students' records, you got the start details as well [...] if you link it all together, so it starts to getting quite powerful. And you can automate things a lot better, and particularly the thing on the space management. At the moment, we can have one room occupied in each building. So, we got to heat the building, we got to put lights on it, for everybody in one building. I think it's getting all that data together, easy to use, easy to understand, right? Log into the computer sleek and then I think we can save a lot of energy, a lot of power and be far more electrician." (UK UNIVERSITY 1, 2019c)
>
> "So one of the potential ways we could use BIM is we were told that a few years ago, that when we have a new building here the engineers, or the architects or whoever's managing the BIM model , they could put in all the assets as if the fire alarms are coming into the systems,

> they could put that information in the BIM model, and then when they deliver the building, they say "here's the BIM model" and then I'd be able to put on the asset information out of BIM model and put in the Archibus , but it hasn't happened, we never had any asset data from the BIM model. So, I think it's all potential, but what we need here is for our business, so the Estates to want that, to drive that forwards. There are people who would like it but is getting into people who are in charge to the building projects to actually say "that's really important that these suppliers provide that data." (UK UNIVERSITY 1, 2019b)

- **Data and Information**

The *Data and Information Category Group* discusses factors involved in gathering, sharing, storing, and updating asset data and information for FM purposes. In this study, the *Accessibility and Availability* category regards to the ability to easily obtain data and information needed over the FM service process and to manage CAFM systems.

All the interviews describe distinct permission levels for accessing data on CAFM software, which depends on the role of the stakeholders in the process. For example, in one of the organizations, suppliers from catering department are not allowed to report faults through the CAFM software, unless requested to the IT team (UK UNIVERSITY 1, 2019b). A similar situation in which specific staff have permission to access the system is described by one of the interviewees:

> "[…] these people are appointed by the head of each sector, usually the head himself. He or some employee, so for example: I have a subordinate who warns, or he sees that there is a tap leaking, there is a burnt-out light, then some of each session (it may be just the boss) comes in and he is authorized to work on the sector, work on BR University CAFM system. But then, the system's privilege level is according to the status of each one, so there are people who only have access to open the order, they do not have access to anything. And in my case, for example, I have access to everything, including the reports." (BR UNIVERSITY, 2019b)[20]

Another aspect is related to the *availability* of information to all FM staff. For example, one of the participants reports that FM service financial information is not available for the IT sector, responsible for managing the CAFM system, hampering the generating of FM service costs:

> "No, because it's not available to me, so I can only give you the labour times so I can tell you how many hours has been recorded against the job, but I don't know anything about the parts. You'd have to speak to finance and see if you can get that kind of information, they do have it cause they'd be able to extract by work order what's been spending including the times." (UK UNIVERSITY 1, 2019b)

According to one of the interviewees, nowadays information related to cutting down tree services, for example, is centralized in the coordinator of the process and not available for the remaining team members.

> "[NAME] is responsible for the trees, so every tree that has to be cut on campus, she goes there, photographs, she has a file that indicates what tree it is and such, but it is very restricted, no one else has access to it ." (BR UNIVERSITY, 2019a)[21]

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[20] Free translation of: "[…] essas pessoas são designadas pelo chefe de cada setor, normalmente o próprio chefe. Ele ou algum funcionário, então por exemplo: eu tenho um subordinado que avisa, ou ele vê que tem uma torneira vazando, tem uma luz queimada, aí alguns de cada sessão (pode ser só o chefe) entra e ele tem autorização pra mexer no setor, mexer no Argos. Mas assim, aí o nível de privilégio do sistema é de acordo com o status de cada um, então tem gente que só tem acesso para abrir a ordem, não tem acesso a nada. E no meu caso, por exemplo, eu tenho acesso a tudo, inclusive os relatórios." (BR UNIVERSITY, 2019b)

[21] Free translation of: "[NOME] cuida de árvores, então cada árvore que tem que cortar no campus ela vai lá, fotografa, ela tem um arquivo que ela indica lá que árvore que é e tal, mas fica assim muito localizado, ninguém mais tem acesso a isso". (BR UNIVERSITY, 2019a)

The *Accuracy and Reliability Category* regards to the precision and integrity of data and information for FM, which is considered a critical aspect by the interviewees: “a model that is not up to date and no one wants to use it, because the information there is rubbish” (UK UNIVERSITY 2, 2018). Examples of inaccurate information and its impacts on FM activities are provided by the participants. One situation is related to the register of spent time in FM services. According to the participant, the mobile application developed to workman recording the time spent in FM services was not correctly utilized, generating incorrect data to the CAFM system: “the workman forgets to hit stop, or they don’t hit start, you know, the data is just not accurate” (UK UNIVERSITY 1, 2019b). Aiming to fix the problem, the IT team has added a new functionality into the application, requesting to the supervisor the time approval.

The second example regards to the asset record drawings (e.g., plan floors and site maps), used by the FM team in activities such as fault location into the CAFM system, maintenance budget setting, and design planning. Due to the imprecision of data, two participants describe the necessity of field surveys for verifying assets measurements and material specifications, a time-consuming and non-value adding activity:

> “I was chatting to a director downstairs, he said “often we’ll in the new build a network plan or network points, where network access point should be, even though we give them the plan to put on into the model, in real life when they come into the building it never matches and they have to get some sense to do a survey […] the access point isn’t where it says on the drawing.” (UK UNIVERSITY 1, 2019b)
>
> “So, everything that needs to be planned, accounted for, in summary, we have to take the measuring tape and go out measuring […]. Because the map we have of the campus, if we measure it over there, it will never be accurate. An example: the external grids of the campus will need to be painted, we had to measure all the grids with the measuring tape and then [NAME] asked him to calculate the area of each face of the grid, multiply… ” (BR UNIVERSITY, 2019a)[22]

In the IoT context, one of the interviewees raises an issue regarding the type and volume of data generated by building sensors, emphasizing the need of a strategic implementation to define the number, type, and location of sensors to support the extraction of relevant data for asset management:

> “I think the interesting thing with sensors is that you can have so many now, you could almost become overwhelmed by data. So, I think that getting a balance right, and also understand getting the right sort of sensor in the right place”. (UK UNIVERSITY 1, 2019c)

b. Process

The *Process Theme* approaches People issues and Strategic, Tactical and Operational FM aspects related to FM services provision.

- ### People issues

Considered one of the most critical factor in BIM implementation (SACKS et al., 2018), in this study *People Issues* approaches the FM service processes from the perspective of the FM team members. The *Awareness* category regards to the individual understanding of BIM and IoT as disruptive solutions to improve

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[22] Free translation of: “Então tudo que precisa ser planilhado, contabilizado, enfim, a gente tem que pegar a trena e sair medindo […]. Porque o mapa que a gente tem do campus, se a gente medir por ali, nunca vai ser fiel. Um exemplo: vai precisar pintar as grades externas do campus, a gente precisou medir com a trena todas as grades e aí [NOME] pediu pra ele calcular a área de cada face da grade, multiplicar…”(BR UNIVERSITY, 2019a)

FM services. Distinct positions were observed among the interviewees. Some demonstrate a good understanding of BIM and IoT definitions, functionalities, standards and impacts on the FM sector, discussing technical, processual, and regulatory challenges for an effective implementation:

> "It would be nice to see your perspective on what IoT is. Because IoT is internet of things and there are a lot of systems that are connected to the network, but they are not accessed through the internet. So, does that mean the internet of things, because that is just a very general concept, or is that not internet of things, is local network of things (LAT)." (UK UNIVERSITY 1, 2019d)
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> "It's the way, every university uses BIM with CAFM." (UK UNIVERSITY 1, 2019b)
>
> "I've identified the data and we want to be able to put into that system and specify the EIR you know, this data has to be in a certain format, so [can it] should be taken into the system at the end. Other many organisations really thought about that." (UK UNIVERSITY 2, 2018)
>
> "[…] we were talking about innovative ways to change how university is working in IT." (UK UNIVERSITY 1, 2019b)

Others reveal an incipient awareness level, in special regarding the BIM implementation driven by a national mandate:

> "We took this information by surprise in the AutoCAD course. And then we started to argue with each other, so we have, of course, an obligation until 2021, but we also have the desire to implement it, to start using Revit, because the projects that come to us will also start arriving in Revit, we have to know, right?" (BR UNIVERSITY, 2019a)[23]

The *Capability* category relates to skills of FM members in managing digital information and is considered a core barrier for ICT implementation. Some interviewees report an insufficient staff for addressing the increasing demand of the sector:

> "These units have their maintenance team, however, they ask us for some things. In the past it was more, but our team has been decreasing and we are unable to attend them." (BR UNIVERSITY, 2019a)[24]

According to one of the participants, the lack of personnel has significantly contributed to the unsuccess of the lighting system, one of the few IoT initiatives in the organization:

> "But the problem ended up in whoever is going to manage it. We were unable to have a person to say "This guy will manage, will test the system, will know how to change the system, will know how to dim, will know how to do, how to sector to be able to try this", so there was no person who was appointed to do that, in addition to some system failures as well. " (BR UNIVERSITY, 2019a)[25]

Difficulties for moving from an analogic to a digital FM process, in special among the craftsman labour force, are described by two interviewees from distinct universities:

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[23] Free translation of: "Pegou a gente de surpresa essa informação lá no curso de AutoCAD. E aí a gente começou a discutir entre nós, assim, a gente tem, claro que tem a obrigação até 2021, mas a gente também tem a vontade de implementar , começar a usar o Revit, porque os projetos que forem chegando pra nós também vão começar a chegar em Revit, a gente tem que saber, né?" (BR UNIVERSITY, 2019a)

[24] Free translation of: "Essas unidades têm sua equipe de manutenção, entretanto, algumas coisas eles pedem pra gente. No passado era mais, só que a nossa equipe foi diminuindo e a gente não consegue atender." (BR UNIVERSITY, 2019a)

[25] Free translation of: "Mas o problema morreu em quem que vai gerenciar. A gente não conseguiu ter uma pessoa pra falar "Esse cara vai gerenciar, vai testar o sistema, vai saber mexer no sistema, vai saber dimerizar, vai saber fazer, setorizar pra poder tentar fazer isso", então não teve uma pessoa que foi designada pra fazer isso, além de algumas falhas do sistema também." (BR UNIVERSITY, 2019a)

> "[…] what you'll get is you get no time recorded for people that have done it in the paper type sheet, so some people didn't use the mobile and they recorded all down on paper and it doesn't come back into here, it's a mix, we are trying to get rid of the paper time sheet and make everyone use mobiles, but we are not there yet." (UK UNIVERSITY 1, 2019b)

> "[…] The tip of the spear are people with low education, this is a difficulty that we have. Because, for example, the bricklayer, excellent bricklayers, but they are not easy with computers, for example. " (BR UNIVERSITY, 2019a)[26]

Besides, the participants report the need of specialized staff to several activities, such as developing IT solutions and managing data information in BIM models:

> "I've noticed that, I think that we need a development team of people and all they do is, say, how can I make it better that system or whatever and they just develop it, just build it." (UK UNIVERSITY 1, 2019d)

> "[...] so you need somebody who has been trained on BIM to build those changes on the model otherwise it's not worth keeping up-to-date (information), and we don't have that, we don't have that capability, (…) so we would struggle to keep it up-to-dated." (UK UNIVERSITY 1, 2019c)

Some participants describe training programmes as key activities to support the adoption of new systems and processes in FM service processes.

> "[…] We had to do this training with the bosses, right, because, I wouldn't be able to put either the time for each employee who is connected to him or all the material, the business, so we had a training, a period with that. In the beginning I helped them a lot, we made more computers available, so nowadays we have the cooperation and they close, they put the hours worked and put what was material." (BR UNIVERSITY, 2019a)[27]

The perception regarding the individual involvement with the digital transformation supported by ICTs is summarized in the *Engagement* category. Most interviewees demonstrate enthusiasm for BIM and IoT implementation, expecting performance gains in FM services.

> "Hopefully [BIM implementation will happen] early next year, maybe the middle of the next year. […] Yeah, I am always very optimistic." (UK UNIVERSITY 2, 2018)

> "I think there's a lot that we can do, can be done a little bit better." (UK UNIVERSITY 1, 2019d)

On the other hand, the resistance of members of the FM team to change traditional practices is emphasized as a challenge to be overcome.

> "I said "would you want me to integrate Archibus with that?" and he said ''no, no, no, I just want to…" […] I see all the alerts, lot of the time I see them, they don't mean anything, it's all just capitalism and if it is important then it goes to see if there's a work request in the Archibus every time an alert came off, it would have a lot of work requests, it would be a lot of administration for him […] he says I'm happy just to work at the BMS council every day and see what alerts are coming out." (UK UNIVERSITY 1, 2019b)

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[26] Free translation of: "[…] a ponta da lança são pessoas que têm baixa escolaridade, isso é uma dificuldade que a gente tem. Porque por exemplo, o pedreiro, excelentes pedreiros, mas não têm facilidade com computador, por exemplo." (BR UNIVERSITY, 2019a)

[27] Free translation of: "[…] a gente teve que fazer esse treinamento com os chefes né, porque assim, eu não ia conseguir colocar a hora de cada funcionário que é ligado a ele e nem de todo o material, o negócio, então a gente teve um treinamento, um período com isso. No começo eu ajudei bastante eles, a gente colocou mais computadores disponíveis, então hoje em dia a gente tem a cooperação e eles fecham, eles colocam as horas trabalhadas e colocam o que foi de material."

Acknowledging peoples' resistance as a cultural barrier for ICT implementation, one of the interviews describes it as imperative for moving AEC industry to a fully digitalized environment:

> "People don't like... it is more comfortable an incremental change, but that is not what we need. We need monumental change! We need to get from a very bad position to a very good position."(UK UNIVERSITY 2, 2018)

The *Satisfaction category* addresses the individuals' sense of achievement related to the FM sector and services. Some participants describe university user's satisfaction in relation to FM problems solution as "a key thing" for the organization (UK UNIVERSITY 1, 2019b). The feedback stage is then considered an opportunity for users demonstrating their level of satisfaction with the FM provided services, thus generating metrics for further improvements (UK UNIVERSITY 1, 2019b). The interruption of energy supply, for example, is a cause for complains among users, since it might cause serious disturbance in research activities:

> "[…] it happens, because sometimes it turns off the entire building, sometimes it turns off half the campus. And then, shutting down half of the campus, this has to do, because the distribution of energy is for all units too, so if the power runs out it will shut down the laboratory. They have uninterruptible power supply, for example, but the autonomy is not so great, right. Maximum two hours, if you stay longer than that, the research will run out of energy. Sometimes a reactor, something connected that will interfere. It can happen, we do have some complaints." (BR UNIVERSITY, 2019a)[28]

Others report the dissatisfaction of staff with internal procedures involved in FM service provision. For example, the sector restructuration is described by one of the interviewees as a possible cause for staff dissatisfaction: "[…] now in the Estates, there's lot of doing restructure of all of the staff, and I think that... people aren't happy at the moment" (UK UNIVERSITY 1, 2019b). A second example regards to the FM sector approach given to BIM implementation: "We should be using Revit, it's the future. […] we are stuck using CAD, it's so decadent. That's unfortunate about it" (UK UNIVERSITY 1, 2019b). The lack of support in ICT developments is also indicated as disappointing, as demonstrated by one of the interviewees:

> "I said to [Archibus vendors] "this were the problems I got, cause I got problems with wi-fi signals not working" so I had to design the app to work offline, so the people would go like into the basements and still records time and stuff, so I designed to work and to be able to synchronize, and I told them all my problems and how I developed and they copied its layer and built their own and sold it back to us, (…) immediately they've made it bigger and it does more things than what mine did, if I had a team of people I could've made it bigger as well." (UK UNIVERSITY 1, 2019b)

- **Strategic, Tactical and Operational FM**

Aiming to implement the strategic objectives from daily to long term activities (THE BRITISH STANDARDS INSTITUTION, 2006), the *Strategic, Tactical and Operational FM Theme* discusses the role played by the organization in the advancement of FM services performance. The first category is related to the *value* given by the organization to the FM services. For some interviewees, services provided to accommodation hospitalities have a high value for the university since the experience and satisfaction of the residents are

[28] Free translation of: "[…] acontece, porque às vezes desliga o prédio inteiro, às vezes desliga metade do campus. E aí, desligando a metade do campus, aí tem a ver, porque a distribuição de energia é pra todas as unidades também, então se acabar a energia vai desligar laboratório. Eles têm o nobreak, por exemplo, mas a autonomia não é tão grande né. Máximo duas horas, se ficar mais que isso começa a faltar energia nas pesquisas. Às vezes algum reator, alguma coisa ligada que vai interferir. Pode acontecer, a gente tem algumas reclamações sim." (BR UNIVERSITY, 2019a)

essential. Besides, from the business perspective, accommodation plays an important role in the private university finance:

> "I think that is the difference in accommodation hospitalities, they are treated as commercial because they make income, even if the income goes back to the University, they still sell the accommodation to the student, they sell the food to the costumer, so they have to be running in a more commercial kind of professional environment." (UK UNIVERSITY 1, 2019b)

In the contrary, infrastructure services, in special underground plumbing and electrical facilities, tend to be lower valued by the organizations, since their benefits are not clearly perceived by the users:

> "Yeah, that's one of them, major floods, electrical, I'm trying to think, things like buried services, so things that run bellows the ground, so drains, electrical cables, which you don't see, and because you don't see you don't worry about them, but if you got a very old electric wires, we've got some here that are 40 years old, they cost lots, lots of money to replace so people don't worry about them because they can't see them being old, but once they crack that goes and kills the power, [NAME] does certain maintenance because you can't see it, so you've spent millions of pounds upgrading a circle but it's all underground, so you don't know it's there so you can't show your chairman or the governors "look we've spent this million pound and look how good it looks' it's just like a building, because it look 'wow', because you've replaced all this cables, you buried, you can see nothing, all you can say is that you know that will look after that building, a nice building, so next 20 old years we haven't got a problem because the impact that goes on. So, that's probably the biggest challenge, is to make people to spend on essential services which you can't see, does that make sense?" (UK UNIVERSITY 1, 2019c)

The *Leadership category* regards to the involvement of the organization in the FM digital transformation through BIM and IoT implementation. As discussed by one of the participants, the digitalization in FM sector is in early stages and must be a priority for the organization:

> "Well, what kind of, probably FM is behind the construction industry as a whole, so we haven't fully digitized yet, but I guess that might come from us as something that we have to look out for." (UK UNIVERSITY 2, 2018)

In this sense, actions for *restructuring* the FM sector and processes are described by some participants, which includes changing the role or the structure of the work teams:

> "We're going through restructuring exercise at the moment, the director of Estates, [NAME], so our boss, he concentrates mainly on the capital. I have been looking after the day-to-day operations or small capital projects, so, my area is a really bit hospitality." (UK UNIVERSITY 1, 2019c)
> "So, it's a bit of a structural change, but the functions at first haven't changed." (BR UNIVERSITY, 2019a)[29]

One of the interviewees emphasizes the importance of the FM sector *support* for BIM implementation, mainly driven by the head of the sector:

> "I think I've been a bit lucky, really. We had, I think about for 2 years now [NAME], who is now the Director of the Estates, he came in a more kind of a [...] level, so he was head of the building surveillance team and he got promoted up to that position. I think before he made that transition, I've spent quite a bit of time with him telling him about the benefits of BIM and he was really onboard when he took that position. So, you know, quite high up we've got support for what we wanna do and it makes a huge difference from the way it was before." (UK UNIVERSITY 2, 2018)

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[29] Free translation of: "Então é uma mudança um pouco estrutural, entretanto as funções a princípio não mudaram." (BR UNIVERSITY, 2019a)

In contrast, the lack of contribution of the FM sector to a significant change in the current FM practices is highlighted as a negative aspect by another interviewee:

> "[…] this is probably one of the biggest problems, is that the Estates don't really drive for this kind of change, so we're saying we think we can do it for you, what would be helpful and they're like "ok maybe, try it out, so we're going to give it a go and just see what happens". (UK UNIVERSITY 1, 2019b)

The *Feasibility* of digital transformation is discussed by the participants from distinct perspectives. For some interviewees, understanding the organizational context for ICTs implementation is crucial for the success of the digital transformation, as exemplified in the context of occupancy:

> "So, giving you an example, so we wanna look at different floor finishes and how were they have last for their life cycle. So, if we take two the exact same carpet types and install one in the library and one in a very [really] used office, we expect to weariness in very different rates. So, without the context of how old utilized spaces being makes it impossible to do any kind of meaningful, this is a good product, this one [is hard] to wear, this lasts a long time, this is a good value for money, let's do more in the future, install more that type of things. So, context of occupancy in buildings is very important and that would be a type of sensor reading we'd need to... if we wanna do that sort of intelligence." (UK UNIVERSITY 2, 2019b)

Other interviewee highlights functional requirements of the university buildings to be considered in IoT implementation, such as flexibility, thus addressing the frequent changes imposed to the university building environment over the years:

> "It works for this environment, but the other thing with universities is that buildings changes their purpose very frequently so (…) architecture here is very successful so it's unlike to change, but it's quite possible it might move from that building to another building, I'd been then might have to divide that building up and do something else with it, so if the sensor and the structure has got to be very, very flexible to allow to change , it's every building that are built so far within 10 years of them being built where you have to change the purpose of that building, so getting that degree of flexibility is quite challenging." (UK UNIVERSITY 1, 2019c)

Besides, organizational, and building characteristics, such as the university establishment time and the age of the buildings, are seen as obstacles for ICTs implementation:

> "So, I think, it's two things to say: a brand new building, absolutely, would be really helpful, but for older building, older state, there's a lot of hole behind the walls, if you know what I mean, that we don't know what goes on because we weren't here when the first fix were done, it's a lot more difficult, does that make you understand?" (UK UNIVERSITY 1, 2019c)

The risks of changes and costs required for ICTs implementation, such as BIM, are indicated as major barriers to be overcome:

> "[…] the universities at the top of the deep tables, they struggle to change, because they have got what they think is… their way… 'it got us here so far', the risk of changes is expensive." (UK UNIVERSITY 1, 2019b)
> "When you've got an established building where you haven't got BIM, you haven't got air conditioning survey, possibly, you haven't got a facility management system set up to that level of detail that'd be very, very expensive to set up." (UK UNIVERSITY 1, 2019c)
> "Yeah, and that's probably where your expenses, is having a team or individual to actually maintain this, and then I know our guys here struggle to maintain just a normal outer catering, so how they maintain BIM models I don't know… It would be something for Estates have to look into." (UK UNIVERSITY 1, 2019b)

According to one of the interviewees (UK UNIVERSITY 2, 2018), even though there is not a systematic procedure for efficiency measurement, time savings have been identified in light bulbs replacements, usually costing £40.000 a year. Traditionally, this process would take around 0,6 to 1,0 hour involving many activities (e.g., visiting the site, standing a ladder, taking the fitting of the bulb, putting it back, leaving the site, going to the stores, coming back to the site, getting documents signed off the client, etc.). By checking the BIM model on a tablet, part of these non-value adding activities would be removed, representing a reduction of time by approximately a third. Given the importance of this service in the whole annual budget, significant savings can be achieved with BIM implementation, showing an optimistic perspective for FM sector performance:

> "For example, if they get a request that says a light fitting needs to be changed, or this light isn't working in this room, they can go to the model on the tablet and check what type of fitting it is, and, OK, it needs this type of replacement part, and go to the stores and get that before, so it would be a third reduction of the time , opposed to travelling to the site, taking it apart, finding out what's wrong with it going all back together and then going to stores and then coming back again to repeat a process. That's how I'm hoping to manage, using information." (UK UNIVERSITY 2, 2019b)

Providing a distinct perception of the costs, one of the interviewees believes the savings might overcome de expenditure in a long run as the stakeholders develop new capabilities, ensuring the feasibility of BIM implementation for FM purposes:

> "I think it often comes costs to the client, asking more information than what is the standard in a delivery. You are asking for a supply chain to work in a different way sometimes to what they're used to. I think in an earlier adoption, there has been addition of cost because of on projects for delivering them, and I think in longer term that will go away. It would be a matter of cost, so you don't have any extra costs. Yeah, but it has been some extras initially." (UK UNIVERSITY 2, 2019b)
>
> "So, BIM is often seen as being a cost and it is a capital expenditure for maintenance savings [...]. So, I think that's an issue and I think that gets resolved when we get better data and the previous the financial saving, that will help, still ending up being a capital cost but it doesn't have to be in a long run, once the supply chain is used to work in this way, once contractors preliminary get benefits from the model, […] and the more people using it along the way the better the data handover. So, I think it is just a transition, maybe." (UK UNIVERSITY 2, 2018)

In this sense, the interviewee highlights the importance of robust data about financial saving in the O&M stage, justifying BIM implementation in FM.

c. Policy

Policy Theme relates to the *Regulatory* and *Contractual* roles involved in Facilities Management services provision.

- **Regulatory**

The interviewees highlight the importance of internal procedures and protocols to support operation and maintenance processes. The Regulatory Category may include services prioritization according to the scale and impact of the problem to the users (i.e., Service Level Agreement), service classification based on the building characteristics (i.e., room type), and budget setting according to FM Key Performance Indicators (KPI's). However, problems are identified in these documents, impacting on the performance of FM services. One example relates to the time scheduled for service attendance according to the faulty priority category, not always followed by the tradesman:

> "[…] let's say I want to put in electrical list in the section electrical services. So, so he (Interviewee 2) was the project manager working with me on this project, so you pick the person and then you could schedule it for next week but most of the time it just goes unscheduled and then the job just appears on the users phone, I'll show you the phone app in a minute, but essentially as soon as they assign it that work will just appear on the work man's mobile phone app and then they can see all the priorities and the target dates then it's up to them they decide when they want to do the work. […] it's just scheduled there for now, it doesn't mean anything the day is there but nobody does anything with it." (UK UNIVERSITY 1, 2019b)

According to one of the interviewees, current procedures for setting university FM budget also lack efficacy, due the complexity of the KPI's and the uncertainty particularly involved in reactive maintenance planning:

> "[…] with inside the association of university directors of estates we've been trying to stablish some KPIs, it's how we measure our performances. And I think what happened is that the sectors are very complicated. We had about 40 or 50 different KPI's, which is almost impossible to measure. So, we're trying to bring it down to 5 or 6." (UK UNIVERSITY 1, 2019c)

According to one of the interviewees, government *mandates* play a key role in FM digital transformation, triggering improvements in the supply chain and the implementation of innovative solutions by the university, such as BIM.

> "I think it started with the UK government mandate building new things, getting BIM information anyway. And it was just a matter of working on how to integrate it with CAFM, because it does solve a big problem, like, getting the supply chain to deliver data it's never been easy and asking them to do a non-standard by a UE specific and coding system etc. It's never been successful, so having BIM and going to be a Uniclass as industry standard has made the process easier." (UK UNIVERSITY 2, 2019b)

Besides, *guidelines* and *standards* addressing data and information management are essential for ensuring the good quality of information and the exchange process among the stakeholders, essential for performance gains:

> "In the same terms, I've identified the data and we want to be able to put into that system and specify the EIR, you know, this data has to be in a certain format, so it should be taken into the system at the end. Other many organisations really thought about that." (UK UNIVERSITY 2, 2018)

Overcoming the fragmentation among systems, the interoperability among file formats and processes is also critical for ensuring the integrity of data. Discussing the relationship between the organization and the supply chain, one of the interviewees highlight the key role of industry standards to ensure the quality of the delivered information:

> "And it was just a matter of working on how to integrate it with CAFM, because it does solve a big problem like getting the supply chain to deliver data it's never been easy and asking them to do a non-standard by a UE specific and coding system etc. It's never been successful, so having BIM and going to be a Uniclass, as industry standard has made the process easier." (UK UNIVERSITY 2, 2018)

Although BIM and IoT systems might support information management, one of the interviewees emphasize the importance of having correct data, since what "BIM doesn't solve is bad information" (UK UNIVERSITY 2, 2019b). In this sense, establishing protocols for data management is vital for achieving good quality information and, consequently, supporting FM decisions.

- **Contractual**

Contractual category group discusses the impact of the FM sector roles and the relationship among stakeholders on the service processes. The participants emphasize that setting roles and *responsibilities* is crucial to ensure that right decisions are taken by the right supplier in each stage of the process. One example is the *charging* process, observed when the Estates provides services to financially independent units (e.g., accommodation, catering). This process brings complexity to service provision since it involves new players and approval stages, as explained by some of the interviewees:

> "We have different routes for staffs, for people to put work in, so from here you've got the faults detected by staff member, you got another layer which is catering. So, in catering, so anyone in the restaurants if they belong in the catering department, they are not allowed that access except if it's requested, if the supervisor needs to go to the report fault, then we put them as user. The reason for this is because of recharging, if catering or accommodation hospitalities whenever they request work for their buildings, not necessarily the restaurants but, if it was like a residential area like accommodation block, Estates charge accommodation hospitalities for the work, you see?" (UK UNIVERSITY 1, 2019b)

> "In the end, the user may or may not get an invoice depending on whether it is chargeable or not. If it is a chargeable piece of work, then he'll get an invoice. If it's not chargeable, then he doesn't get to see anything, doesn't get an invoice. But I might have the invoice, because I will have to authorize it to the university." (UK UNIVERSITY 1, 2019c)

Compliance issues related to the external suppliers are approached by one of the interviewees. Even setting clear responsibilities and BIM data requirements, the FM team faces obstacles in receiving appropriate products and services, leading to inaccuracies in the BIM model:

> "So, supply chain capability and the supply chain understanding of FM, as we spoke about already, so you often get loads of problems with the BIM handover, especially from the design team to the contractor team, you get gaps and it can be still in the client's contract and how they've contracted, how they want the information […] and you can end up with gaps in the model." (UK UNIVERSITY 2, 2018)

4.3.3. Descriptive Analysis of Work Requests

The main purpose of the Work Requests analysis is to characterize FM requests and to identify the most critical problems in the universities' infrastructure over the studied period. For this work, criticality is based on the relation between severity and recurrence of problems. Initially, a general approach covers the total requests focusing on the service characteristics, followed by a restricted analysis of reactive maintenance requests and the related building characteristics. The Work Request variables for analysis are shown in Table 20.

Complementary analysis raises correlations among building characteristics variables which might impact the occurrence of reactive maintenance problems and the spent time for solution. Also, the data analysis supports the identification of potential opportunities for services improvements through BIM and IoT solutions application.

Table 20: Work Requests variables for analysis

Group	Variable	Description
Services	FM Area	Corresponding to the FM areas purposed by Barrett and Finch (2014) (i.e., Building operations and maintenance, Facility planning, Real estate and building construction, General/Office service)
	FM Group	Corresponding to the FM groups purposed by Barrett and Finch (2014) (i.e., Reactive Maintenance, Preventive Maintenance, Operations, Fire, Reprographic Services and Safety Critical, etc.)
	Month and Year	Corresponding to the month and year of service requesting (i.e., September 2017, October 2018, etc.)
	Site ID	Corresponding to the name of universities sites (i.e., Campus A, Campus B, Site BA, etc.)
	Service Category	Corresponding to the categories of services related to asset systems (i.e., Building, Mechanical, Electrical, External Areas)
	Service Subcategory	Corresponding to the subcategories of services related to asset system components (i.e., Door, Wall, Plumbing, Heat/Cool/Vent, Lighting, Power, etc.)
	Priority Level	Corresponding to the classification of services based on the Service Level Agreement of the UK University 1 into five categories, presented in descendent order of importance: Priority 1 for requests responded in 2 hours (in this analysis, responded at the same day); Priority 2, requests attended in 1 day; Priority 3, requests responded in 3 days; Priority 4, requests addressed in 7 days; Priority 5, requests attended according to the time agreed with the client.
	Average Spent Time	Corresponding to the average time spent for service provision measured in days (i.e., 3,01 days, 9,71 days)
Building characteristics	Room Type	Corresponding to the room function (i.e., Bedroom, Toilet, Kitchen, Laboratory, Lecture Theatre, etc.)
	Number of Floors	Corresponding to the number of building levels (i.e., 1, 2, 3, etc.)
	Floor ID	Corresponding to the identification of a building floor level (i.e., 1, 2, 3, Roof, etc.)
	Building Year of Construction	Corresponding to the opening year of a building (i.e., 1970, 1850)
	Building Heritage Status	Corresponding to the building classification according to the heritage status in Listed or Unlisted.
	Building Built Area	Corresponding to the total floor area of a building in square meters (i.e., 6.000m^2, 3.250m^2, etc.)

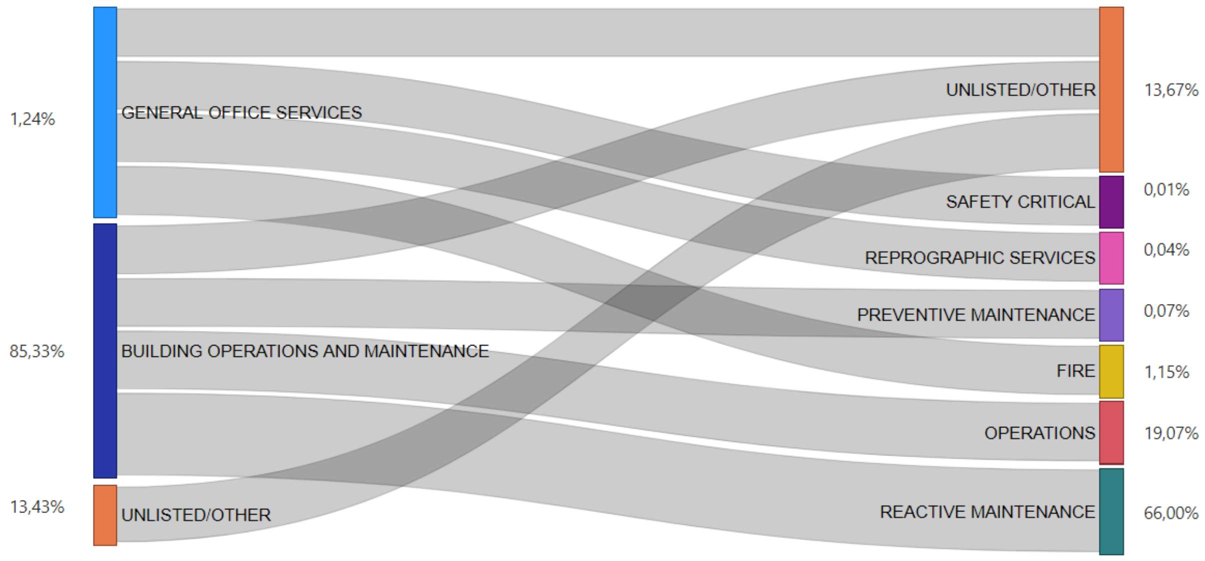
Source: Author (2021)

a. UK University 1

The whole database includes 66.515 Work Requests from different FM areas, such as Building Operations and Maintenance and General Office Services, reported to the FM sector between 2017 and 2018, as following analysed. Among those, 43.903 requests are related to Reactive Maintenance Services.

Figure 41 depicts the distribution of Work Requests per FM areas and FM groups. Building Operations and Maintenance is the most recurrent FM area with 85,33%% of the whole requests, followed by General Office Services with 1,24% and Unlisted/Other areas with 13,43%. Regarding FM groups, Reactive Maintenance is responsible for 66,00% of the requests, followed by Operations with 19,07% and Unlisted/Other groups with 13,67%. Fire, Preventive Maintenance, Reprographic Services and Safety Critical address together 1,26% of the whole Work Requests.

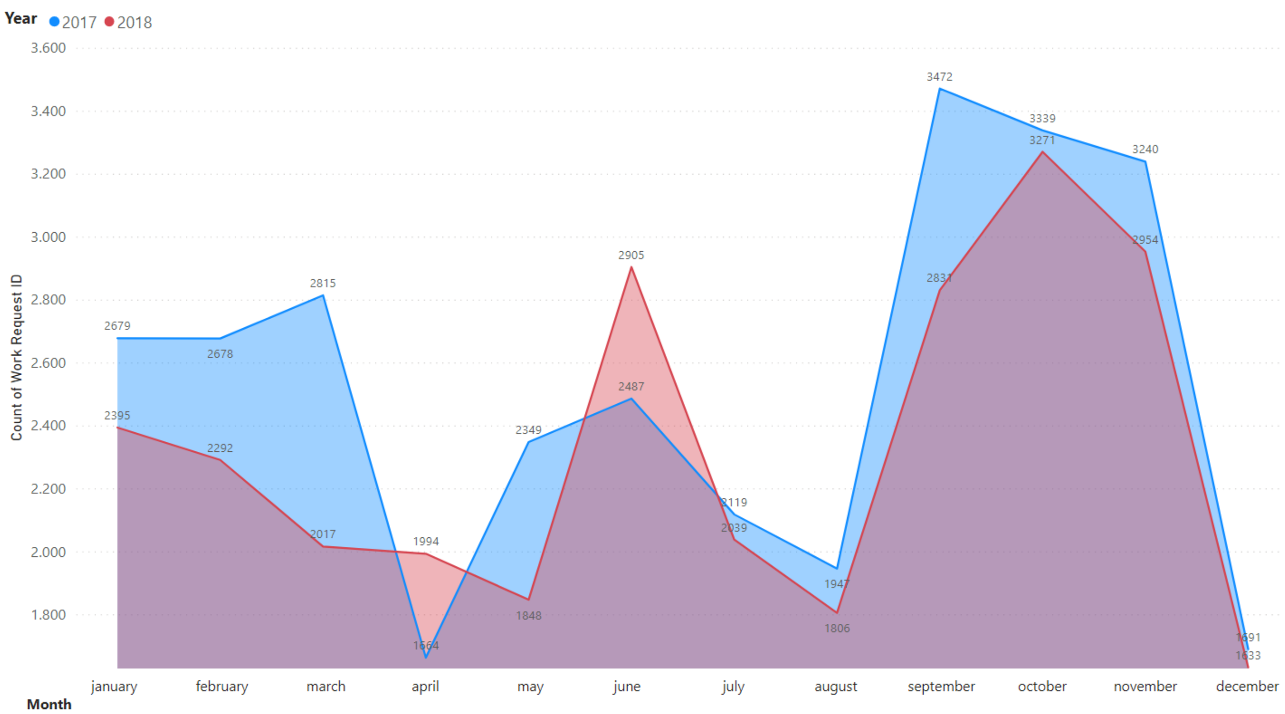
Figure 41: UK University 1 Distribution of Work Requests per FM areas and FM groups



Source: Author (2021)

Figure 42 shows the monthly distribution of the total Work Requests in 2017 and 2018. A total of 30.480 Work Requests were carried out in 2017, with peaks in September (3.472), October (3.339) and November (3.240). With a significant decrease, 27.958 were requested in 2018, mostly in July (2.905), October (3.271) and November (2.954). A sum of 8.050 Work Requests has no date request information and were disregarded for this analysis.

Figure 42: UK University 1 Monthly distribution of the total Work Requests in 2017 and 2018



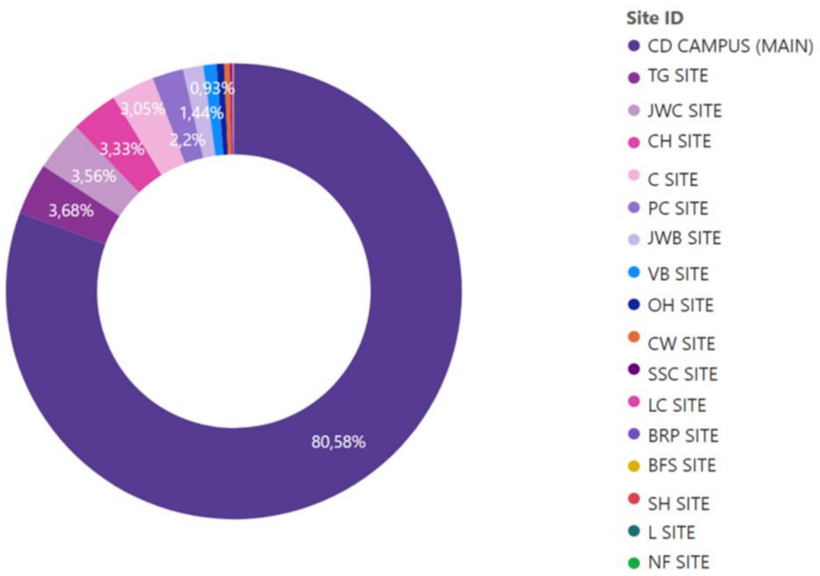
Source: Author (2021)

The distribution of Work Requests per Site[30] is depicted in Figure 43. The main Campus (CD) concentrates 80,58% of the whole requests, followed by TG Site (3,68%), JHC Site (3,56%), CH (3,33%), C Site

[30] Site names were replaced by codes to maintain the confidentiality of the university.

(3,05%), PC Site (2,2%), JHB Site (1,44%), and VB Site (0,93%). The 9 remaining sites sum 1,23% of the total requests.

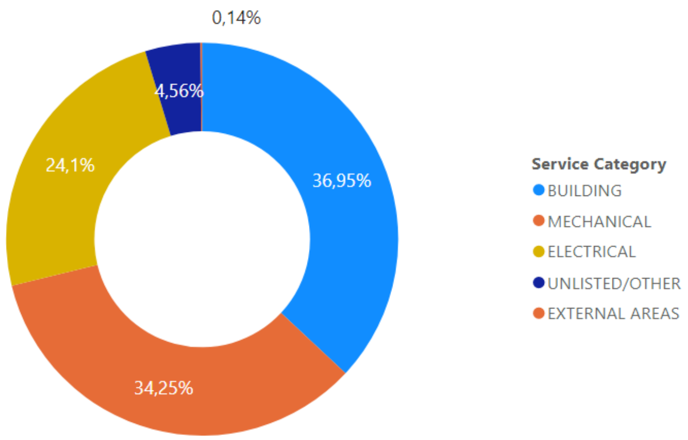
Figure 43: UK University 1 Distribution of Work Requests per Site



Source: Author (2021)

Reactive Maintenance Area is the focus of the next graphs. Figure 44 draws the distribution of the Work Requests in five categories: 36,95% of the Work Requests regard to Building services; 34,25% are Mechanical and 24,10% are Electrical. Unlisted/Other and External Areas services represent 4,70% of the total requests.

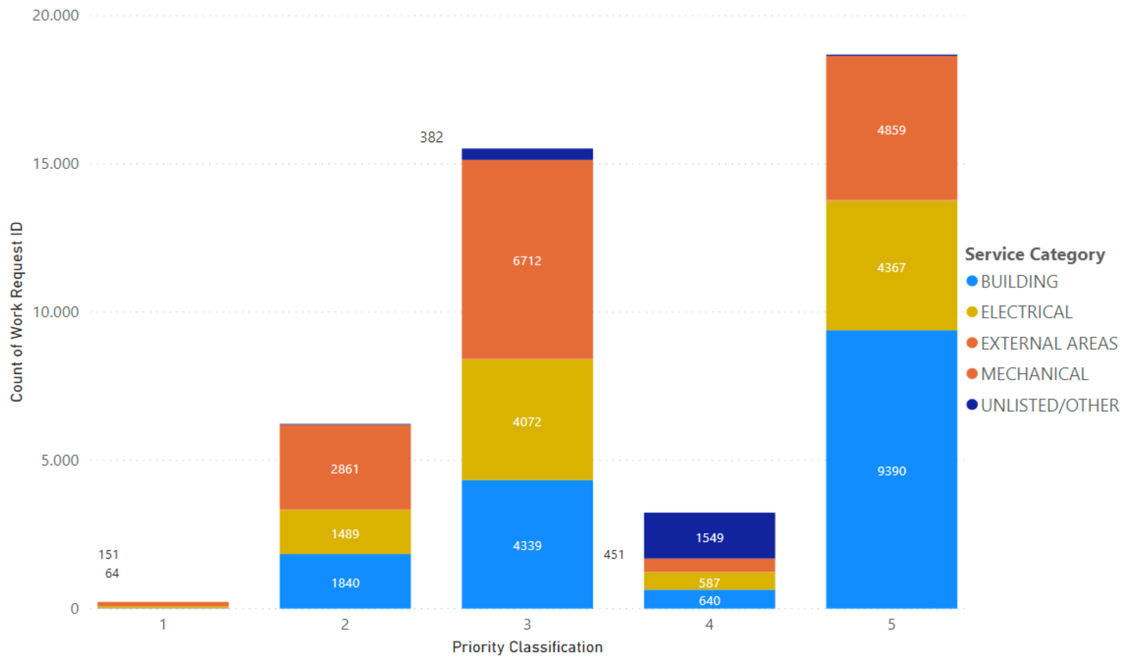
Figure 44: UK University 1 Distribution of the Work Requests per Service Category



Source: Author (2021)

Figure 45 depicts the distribution of Reactive Maintenance services category per Priority Level based on the Service Level Agreement of the UK University 1. A small number of Work Request classified as Priority 1, including *Mechanical* (151) and *Electrical* services (64), is observed. For Priority 2, the most recurrent Service Category is *Mechanical* with 2.861 Work Requests, followed by *Building* (1.840) and *Electrical* (1.489). Priority 3 services mostly include *Mechanical* with 6.712 Work Requests, followed by Building (4.339) and *Electrical* (4.072). For Priority 4, *Unlisted/Other* (1.549) and *Building* (640) service categories are predominant, followed by *Electrical* (587) and *Mechanical* (451). Most requests are classified as Priority 5, including 9.390 *Building*, 4.859 *Mechanical* and 4.367 *Electrical* services. No significant *External Areas* services were identified in any category.

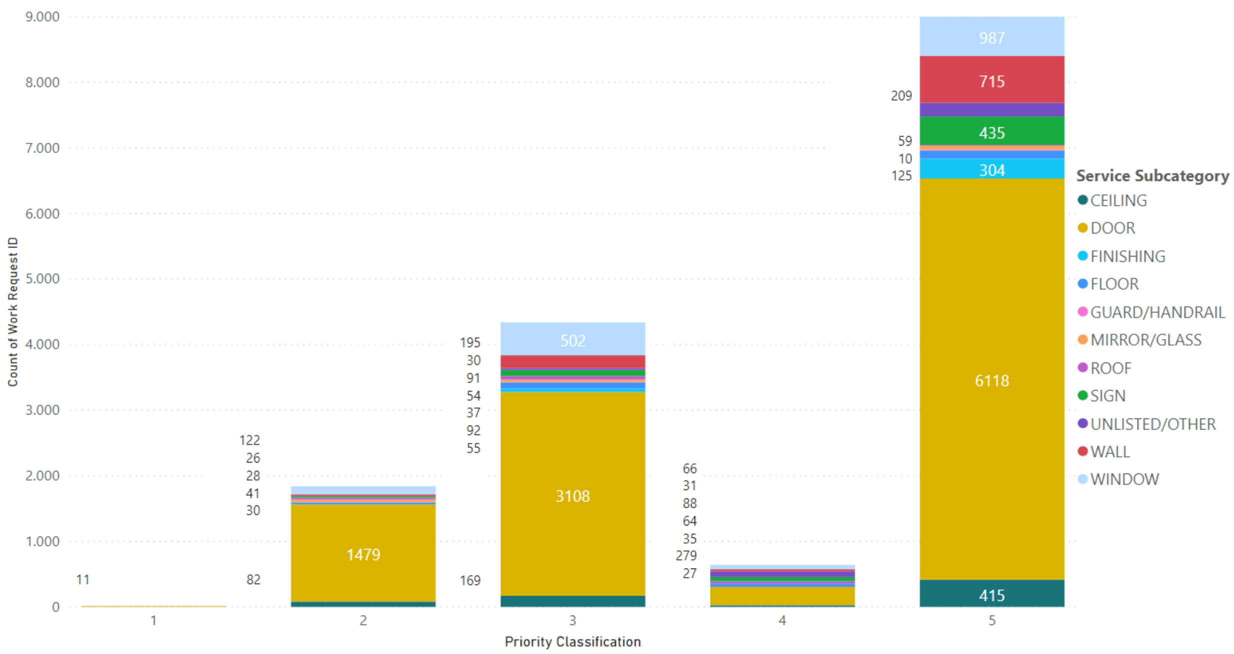
Figure 45: UK University 1 Distribution of Reactive Maintenance Services Category per Priority Level



Source: Author (2021)

The following graphs detail the distribution of Work Requests per the main Services Subcategory according to the Priority levels. Regarding Building Category, Figure 46 shows that Door services were the most requested in all priority levels, with 11 requests in Priority 1, 1.479 requests in Priority 2, 3.108 requests in Priority 3, 279 in Priority 4 and 6.118 in Priority 5. Among the remaining Subcategories, the most significant are identified in Priority 5, including Window services with 987 requests, Wall with 715 requests, Sign with 435 requests and Ceiling with 415 requests. Most of the services were classified as a Priority 5 level, reaching a total of 57,88% of the whole Building services.

Figure 46: UK University 1 Distribution of Building Work Request per Service Subcategory according to the Priority Level

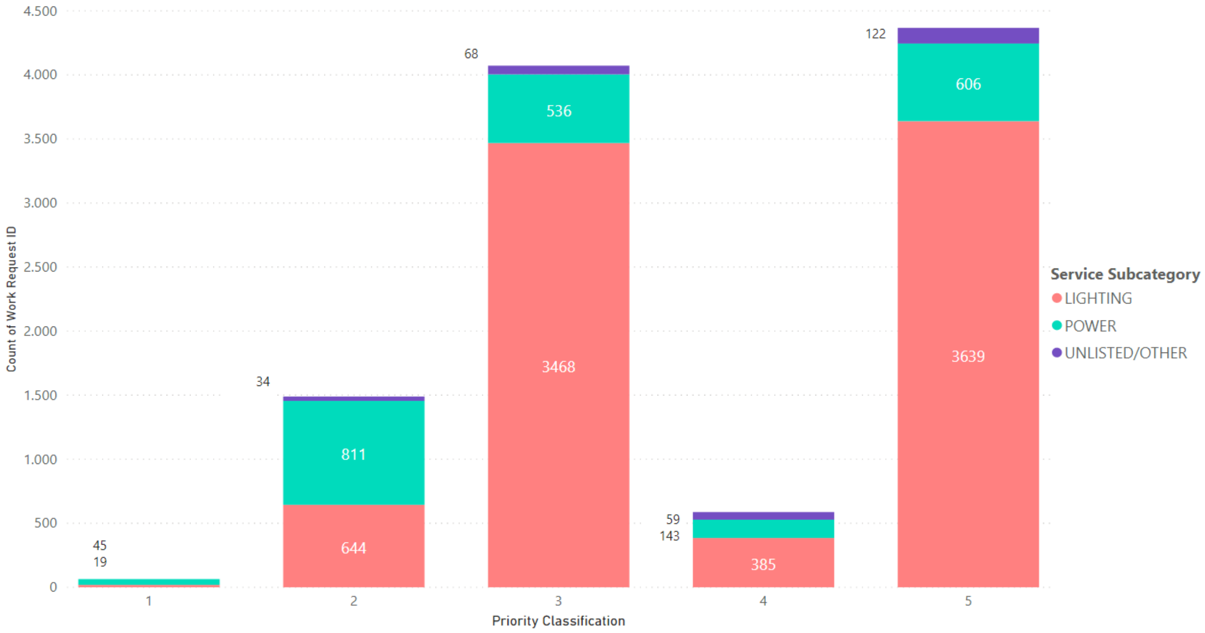


Source: Author (2021)

The distribution of Electrical Work Requests per priority level is drawn in Figure 47. For Priority 1 and 2, Power is the most requested subcategory service with 45 and 811 requests, respectively. On the other hand, Lighting subcategory is predominant in the remaining categories with 3.468 requests in Priority 3, 385 requests in Priority 4 and 3.639 requests in Priority 5 services. Most of the services were classified as a Priority 5 level, reaching a total of 41,26% of the total requests.

The distribution of Mechanical Services per priority level is shown in Figure 48. In all priority levels, Plumbing is the most recurrent Service subcategory, with 77 requests in Priority 1, 1.702 in Priority 2, 4.779 in Priority 3, 251 in Priority 4 and 3.219 in Priority 5. Heat/Cool/Ventilation subcategory is the second most requested, with 62 requests in Priority 1, 771 in Priority 2, 1.802 in Priority 3, 133 in Priority 4 and 1.431 in Priority 5. Lift services are significant only for Priority 2 with 344 requests. In general, Gas and Fume Cupboards/Lev services are little representative. Among the priority levels, Priority 3 concentrates most requests, with 44,63% of the whole request.

Figure 47: UK University 1 Distribution of Electrical Work Request per Service Subcategory according to the Priority Level

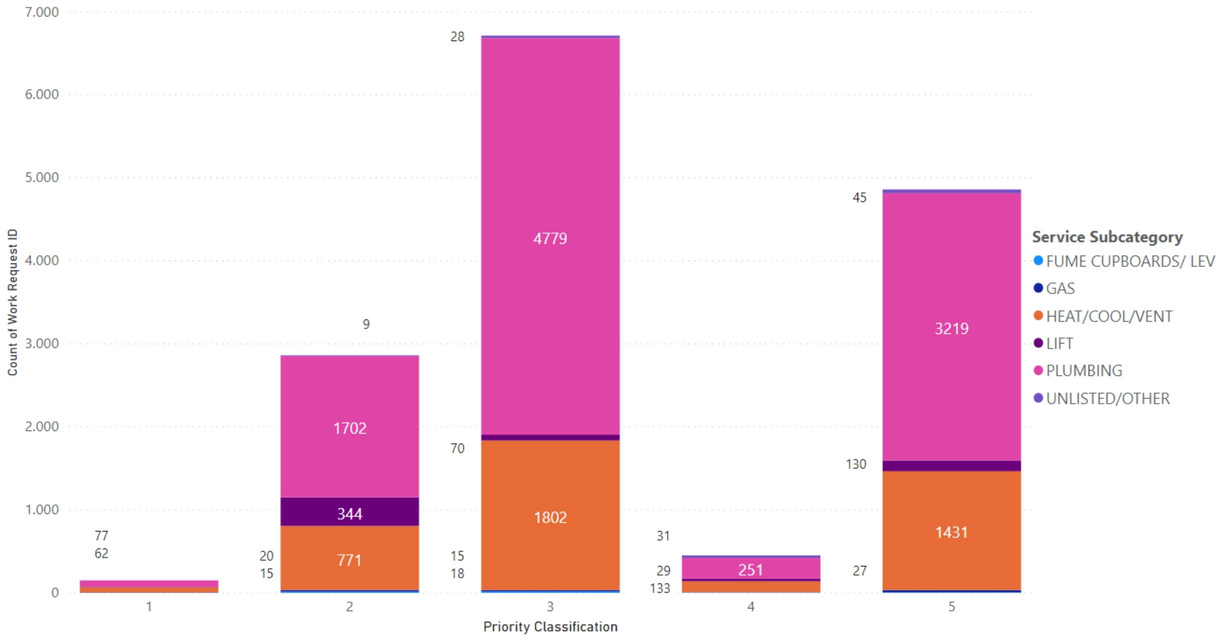


Source: Author (2021)

Figure 49 depicts the average spent time for each priority service level and the percentage of requests attended on time (compliance), a significant index for efficiency measures. Although the Department of Estates target set of 100% response rate for Priority 1 services and 85% response rate for priorities 2, 3, 4 e 5, the graph shows that most services were not attended on time: 36% for Priorities 1 and 2, 32% for Priority 3 and 31% for Priority 4. 100% of Priority 5 services were attended according to the time agreed with client.

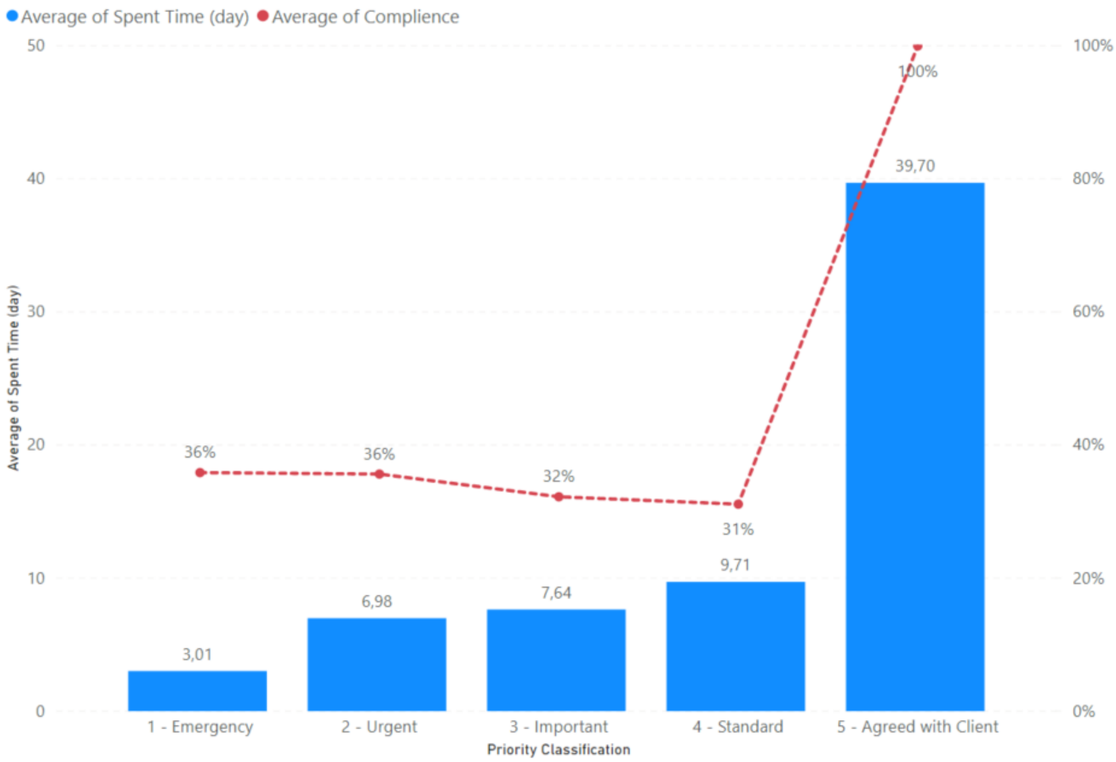
Figure 50 depicts the distribution of average spent time per main Service Category and Subcategory. The Electrical category have 10.215 requests with the average spent time of 6,9 days for Lighting, 9,7 days for Power, and 13,9 days for Unlisted/Other services. With 14.082 requests, Mechanical category has spent in average 3,3 days for Lift services, 9,7 days for Plumbing, 10,6 days for Heat/Cool/Ventilation, 10,9 for Fume Cupboards/Lev, 14,2 for Unlisted/Other and 30,4 for Gas. Finally, Building category sums 15.200 attended work requests in various subcategories, with the average spent time between 12,9 days (Ceiling) and 416 days (Wall), with Door spending 18,8 days.

Figure 48: UK University 1 Distribution of Mechanical Work Request per Service Subcategory according to the Priority Level



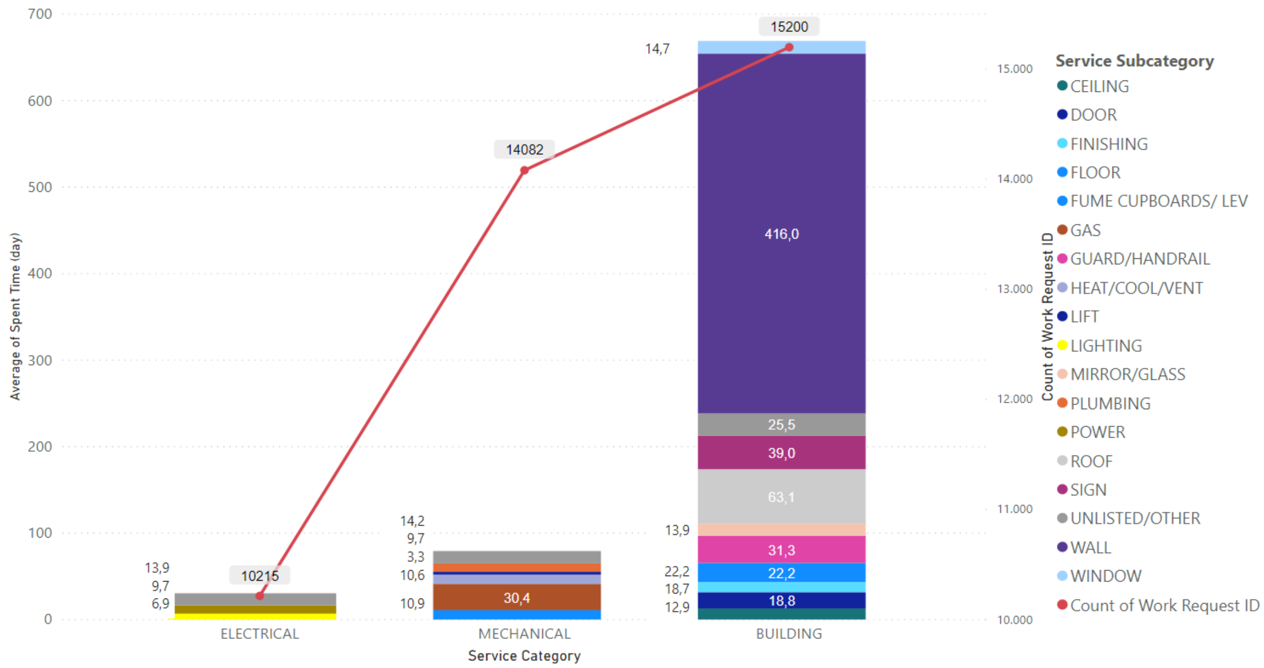
Source: Author (2021)

Figure 49: UK University 1 Average spent time for each Priority service level and the Percentage of compliance attendance requests attended on time



Source: Author (2021)

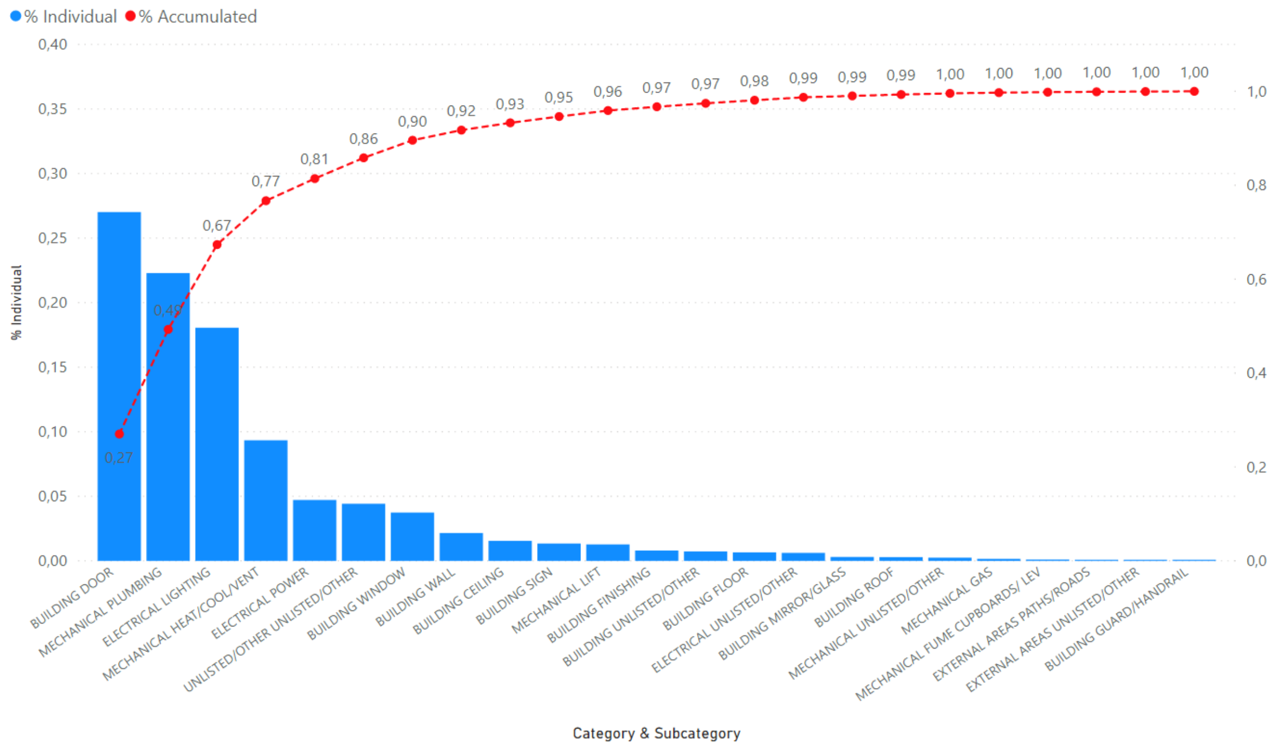
Figure 50: UK University 1 Distribution of average spent time per Service Category and Subcategory



Source: Author (2021)

The Pareto Graph in Figure 51 draws the frequency of Reactive Maintenance services according to the Category & Subcategory and the total accumulated percentage. The most frequent problem is Building-Door with 27% of total requests, followed by Mechanical-Plumbing (22,3%), Electrical-Lighting (18,1%), Mechanical-Heat/Cool/Ventilation (9,3%) and Electrical-Power (4,7%). In total, these five Categories-Subcategories cover 81% of the whole requests, thus considered the most relevant services for the organisation.

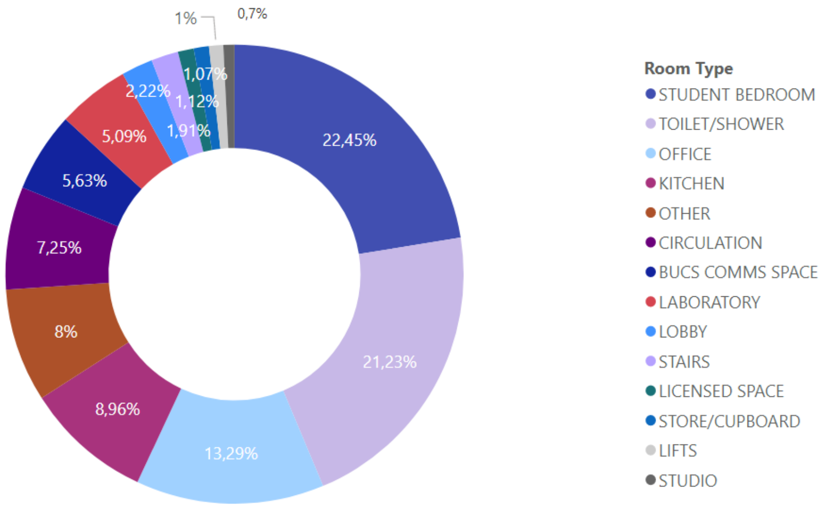
Figure 51: UK University 1 Pareto Graph



Source: Author (2021)

Building characteristics related to reactive maintenance services are followed approached. The distribution of Work Requests per identified Room Type is drawn in Figure 52. Student Bedroom respond for 22,45% of the total requests, followed by Toilet/Shower with 21,23%, Office (13,29%), Kitchen (8,96%), Circulation (7,25%), BUCS Comms Space (5,63%), Laboratory (5,09%) Lobby (2,22%) and Stairs (1,91%). The remaining requests (11,97%) are distributed over 45 other categories, including Licensed space, Store/Cupboard, Lifts, Studio and Lecture Theatre.

Figure 52: UK University 1 Distribution of Work Requests per Room Type



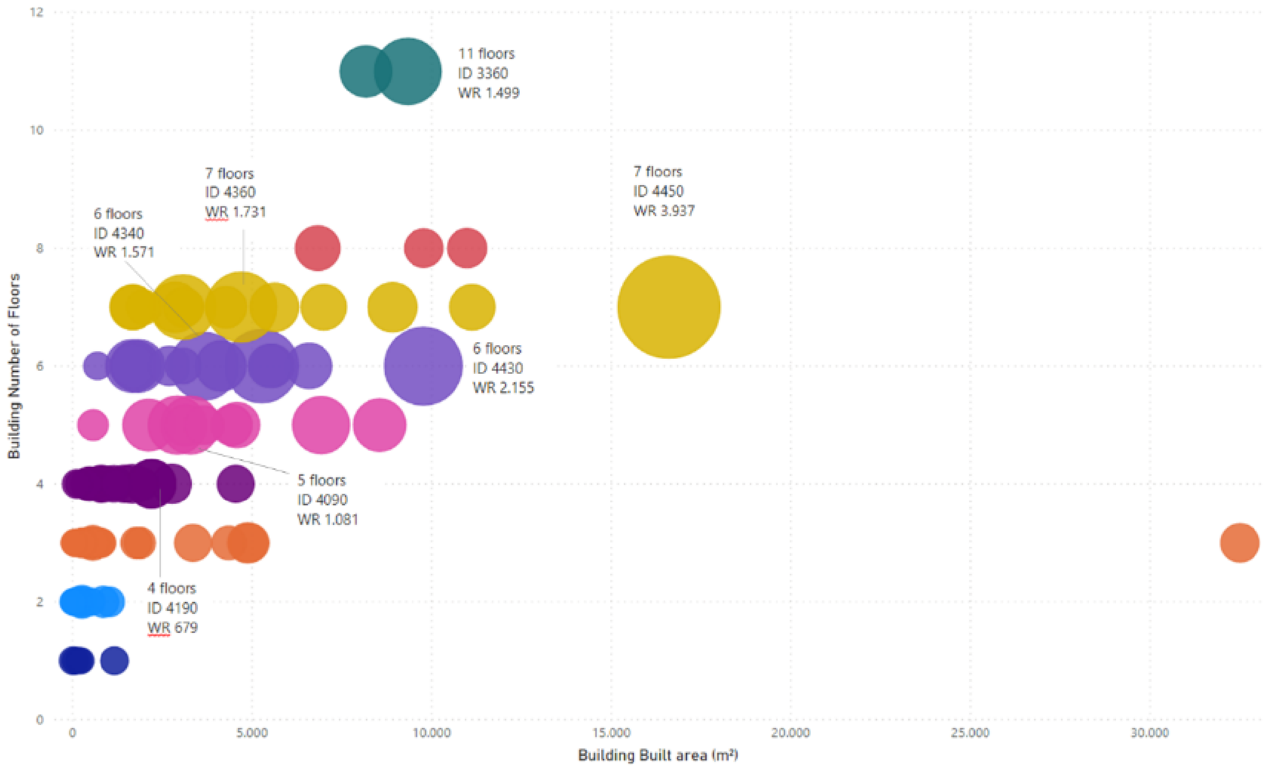
Source: Author (2021)

Figure 53 shows the distribution of Work Requests per Building Number of Floors according to the Building Built Area. Most requests are concentrated in buildings between 1 and 7 floors and with built area inferior to 5.000m². Some outliers are identified in this cluster. Among buildings with 4 floors, Building ID 4190 predominate with 679 requests. In buildings with 5 floors, Building ID 4090 responds for 1.081 requests, while in buildings with 6 floors, Building ID 4340 sums 1.571 requests. Finally, among buildings with 7 floors, Building ID 4360 have 1.731 service requests. Other significant number of requests is observed in buildings with built area superior to 5.000, including the 6 floors Building ID 4430 with 2.155 requests; the 7 floors Building ID 4450 with 3.937 requests; and the 11 floors Building ID 3360 with 1.499 requests.

Figure 54 shows the distribution of Work Requests per Building Number of Floors according to the building service Floor ID. A group of 39 Buildings with 5, 6 and 7 floors concentrate most requests with a similar distribution among the floors 1, 2 and 3. The distribution of requests per floor is balanced in buildings with 1 and 2 floors. In buildings with 3 floors, requests are predominant on floor 1 while in buildings with 4 floors, requests are mostly from the floor 0. In buildings with 11 floors, the floors 2 and 3 are predominant. In the remaining buildings, requests are similarly distributed among floors.

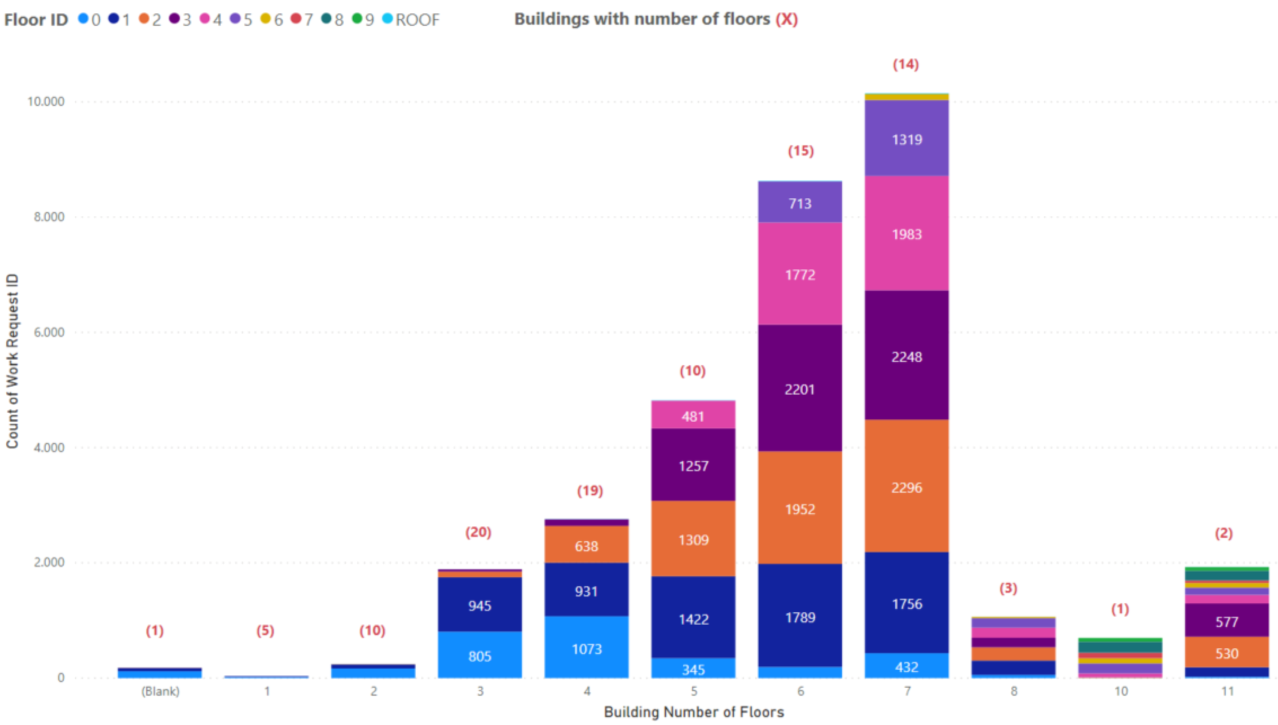
The distribution of Work Requests according to the buildings Year of Construction and Heritage Status is depicted in Figure 55. Most requests come from unlisted buildings constructed between 1970 and 2015. Unlisted buildings from 1970 concentrate approximately 6.000 requests, followed by buildings from 2014 with around 4.000 requests, buildings from 1990 and 1998 with around 3.000 requests each. Together, listed buildings have demanded only 128 work requests.

Figure 53: UK University 1 Distribution of Work Requests per Building Number of Floors according to the Building Built Area



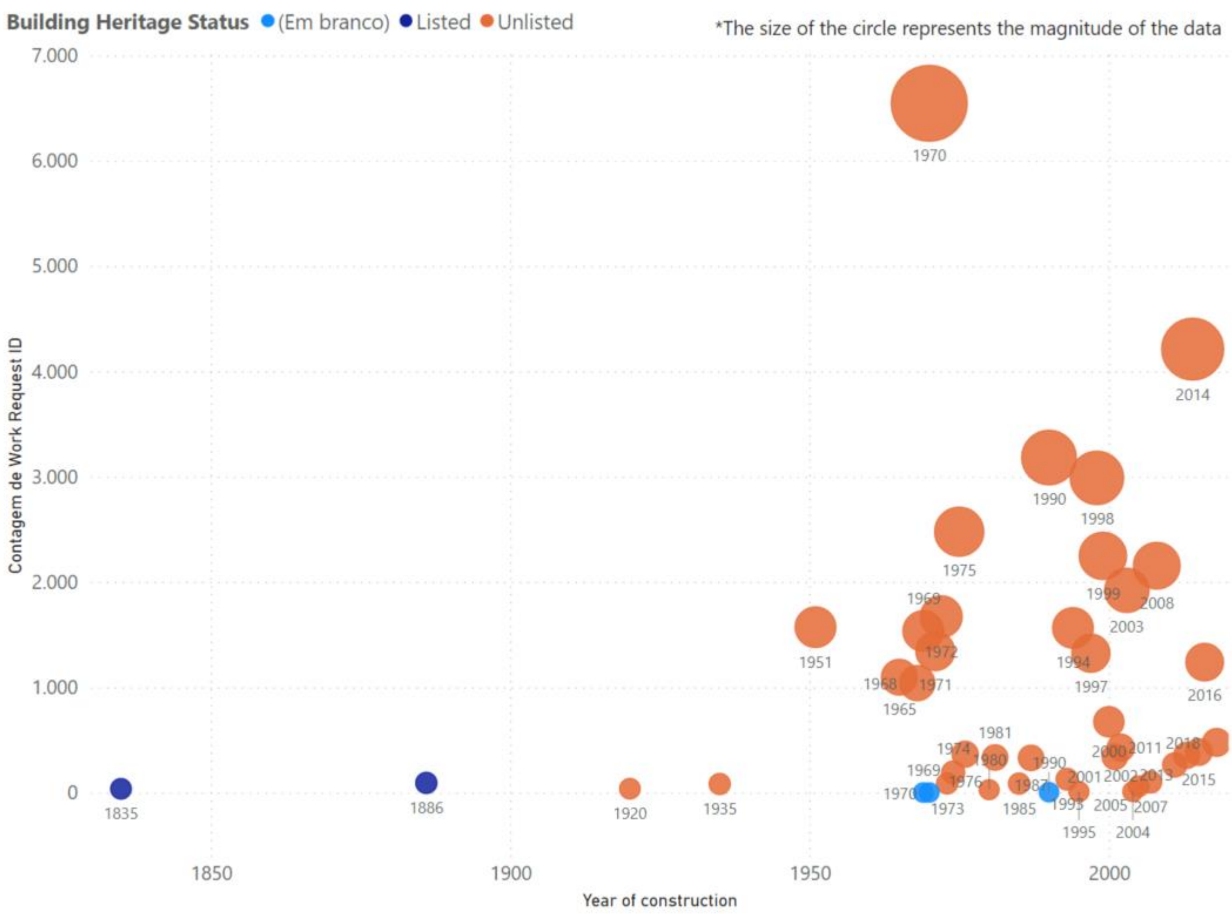
Source: Author (2021)

Figure 54: UK University 1 Distribution of Work Requests per Building Number of Floors according to the building service Floor ID



Source: Author (2021)

Figure 55: UK University 1 Distribution of Work Requests according to the buildings Year of Construction and Heritage Status



Source: Author (2021)

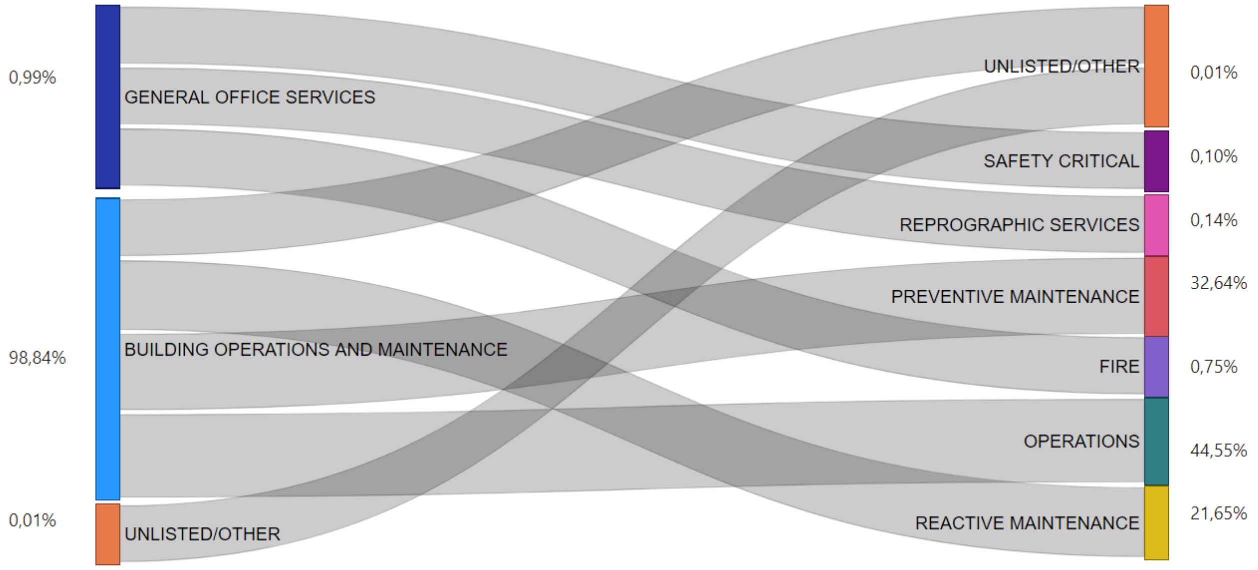
b. UK University 2

The database includes a total of 229.219 requests from different FM areas, such as Building Operations and Maintenance and General Office Services, attended by the FM sector in all university sites during 2017 and 2018 (UK UNIVERSITY 2, 2019a). From the total, 49.591 requests are related to Reactive Maintenance services. Since a priority level classification criterion has not been identified for UK University 2 O&M services, this factor was not considered in this analysis.

Figure 56 shows the distribution of Work Requests per FM areas and FM groups. Building Operations and Maintenance is the most recurrent FM area with 99,84% of the whole requests, followed by General Office Services with 0,99% and Unlisted/Other areas with 0,01%. Regarding FM groups, Operations is responsible for 44,55% of the requests, followed by Preventive Maintenance with 32,64% and Reactive Maintenance with 21,65%. Fire, Reprographic Services, Safety Critical and Unlisted/Other groups address together 1,16% of the whole Work Requests.

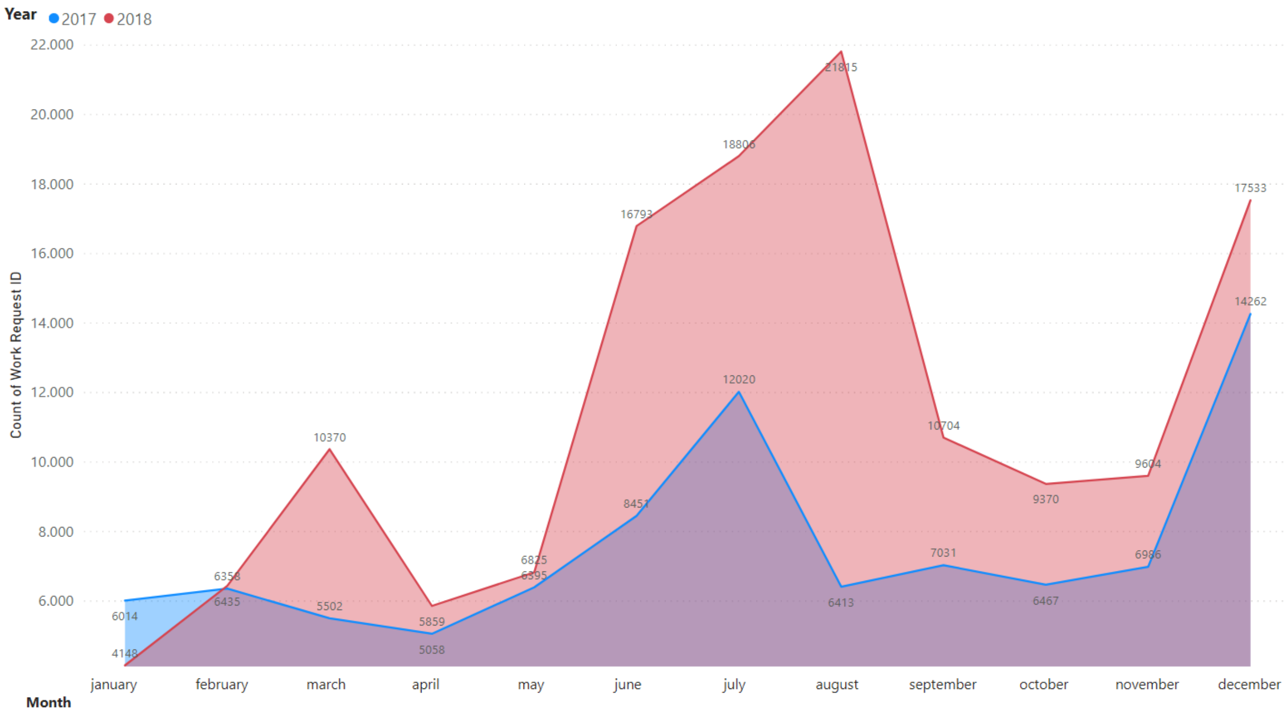
Figure 57 depicts the monthly distribution of the total Work Requests in 2017 and 2018. A total of 90.957 Work Requests were registered in 2017, with peaks in July (12.020) and December (14.262). There is a significant increase of total requests in 2018 reaching 138.262, mostly in July (18.806), August (21.815) and December (17.533).

Figure 56: UK University 2 Distribution of Work Requests per FM areas and FM groups



Source: Author (2021)

Figure 57: UK University 2 Monthly distribution of the total Work Requests in 2017 and 2018



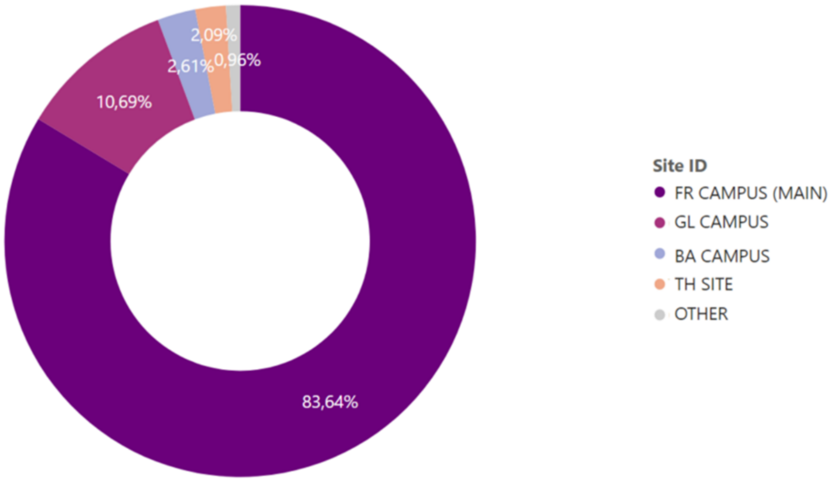
Source: Author (2021)

The distribution of Work Requests per Site[31] is presented in Figure 58. FR Campus concentrates 83,64% of the whole requests, followed by GL Campus (10,69%), BA Campus (2,61%) and TH Site (2,09%). The remaining Work Requests (0,96%) is divided by 7 other sites.

Emphasizing Reactive Maintenance Area, Figure 59 depicts the distribution of the Work Requests in five categories, with a balance among the three most important ones: 36,31% of the Work Requests are Mechanical; 33,97% are Building and 26,97% are Electrical. External areas and Unlisted/Other services represent 2,75% of the total requests.

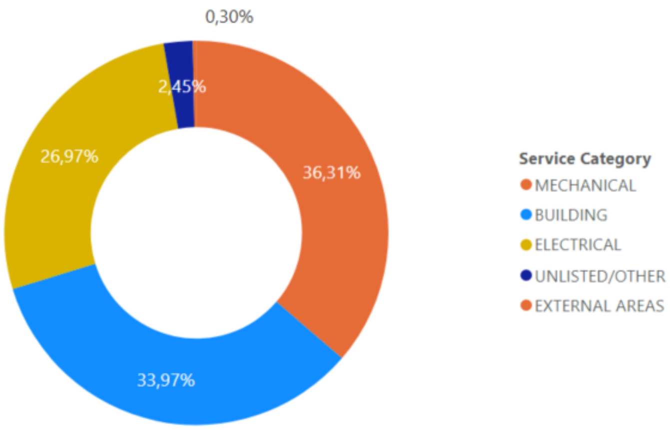
[31] Site names were replaced by codes to maintain the confidentiality of the university.

Figure 58: UK University 2 Distribution of Work Requests per Site



Source: Author (2021)

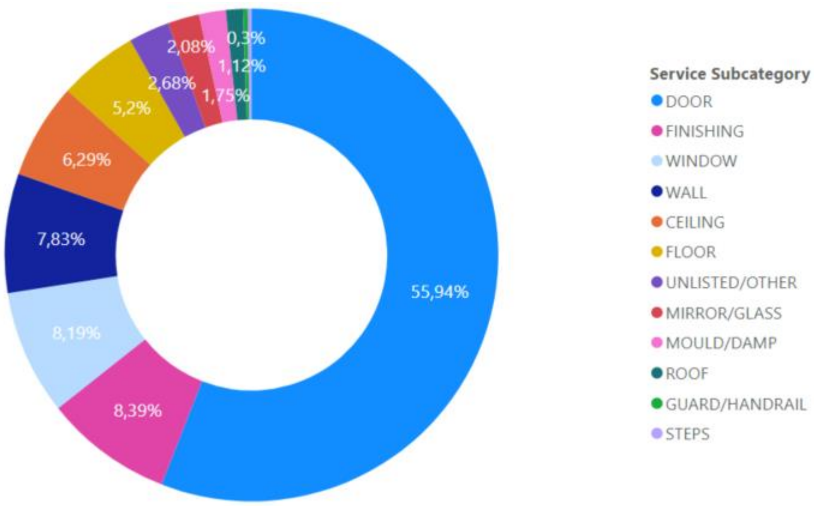
Figure 59: UK University 2 Distribution of the Work Requests per Service Category



Source: Author (2021)

The following graphs detail the distribution of Work Requests per the main Services Subcategory. Figure 60 draws the distribution of Building Work Requests per Service Subcategory. Door services were the most frequent with 55,94% of the total requests, followed by Finishing (8,39%), Window (8,19%), Wall (7,83%), Ceiling (6,29%), and Floor (5,2%). Remaining services sum 8,16% of the requests.

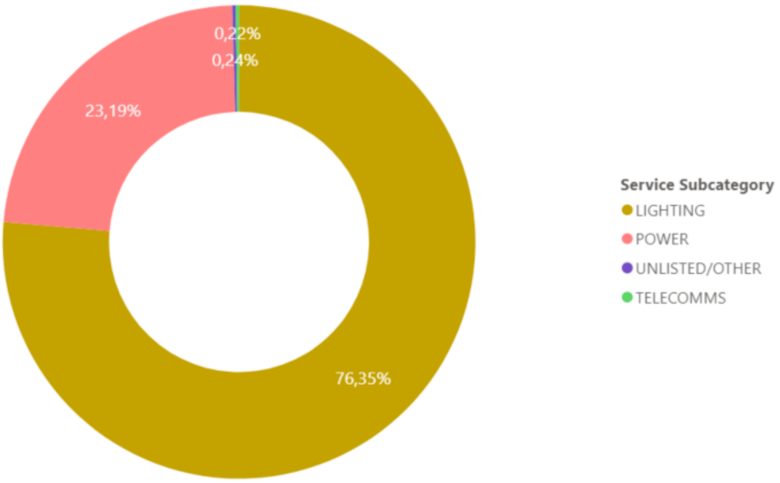
Figure 60: UK University 2 Distribution of Building Work Request per Service Subcategory



Source: Author (2021)

The distribution of Electrical Services per priority level is depicted in Figure 61. Lighting is the most requested category with 76,35% of the total requests, followed by Power with 23,19% of requests. Unlisted/Other and Telecomms requests sum 0,46% of the whole number.

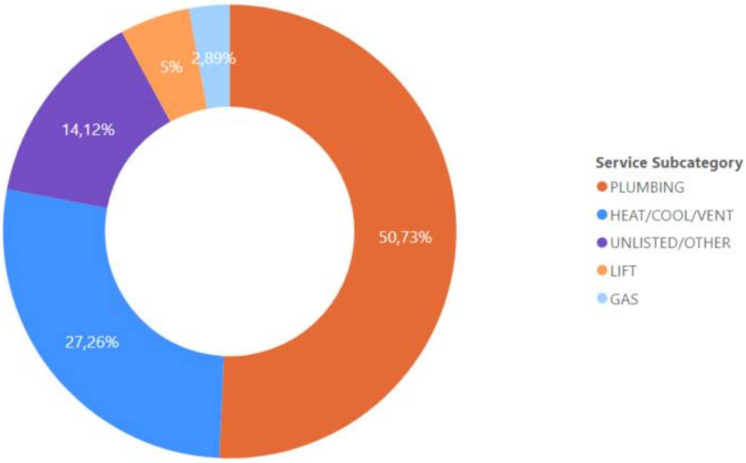
Figure 61: UK University 2 Distribution of Electrical Work Request per Service Subcategory



Source: Author (2021)

With regard to Mechanical Services Subcategory, Figure 62 shows that Plumbing services were predominant with 50,73%, followed by Heat/Cool/Ventilation (27,26%), Lift (5%), and Gas (2,89%). Unlisted/Other subcategories represent 14,12% of the total requests.

Figure 62: UK University 2 Distribution of Mechanical Work Request per Service Subcategory



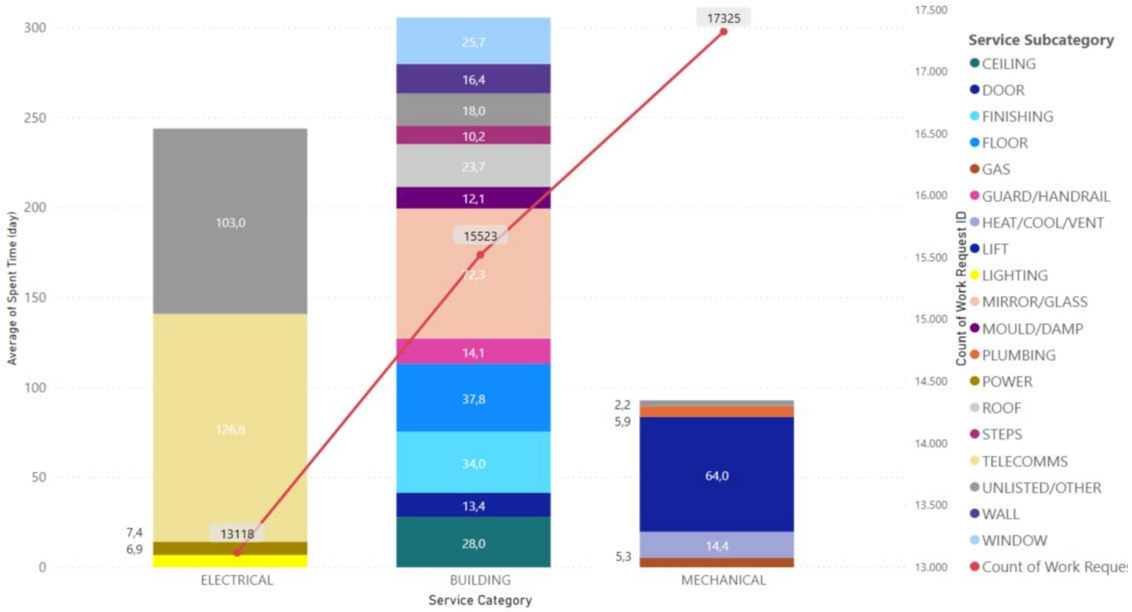
Source: Author (2021)

Figure 63 depicts the distribution of average spent time per main Service Category and Subcategory. The Electrical category have 13.118 requests with the average spent time of 6,9 days for Lighting, 7,4 days for Power, 126,8 days for Telecomms, and 103 days for Unlisted/Other services. Building category sum 15.523 attended work requests in various subcategories, with the average spent time between 10,2 days (Steps) and 72,3 days (Mirror/Glass), with Door spending 13,4 days. Finally, Mechanical category (17.325 requests) has spent in average 3,2 days for Unlisted/Other services, 5,3 days for Gas, 5,9 days for Plumbing, 14,4 days for Heat/Cool/Ventilation, and 64 days for Lift.

The Pareto chart (Figure 64) shows the frequency of Reactive Maintenance services according to the Category-Subcategory and the total accumulated percentage. The most frequent problem is Eletrical-Lighting with 20,6% of total requests, followed by Building-Door (19,0%), Mechanical-Plumbing (18,4%), Mechanical-

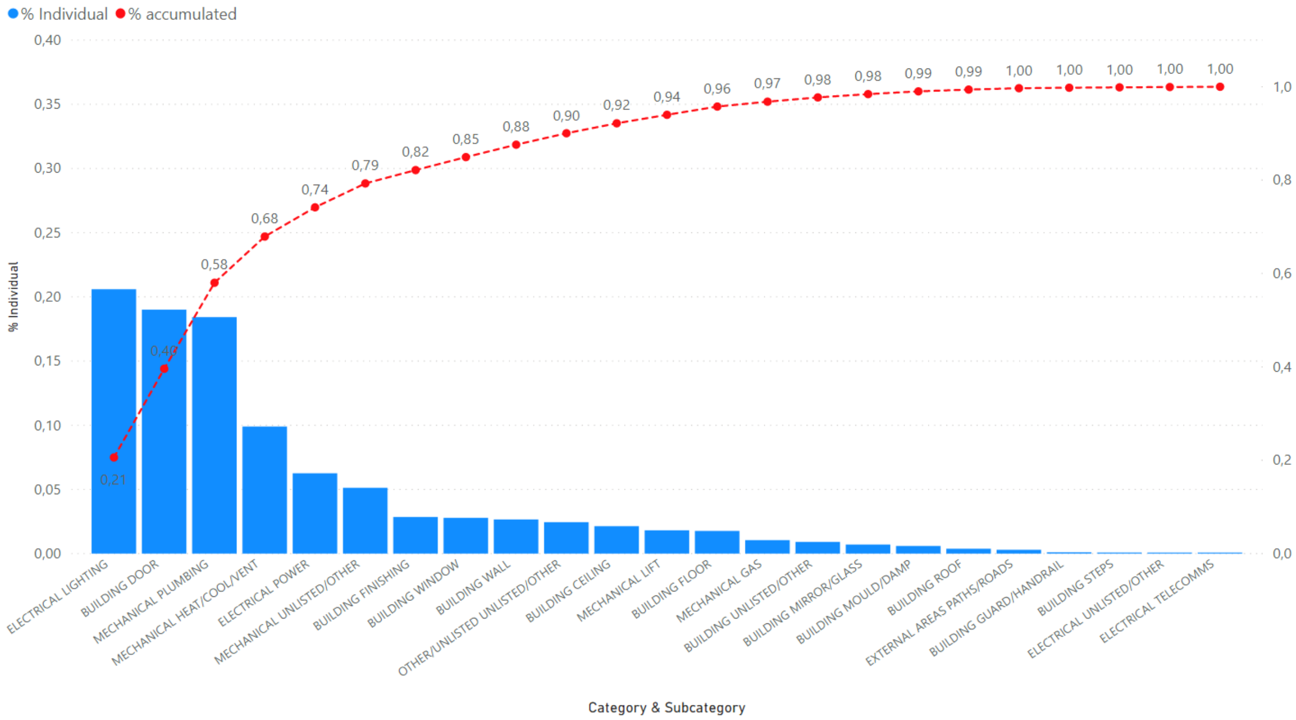
Heat/Cool/Vent (9,9%), Electrical-Power (6,3%), Mechanical-Unlisted/Other services (5,1%) and Building-Finishing (2,9%). In total, these seven Categories-Subcategories cover 82,2% of the whole requests, thus considered the most relevant services for the organisation.

Figure 63: UK University 2 Distribution of average spent time per Service Category and Subcategory



Source: Author (2021)

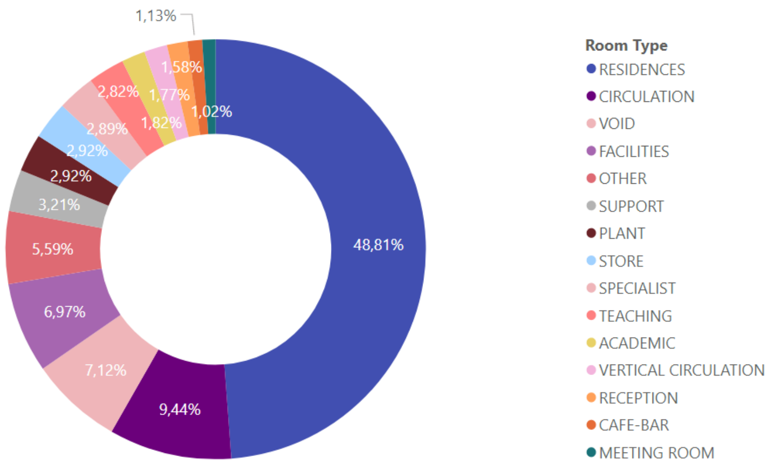
Figure 64: UK University 2 Pareto Graph



Source: Author (2021)

Figure 65 shows the distribution of Work Requests per Room Type. Residences are responsible for 48,81% of the total requests, followed by Circulations (9,44%), Void spaces (7,12%), Facilities (e.g., toilet, lifts, office) (6,97%), Support rooms (e.g., office, toilet, kitchen) (3,21%), Plant (e.g., boiler, switch, toilet) (2,92%), Store (2,92%), Specialist (2,89%), Teaching (2,82%) and Academic (1,82%). The remaining percentage (11,09%) is distributed over 20 other categories, including Lecture, Recreation and Research environments.

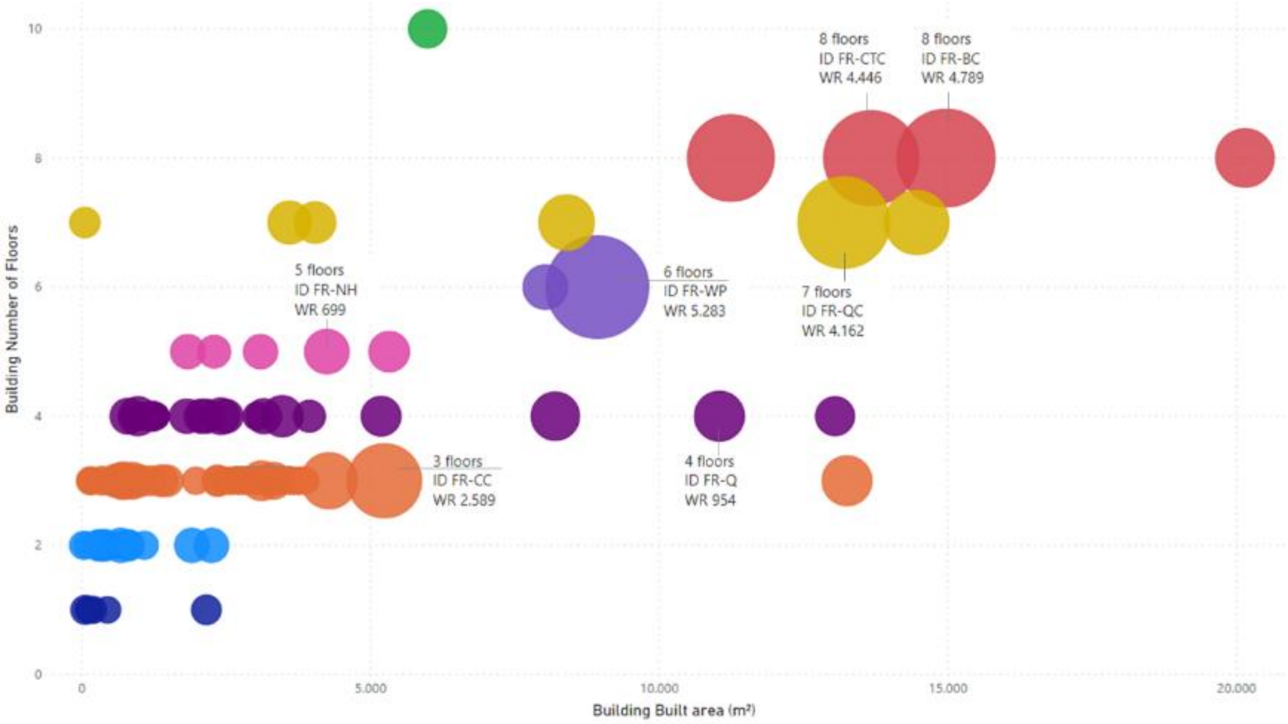
Figure 65: UK University 2 Distribution of Work Requests per Room Type



Source: Author (2021)

The distribution of Work Requests per Building Number of Floors according to the Building Built Area is shown in Figure 66. Most requests are concentrated in buildings with 6, 7 and 8 floors and with built area superior to 8.000m². This cluster includes Building ID FR-WP with 5.283 requests, Building ID FR-QC with 4.162 requests, Building ID FR-CTC with 4.446 requests and Building ID FR-BC with 4.789 requests. Other significant number of requests is observed in buildings with built area inferior to 5.000 m², including the 3 floors Building ID FR-CC with 2.589 requests and the 5 floors Building ID FR-NH with 699 requests.

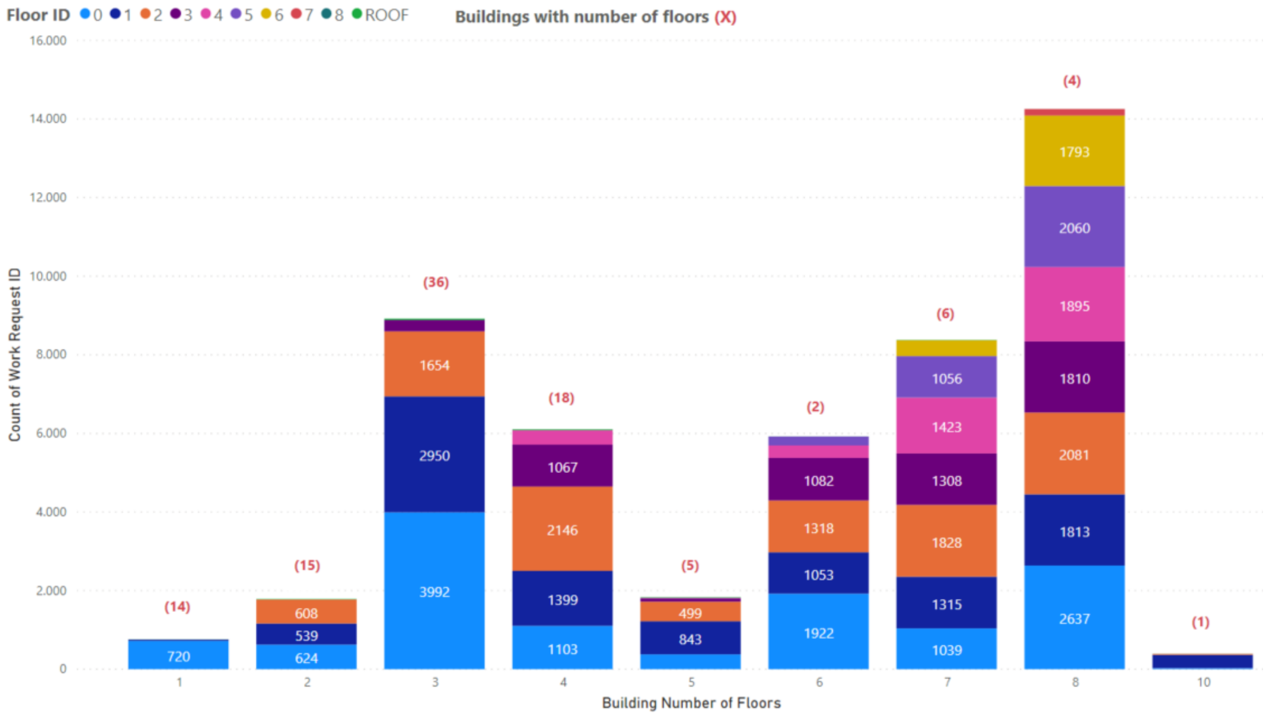
Figure 66: UK University 2 Distribution of Work Requests per Building Number of Floors according to the Building Built Area



Source: Author (2021)

Figure 67 shows the distribution of Work Requests per Building Number of Floors according to the building Floor ID. A group of 46 buildings with 3, 7 and 8 floors concentrate most requests. Requests related to the floor 0 are predominant in buildings with 1, 2, 3, 6 and 8 floors. In buildings with 5 and 10 floors, most requests are from floor 1, while in buildings with 4 and 7 floors, floor 2 is predominant.

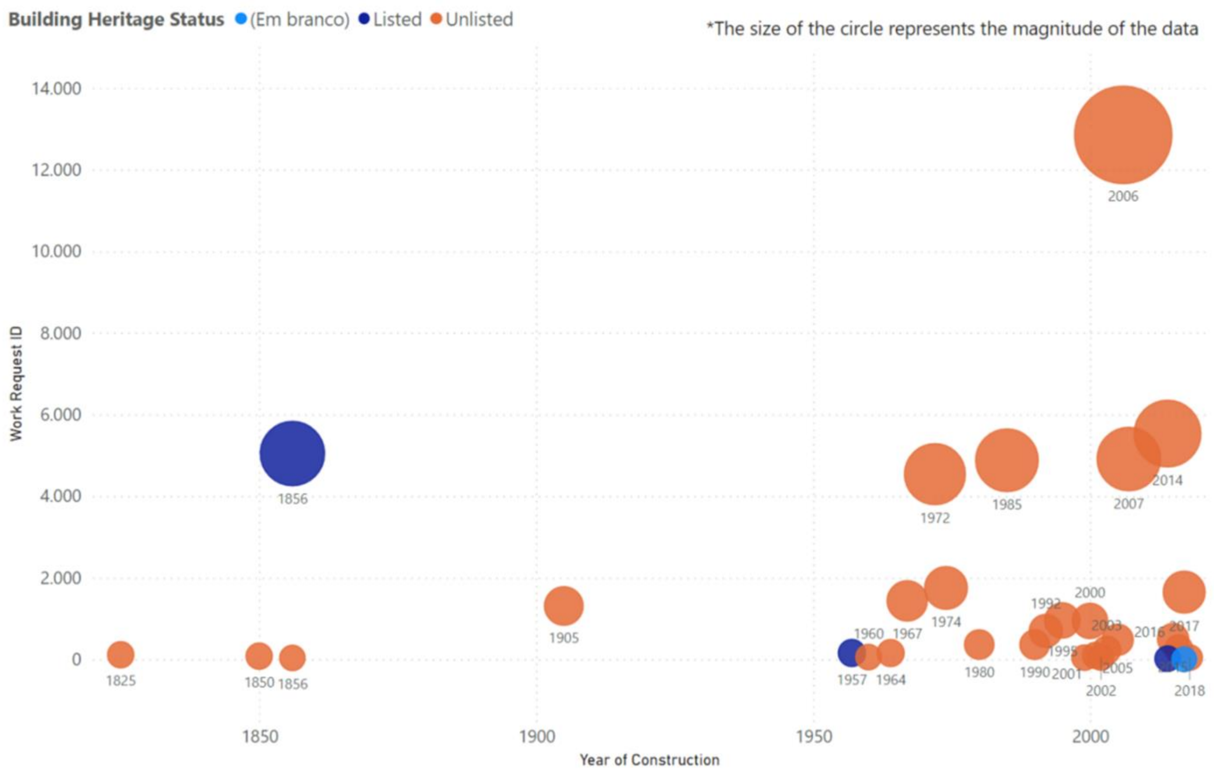
Figure 67: UK University 2 Distribution of Work Requests per Building Number of Floors according to the building Floor ID



Source: Author (2021)

The distribution of Work Requests according to the buildings Year of Construction and Heritage Status is depicted in Figure 68. Most requests come from unlisted buildings constructed between 1967 and 2017. In the Unlisted category, buildings from 2006 concentrate 12.852 requests, followed by buildings from 2014 with 5.531 requests, 2007 (4.909 requests), 1985 (4.878 requests), and 1972 (4.538 requests). Listed buildings from 1856 have demanded a significant number of 5.043 work requests.

Figure 68: UK University 2 Distribution of Work Requests according to the buildings Year of Construction and Heritage Status



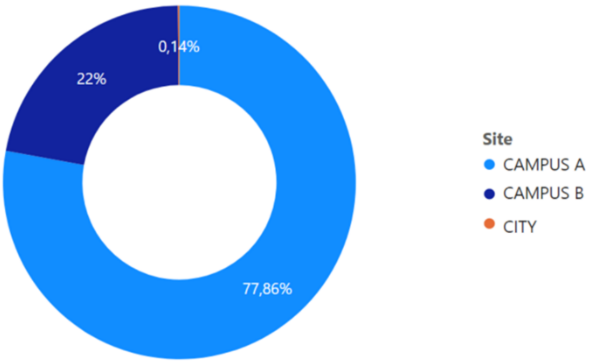
Source: Author (2021)

c. BR University

The Work Requests analysis aims to characterize FM requests and to identify the most critical maintenance problems in the infrastructure of the BR University over the studied period. The database contains a total of 1.441 Work Requests attended by the FM Sector in all university sites from December 2018 to December 2019 (BR University, 2020).

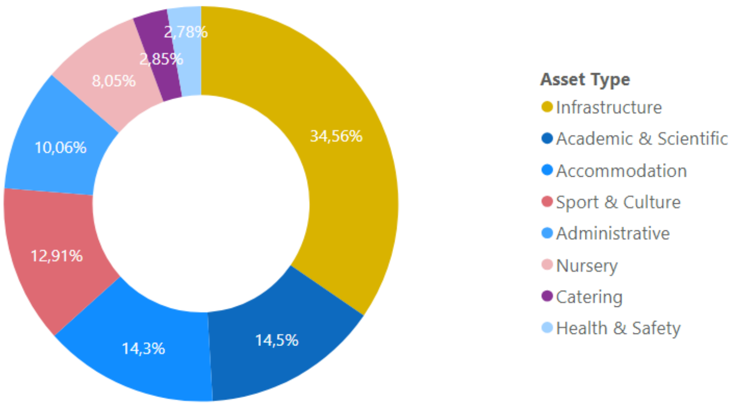
The first stage analysis regards to the general services provided in the period. The distribution of Work Requests per Site[32] is presented in Figure 69. Campus A concentrates 77,86% of the whole requests, followed by Campus B with 22% and City with 0,14%. The pizza chart (Figure 70) draws the distribution of Work Requests per Asset Type over the university sites. *Infrastructure* is the most requesting services with 34,56% of the total requests. In the built environment, *Academic & Scientific* and *Accommodation* buildings correspond to approximately 14% of the whole requests each, followed by *Sport & Culture* (12,91%), *Administrative* (10,06%), *Nursery* (8,05%), *Catering* (2,85%), and *Health & Safety* (2,78%).

Figure 69: BR University Distribution of Work Requests per Site



Source: Author (2021)

Figure 70: BR University Distribution of Work Requests per Asset Type



Source: Author (2021)

The distribution of Work Requests per Asset ID is showed in Figure 71. The *Infrastructure* of Campus A and 2 corresponds to 446 Work Requests. The most requesting building was the Children's Community Centre with 116 requests, followed by *the* Didactic Support Building (71), Student Accommodation B (58), Student Accommodation A (53) and Student Accommodation E (52). Together, all the Student Accommodation Buildings required 206 services.

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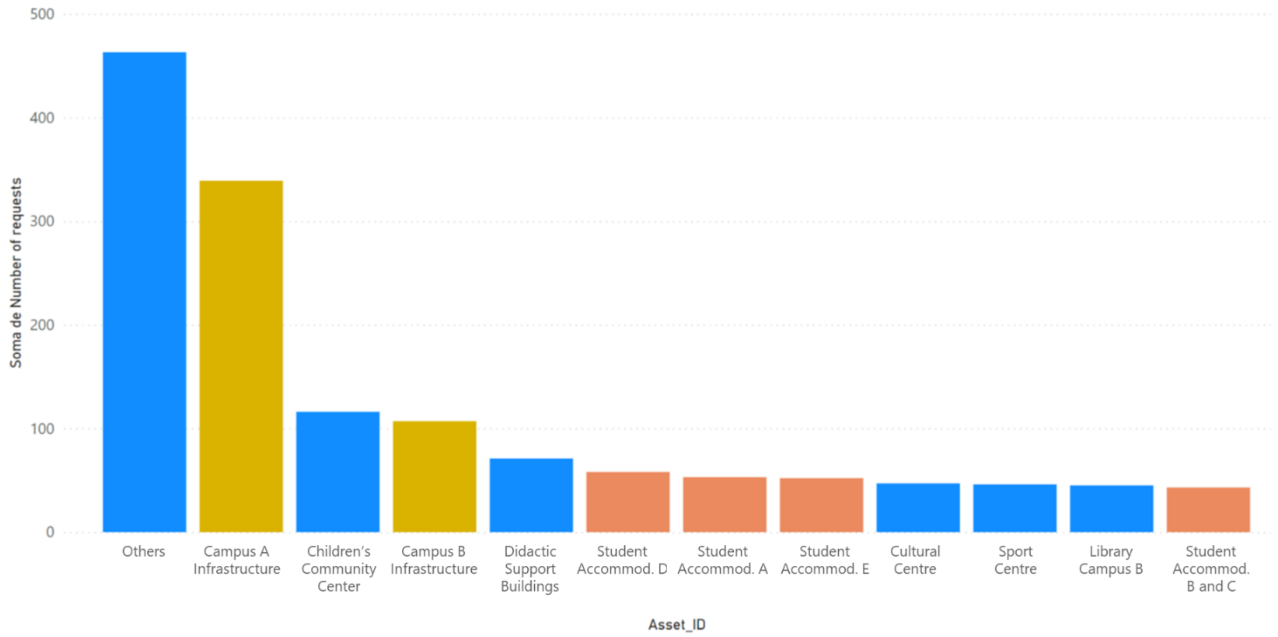
[32] Site names were replaced by codes to maintain the confidentiality of the university.

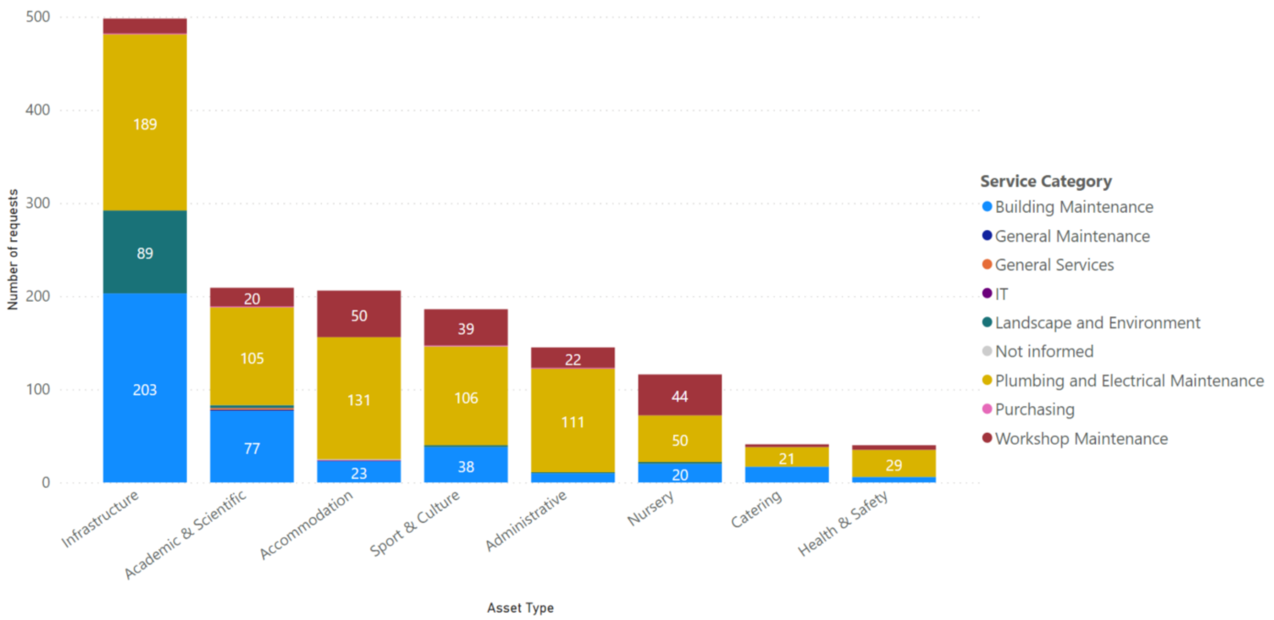
Figure 71: BR University Distribution of Work Requests per Asset ID



Source: Author (2021)

The distribution of Work Request per FM Service Category according to the Asset type is shown in Figure 72. *Plumbing and Electrical Maintenance* is the main service section over the selected period with 51,6% of the total requests, followed by *Building Maintenance* with 27,3%, *Workshop Maintenance* with 13,79%, and *Landscape and Environment* with 6,75% of the total Work Requests. Most of *Infrastructure* requests relate to *Building Maintenance* services (203), followed by *Plumbing and Electrical Maintenance* (189) and *Landscape and Environment* (89). For *Academic & Scientific* assets, 105 requests regard to *Plumbing and Electrical Maintenance* and 77 to *Building Maintenance*. For *Accommodation* buildings, *Plumbing and Electrical Maintenance* is the main service category with 131 requests, followed by *Workshop Maintenance* with 50 and *Building Maintenance* with 23. *Plumbing and Electrical Maintenance* is also predominant is the remaining Asset Categories (i.e., *Administrative, Sport & Culture, Nursery, Health & Safety,* and *Catering*).

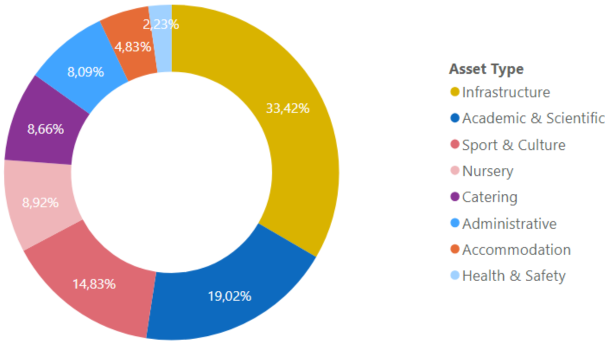
Figure 72: BR University Distribution of Work Request per FM Service Category according to the Asset type



Source: Author (2021)

Figure 73 shows the distribution of Work Requests per service spent time according to the Asset Type. *Infrastructure* is the most time-consuming category with 33,42% (roughly 9.700 hours) of the whole spent time, followed by *Academic & Scientific* with 19,02% and *Sport & Culture* with 14,86%. *Accommodation* and *Health & Safety* spent less time with 4,83% and 2,23%, respectively.

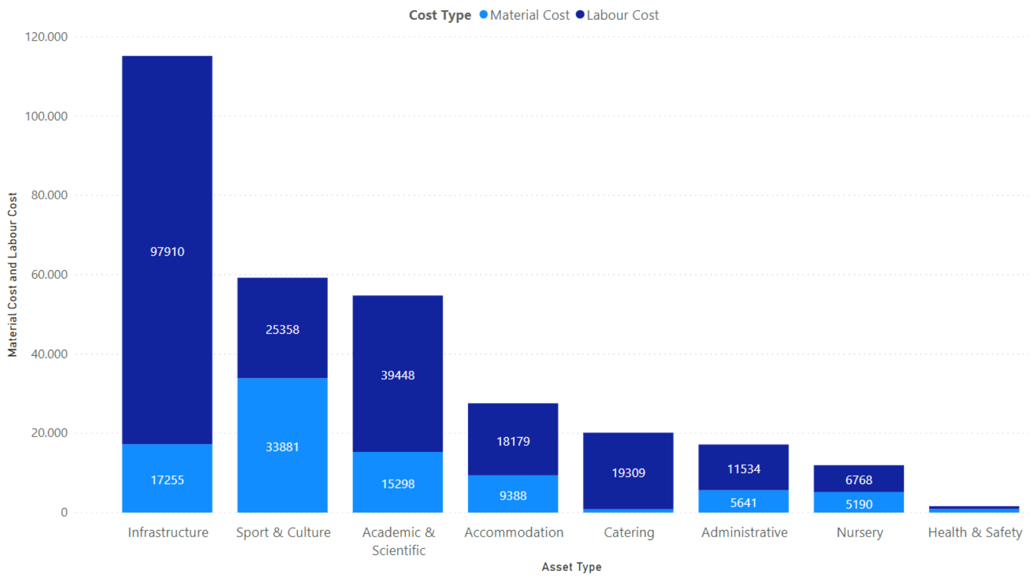
Figure 73: BR University Distribution of Work Requests per service spent time according to the Asset Type



Source: Author (2021)

The distribution of Work Requests per labour and material service costs according to the Asset Type is depicted in Figure 74. *Infrastructure* has the highest cost of FM services, spending R$97.910 with labour and R$17.255 with material, followed by *Sport & Culture* (R$25.358/labour and R$33.881/material), *Academic & Scientific* (R$39.448/labour and R$15.298/material) and *Accommodation* (R$18.179/labour and R$9.388/material)[33]. Labour costs are predominant in the remaining Asset Types.

Figure 74: BR University Distribution of Work Requests per labour and material service costs according to the Asset Type



Source: Author (2021)

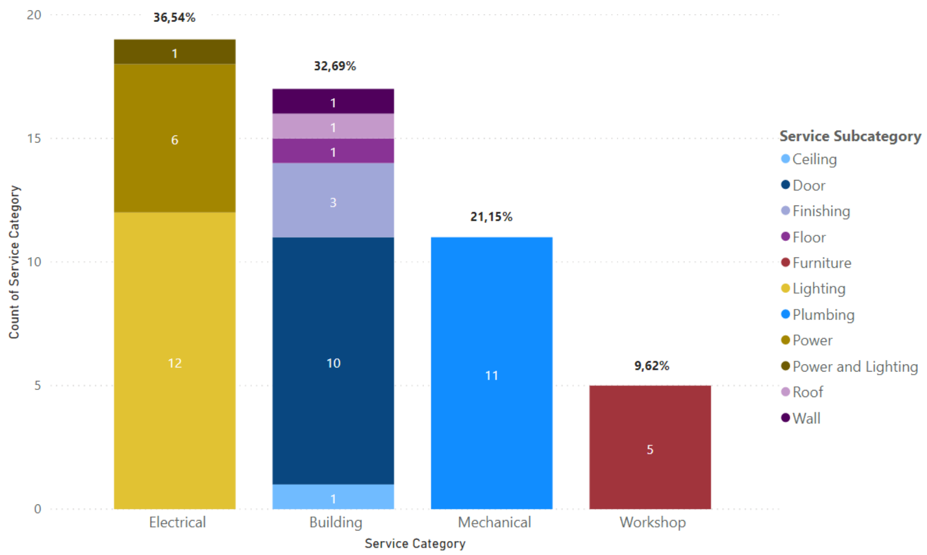
Focus on the Student Accommodation E data, 52 Work Requests from in the period were provided for analysis. The distribution of Work Requests per Service Category and Subcategory is drawn in Figure 75. *Electrical* is the most recurrent category with 36,54% of the whole requests, followed by *Building* repairs (32,69%), *Mechanical* (21,15%) and *Workshop* (9,62%). With respect to *Electrical* category, the graph shows that Lighting services were the most requested (12), followed by Power (6) and the combined categories (1); for

[33] Note: 1£ (Sterling Pound - GBP (540)) = R$7,2281 (Real - BRL (790)) (BCB, 2021).

Building, Door services are predominant (10), followed by Finishing (3); for Mechanical, only Plumbing services were done (11); and for Workshop, 4 requests related to *Furniture* were attended.

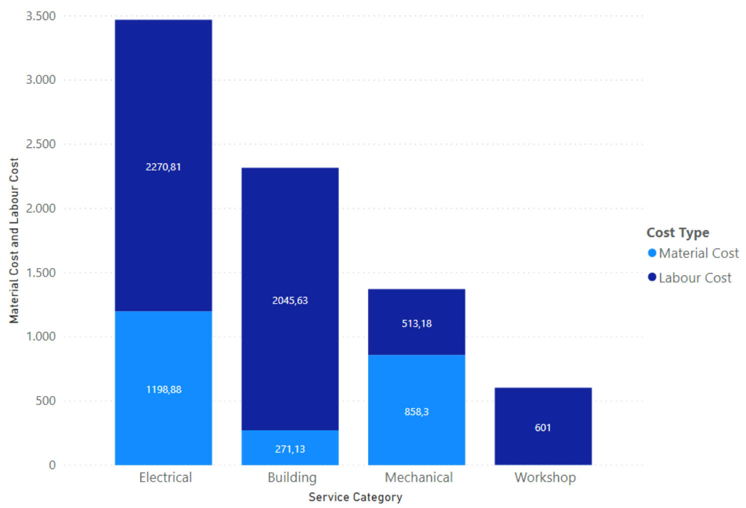
Figure 76 shows the distribution of labour and material service costs per Service Category. *Eletrical* is the costliest service, spending R$2.270,81 with labour and R$1.198,88 with material, followed by *Building* (R$2.045,63/labour and R$271,13/material), Mechanical (R$513,18/labour and R$858,30/material), and Workshop (R$601 with labour)[34].

Figure 75: BR University Distribution of Work Requests per Service Category and Subcategory



Source: Author (2021)

Figure 76: BR University Distribution of Labour and Material service costs per FM Service Category



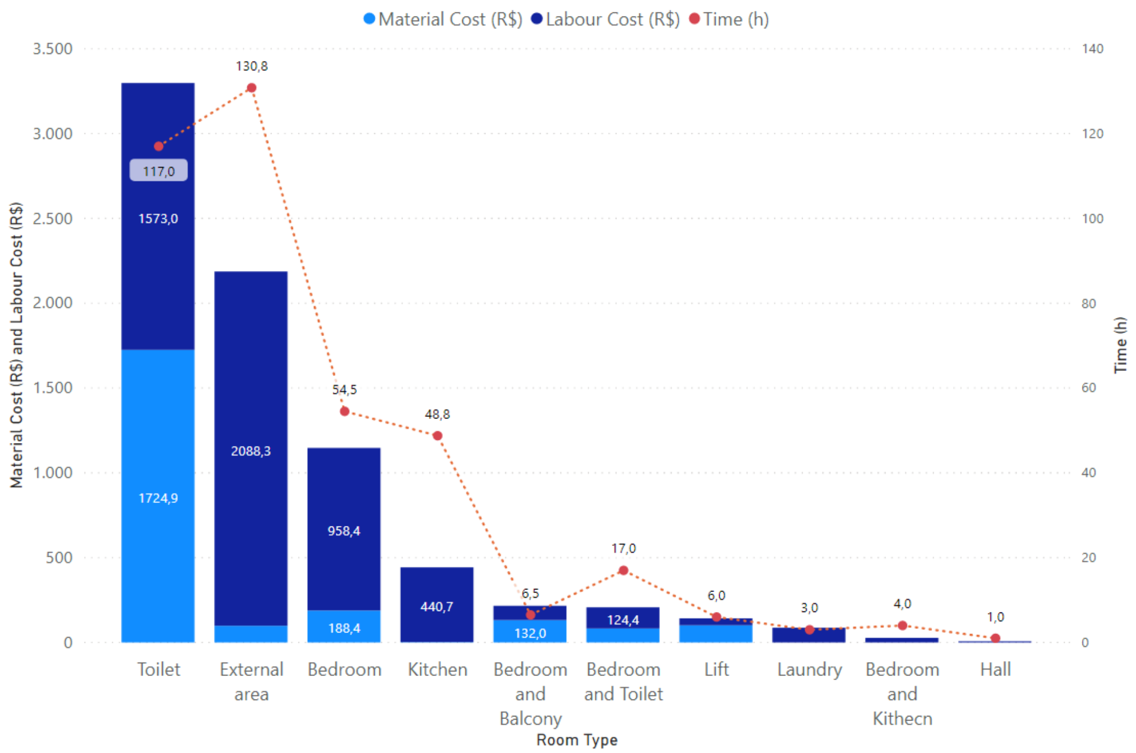
Source: Author (2021)

Figure 77 depicts the distribution of material and labour costs and spent time according to the Room Type. *Toilet* is the costliest room, spending R$1.573,0 with labour and R$1.724,9 with material, followed by *External Areas* (R$2.088,3 with labour and R$98,6 with material), *Bedroom* (R$958,4 with labour and R$188,4 with material), and *Kitchen* (R$440,7 with labour)[35]. Regarding to spent time, External area is the most time consuming (about 130 hours), followed by Toilet (117 hours) and Bedroom (about 54 hours).

[34] Note: 1£ (Sterling Pound - GBP (540)) = R$7,2281 (Real - BRL (790)) (BCB, 2021)
[35] Note: 1£ (Sterling Pound - GBP (540)) = R$7,2281 (Real - BRL (790)) (BCB, 2021)

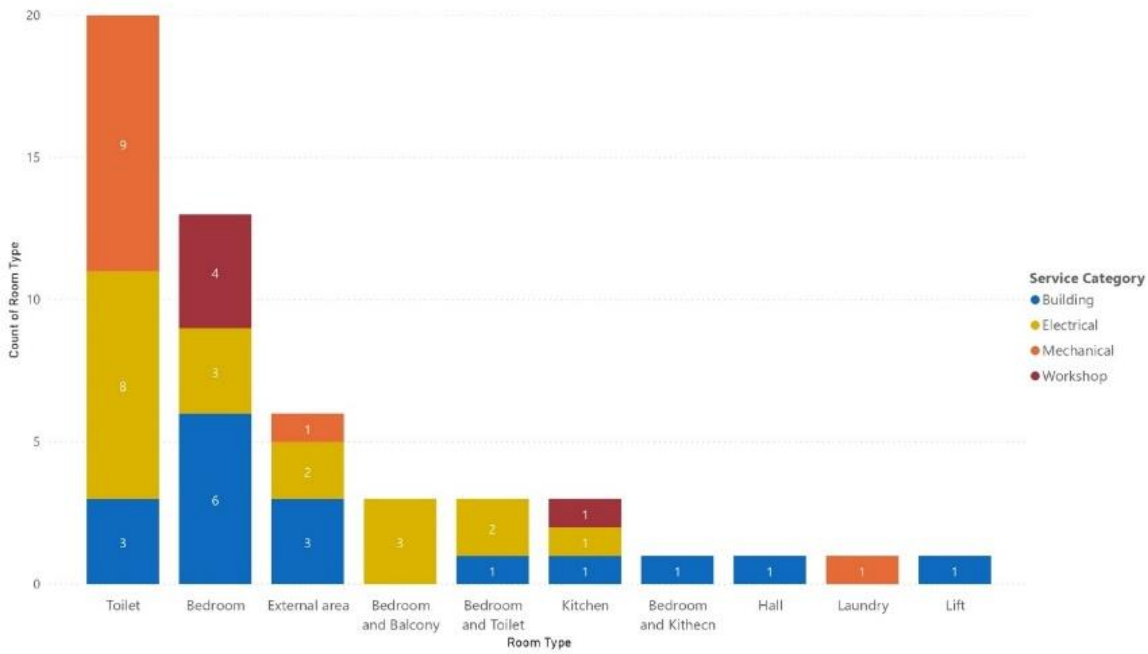
The distribution of Work Requests and Service Categories per Room Type is shown in Figure 78. *Toilet* is the most requiring services room, with 9 *Mechanical* issues, 8 *Electrical* and 3 *Building*, followed by *Bedroom* with 6 *Building*, 4 Workshop and 2 *Electrical* issues. Some requests were shared between rooms, such as 3 *Electrical* between *Bedroom and Balcony* rooms, 2 *Electrical* and 1 *Building* between *Bedroom and Toilet*. *External areas* requested 3 *Building*, 2 *Electrical* and 1 *Mechanical* services. Other rooms include Laundry (1), Lift (1) and Hall (1).

Figure 77: BR University Distribution of Work Requests per Material and Labour costs and Spent time according to the Room Type



Source: Author (2021)

Figure 78: BR University Distribution of Work Requests and Service Categories per Room Type



Source: Author (2021)

4.3.4. Statistical Analysis of Reactive Maintenance Work Requests of the UK universities

Statistical analysis of UK University 1 and UK University 2 Work Requests data was conducted aiming to determine the influence of building characteristics in problem occurrence and time response. To do so, a series of steps were taken. First, only the Work Requests categorized as "reactive maintenance" in the FM Group were selected, corresponding to 88.824 Work Requests. Second, the unit of analysis was determined aiming to cluster identical requests according to the variables University ID, Site ID, Building ID, Room ID, Room Type, Floor ID, Service Category, and Service Subcategory. This process resulted in 45.143 Work Requests. In sequence, requests with missing building characteristics data were excluded, remaining 41.933 Work Requests.

Based on that, the dependent variables were defined, including *i. problem occurrence*, calculated from the number of requests per square meter, and *ii. time response*, corresponding to the average time spent on reactive maintenance service subcategories. The decision of dividing the number of requests per square meter was taken aiming to standardize the unity of analysis and avoid the bias of bigger buildings. Similar strategy was adopted by Gunay et al. (2018) in the investigation on HVAC work order frequency analysis. The independent variables were selected according to their potential to influence the number of requests and the length of time for service execution, and classified in two classes: metric, including Site Area (m^2), Site Built Area (m^2), Building Built Area (m^2), Building Number of Floors, and Year of Construction; and nonmetric, comprehending Floor ID, Room Type, and Building Heritage Status. Table 21 depicts the dependent and independent variables selected for analysis, organized according to the code, name, definition and level of measurement.

Table 21: Statistics Analysis Variables

Dependent Variables (Services characteristics)			
Code	Name	Definition	Level of measurement
WR/m2	Occurrence	Corresponding to the number of requests per square meter (e.g., 100/ m^2)	Metric
TIME	Time Response	Corresponding to the average time spent on reactive maintenance service subcategories measured in days (e.g., 10,5 days)	Metric
Independent Variables (Building characteristics)			
Code	Name	Definition	Level of measurement
Site_Area_m2	Site Area (m^2)	Corresponding to the site area in square meters (e.g., 30.000 m^2)	Metric
Site_Built_Area_m2	Site Built Area (m^2)	Corresponding to the site built area in square meters (e.g., 250.580 m^2)	Metric
Building_Built_Area_m2	Building Built Area	Corresponding to the total building built area in square meters (e.g., 6.150 m^2)	Metric
Building_Number_Floors	Number of Floors	Corresponding to the building number of floors (e.g., 7)	Metric
Year_Construction	Year of Construction	Corresponding to the year the buildings was constructed (e.g., 1995)	Metric
Floor_ID	Floor ID	Corresponding to the floor level identification (e.g., 1; 5; roof; etc.)	Nonmetric
Room_Type	Room Type	Corresponding to the functional type of room (e.g., bedroom, kitchen, etc.)	Nonmetric
Building_Heritage_Status	Building Heritage Status	Corresponding to the building heritage status (i.e., listed; unlisted)	Nonmetric

Source: Author (2021)

A descriptive analysis of the metric variables was carried out using the software *SAS University Edition*, as show in Table 22. Aiming to select the most appropriate method for inferential analysis, conditions of normality of data (Table 23) and collinearity (Table 24) were verified. The lack of normality in all data (i.e., p<0.01) and the multicollinearity among variables (i.e., Correlation Estimate>0,5) supported the selection of the Partial Least Squares regression (PLS) method.

Table 22: Data Descriptive Statistics

Variable	Site_Area _m2	Site_Built_ Area_m2	Building_ Built_ Area_m2	Building_ Number_ Floors	Year_ Construction
Mean	611773,84	175887,62	8403,27	6,00	1984,71
Std Dev	198293,48	159140,55	5433,42	2,05	40,10
Minimum	102,00	50,00	21,77	1,00	1825,00
Maximum	746240,00	324285,37	32506,29	11,00	2018,00
Median	633287,00	324285,37	8928,00	6,00	2003,00
N	41933,00	41933,00	41933,00	41933,00	41933,00
Std Error	968,35	777,15	26,53	0,01	0,20
Variance	39320303382,00	25325713864,00	29522013,59	4,20	1608,03
Mode	633287,00	324285,37	14969,72	8,00	2006,00
Range	746138,00	324235,37	32484,52	10,00	193,00
Lower 95% CL for Mean	609875,87	174364,40	8351,26	5,98	1984,33
Upper 95% CL for Mean	613671,82	177410,84	8455,28	6,02	1985,09
Coeff of Variation	32,41	90,48	64,66	34,12	2,02
Skewness	-2,20	-0,14	0,18	-0,13	-2,28
Kurtosis	3,53	-1,97	-0,89	-0,49	4,71

Source: Author (2021)

Table 23: Goodness-of-Fit Tests for Normal Distribution - Kolmogorov-Smirnov

Parameter	Kolmogorov-Smirnov	p Value
Site_Area_m2	0.43424	<0.010
Site_Built_Area_m2	0.35876	<0.010
Building_Built_Area_m2	0.128145	<0.010
Building_Number_Floors	0.17229	<0.010
Year_Construction	0.23676	<0.011

Source: Author (2021)

The diverse nature of the independent variables (i.e., metric and nonmetric) imposed restrictions to establish a relationship among them and, consequently, to define the most appropriate analysis method to be adopted. Besides, the high correlation among the predictor variables required a joint analysis of the data.

Partial Least Squares regression (PLS) analysis was developed in the 1960', primarily for the econometric area. Later, it was adopted by the chemical, pharmaceutical, food and plastic sectors, since it does not require a defined distribution of errors (BASTIEN; VINZI; TENENHAUS, 2005). In this context, a common application of PLS was modelling the relationship among spectral measurements (NIR, IR and UV) of several correlated variables with the chemical composition or other physical-chemical properties. Currently, PLS regression is mostly used to develop predictive models and is a standard tool for modelling linear relationships between multivariate measurements, particularly in the field of chemometrics and in studies using DNA gene expression data to classify samples into categories, such as types of cancer (NGUYEN; ROCKE, 2002).

Table 24: Matrix of Correlations

Variable	With Variable	Correlation Estimate	95% Confidence Limits		P Value
			Lower	Upper	
Site_Area_m2	Site_Built_Area_m2	0,08	0,07	0,09	<.0001
Site_Area_m2	Building_Built_Area_m2	0,30	0,29	0,31	<.0001
Site_Area_m2	Building_Number_Floors	0,38	0,37	0,38	<.0001
Site_Area_m2	Year_Construction	0,71	0,71	0,72	<.0001
Site_Area_m2	Spent_Time_Day	-0,02	-0,03	-0,01	0.0009
Site_Area_m2	Work_Request_ID_m2	-0,11	-0,12	-0,10	<.0001
Site_Area_m2	Count_Work_Request_ID	-0,18	-0,19	-0,17	<.0001
Site_Built_Area_m2	Building_Built_Area_m2	0,46	0,45	0,47	<.0001
Site_Built_Area_m2	Building_Number_Floors	0,20	0,19	0,21	<.0001
Site_Built_Area_m2	Year_Construction	0,38	0,37	0,39	<.0001
Site_Built_Area_m2	Spent_Time_Day	-0,02	-0,03	-0,01	0.0001
Site_Built_Area_m2	Work_Request_ID_m2	-0,10	-0,11	-0,09	<.0001
Site_Built_Area_m2	Count_Work_Request_ID	-0,10	-0,11	-0,09	<.0001
Building_Built_Area_m2	Building_Number_Floors	0,65	0,65	0,66	<.0001
Building_Built_Area_m2	Year_Construction	0,56	0,55	0,57	<.0001
Building_Built_Area_m2	Spent_Time_Day	-0,06	-0,07	-0,05	<.0001
Building_Built_Area_m2	Work_Request_ID_m2	-0,18	-0,19	-0,17	<.0001
Building_Built_Area_m2	Count_Work_Request_ID	-0,14	-0,15	-0,13	<.0001
Building_Number_Floors	Year_Construction	0,43	0,42	0,44	<.0001
Building_Number_Floors	Spent_Time_Day	-0,02	-0,03	-0,01	<.0001
Building_Number_Floors	Work_Request_ID_m2	-0,16	-0,17	-0,15	<.0001
Building_Number_Floors	Count_Work_Request_ID	-0,10	-0,11	-0,09	<.0001
Year_Construction	Spent_Time_Day	-0,04	-0,05	-0,03	<.0001
Year_Construction	Work_Request_ID_m2	-0,14	-0,15	-0,13	<.0001
Year_Construction	Count_Work_Request_ID	-0,26	-0,27	-0,25	<.0001
Spent_Time_Day	Work_Request_ID_m2	0,03	0,02	0,04	<.0001
Spent_Time_Day	Count_Work_Request_ID	0,06	0,05	0,07	<.0001
Work_Request_ID_m2	Count_Work_Request_ID	0,10	0,10	0,11	<.0001

Source: Author (2021)

The Nonlinear Iterative Partial Least Squares (NIPALS) algorithm was applied to calculate the components of the PLS analysis, as shown in Table 25. The large number of explanatory variables and their high correlation might impose overadjustment, leading to a well-adjusted model with little or no predictive power. Therefore, it was necessary to measure the predictive power for each added component through a cross-validation. This technique is a practical solution for measuring predictive power and is built into most of the available statistics software.

The cross validation works by partitioning the data into groups and subgroups and omitting one group at a time for analysis. The data from the other groups were used to build a model. This model was used to predict the Y values of the omitted data, and the predictions are compared with the omitted values, reserving these predictions residuals. This process was repeated until each group is omitted once, supporting calculation of the total sum of the squares of these differences, named Predictive Residual Sum of Squares (PRESS) value. Components were added to the model until the next component has increased the PRESS value. In the sequence, the Variable Importance in Projection (VIP) was calculated to select the most important independent variables for the model. To do so, the variables with values superior to 0,8 were selected, addressing the criteria of importance established by the adopted method. Finally, the Parameter Estimative of PLS analysis was determined for the dependent variables.

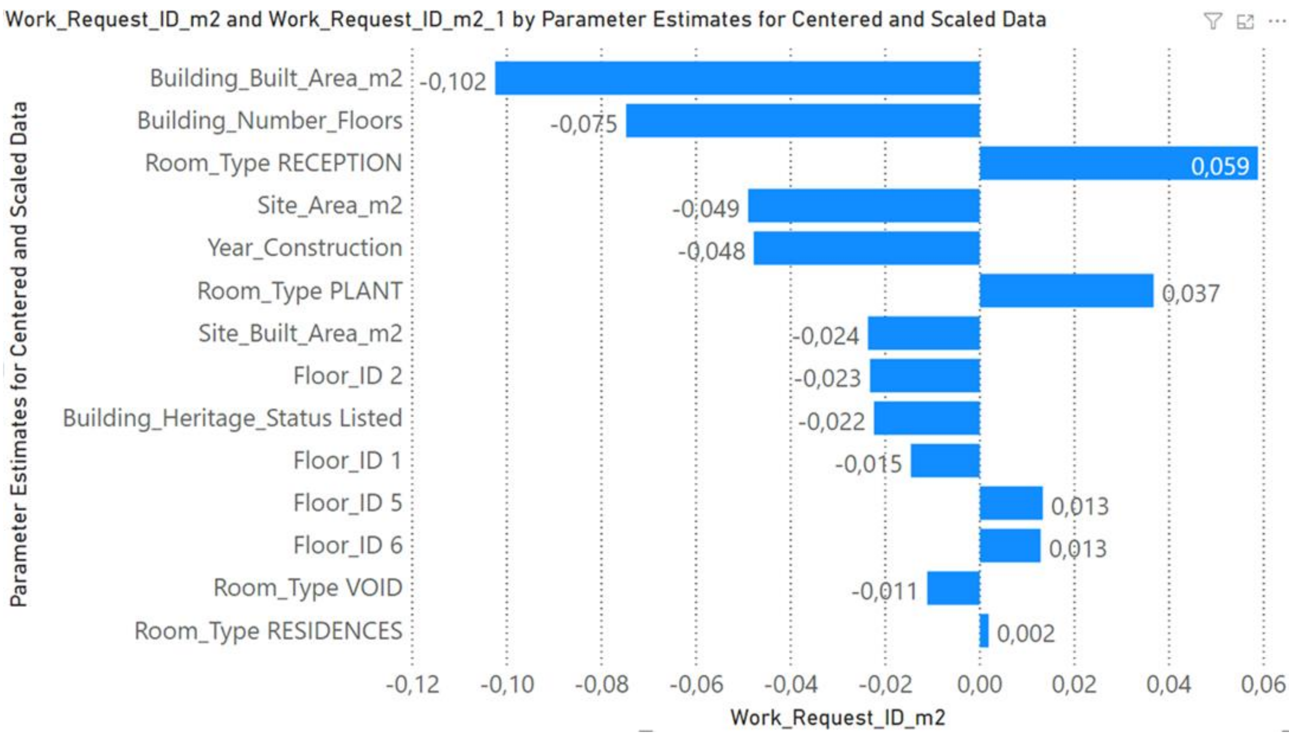
Table 25: Components of the PLS analysis

Item	
Factor Extraction Method	Partial Least Squares
PLS Algorithm	NIPALS
Number of Response Variables	1
Number of Predictor Parameters	91
Missing Value Handling	Exclude
Maximum Number of Factors	15
Validation Method	10-fold Random Subset Validation
Random Subset Seed	39410706
Validation Testing Criterion	Prob T**2 > 0.1
Number of Random Permutations	1000
Random Permutation Seed	39410749
Number of Observations Read and Used	41933

Source: Author (2021)

Figure 79 shows the independent variables most in most influencing the problem occurrence by decrescent order of importance. The variables with negative influence were Building_Built_Area_m2, Building_Number_Floors, Site_Area_m2, Year_Construction, Site_Built_Area_m2, Floor_ID 2, Building_Heritage_Status Listed, Floor_ID 1, Room_Type VOID. On the other hand, the variables with positive influence were Room_Type RECEPTION, Room_Type PLANT, Floor_ID 5, Floor_ID 6, and Room_Type RESIDENCES.

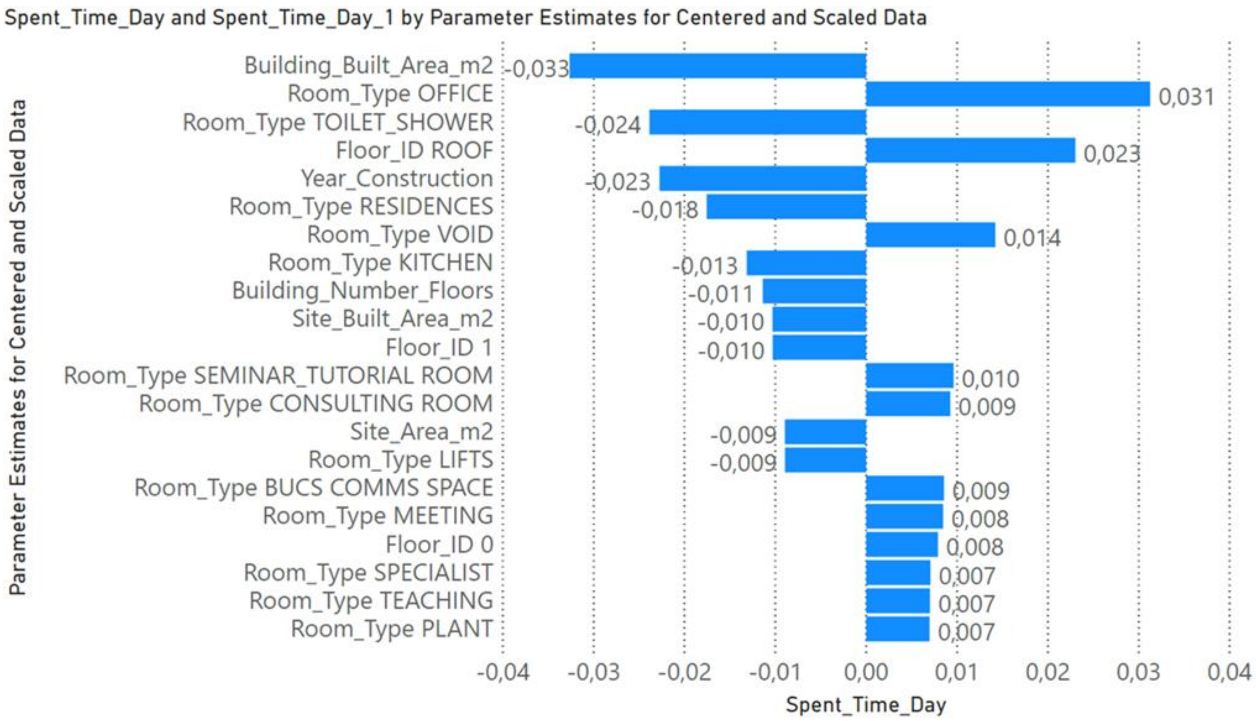
Figure 79: Parameter Estimative of PLS analysis tested for the dependent variable WR/m^2 sorted by absolute value



Source: Author (2021)

The independent variables most in most influencing the time response are depicted in Figure 80 by decrescent order of importance. The variables with negative influence were Building_Built_Area_m2, Room_Type TOILET_SHOWER, Year_Construction, Room_Type RESIDENCES, Room_Type KITCHEN, Building_Number_Floors, Site_Built_Area_m2, Floor_ID 1, Site_Area_m2, Room_Type LIFTS. In contrast, the variables with positive influence were Room_Type OFFICE, Floor_ID ROOF, Room_Type VOID, Room_Type SEMINAR_TUTORIAL ROOM, Room_Type CONSULTING ROOM, Room_Type BUCS COMMS SPACE, Room_Type MEETING, Floor_ID 0, Room_Type SPECIALIST, Room_Type TEACHING, Room_Type PLANT.

Figure 80: VIP values of PLS analysis tested for the dependent variable TIME



Source: Author (2021)

4.4. Discussion

4.4.1. Characterization of FM sectors and reactive maintenance services and processes

The descriptive analysis of the data provided in the interviews and focus group supported the characterization of the universities' FM sector and the reactive maintenance services and processes. In this section, the cross-case discussion approaches aspects related to the institution (i.e., year of creation, city, main campus, main campus area, main campus built area, number of sites, number of students and number of staff), the FM sector (i.e., name, scope, organizational structure, predominant modality of service execution, staff, budget, CAFM system, additional ICTs, status of BIM and IoT implementation for FM), and the reactive maintenance services (i.e., stages, stakeholders, flows, activities, gateways, etc.). Table 26 shows a summary of the main institutional and FM sector aspects.

Exploring the universities organizational aspects supports the understanding of the context in which FM problems are generated, managed, and solved. The UK University 2 has the biggest population of students and staff, followed by the UK University 1, and the BR University. All the universities are multi-site, including individual buildings (e.g. located in the city centre) and structured campuses, which requires specific approaches in comparison to single site organizations (BARRETT; FINCH, 2014). According to Abdul-Lateef

(2010, p. 58), the lack of a well-defined organizational structure is a very influential factor on university building maintenance management, impacting on "the scope and quality of maintenance".

Although created at distinct times, the construction of the three universities main site has started between the 1960s and 1970s, an important period of development and endorsement of university campuses as the prevailing form of spatial organization (BUFFA; PINTO, 2017; FIALHO, 2012). Thus, in all cases a similar age of assets, variety of building functions, and complexity of the infrastructure is observed. Among the three main sites, the UK University 1 Campus A covers the biggest ground area, while the UK University 2 Campus A counts with the biggest building-built area, which might influence the demand for maintenance and operation services, respectively, in external and internal areas.

Regarding to FM sector aspects, singularities among the three cases were verified. In general, similar services are provided by all universities corresponding to the traditional FM areas of Facility Planning, Building operations and maintenance, General office service and Real estate and building construction (BARRETT; FINCH, 2014). However, while the FM Sector of the UK University 2 covers a broader scope driven to all university assets, the others have some restrictions in service attendance: the UK University 1 FM sector focuses on academic, research, administrative, sport, and medical assets, with supplementary support to accommodation and catering hospitalities, which have their own work force able to do small fixes; the BR University FM Sector focuses on administrative, accommodation, catering, sport, and medical assets, occasionally supporting academic and research institutes and schools, which have their individual FM team. In fact, the decision about the scope of services to be provided may consider the necessities of each organization over time (BARRETT; FINCH, 2014).

The modality of service execution and the FM team size were analysed. At UK University 2, FM services are predominantly provided by a main subcontracted company, also supported by a group of about 80 professionals of the FM Sector, 36 of them involved with maintenance. On the contrary, at UK University 1 and BR University most maintenance services are in-house supported by approximately 50 professionals. In all cases, the complexity of the problem influences the necessity of purchasing material and hiring external suppliers, thus impacting the service attendance performance.

As discussed by Chanter and Swallow (2007) and Barrett and Finch (2014), both modalities may be advantageous to organizations, either individually or combined, depending on the particular requirements. Besides, the size of the FM sector may be proportional the scale of the organization and to the amount of facilities work carried out. Issues related to outsourced services were raised by Abdul-Lateef (2010, p. 58) (e.g. confidence and trust in external suppliers; redundancy with in-house staff) and might be considered in establishing the modality of service execution to effectively perform maintenance activities (OFORI; DUODU; BONNEY, 2015).

A heterogeneous budget data was provided by the three universities. In 2019, UK University 1 FM budget was approximately £17.000.000, roughly 9% directly applied to reactive maintenance material; at UK University 2, about £5.000.000 were related to maintenance services; at BR University, about R$17.000.000 were driven to FM services, roughly 9% related to building maintenance, road system maintenance, external areas maintenance, and construction[36].

[36] Note: 1£ (Sterling Pound - GBP (540)) = R$7,2281 (Real - BRL (790)) (BCB, 2021)

Table 26: Institutional and FM sector aspects of the universities

Item		University		
		UK University 1	UK University 2	BR University
Institutional	Region	Southwest England, UK	Southwest England, UK	Southeast, Brazil
	Year of creation	1965	1992	1934
	Population (students and staff)	20.703 Students:18.103; Staff: 2.600 (UK University 1, 2018)	33.700 Students: 30.000; Staff: 3.700	9.471 Students: 7.867; Staff: 1.604
	Number of sites	17	11	4
	Main Campus opening year	1965	1975	1970'
	Main Campus area	75 ha	63 ha	32 ha
	Main Campus built area	289.904 m²	324.000 m²	33.617 m²
FM Sector	Scope	Projects of new buildings and the refurbishment, maintenance and operation of existing buildings and infrastructure. Focus on academic, research, administrative, sport, and medical assets, with supplementary support to accommodation and catering assets.	Provision and care of buildings and infrastructure through FM, business, accommodation, and health and safety services.	Provision of administrative and physical support for university activities development. Focus on administrative, accommodation, catering, sport, and medical assets, with supplementary support to academic and research assets.
	Provided services	Maintenance and repairs, capital projects and refurbishment, landscapes, portering, cleaning, mail services, telecommunications, central stores, waste and recycling, energy, administration and records management	Planned and reactive maintenance, energy and environmental management, space management, cleaning, portering, post, transport, car parking and security, catering, conferencing, accommodation services, printing and stationery, sports, and health and safety	Maintenance and construction, safety and security, transport, catering, library, communication, social support, nursery, informatics, and waste management
	Predominant modality of service execution	In-house	Outsourced	In-house
	Number of staff	About 212 About 50 involved with maintenance	About 80 About 36 involved with maintenance	210 55 involved with maintenance and operations
	Budget	About £17.000.000 for FM About £1.500.000 for reactive maintenance material (2019)	About £5.000.000 for maintenance (2019)	About R$17.000.000 for FM About R$1.600.000 for building maintenance, road system maintenance, external areas maintenance, and construction (2019)
	CAFM software	Archibus CAFM System	Archibus CAFM System	BR University CAFM system
	Additional ICTs (non-exhaustive list)	Space Management system Agresso Finance system Building Management System (BMS) RapidACCESS Share Point	Agresso Finance system Building Management System (BMS) CAD system BIM Software Autodesk Revit and Vizerra Revizto	AutoCad Autodesk
	Actions towards BIM implementation for FM	Null	Some	Null
	Actions towards IoT implementation for FM	Few	Few	Few
	Actions towards IoT implementation for FM	Few	Few	Few

Source: Author (2021)

As explained by one of the interviewees (UK UNIVERSITY 1, 2019e), a significant variation of FM budget is identified among UK universities, in parts, due to their individual aspects of scope, size, and organizational structure. In most cases, budget setting is based on the cost per square meter, what might not necessarily address rooms specificities (e.g., laboratory, classroom, bedroom, etc.). The complexity of budget formulation is described in the literature. Based on the analysis of Maintenance & Operations cost models, Krstić and Mareniak (2012) have identified aspects hampering cost definition and, accordingly, budgeting activities. Most aspects relate to lack of standardized procedures and lack of information, either about previous maintenance works or building characteristics:

> "- Existing models are usually not based on historical cost records.
>
> - Models founded on historical cost records are mainly developed based on the available cost structure, rather than on the predefined cost structure.
>
> - There are no databases containing records about maintenance and operation costs that could be used for future research to update or improve the existing models.
>
> - There is no framework for the systematization of data.
>
> - There is no simple model for predicting maintenance and operation costs that would be based on building characteristics, policy and user characteristic." (KRSTIĆ; MARENIAK, 2012, p. 297)

Since the availability of enough financial support is crucial for maintenance work (OFORI; DUODU; BONNEY, 2015; OUBODUN, 1996; PERERA; ILLANKOON; PERERA, 2016; SALLEH et al., 2016), Chanter and Swallow (2007) recommend that budgets must be dynamic and flexible and build upon a "high-quality management information" (e.g., previous costing data), "medium- and long-term maintenance programmes", and contingency for unexpected item.

Besides, a significant reduction of financial resources for maintenance is observed in the studied organizations. For example, at the BR University the maintenance budget moved from a ratio of R$19,92/m² in 2011 to R$ 10,42/m² in 2017, representing a 48% reduction (BR UNIVERSITY, 2017). In this scenario, solutions for optimizing maintenance services, such as identifying priorities and avoiding waste in service execution (JASPERS; TEICHOLZ, 2012), are imperative to ensure the quality of attendance and the university operation.

ICT solutions supporting FM activities were identified. The commercial Archibus CAFM System has been adopted by UK University 1 and UK University 2, while the in-house BR University CAFM system has been used by BR University for managing operation and maintenance requests. Besides, interviewees from the British universities have provided a non-exhaustive list of other systems, software, and database (e.g., Agresso Finance System, Building Management System, Autodesk Revit, etc.), while interviewees from the BR University only mentioned a software for designing and managing built environment information. Technical, process and policy issues related to ICT implementation are discussed in Section 5.4.2.

Different statuses of BIM and IoT implementation for FM purposes were observed among the universities, as deeply discussed in Section 5.4.2. At the time the interviews were undertaken, important actions towards BIM implementation have been taken by UK University 2, including software acquisition, BIM professional hiring, guideline development and university assets modelling in BIM platform (UK UNIVERSITY 2, 2018, 2019b). On the other hand, the FM sectors of UK University 1 and BR University have not implemented actions in this direction, even though positive expectations regarding BIM have been highlighted by the interviewees.

The Reactive Maintenance Service Process models (Figures 36, 38 and 40) generated for each university supported the characterization of main stakeholders, flows, activities, and gateways involved in service provision, and the identification of bottlenecks and potential areas to be improved through BIM and IoT implementation. In general, a similar sequence of activities and relationship among agents are observed in all cases. With respect to fault detection, the identification of a problem or issue is mainly based on human perception and discomfort with the circumstance, what can be a subjective decision (OUBODUN, 1996). Addressing HVAC issues, Gunay et al. (2018, p. 179) have identified that most requests have been based on user complaints, which were considered "severely enough to trigger complaint calls".

Likewise, reporting an issue to the FM sector involves human communication and individual initiative. As discussed by Abdul-Lateef (2010, p. 60), communication channels must facilitate problem reporting, avoiding time consuming contacts and hard access systems, since users "prefer one point of communication and do not want complications. They want someone to talk to if a problem arises". Although in the British universities most facilities are monitored and controlled by BMS, a self-reporting mechanism has not yet been developed. Beyond phone call, e-mail, and personal communication, in all the universities faults are mainly reported through digital interfaces, even though BR University still provides analogic paper-based forms to specific users.

Providing an example of a paper-based work order record, Akcamete, Akinci and Garrett Jr (2011) highlight the difficulty to update information into FM databases through a "labor intensive and error-prone" process, leading to inaccuracies and inconsistencies in facility information. Other obstacles are caused by the association of various components and spaces in one single work order and the inaccuracy of problem description in work orders (AKCAMETE et al., 2011).

The variety and lack of interoperability among reporting interfaces and CAFM tools hamper the capture, processing, and analysis of the request, impacting on service performance, as approached in Section 5.4.2. Regarding service prioritization, while at UK University 1 the activity is based on the Service Level Agreement document, a clear criterion was not identified in the UK University 2 and BR University. Establishing a priority coding is fundamental to plan work attendance, in special for unplanned requests addressing issues according to their risks to health and safety (BARRETT; FINCH, 2014; CHANTER; SWALLOW, 2007; JASPERS; TEICHOLZ, 2012; MÁRQUEZ, 2007).

In the stage of problem location and inspection, UK University 1 and BR University are mainly supported by fragmented statutory and building documents, while UK University 2 is also supported by the BIM model, providing a centralized and updated source of information, and enabling virtual inspections. As discussed by Becerik-Gerber et al. (2012, p. 434), the support of BIM models could benefit the work by streamlining the repetitive, "time- and labor consuming task" of equipment location, in special during emergencies or when external suppliers take responsibility for the service. In addition, supported "navigation capabilities" and mobile digital devices, the FM team is able to manage the target component into the model, also reducing the necessity of "paper-based systems" (BECERIK-GERBER et al., 2012, p. 434).

Despite the similarities, BR University service execution planning contains a particular characteristic in comparison to the other universities: the occasional requirement of bidding process. Applicable to Brazilian public organizations, this administrative procedure is mainly ruled by Law No. 8.666/1993 - Bidding and Contracts of the Public Administration (BRASIL, 1993), which establishes guidelines for public contracts. Previous studies have identified obstacles imposed by this legislation for managing services related to public buildings. First, the inherent bureaucracy which discourage the participation of competent companies in design and construction activities (BRASIL; SALGADO; LOMARDO, 2013; BRASIL, 2010). Depending on the complexity of the object, this process may take a significant amount of time, impacting on service performance. Second, the usual prioritization of the "lowest price" criterion rather than the "technique and price" criterion for selecting the most advantageous proposal for the contractor (BRASIL; SALGADO; LOMARDO, 2013; CAMPOS, 2010; ESTEVES, 2013), influencing the quality of services and material.

The stages of repair, check-out, delivery, and feedback are similarly undertaken in all universities. Although the user feedback is a requirement for closing the request, a clear strategy of using this information as a metric for assessing service performance and proposing improvements was not observed. As discussed by Pin, Medina, and McArthur (2018), users are more motivated to provide feedback in case of dissatisfaction, which must be considered by the FM sector an indicative of priority areas for service attendance (ALI et al., 2010).

4.4.2. Characterization of the scenario for current and potential applications of BIM and IoT-based solutions for FM and reactive maintenance services

The content analysis of the interviews and focus group transcriptions supported the achievement of one of the research purposes, namely characterization of the scenario for current and potential applications of BIM and IoT-based solutions for FM services, in particular for maintenance services. Addressing the final stage of content analysis, this section discusses the inferences and interpretations that evidence hidden meaning of the empirical data. The balance among the three thematic pillars – Technology, Process and Policy – was reinforced as crucial for FM digital transformation (LEWIS, 2012).

From the technological point of view, a gap between the available default solutions and the FM sector requirements and needs is observed. As described by the interviewees, despite the progress of IoT technologies, the rigid structure and technical limitations of commercial systems and software hamper the execution of FM current activities and the exploration of new business opportunities (JIA et al., 2019; RASHID; LOUIS; FIAWOYIFE, 2019). This perception is corroborated by the literature, which provides examples of restrictions related to CAFM software (e.g. visualization based only on 2D drawings and images (AZIZ; NAWAWI; ARIFF, 2016)), BAS systems (e.g. lack of capability to inspect algorithms for smart analytics (MISIC; GILANI; MCARTHUR, 2020)), and BIM software (e.g. lack of flexibility for adjustments and modifications (PARN; EDWARDS; DRAPER, 2016)).

Another limitation stated by the literature is the lack of involvement of software providers, "including fragmentation among different vendors, competition, and lack of common interests" (BECERIK-GERBER et al., 2012). Such issues might affect the confidence of organizations in these technologies (MISIC; GILANI; MCARTHUR, 2020), discouraging robust investments. Besides, the commitment of stakeholders to technological solutions is influenced by their individual abilities to easily operate these interfaces.

Although some organizations develop in-house solutions, difficulties in managing and updating such systems were identified, thus bringing uncertainty regarding their implementation. As approached in previous studies (ARSLAN et al., 2014; BECERIK-GERBER et al., 2012; EDMONDSON et al., 2018; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; LEWIS, 2012; MARMO et al., 2019; PARN; EDWARDS; DRAPER, 2016; TALAMO; BONANOMI, 2016), the lack of interoperability among systems and devices over building lifecycle is at the centre of the discussion, hampering collaboration, one of the basic principles of BIM (ARASZKIEWICZ, 2017).

In this sense, developing methodologies considering all involved stakeholders (PINTI et al., 2018), strengthening the relationship between IT developers and users (JIA et al., 2019), and supporting open platform developments are vital for FM sector progress towards full digitalization, as reinforced by Kassem et al. (2015, p. 272): "the differing life span of technologies and buildings suggests that there is a requirement for open source standards that aid in maintaining the usability of models". A strategic approach is imperative for defining the systems and devices that will better address FM sector needs in medium and long term, taking the concepts of functionality, flexibility, scalability, and interoperability into account.

Accessibility, availability, accuracy, and reliability of information over FM processes have emerged as essential requirements for improving FM service performance (BECERIK-GERBER et al., 2012; KASSEM et al., 2015; LEE; AKIN, 2009; PINTI et al., 2018; ZHAN et al., 2019) and effectively implementing BIM (AKCAMETE; AKINCI; GARRETT JR, 2010; CAVKA; STAUB-FRENCH; POTTINGER, 2015; KENSEK, 2015; LEWIS, 2012; ZADEH; STAUB-FRENCH; POTTINGER, 2015) and IoT solutions (MIRARCHI et al., 2018). Although security aspects must be considered for the establishment of tiers of information access (LEWIS, 2012), strategies that ensure a uniform distribution of reliable and effortlessly retrievable and traceable information among stakeholders must be assured (BECERIK-GERBER et al., 2012).

From strategic to operational levels, the importance of precise and available information for improving service performance and decision-making was evidenced. As exemplified by the participants, updated asset drawings and BIM models can save significant time and resources in non-added value tasks, such as field surveys, engaging the staff with core activities. The real-time monitoring of facilities must generate a rich database of performance records, driving efforts to critical asset at the right moment. In this perspective, technological solutions that optimize data gathering, storing, and sharing must be prioritized by organizations.

Information overload was described as a concern by one of the participants, what is corroborated by the literature. At the strategic level, Barrett and Finch (2014) proposed a decentralized decision-making structure, reducing the dependence of the facility manager on problems solving. At the operational level, Akcamete, Akinci and Garrett Jr (2010, p. 8) recommend the use of approaches that enable "to query and visualize only the required fraction of the history data". The same logic with respect to BIM was discussed by the European Federation of Engineering Consultancy Associations (2019), Sacks et al. (2018) and McArthur (2015) – this author recommended the generation of a simplified copy of the construction model which should include only essential data for operations.

Apart from technological aspects, *People issues,* and *Strategic, Tactical and Operational FM* drive the ICT implementation in the university context. The several levels of *awareness* of FM team members and sectors regarding BIM and IoT might be explained by the distinct professional backgrounds (e.g., computer science, civil engineering, architecture), job positions (e.g., BIM manager, FM manager, designer, CAD technician, etc.), and years of experience. Moreover, a clear understanding of ICT applications and requirements might influence the interest of individuals in developing specialized skills, hence, supporting technological implementations.

A correlation between the interviewee's BIM and IoT *awareness* and *engagement* levels and the FM sector *initiatives* towards digital transformation was observed. In general, benefits of these solutions for FM performance described in the literature were emphasized by the participants, such as navigation and visualization of building components characteristics in BIM models for diagnosis and repair, thus reducing period of disruption (COSTIN; PRADHANANGA; TEIZER, 2014; KASSEM et al., 2015; PATACAS; DAWOOD; KASSEM, 2016), prediction of problems (e.g. monitoring of facilities performance particularly in places with no visibility or human presence), space management (e.g. information on room occupation), and emergency management (e.g. information on users' location and evacuation routes (BECERIK-GERBER et al., 2012)).

As stated by one of the interviewees, in a bottom-up strategy, individual efforts towards persuading the head of department on the benefits of BIM were decisive for its implementation. Accordingly, a top-down response was generated through the hiring of specialized professionals and acquisition of supportive technological solutions. In fact, the engagement of stakeholders from all FM sector levels and the establishment of a clear strategy of implementation addressing the business goals (BARRETT; FINCH, 2014; LEWIS, 2012; MUNIR; KIVINIEMI; JONES, 2019) may trigger significant actions towards digital transformation.

Moreover, some staff members reported *dissatisfaction* in relation to the FM sector strategies to manage services and to drive digital transformation, expressing disappointment at not being involved in decision-making processes (i.e., setting parameters for the acquisition of new CAFM systems versions) or encouraged to develop in-house ICT solutions (i.e., systems and mobile applications). This scenario was described by Abdul-Lateef (2010, p. 57), who emphasized the maintenance sector "is not always contacted on issues that relate to new development". Despite challenging for improving maintenance process (MÁRQUEZ et al., 2009), the approximation among the FM staff from all hierarchical levels must be considered an opportunity for the development of a more collaborative and creative environment.

Besides the individual and organizational willingness to move FM to a fully digitized status, FM team capabilities are a matter of concern. Since ICT implementation (i.e., BIM) imposes technological, managerial, and regulatory changes, new skills and roles are required from all FM stakeholders (BECERIK-GERBER et al., 2012; KASSEM et al., 2015; LEWIS, 2012; LIN; SU; CHEN, 2014; MARMO et al., 2019; MOBLEY; HIGGINS; WIKOFF, 2008; TEICHOLZ, 2012). Cultural changes are frequently perceived as threat by FM team members, leading to resistance behaviours (BARRETT; FINCH, 2014; LEWIS, 2012). Besides, some interviewees reported limitations of FM team's expertise and size influence not only the scope and performance of the provided services, but also opportunities to advance towards ICT implementation. Given that labour cost represent approximately 70% of the total maintenance cost (ABDUL-LATEEF, 2010), investments in staff capabilities are crucial for improving both the engagement of professionals with the activities and the service performance (OFORI; DUODU; BONNEY, 2015).

Upskilling actions, such as training and education programmes (ABDUL-LATEEF, 2010; LEWIS, 2012; SACKS et al., 2018), workshops with other AEC and FM sector stakeholders (DE SOUZA et al., 2021), and adoption of intuitive interfaces (i.e., those that demand elementary IT skills) might contribute to improve the capabilities of the team (JOHNSON; WYTON, 2015), as reinforced by Lewis (2012, p. 237) "when team members understand why they are doing something, they are more likely to buy in to new ideas and support organizational change". The optimization of FM processes focusing on core activities and critical assets might improve service performance. ICT solutions play a key role in the operational level (i.e., automatizing tasks, broadening the access of information, guiding information exchange), thus supporting more proactive decision-making.

The interviewees discussed the feasibility of ICT implementation from distinct perspectives, and, apart from technological and human factors, budget restrictions were described as crucial barriers for FM digital transformation, particularly in the public sector, as corroborated by some authors (ABDUL-LATEEF, 2010; MARTINS, 2014; PINTI et al., 2018). The costs involved in the development and implementation of new systems and devices (ARSLAN et al., 2014), adaptation of data information structure, and training of staff can be high (AKCAMETE; AKINCI; GARRETT JR, 2010) are commonly seen as expenses with no clear return. In fact, the purchase of technologies is only the first step (LEWIS, 2012) of a consistent implementation plan.

However, as explained by one of the interviewees, although the transition from the current status to a fully digitized one requires capital investments at the beginning and might be solved with financial savings in a long run, as endorsed by the literature. Investigating the application of BIM for FM at a university complex, Kassem et al. (2015) estimated potential savings from both reduction of CAD technician labour time (approximately £25.000/year salary) and future improvements in work orders attendance. The financial return of BIM would also come with the development of maintainability studies for preventive maintenance, supporting the achievement of "optimum performance throughout the life span of a facility with a minimum life cycle cost" (BECERIK-GERBER et al., 2012, p. 436).

The Return on Investment (ROI) analysis based on earning and costs variables might be considered for supporting the organization in identifying the most appropriate technologies and training programmes towards the expected productivity gains. Regarding BIM implementation, Kassem et al. (2015, p. 272) recommended FM sectors should take into consideration a "long-term view" of at least five years and diverse information formats and standards.

University functional, organizational, and building characteristics were also considered obstacles for the ICT implementation. Even more complex organizations, such as hospitals and airports, have been working towards overcoming barriers and digitizing their assets. In this sense, diagnosing inner organization characteristics (CODINHOTO et al., 2021) is a prior and fundamental step for the development of a realistic ICT implementation, which considers all the necessary resources and organizational changes.

The *value* of FM services perceived by the university community might contribute to the obtaining of investments for service performance improvement and digital transformation. As stated by Desogus et al. (2017), addressing users' requirements and expectations is vital since buildings have been assuming a new role of services provider rather than a container of activities. Such perception is supported by UK University 1 (2019b), who claimed that accommodation residents are key clients for the FM sector because they generate income for the university. The interest in ensuring user's satisfaction by the supply of services might trigger the ICT implementation in this group of assets, towards improved service performance.

In fact, the perception on FM has significantly shifted from a support service to a strategic and core business function (KULATUNGA; LIYANAGE; AMARATUNGA, 2010). As discussed by Pinti et al. (2018), maintenance activity has moved to a new status, due to its potential to extend building lifespan and, consequently, generating financial and environmental savings. Abdul-Lateef (2010) considers maintenance a multidisciplinary business, since it integrates areas such as economy, engineering, technology, and must focus on the preservation of the performance of buildings, rather than react to their inadequacies.

Finally, Regulatory and Contractual factors were approached as fundamental parts of the digital transformation process. The interviews revealed the establishment of internal protocols and procedures for supporting operation and maintenance processes is crucial for service performance, but not enough. Their efficacy requires permanent updates of documents according to the organization circumstances and training of FM stakeholders on following instructions.

The complexity of FM processes, especially after ICT implementation, demands the setting of clear responsibilities and requirements to FM stakeholders, towards the right output of each stage. As exemplified by one of the interviewees, an obstacle to be overcome is the supply chain's lack of compliance with BIM handover, which generates poor-quality information. In this sense, government mandates, guidelines and standards might trigger and drive ICT implementation since they establish contractual and procedural bases that support AEC supply chain on service delivery.

Given the complexity of BIM data and information management for FM (HOSSEINI et al., 2018), some authors have emphasized the importance of developing open and specific BIM standards and technologies (i.e., templates, specifications, formats, platforms) (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; KASSEM et al., 2015; MUNIR; KIVINIEMI; JONES, 2019), identifying user's information needs (MUNIR; KIVINIEMI; JONES, 2019), and defining owner's BIM requirements already in the design and construction stage (BECERIK-GERBER et al., 2012; MARMO et al., 2019; PATACAS; DAWOOD; KASSEM, 2016; PINTI et al., 2018) towards digitalized, accurate, and consistent asset data. The adaptation of contracts and specifications (SACKS et al., 2018) and development of BIM Execution Plan (BEP) driven to designers and contractors are essential to assist the adoption of BIM processes and technologies. For instance, BEP might contribute for overcoming inaccuracies in BIM models by frequently including either excessive, or incomplete information for operation activities (MCARTHUR, 2015).

Nevertheless, the adoption of such mandates, guidelines and standards is not a straight way for inexperienced professionals and organizations since it requires individual skills for the translation of complex concepts into effective practices. As discussed by Souza et al. (2021), although most of such skills are gradually developed throughout the professional career, a more collaborative environment with participation of AEC industry stakeholders might support the upskilling process.

4.4.3. Identification of critical scenarios for reactive maintenance problems

The Work Request data provided by the three universities supported the identification of critical scenarios for reactive maintenance problems. Since the data analysed differ among the organizations, the discussion is structured in two stages - one related to the UK University 1 and UK University 2, corresponding to Group 1, and another related to the BR University, corresponding to Group 2.

For Group 1, the discussion involved aspects related to the problem (i.e., type, frequency), the building characteristics (i.e., room type, floor, area, age, etc.), and the service (i.e., time response, priority classification), analysed in Section 5.3.3. The statistical analysis of reactive maintenance Work Requests, described in Section 5.3.4, was focused on the degree of influence of building characteristics (i.e., room type, floor, area, year of construction, etc.) on both problem occurrence and time response, two key metrics for improving service performance (BARRETT; FINCH, 2014). For Group 2, the approached aspects were related to the problem (i.e., type, frequency), the building environment (i.e., asset type, room type), and the service (i.e., time response, cost), analysed in Section 5.3.3.

a. UK Universities 1 and 2

The descriptive and statistics analysis of Work Requests generated by UK Universities 1 and 2 between 2017 and 2018 supported a cross-section discussion of the cases, focusing on service and building characteristics variables (Table 27).

Table 27: UK Universities 1 and 2 Work Request variables for discussion

Descriptive analysis			
Group	Description	University 1	University 2
Services	WR x FM area x FM Group	x	x
	WR x Month x Year	x	x
	WR x Site	x	x
	RM WR x Service Category	x	x
	RM WR x Service Category x Priority Level	x	-
	RM WR x Service Subcategory x Priority Level	x	-
	RM WR x Average Spent Time x Priority Level	x	-
	RM WR x Average Spent Time x Service Category & Subcategory	x	x
	RM WR x Frequency x Service Category & Subcategory (Pareto Graph)	x	x
Building characteristics	RM WR x Room Type	x	x
	RM WR x Number of Floors	x	x
	RM WR x Building Year of Construction x Building Heritage Status	x	x
	RM WR x Building Built Area x Site ID	x	x
	RM WR x Number of Residents x Building ID	x	-
Statistical Analysis			
Group	Description	University 1	University 2
Service	Time response (RM WR x Average Spent Time x Service Category & Subcategory)	x	x
	Problem occurrence (RM WR x Frequency x Service Category & Subcategory)	x	x
Building characteristics	Site Area	x	x
	Site Built Area	x	x
	Building Built Area	x	x
	Building Number of Floors	x	x
	Year of Construction	x	x
	Building Heritage Status	x	x
	Floor ID	x	x
	Room Type	x	x
RM = Reactive Maintenance WR = Work Request			

Source: Author (2021)

A comparative discussion on the distribution of all Work Requests per FM areas and FM groups was proposed (Figures 41 and 56). A similar distribution of requests per FM area is verified for both universities, revealing that *Building Operations* and *Maintenance Services* corresponded to more than 85% of the total sample; however, a distinct pattern for FM Groups in each university was observed. The *operations service* *group* represents 19,07% of UK University 1 requests and 44,55% of UK University 2 requests and Unlisted/Other services sum 13,67% of UK University 1 requests and 0,01% of UK University 2 requests.

Reactive Maintenance services are the most representative category for UK University 1, with 66% of all requests; however, they represent only 21,65% of UK University 2 requests. On the other hand, Preventive Maintenance sums 0,07% of UK University 1 requests and 32,64% of UK University 2 requests. At first, data on UK University 1 reactive maintenance corroborated the literature, which estimates its predominance among other maintenance categories (SULLIVAN et al., 2010). However, the overall disparity among universities data might be explained by the application of different parameters for service classification by each FM sector or by the adoption of a more preventive approach by UK University 2.

The monthly distribution of Work Requests in 2017 and 2018 followed distinct patterns in each university (Figure 42 and 57). UK University 1 registered peaks of services in September, October, and November 2017, which coincided with the beginning of the first semester. An approximately 8% decrease was observed in UK University 1 requests from 2017 to 2018, particularly in March, May, and September. Possible explanations include improvements in the building systems performance (e.g., heating, powering) in the coldest season and reduction of user's time at the university's facilities. On the other hand, the number of requests in UK University 2 in 2018 increased 50% in comparison to the previous year, with peaks in July, August, and December. The increment in the building built area (approximately 3.000 m^2), the decrease in the equipment's performance, or the extension of research, teaching and sport activities may explain such results.

Since both universities are multi-site, a concentration of requests was identified in the main campuses (Figure 43 and 58), with 80,58% of all UK University 1 requests and 83,64% of the total UK University 2, thus considered the focal points for FM services improvements. Such a concentration may be due to the high number of users, buildings (approximately 100 at UK University 1 and 80 at UK University 2) and building built area (around 290.000m^2 at UK University 1 and 320.000m^2 at UK University 2). Whereas the remaining UK University 1 requests are distributed only among individual buildings, UK University 2 requests come also from structured campuses, evidencing the distinct spatial approaches of each university.

Given the general scenario, discussions on Reactive Maintenance Area were proposed for both universities. A balanced distribution of the Work Requests per Building, Mechanical and Electrical service categories was verified (Figures 44 and 59), showing the relevance of the three categories for the FM sector planning. Building Services are predominant at UK University 1 (36,95%) and Mechanical Services (36,31%) are predominant at UK University 2. Since the difference between such categories is not significant, an explanation for their recurrence is the high number of mechanical equipment (i.e., heating, lifts) and building components in the group of assets. In both, Electrical Services are the third most representative group, with approximately a quarter of all requests, probably due to the existence of only two main systems (lighting and power) to be maintained.

The distribution of Work Requests per Service Category and Subcategory based on the service priority level was discussed only for the UK University 1 data, since this classification was not applied by UK University 2. As shown in Figure 45, most requests were classified as Priority 5, predominantly Building Services, attended in a flexible time, according to the user's demands and FM staff availability. As explained by one of the interviewees, work request are usually classified by default as "7-day standard priority", which might explain the result (UK UNIVERSITY 1, 2019b). Examples of such services include painting, furniture repair, and plaster redecoration, commonly requested from the students' accommodations.

Priorities 3 and 2 are the second and third most relevant levels - especially Mechanical Services involving faulty facilities (i.e., heating system and sanitary fitting), which might create problems in the short and long term for the whole university community in several assets, from individual rooms (e.g., offices, student bedrooms) to common areas (e.g., library, classrooms, laboratories), thus explaining the significant number of requests. Priority 4 concentrates Unlisted/Other and Building services, followed by Priority 1, with Mechanical and Electrical services. The low percentage of emergency services might be due to preventive actions anticipating failures or inaccuracies in service classification. Yet, Priority 1 services exert the biggest impact on personal safety and asset security, requiring special attention from the FM staff.

Focusing on Service Subcategories, an analogous sequence of priorities is observed for Building and Electrical services, with concentration of Priority 5, 3 and 2. Among the Building services, Door issues predominate in all levels (Figure 46). For Priority 1, most problems refer to failures in doors components (i.e., Fire alarm, locks, handles) installed in distinct rooms (i.e., toilet, bedroom, kitchen, corridor), generating insecurity to the building and safety risks to the users.

Most doors, particularly in entrances and common areas, has automatic mechanisms for opening composed by sensors and mechanical machinery, which might justify the likelihood of defects. The quality of materials and components might also influence the maintenance management of buildings (ABDUL-LATEEF, 2010; OFORI; DUODU; BONNEY, 2015; YACOB; SHAH ALI; AU-YONG, 2019). However, a more accurate explanation is provided by Codinhoto et al. (2021). According to the University's facilities managers, an external factor triggered the increased door service requests: in June 2017, a fire broke out in the Grenfell Tower residential building in London, killing 72 residents. Preventively, the FM team opted for check all doors within the campus facilities regarding their fire-rate and functionality.

For Electrical, Power issues prevail in Priority 1 and 2 Levels (Figure 47), since the loss of electrical supply might directly impact on the equipment usage and the lighting, heating, and ventilation systems performance. On the other hand, Lighting problems are recurrent in Priorities 3, 4 and 5, probably because their failure do apparently not offer important safety risks to the users, except when involving the emergency lighting system (UK University 1, 2018c).

The sequence of priority levels for Mechanical Services (Figure 48) is altered, with a predominance of Priority 3 services, mostly involving Plumbing issues (i.e., minor floods, blocked drains, and loss of water supply) and Heating/Cooling/Ventilation component systems (i.e., air conditioning, heaters, boilers). These subcategories are also significant in Priority 1, thus referring to substantial flood or leakage of water into the rooms or to incidents interrupting teaching and research activities, as described by the Service Level Agreement (UK UNIVERSITY 1, 2018c).

The priority service level classification of reactive maintenance services provided from UK University 1 has supported de analysis of the mean spent time for each priority level and the percentage of requests attended on time (Figure 49). The analysis has shown that 100% of Priority 5 services was attended on time, while for Priorities 1, 2, 3, and 4 the percentage is about 33%. The lower rate of compliance is more impactful for Priority 1 services since delays in service response can cause severe damages to the safety of users and security of buildings.

One possible explanation to this observed phenomenon is the inaccuracy in classifying the work request priority level according to the description provided by the solicitor. In some cases, the issue can be more complex than initially expected, taking more time to be addressed. Another reason might be the insufficiency of labour and material resources to execute the service on time. New buildings were opened to users in 2018, which might have generated additional demands for the FM team. Therefore, inconsistencies between the Service Level Agreements criteria and the FM sector capability for service attendance are observed. A review of this standard is recommended to improve the performance of the services, especially the critical ones, and the safety and satisfaction of university community.

The distribution of Work Requests per Service Subcategory is also carried out for UK University 2. In the Building category, Figure 60 shows a predominance of Door services, followed by Finishing, Window and Wall. The same preventive approach taken by UK University 1 face the fire in London might justify the representativeness of Door services. Electrical services are mostly related to the lighting system, probably because the extensive number of equipment, including emergency lighting (Figure 61). Finally, in the Mechanical category Plumbing services correspond to half of the total requests, which might be explained by the significant number of toilets, bathrooms, and kitchens over the residential buildings (Figure 62). An extensive and complex number of components are present in these rooms, impacting in the service demand.

The distribution of the average spent time per main Service Category and Subcategory was analysed for both universities, supporting a comparative discussion (Figure 50 and 63). Substantial variation in the average spent time was identified for some service subcategories. Regarding Wall services, UK University 1 has spent around 416 days and UK University 2 16 days for attendance; for Mirror/Glass, UK University 1 has spent around 14 days and UK University 2 72 days; and for Door services, UK University 1 has spent around 19 days while UK University 2 13 days. In Mechanical category, UK University 1 has spent about 30 days for Gas services while UK University 2 5 days; for Heat/Cool/Ventilation, UK University 1 has spent about 10 days and UK University 2 14 days; for Plumbing services, UK University 1 has spent about 10 days and UK University 2 6 days. Similar average spent time was observed for Electrical services in both universities, with around 7 days for Lighting and 8,5 days for Power services.

The variation in the average spent time of services might be due to some reasons. The strategies adopted by each university FM sector for problems attendance might have impacted the service performance. While UK University 1 services are mostly provided by the FM internal staff, at UK University 2 the O&M services are predominantly outsourced. Another factor is the complexity of the facilities and failure to be fixed, that can vary from one organisation to another. Also, the criteria for service prioritization might be specific for each university, thus influencing the time response for similar problems.

The frequency of reactive maintenance problem subcategories and their cumulative impact on the overall picture were previously analysed through a Pareto graph (Figure 51 and 64). Five service Subcategories are the most recurrent in both universities (i.e., Building-Door, Mechanical-Plumbing, Electrical-Lighting, Mechanical-Heat/Cool/Ventilation and Electrical-Power), representing 81% of the whole UK University 1 requests and 74% of the UK University 2 requests. The results show a pattern in the frequency of reactive maintenance problems despite the individual characteristics, which might potentially be extrapolated to other similar organisations. Strategies for services improvements must take into consideration the highlighted problems, also associated to a risk assessment matrix.

Given the services characterization, a discussion about the reactive maintenance Work Requests according to building characteristics variables is also proposed. The distribution of request per Room Type is the first analysed aspect (Figures 52 and 65). At UK University 1 the most recurrent damaged rooms are Student Bedroom, Toilet/Shower, Office, Kitchen, and Circulation, representing around 73% of the total requests, while at UK University 2, Residences, Circulation, Void, Facilities, and Support sum approximately 75% of the requests. The UK University 2 criteria for room classification lacks clarity, since various room types (i.e., toilet, lifts, office, kitchen) were classified as Facilities, Support, Void or Plant in different Work Requests.

In general, student accommodation facilities, circulations and offices are predominant in both universities. The intense use of bedroom, toilet and kitchen by the residents might justify the likelihood of problems occurrence and the interesting in reporting faults, given the disruption caused to the students' routine. Common spaces such as toilet, kitchen, office, and circulations are also shared by a huge and diverse number of users over the day, increasing the probability of problems occurrence. Besides, toilet and kitchen have complexes facilities like plumbing and ventilation systems which tend to require maintenance more often than less complex rooms, such as meeting room and classroom.

The distribution of Work Requests per Building Number of Floors according to the Building Built Area (Figures 53 and 66). At UK University 1, a linear relationship between the number of floors or the building built area and the work requests recurrence was not observed. On the other hand, at UK University 2, a trend for requests increasing in bigger buildings was noted. Figures 53 and 66 highlight the seven most requesting buildings in each university. A predominance of residential buildings is observed, with six buildings at UK University 1 (hosting around 1.600 students) against one Administrative building, and five at UK University 2 against one Administrative and one Academic building.

In the UK University 1 group, the Buildings 4430 and 4450 concentrates more requests per floor (i.e., 359 and 532), while the Buildings 4360 and 4090 concentrates more requests per square meter (i.e., 0,37 and 0,33). Building ID 4340 stands out in both categories, with 262 requests per floor and 0,43 requests per square meter. At UK University 2, the Buildings ID FR-WP and FR-CC concentrates more requests per floor (i.e., 881 and 863) and per square meter (i.e., 0,59 and 0,49). Two other residential buildings stand out, namely Building ID FR-BC with 599 requests per floor and Building ID FR-CTC with 0,33 requests per square meter. A bigger concentration of requests per floor and per square meter is observed in UK University 2 buildings.

A complementary analysis has considered the distribution of Work Requests per Building Number of Floors according to the building Floor ID is shown in Figures 54 and 67. A clear relationship between the number of floors and the occurrence of problems was not identified. At UK University 1, 39 buildings with 5, 6, and 7 floors concentrate most requests with a similar distribution among the floors 1, 2 and 3. Observing the 3 most requesting building in each predominant floor, only residential buildings are identified, hosting around 2300 students. Among the 5 floors buildings, Building ID 4090 is the most significant with 1.081 requests, followed by Building ID 4380 with 1.057 requests, and Building ID 4400 with 1.047 requests. The 6 floors buildings cluster includes Building ID 4430 with 2.155 requests, followed by Building ID 4390 with 1.885 requests, and Building ID 4340 with 1.571 requests. Finally, the most requesting 7 floors buildings are Building ID 4450 with 3.937 requests, Building ID 4360 with 1.731 requests, and Building ID 4330 with 1.406 requests.

At UK University 2, a concentration of requests is observed in 40 buildings with 3 and 8 floors, particularly on the floor 0, and in 6 buildings with 7 floors, in special on the second floor. Among the 3 most requesting buildings in each floor, a predominance of residential buildings is observed (5), followed by Academic & Research (2), and Support & Commercial (1). The 3 floors buildings include the residential Building ID FR-CC with 2.589 requests, followed by the Academic & Research Building ID FR-T with 988 requests and Building ID FR-U with 486 requests. The cluster of buildings with 7 floors comprehend residential Building ID FR-QC with 4.162 requests, followed by the Academic & Research Building ID FR-D with 1.825 requests and Building ID FR-E with 1.287 requests. Among the 8 floors group, FR-BC is the most requesting with 4.789 requests, followed by FR-CTC with 4.446 requests and FR-MC with 3.699 requests.

The distribution of reactive maintenance Work Requests according to building Year of Construction and Heritage Status were analysed (Figure 55 and 68). In general, unlisted buildings were the most service requesting. A relationship between the building age and the problem occurrence was not observed. At UK University 1, listed buildings are little representative with a small number of requests in the studied period. Among the oldest facilities, the 2 residential listed buildings have a minor built area (around 650 m^2 each) in comparison to other assets, and consequently a smaller number of components, equipment, and users, which might explain the scenario.

In the unlisted cluster, buildings from 1970 are the most service requesting (6.540), including 8 student accommodation buildings (Building ID's 120, 3270, 3420, 4070, 4110, 4120, 4130, 4330), 5 Academic & Research buildings (ID's 3050, 3090, 3130, 3250 and 3510), and 1 sportive asset (ID 6300). Together, these buildings sum approximately 50.000 m^2 of built area and 750 residents. In the sequence, 2 buildings from 2014 sum 4.211 requests, including 1 student accommodation (ID 4450) for 708 residents, with about 16.000 m^2 and 3.937 requests, and 1 catering building (ID 3520), with a total built area of around 3.350m^2 and only 274 requests. In the third position, 10 buildings from 1990 have registered 3.013 requests, including 9 accommodation buildings (ID 4080, 4140, 4150, 4160, 4170, 4180, 4190) for about 650 residents with around 9.300 m^2, and 1 administrative building (ID 3190), with about 75m^2 and only 4 requests.

Similarly, UK University 2 unlisted buildings are the most representative in the overall work requests context, particularly those buildings constructed in 2006, 2014 and 2007. The group of buildings from 2006 sum 12.852 requests and includes 3 student accommodation buildings (ID FR-CTC, FR-MC, FR-QC) with about 38.000m^2 and 545 requests, and 1 sportive asset (ID FR-CFS), with about 3.500 m^2 and 545 requests. Buildings from 2014 include 1 student accommodation (ID FR-WP), with approximately 8.900m^2 and 5.283 requests, 1 Academic & Research building (ID BA-EB) with 26 requests, and 1 support asset with 222 requests. The third group involves two buildings from 2007, 1 student accommodation (ID FR-BC), with around 15.000m^2 and 4.789 requests, and 1 Healthy asset (ID FR-DCN), with 120 requests.

Besides, 24 listed buildings from the Glenside Campus have also a significant number of requests (5.043). The three most requesting buildings in this group are 2 student accommodations, including the Building ID GL-SYC, with approximately 970m^2 and 432 requests, and Building ID GL-POP, with 714m^2 and 379 requests, followed by the Academic Building ID GL-H, with about 6.000m^2 and 418 requests.

The statistics analysis of the UK University 1 and UK University 2 reactive maintenance Work Requests supported the identification of the degree and direction of influence of the selected building characteristics on reactive maintenance problem occurrence per square meter and time response.

Regarding problem occurrence, the results show nine variables with negative influence and five variables with positive influence. Building Built Area, Building Number of Floors, Site Area and Site Built Area are among the most important variables with negative influence, meaning that the increase of building and site sizes contributes to the reduction of reactive maintenance problems occurrence. Even though larger buildings and sites tend to have more complex facilities and equipment, the occurrence of problems might be more associated to functionality of the environment than to the asset size. In their study, Yacob, Shah Ali and Au-Yong (2019) have not identified a significant contribution of building size to the occurrence of defects, which was corroborated in this research. On the other hand, previous research have discussed the positive impact of building area and height on maintenance costs (ALI et al., 2010; KRSTIĆ; MARENIAK, 2012; OLANREWAJU; ABDUL-AZIZ, 2015; PERERA; ILLANKOON; PERERA, 2016; SALLEH et al., 2016), which could not be examined in this work.

Year of Construction variable had also a negative impact, which demonstrates that the older the building, the greater the problem occurrence. The deterioration of buildings components and the necessity for technological improvements over time might contribute to this result, as previously discussed (BORTOLINI; FORCADA, 2020; OFORI; DUODU; BONNEY, 2015; TALIB et al., 2014; YACOB; SHAH ALI; AU-YONG, 2019). For example, Gunay et al. (2018) have identified a predominance of HVAC work requests in the group of oldest buildings, indicating a necessity of more maintenance efforts. Similarly, Abdul-Lateef (2010) have verified that building age was one of the most influential criteria with relation to university building maintenance management. In addition, some studies describe the influence of building age on maintenance costs (ALI et al., 2010; KRSTIĆ; MARENIAK, 2012; PERERA; ILLANKOON; PERERA, 2016; SALLEH et al., 2016), as highlighted by one of the case studies interviewees: “the older a university, the more money you need to keep it up to date” (UK UNIVERSITY 1, 2019e).

The negative influence of Building Heritage Status Listed was detected, meaning that listed buildings tend to have less reactive maintenance problems in comparison to unlisted buildings. Although the building age of building has contributed to problem occurrence, the functionality of listed buildings (i.e., academic) and the number of users might have contributed to the result. Guiding maintenance budget setting, BR University (2017) has foreseen an additional index for listed buildings and historic centres, considering their influence on maintenance costs.

Distinct influences were observed among room category variables. Reception, Plant, and Residences Room Types had a positive impact on service occurrence, which means that those environments tend to have more reactive maintenance problems. The intense occupation for several users and the high likelihood of a failure be detected and communicated by a passer-by might justify the significance of Reception. A similar condition is verified in Residences, in which the permanent use of complex facilities (i.e., toilet, kitchen) and the willingness of users to report faults might contribute to the result. On the other hand, Room Type Void had a negative influence, meaning that this room category does not contribute to increasing problem occurrence. With regard to the Plant and Void room types, the results might not be conclusive, since both include several room categories (e.g., corridor, lift, pavilion, car parking, toilet, lifts, office, kitchen, etc.). Accurate room classification must support a better understanding of their impact on problem occurrence.

Finally, a set of Floor ID variables were identified. Floor ID 2 and Floor ID 1 had a negative influence, which demonstrates that the first and second building floors do not contribute to increasing problem occurrence. The predominance of open spaces (e.g., halls, lobbies) with low complexity on the first floors might explain the result. On the other hand, Floor ID 5 and Floor ID 6 had a positive influence, meaning a higher likelihood of problems on these floors. As previously discussed, a predominance of residences among the buildings with five, six and seven floors might be associated to the problem incidence.

With respect to time response, ten variables with negative influence and eleven variables positive influence were identified. The variables related to asset size - Building Built Area, Building Number of Floors, Site Area and Site Built Area – had negative influence on time response, which means that increasing building and site sizes contributes to the reduction of time response. Bigger assets tend to impose to FM team difficulties in service attendance, for example in finding updated information on building components and systems in FM database, hampering service location, diagnosis, and acquisition of material for repair. On the other hand, other aspects might trigger time savings in service response, such as the presence of a great number of users affected by the problem and the concentration of a variate of functionalities (e.g., teaching, administrative, residential, catering), causing a significant impact on user's safe and comfort and on university activities.

Similarly, the variable Year of Construction had a negative impact, demonstrating that the older the building, the greater the time response. Some aspects might contribute to this result. For example, obstacles in finding information in FM database (occasionally on physical documents) and on accessing hidden components (e.g., pipes, tubes) might hamper problem diagnosis. As previously discussed, the deterioration of buildings systems and the difficulties in acquiring specific spare parts on the market might also influence time repair.

Variables related to Room Type had distinct impact on time response. Toilet Shower, Residences, Kitchen and Lifts Room Types had a negative influence, meaning that fixing problems in these locations takes less time than in other rooms. Toilet shower and kitchen facilities are essential for users' permanence in university buildings, in particular for residents, which might explain a quicker response. Besides, the complexity of plumbing and electrical systems tends to be inferior in comparison with other rooms (e.g., laboratories), facilitating the diagnosis, acquisition of spare parts, and repair. With regard to the vertical transportation equipment, the short time response might be justified by the necessity to ensure user's safety and accessibility in multi-storey buildings, particularly in cases involving people getting stuck in the lift. Also, lift maintenance in generally carried out by specialized outsourced providers, that must attend service calls according to contractual requirements.

On the other hand, a set of room type variables have positively influenced time response, i.e., Void, Plant, Office, Seminar Tutorial Room, Teaching, Meeting, Consulting Room, Specialist, and Bucs Comms Space, which means that reactive maintenance services in these places take longer than in other rooms. As aforementioned, the lack of precision in classifying Void and Plant rooms is an obstacle for drawing conclusions about the results. The remaining variables refer to common spaces, occupied by a variety of users to develop administrative, academic and leisure activities. Inaccurate description of problem type and location, difficulties in accessing busy spaces for problem diagnosis, and the occasional necessity of interrupting activities for service repair might justify a prolonged time response.

Lastly, a group of Floor ID variables were identified. Floor ID 1 had a negative influence, which demonstrates that the first building floor do not contribute to increasing time response. On the contrary, Floor ID 0 and Floor ID Roof positively influenced time response, meaning that time response tend to be longer on these floors in comparison with others. The low prioritization of services in open spaces (i.e., reception, circulation) and the difficulty in interrupting activities for service repair might explain the results related to Floor ID 0. Regarding Floor ID Roof, the result might be justified by difficulties in accessing external areas, requiring specific safety and transport equipment and, accordingly, more time for problem location, diagnosis, and repair.

The results will enable a weight for each variable to be assigned, producing a Variable Importance in Projection (VIP) scale of the impact of variables on reactive maintenance occurrence and time response. Among the applications for this work, knowing the most likely scenario for RM problems incidence will point out areas to be potentially improved with the implementation of BIM and IoT combined solutions. Furthermore, the results may support the organisations in preventive actions forecasting failures occurrence and in planning financial, administrative, and logistical requirements for their attendance.

b. BR University

The individual Descriptive Analysis of Work Requests generated by the university FM Sector between 2018 and 2019 supports the discussion of the case, focusing on the service variables shown in Table 28. Regarding the distribution of Work Requests per site, Figure 69 shows a concentration of requests in Campus A, equivalent to three quarter of the total requests. This scenario might be explained by the high number of users and building built area, four times bigger than the Campus B. Besides, Campus A is the most consolidated site, including buildings from the 1950's, in which maintenance repairs are often necessary.

Table 28: BR University analysed Work Request Variables for Discussion

Group	Description
Services and Building characteristics	WR x Site
	WR x Asset Type
	WR x Asset ID
	WR x Service Category x Asset Type
	WR x Service Spent Time x Asset Type
	WR x Labour and Material Service Costs x Asset Type
	SAE WR x Service Category
	SAE WR x Service Subcategory
	SAE WR x Labour and Material Service Costs x FM service category
	SAE WR x Labour and Material Service Costs x Room Type
WR = Work Request; SAE = Student Accommodation	

Source: Author (2021)

The distribution of Work Requests per Asset Type and per Asset ID over the university sites were analysed in Figures 70 and 71. The predominance of Infrastructure services might be justified by the scope of services provided by the university FM Sector, mostly focused on common assets. Even though Academic & Scientific requests are in general addressed by the institutes and schools, complementary services were provided by the BR University FM Sector to 11 buildings, including the New Library Campus B and the Didactic Support Buildings (CAD). The complexity of the service and the availability of workforce might explain the results.

Among the remaining asset types, student Accommodation were the most demanding, with 206 requests. This group includes 5 Accommodation Buildings (A, B & C, D, E) for approximately 250 students built between 1963 and 2010, covering around 4.700m^2. As discussed in Section 5.4.3.a, the permanence time of the residents in the buildings, the complexity of the toilet and kitchen facilities, and the high built area might justify the elevated number of requests. In addition, legal requirements imposed to Brazilian public sector for hiring labour and material might impact the quality of services, mostly prioritizing low cost rather than high technical quality.

The analysis of the distribution of Work Request per FM Service Category according to the Asset type (Figure 72), shows a predominance of *Plumbing and Electrical Maintenance* on most asset types, except in Infrastructure that concentrates Building Maintenance Services. The significancy of this category might be due to the wide range of provided services, such as toilet and kitchen facilities maintenance, luminaire replacement, and power supply components repairs.

The distribution of Work Requests per service spent time according to the Asset Type (Figure 73), shows that Infrastructure and Academic & Scientific assets were the most requesting and time-consuming. This result might be justified by the volume and complexity of activities involved in external services and research facilities, as well as the necessity of hiring specialized labour and material. Although Accommodation is the third most requesting asset type, the time spent on maintenance service was one of the least significant. The availability of in-house resources and the familiarity with the services might explain the result.

With regard to the distribution of Work Requests per labour and material service costs according to the Asset Type, Figure 74 shows a prevalence of labour cost in most asset types, except for Sport & Culture facilities. In general, labour costs tend to be superior to material costs, since the scarcity of workforce and the taxes involved in public hiring impacts on the final costs. According to Abdul-Lateef (2010), labour cost might represent approximately 70% of maintenance costs. In the Sport & Culture group, approximately 90% of the material costs were related to Building Maintenance Services addressed to only one building of the Physical Education Center Sport and Recreation (CEFER), probably involving repairs in roofs and finishing.

Focusing on the Student Accommodation E, Figure 75 shows the distribution of Distribution of Work Requests per Service Category and Subcategory. A predominance of Electrical services is observed, particularly involving the replacement of faulty lamps. As detailed in Figure 78, Toilet, Bedroom and Balcony concentrate most electrical services, which might be explained by the intense use and the complexity of the toilet and kitchen facilities, as discussed in Section 5.4.3.a. The second most significant Subcategory was Building, in special services related to the repairs or replacement of Door handles and locks in bedrooms. Once again, the intensity of use and the eventual low quality of the material might justify the recurrence of door problems.

The distribution of labour and material service costs and Spent Time according to Service Category and Room Type are shown in Figures 76 and 77. Labour costs predominate in most Service Categories and Room Types, as identified by Abdul-Lateef (2010). The exception is related to Plumbing services particularly in Toilet, in which the material costs for fixing sinks, showers and toilets were superiors to the labour ones. External area was the most time consuming, particularly in services of finishing replacement on the external façades and roofs (96 hours), probably due to the scale of the service and the necessity of specific material, labour, and infrastructure (i.e., scaffolds). In the sequence, repairs in Toilet rooms were the most time consuming, mostly spent with door repairs (68 hours). The number of doors and the level of the damage might explain the elevated spent time.

4.5. Summary

In this chapter, the analysis of empirical evidence provided by the Multiple Case Study through interviews, focus group and document collection supported the achievement of research goals: characterization of FM sector and reactive maintenance services and processes; identification of most critical reactive maintenance problems; investigation of current and potential application of BIM and IoT-based solutions for FM services, in particular, for maintenance services.

Initially, the investigation regarding FM sector structure, scope and services has demonstrated the complex requirements for addressing university user's needs. Institutional aspects, such as the size of population, number of sites, building stock, and campus area, directly influence the features and scale of services to be managed by the FM sector. Such aspects must be considered to define FM inner factors, including the scope of services, the size of staff, the predominant modality of execution, the budget allocation, and the supporting ICTs. Accordingly, the FM factors must support setting general service performance metrics and developing strategies for provision improvement. With respect to reactive maintenance processes, information management bottlenecks were identified over several stages, mostly associated to the dependence on human communication, the inefficiency of protocols and tools for information visualizing, storing, and sharing, and the negligence of user feedback as a parameter of service performance. In this context, BIM and IoT capabilities have emerged as potential solutions for streamlining activities and triggering digital transformation.

A deeper understanding of technological, processual and policy aspects involved in the implementation of BIM and IoT-based solutions in FM activities was provided by this study. Clear benefits for FM service performance were highlighted, such as improving the identification, visualization, and diagnosis of problems. Interoperability, flexibility, and user friendliness were highlighted as key requirements for making software, systems, and devices suitable for FM purposes. Encouraging the development of open platforms and strengthening the relationship among FM team members, IT developers, and providers are imperative for addressing this issue. Besides, effective information management plays a key role for supported FM decision-making, providing accessible, accurate and reliable information to the involved stakeholders.

Understanding technology as a support for human activities, the investigation of process aspects regarding BIM and IoT implementation revealed distinct levels of awareness, engagement, satisfaction, and capabilities among FM team members towards digital transformation. Beyond the individual willingness to embrace a new approach of work, the importance of upskilling actions and establishing a clear strategy of implementation adherent to the university business goals were reinforced. Besides, the FM sector budget restrictions emphasized the necessity of investments in technology based on Return on Investment (ROI) analysis to achieve the expected productivity gains. The ongoing process of moving FM services from an operational to a strategic position contributes to gradual advancements in BIM and IoT implementation process.

In addition, regulatory and contractual aspects to conduct FM activities in a digitalized environment have emerged. Standards and guidelines were considered essential to structure FM services, such as budgeting setting and allocation, service group classification (i.e., reactive, preventive), and service prioritization (i.e., emergency, urgency, etc.), and to support information management, setting roles, responsibilities, and information requirements. To ensure their efficacy, these documents must follow not only external references (i.e., mandates, technical normalisation, professional bodies) but also individual needs of the organization. In fact, a balance among the technological, processual and policy issues is decisive for a successful implementation of BIM and IoT.

Finally, the identification of critical scenarios for reactive maintenance problems was undertaken based on the work requests analysis, considering characteristics of problems, buildings, and services. The descriptive analysis of data from the UK Universities 1 and UK 2 revealed a series of patterns: i. a concentration of requests in the principal campuses; ii. a balanced distribution of requests per Building, Mechanical and Electrical service categories; iii. a predominance of low priority level services; iv. a low rate of compliance in attending priority services; v. a cumulative impact on the overall picture of five problem subcategories i.e., Building-Door, Mechanical-Plumbing, Electrical-Lighting, Mechanical-Heat/Cool/Ventilation and Electrical-Power; vi. a predominance of problems in student accommodation facilities, circulations, and offices; vii. a concentration of requests in unlisted buildings.

In addition, the statistics analysis of UK University 2 and UK University 1 reactive maintenance requests supported the identification of building characteristics with significant influence on reactive maintenance problem occurrence and time response. The variables were divided in two groups: i. with negative influence, meaning they do not contribute to the observed phenomenon; ii. with positive influence, which means that they do contribute to the observed phenomenon. In both cases, variables related to asset size and age had a negative contribution to the observed phenomenon, while variables associated to room function and location over building floors had a positive contribution.

The descriptive data analysis of the BR University general work requests has shown that i. Infrastructure and Academic & Scientific assets as the most requesting and time-consuming; ii. a concentration of Plumbing and Electrical Maintenance on most asset types; iii. a prevalence of labour cost in detriment of material cost in most asset types; iv. a predominance of requests from student accommodations, among the building assets. Focusing on Student Accommodation E, the findings include i. a predominance of Electrical services, particularly involving the replacement of faulty lamps, and Building services, in particular replacement of Door handles and locks; ii. a concentration of problems on Toilet, Bedroom and Balcony Room Types; iii. a predominance of labour costs in comparison to material costs; iv. external area as the most time-consuming Room Type.

5. Development of the Smart lighting maintenance system prototype

This chapter addresses the development process of a BIM- and IoT-based smart lighting maintenance system prototype. From the previous sections, the Systematic Literature Review classified BIM and IoT devices and solutions recently applied to FM, particularly to reactive maintenance services. The main areas, activities, and applications were identified, and positive and negative outputs of BIM and IoT implementation were highlighted (Chapter 3). A Multiple Case Study characterized the FM sector and services and identified critical scenarios for reactive maintenance. Besides, opportunities for improvements through BIM and IoT implementation were identified considering their capability of predicting potential failures, improving service performance and reducing disruptions (Chapter 4).

As discussed in Chapter 3, commercial solutions available in the market, such as smart homes and BMS, support the automation and management of buildings based on smart sensors data. However, limitations of such systems (i.e., lack of both integration with other FM systems and flexibility for the addition of new capabilities, and restrictions for data analysis) hamper the execution of FM activities and the exploration of new business opportunities (ARASZKIEWICZ, 2017; IBRAHIM et al., 2016; JIA et al., 2019; MISIC; GILANI; MCARTHUR, 2020; PARN; EDWARDS; DRAPER, 2016; RASHID; LOUIS; FIAWOYIFE, 2019; UK UNIVERSITY 2, 2018). Moreover, the implementation of such technologies is mostly focused on their acquisition and installation than on the process issues required for their operation and maintenance over time (LEWIS, 2012).

In view of the stated problems, the following questions were raised:

- How can technical and functional requirements and strategies for prototyping be established?
- How can BIM, IoT, and FM devices and tools be integrated, generating a Digital Twin?
- How can intelligence be generated from real time data and automatically inform the FM team on current and potential failures?
- How can BIM software and other maintenance-oriented interfaces provide the visualization of real time and historical information?
- What are the potential impacts of a smart system on maintenance performance and contributions to the design phase?

This chapter characterizes the strategies and decisions involved in the prototyping process of a smart maintenance system, identifying its potential impacts on service performance and contributions to the design phase. The process described in Figure 8 (Chapter 2) comprises the six following steps:

- development of a Classification Matrix of Luminaire Priority Level that supports the maintenance team in classifying critical luminaire for university activities;
- development of a Conceptual framework of the BIM & IoT Assisted Predictive Maintenance Process, mapping the process flowchart and the conceptual application of ICT solutions in maintenance activities;
- establishment of technical and functional strategies and BIM requirements for the development of the prototype;

- development of the Architecture of the prototype, integrating BIM, IoT, and FM solutions to support lighting predictive maintenance;
- demonstration of the application of the Architecture through a proof-of-concept, exploring the limitations and capabilities of the system in an experimental environment; and
- identification of impacts of the prototype system on maintenance management and potential contributions to the design phase.

Some reasons have driven the selection of the lighting system for this study. First, it is among the five most significant reactive maintenance service subcategories identified by the multiple case study. Second, it plays a key role in energy efficiency, an important issue for smart building agenda (KING; PERRY, 2017; LEWIS, 2012; SACKS et al., 2018). Third, it has been investigated by this research partners from the Distributed Systems and Concurrent Programming Laboratory (LaSDPC/ICMC)[37] of USP, enabling the exploration of ongoing IoT artefact developments applied to FM activities. Lastly, its solutions can be expanded to other electrified building systems, such as HVAC.

The FM sector of the BR University was adopted as a reference for the construction of the prototype. The scenario involved the luminaire of a students' accommodation bedroom, identified as a critical room type according to the case studies. Since the selected building lacks a BMS, the prototyping involved the development of a system for monitoring and controlling luminaires.

Section 5.1 presents the conceptual inputs for the prototyping from the development and validation of the Classification Matrix of Luminaire Priority Level and the Conceptual framework of BIM & IoT Assisted Predictive Maintenance Process. It also provides results of online interviews with AEC and IT professionals. Section 5.2 introduces the Prototyping Process, involving the steps of Planning, Development, Implementation and Testing, and Results and assessment. Section 5.3. discusses the findings, and Section 5.4. summarizes the chapter.

[37] Under supervision of Dr Julio Cezar Estrella, researchers from the Distributed Systems and Concurrent Programming Laboratory (LaSDPC) and students from the "Internet of Things" graduation course of *Instituto de Ciências Matemáticas e de Computação* (ICMC) at University of Sao Paulo (USP), have been developing computational solutions to track objects and automatize lighting and HVAC systems.

5.1. Conceptual inputs for prototyping

This Section presents the two theoretical tools developed to support the prototyping process, namely Classification Matrix of Luminaire Priority Level and Conceptual framework of BIM & IoT Assisted Predictive Maintenance Process. The development, validation, and analysis of their results are described in Sections 5.1.1. and 5.1.2, and contributions from online interviews for the prototype development are provided in Section 5.1.3.

Taking the building luminaire as the object of investigation, the Classification Matrix of Luminaire Priority Level was developed to support maintenance teams in identifying critical luminaires and planning effective service responses. By supporting the prioritization of services, the matrix can guide the teams in targeting environments and equipment for a potential BIM and IoT implementation.

Complementary, a Conceptual framework of BIM & IoT Assisted Predictive Maintenance Process was generated to highlight the main aspects of the traditional maintenance process (i.e., stages, stakeholders, ICTs) improved by the implementation of BIM and IoT solutions. Demonstrating such a transformation, the framework assists the FM sector in identifying aspects related to process, technology and policy for the implementation of smart maintenance systems. In this research, the framework supported the identification of obstacles, barriers, and benefits involved in making maintenance smarter. Besides, it identified technical and functional requirements for the development of the smart lighting maintenance system prototype, as described in Section 6.1.2.

The theoretical tools were validated through questionnaires applied to experts in the field between October 2020 and January 2021. The group was comprised of 15 professionals (architects, and civil and electrical engineers) involved with university maintenance services from five Brazilian public universities. The questionnaires were developed in the Google Forms interface and sent to the participants via e-mail. The communication was made in Portuguese, and further translated into English.

An online interview was undertaken with an IT professional from the BR University FM sector towards the identification of technical requirements and construction of the prototype, and with professionals from the Brazilian AEC industry for the refining of strategies for its development. The interviews were conducted between June 2020 and December 2020 on the Google meet platform and registered through written notes and video records. The results of both questionnaires and interviews supported the prototyping process and the discussion of the research findings.

5.1.1. Classification Matrix of Luminaire Priority Level

a. Development

This section describes the activities involved in the development of the Classification Matrix of Luminaire Priority Level. Figure 81 illustrates the matrix, whose design was based on variables related to the Room and Lighting system, classified according to their Importance Degree (I.D.). Four Room variables were proposed, namely Typology (i.e., Sports & Leisure, Support & Commercial, Administrative & Residential, Academic & Circulation, and Research & Health), Function (e.g., Gymnasium, Toilet, Student bedroom, Classroom, Stairs and Ramps), Predominant period of use (i.e., Morning, Afternoon, Night, Integral), and

Number of users (i.e., Individual, Public (2-10 people), Public (11-50 people), Public (51-100 people), and Public (>100 people)) were proposed. On the other hand, the two Lighting system variables corresponded to Function (i.e., Decorative Lighting, General Lighting, Working Lighting, Special Lighting (Research, Medical), and Emergency Lighting and Night Lighting) and Number of luminaires (i.e., ≥5, 4, 3, 2, and 1).

A 5-level Likert scale classified the variables according to their Importance Degree (I.D.), i.e., Very Low, Low, Medium, High, and Very High. Four Luminaire Priority Levels (LPL) were generated from the classification in a decreasing order of priority attendance (e.g., LPL1 (red), corresponding to services addressed within 2 hours, LPL2 (orange), for services attended within 24 hours, LPL3 (yellow), for services attended within 3 days, and LPL4, for services provided in a date agreed with the solicitor).

Figure 81: Classification Matrix of Luminaire Priority Level (LPL)

Class	**Variable**	**Importance Degree (I.D.)**				
		Very Low	**Low**	**Medium**	**High**	**Very High**
Room	**Typology**	Sports & Leisure	Support & Commercial	Administrative & Residential	Academic & Circulation	Research & Health
Room	**Function**	Swimming pool, Tennis Court, Gymnasium, Storage	Kitchen, Toilet, Workshop, Cafe, Restaurant	Office, Meeting room, Student bedroom	Library, Classroom, Teaching Laboratory, Lecture Theatre, Corridor	Research Laboratory, Medical Centre, Nursery, Stairs and Ramps
Lighting System	**Function**	Decorative Lighting	General Lighting	Working Lighting	Special Lighting (Research, Medical)	Emergency Lighting and Night Lighting
Room	**Predominant period of use**	Morning and Afternoon	Morning and Afternoon	Integral	Night	Night
Room	**Number of users**	Individual	Public (2-10 people)	Public (11-50 people)	Public (51-100 people)	Public (>100 people)
Lighting System	**Number of luminaires**	≥5	4	3	2	1

LEGEND

Luminaire Priority Level (LPL)	LPL4	LPL3	LPL2	LPL1

Source: Author (2021)

A dynamic and user-friendly version of the matrix was developed in Microsoft Excel to assist maintenance team members (and other interested users, such as designers and researchers) in its implementation. The *option button* functionality grouped the predefined variables into classes, enabling the user to select the options related to the target luminaire. After selection, the Luminaire Priority Level Result (LPL) was automatically generated at the bottom of the matrix and coloured according to the prioritization criteria. Figure 82 shows an example of a luminaire classified as LPL1. A demonstrative video was developed to assist the user in operating the dynamic matrix in Excel.[38]

[38] Available at: https://youtu.be/X5-Lr6Gcdoc

Figure 82: Dynamic Classification Matrix of Luminaire Priority Level (LPL)

Classification Matrix of Luminaire Priority Level

CLASS AND VARIABLES

Room				***Lighting System***	
Typology	Function	Predominant period of use	Number of users	Function	Number of luminaires
○ Research & Health	○ Research Laboratory, Medical Centre, Nursery, Stairs and Ramps	○ Night	● Coletivo (>100 pessoas)	○ Emergency Lighting and Night Lighting	○ 1
○ Academic & Circulation	● Library, Classroom, Teaching Laboratory, Lecture, Theatre, Corridor	○ Night	○ Coletivo (51-100 pessoas)	○ Special Lighting (Research, Medical)	○ 2
○ Administrative & Residential	○ Office, Meeting room, Student bedroom	○ Integral (Morning, Afternoon, Night)	○ Coletivo (11-50 pessoas)	○ Working Lighting (Desk, Fume Cupboard)	○ 3
○ Support & Commercial	○ Kitchen, Toilet, Workshop, Cafe, Restaurant	○ Morning and Afternoon	○ Coletivo (2-10 pessoas)	● General Lighting	● 4
○ Sports & Leisure	○ Swimming pool, Tennis Court, Gymnasium, Storage	○ Morning and Afternoon	○ Individual	○ Decorative Lighting	○ ≥5
● Other	○ Other	● Other	○ Other	○ Other	○ Other

Luminaire Priority Level Result (LPL)

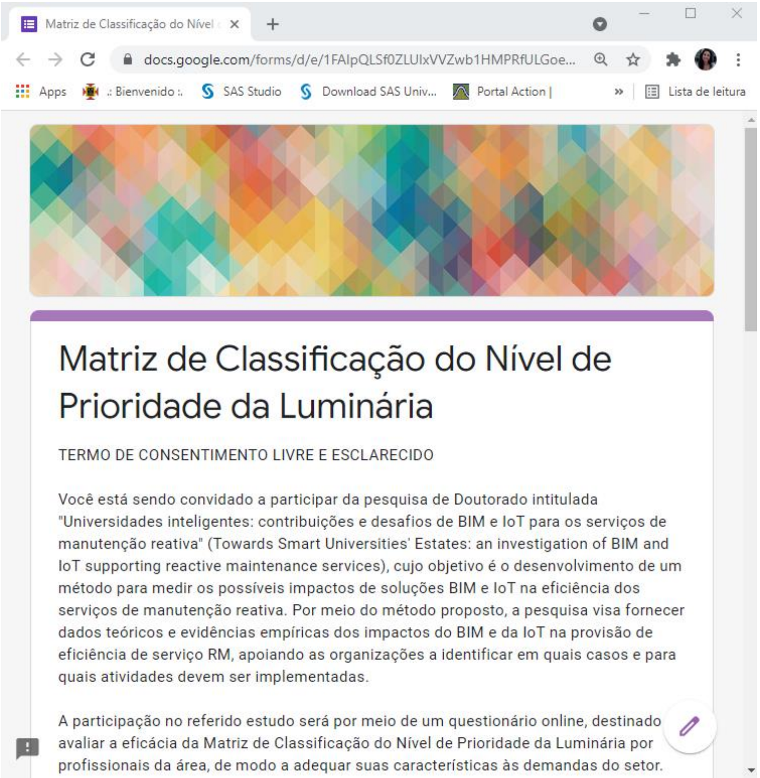
LPL1

Source: Author (2021)

b. Validation

This section describes the validation of the Classification Matrix of Luminaire Priority Level. The aim was to evaluate whether the matrix addressed the needs of university maintenance sector, and an online questionnaire with multiple-choice and open-ended questions was developed for the experts to assess its efficacy. 14 professionals participated, and Figure 83 shows a partial view of the questionnaire on the Google Forms interface. A complete version of the questionnaire written in Portuguese is provided in Appendix **I**. The document was organized into three sections: Section 1, which presents the research goals and the informed consent, Section 2, which describes the questionnaire scope and raises profile information of the participants, and Section 3, which provides instructions and the questions for the assessment.

Figure 83: Partial view of the online questionnaire for the assessment of the Classification Matrix of Luminaire Priority Level written in Portuguese



Source: Author (2021)

The efficacy of the matrix was assessed in terms of adequacy of its classes (i.e., room, lighting system), variables (i.e., typology, function, predominant period of use, number of users, number of luminaires), degrees of importance (i.e., very low, low, medium, high, and very high), and Luminaire Priority Levels (i.e., LPL1, LPL2, LPL3, LPL4) for luminaire classification. The applicability of the matrix by the participants' maintenance sector was also evaluated. A demonstrative video on the dynamic matrix in Excel was provided to the experts to support their responses[39].

[39] Available at: https://youtu.be/X5-Lr6Gcdoc

c. Results

This section reports on a qualitative analysis of the answers to the questionnaire for the validation of the Classification Matrix of Luminaire Priority Level. Section 2 of the questionnaire provides information on the 14 respondents' profiles. Regarding professional background, the results show a predominance of civil engineers (50%), followed by electrical engineers (36%) and architects (14%), whereas job position shows a higher number of construction inspectors (36%), followed by designers (29%), technical supervisors (21%), and chief/coordinators (14%). According to time in the job position, 43% reported 5 to 10 years, followed by 21% between 10 and 15 years, 21% between 2,5 and 5 years, and 15% over 15 years. In Section 3 of the questionnaire, the respondents assessed the components of the matrix. Consulted if the room (i.e., typology, function, predominant period of use, number of users) and lighting (i.e., function, number of luminaires) variables were adequate for the classification of the luminaire priority level, 93% answered "yes" and 7% answered "no". They also suggested adjustments in both variables and categories, as shown in Table 29.

Table 29: Suggestions of adjustments to the proposed variables and categories of the matrix

Class	Variable	Adjustment and rationale
Room	Number of users	This variable was considered less relevant than the activity conducted in the room. As exemplified by a respondent, "many people may be in a room undertaking an activity which does not require a good lighting level." (EXPERTS, 2021a)
Lighting system	Number of luminaires	This variable is insufficient for the assessment of the importance degree if the position of the luminaires and the area of the room are considered. As exemplified by a respondent, "the room may be very big and the lamps to be replaced may be located in strategic positions, and not evenly distributed". (EXPERTS, 2021a)
	Function	Variable "Outdoor night lighting" must be added with a Very High importance degree, due to its relevance for maintenance prioritization.

Source: Author (2021)

Eight suggestions were provided regarding the necessity of new variables in the classification matrix (EXPERTS, 2021a). Table 30 shows the suggested variables and the rationale for their adoption.

Table 30: Suggestions of new variables for the matrix

Variable	Rationale
Natural lighting	Some rooms keep a good lighting level even with no artificial lighting, particularly in the morning and in the afternoon.
	Natural lighting must benefit some rooms with glass envelope (e.g., courts and swimming pools in sport areas, and offices).
Ceiling height	Depending on the room height, the repair requires the use of special equipment, and since it might impact the activities undertaken in the room, it must be previously scheduled.
Specification of lamp and luminaire	Since some older models of lamps and luminaires are less efficient and economic, their replacement must be prioritized in relation to newer models.
	Due to the large variety of types and models, the manufacture of several lamps and luminaires must also be assessed.
Maintenance records	The luminaire data of installation must be considered for prioritization of services.
Property security	Questions related to property security are important for the prioritization of lighting maintenance.
Contractual compliance	Some contracts between the university and external suppliers set the priority luminaires to be maintained. The lack of compliance might impose financial penalties to the university maintenance sector.
Standard lighting levels	The lighting levels recommended by technical standards must be considered for the prioritization of services.
Activity risks	The risks involved in activities developed in the rooms must be considered for the prioritization of services.

Source: Author (2021)

Consulted whether the variables were correctly classified according to their Importance Degree (I.D.), 93% of the participants replied "yes" and 7% answered "no" (EXPERTS, 2021a), and five suggestions were reported regarding the necessity of adjustments in Importance Degree (I.D.). Table 31 shows the adjustments suggested according to the classes and variables, and the rationale for their acceptance. 93% of the responses were "yes" and 7% were "no" for the appropriateness of the proposed Lighting Priority Levels (LPL) (EXPERTS, 2021a), and two suggestions were made, i.e., classification of Special Lighting as an LPL1, due to its high priority for the Research and Medical activities, and review of the time response considering the capacity of attendance of each organization. As explained by a participant, the time response depends on the availability of staff to attend emergent requests and preventive maintenance, and existence of a full computerized system (e.g., CAFM), from the request opening to its attendance.

Table 31: Suggestions of adjustments to Importance Degree (I.D.) of the matrix

Class	Variable	Category	Adjustment and rationale
Room	Function	Sport	It must be classified as High I.D. because it requires a higher lighting level.
		Kitchen and workshop	It must be classified as High I.D. because the activities developed in the rooms require sharp drilling and cutting tools, thus involving safety risks.
			It must be classified as Higher priority level in comparison to bedrooms.
Lighting system	Function	Emergency lighting	The High I.D. of emergency lighting must not be considered for the opening of a Work Order, since it refers to regular preventive maintenance.
			The emergency lighting I.D. is considered less important than Working and Special lighting, since its rarely used.

Source: Author (2021)

The participants were asked if and why the Classification Matrix of Luminaire Priority Level could assist the maintenance team in both identification of critical luminaires and prioritization of services. The participants agreed the matrix is an effective tool for performance improvements due to the reasons shown in Table 32. The understanding of lighting maintenance as a critical service was emphasized, thus demanding the optimization of scarce financial and labour resources (EXPERTS, 2021a).

Table 32: Reasons on the effectiveness of the matrix as a tool

Focus	Reason
Objective prioritization of service attendance	The matrix might support the prioritization of lighting service attendance, which is highly demanding due to its importance in providing adequate work conditions to the university users.
	The matrix might support the maintenance team in fast and objectively identifying places with priority attendance.
	The functional criteria of the matrix might replace the current criteria for service attendance according to the requesting order, which is particularly a problem in case of simultaneous requests.
Planning services	The matrix might contribute to both service attendance and more organized and structured maintenance planning.
Staff sizing	By supporting the prioritization of services, the matrix might contribute to the maintenance staff sizing, thus providing better responses to the users.
Resources distribution	By supporting the prioritization of services, the matrix might contribute to the distribution of resources.
Management of outsourced services	The matrix might support the new maintenance professionals with no expertise in the field in managing outsourced services, which are a trend in the university FM sector.
	The matrix might support the management of contracts and activities related to outsourced services. In the public sector, governmental guidance reinforces the necessity of strategies to control services provided by outsourced firms.
Time savings	By supporting the prioritization of services, the matrix might optimize service attendance, saving time and avoiding interruptions in the university key activities.

Source: Author (2021)

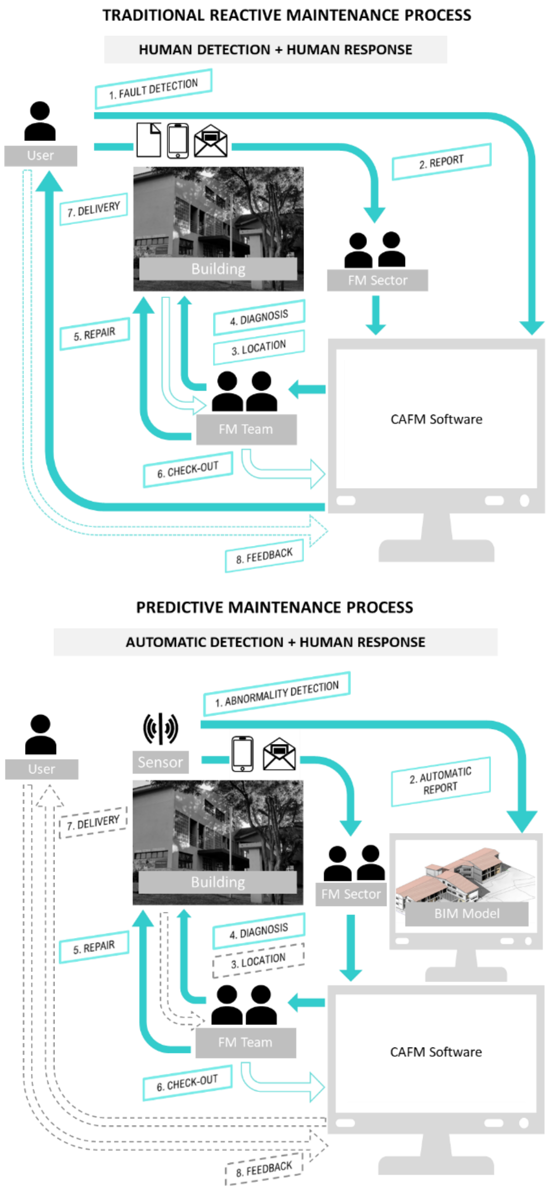
Finally, the participants provided additional suggestions for improving the overall matrix. The first refers to the matrix design, which should be simpler and more objective, thus providing synthesized and clear information. According to the participant, this adjustment would be particularly important to the maintenance team managing urgent and emergent requests at night and under extreme conditions. The second suggestion is related to "number of luminaires", whose meaning should be more evident to the matrix user (EXPERTS, 2021a), since its relation with number of luminaires per room or quantification of equipment to be registered for maintenance control was not clear for the participant. The third refers to the frequency of maintenance of luminaires, which could be used in the evaluation of their lifetime.

5.1.2. Conceptual framework of BIM & IoT Assisted Predictive Maintenance Process

a. Development

This section describes the activities conducted for the development of the Conceptual framework of BIM & IoT Assisted Predictive Maintenance Process, also called "smart maintenance process" (see Figure 84).

Figure 84: Conceptual framework of BIM & IoT Assisted Predictive Maintenance Process



Source: Author (2021)

The first component is the stages of maintenance process, established according to ISO EN 13306: 2017, namely, 1. Detection, 2. Report, 3. Location, 4. Diagnosis, 5. Repair, 6. Check-out, 7. Delivery, and 8. Feedback (THE BRITISH STANDARDS INSTITUTION, 2017). The framework is also integrated by the stakeholders (i.e., user, sensor, FM sector) and communication and information management tools and interfaces used in the lighting maintenance process (i.e., telephone, form, e-mail, CAFM tools, BIM software).

Two scenarios, namely traditional reactive maintenance process and smart maintenance process were represented in the framework. The former is predominantly centred on a reactive approach solving problems after their occurrence. It is characterized by a great dependence on human actions for detecting, communicating, locating, and recording failures. Although mediated by ICTs, such as e-mail and CAFM tools, inefficiencies in the services are often observed.

On the other hand, the smart maintenance process streamlines non-value adding stages and improves both quality and accessibility of information, anticipating problems prior to their occurrence. Failures in the luminaire are no longer detected and communicated by users. Instead, the sensor identifies abnormalities and informs the FM sector and BIM in real time. Therefore, the maintenance team can visualize luminaire information (i.e., performance status, location, technical specification) accurately and quickly, supporting the planning of repair.

b. Validation

This section presents the activities involved in the validation of the Conceptual framework of BIM & IoT Assisted Predictive Maintenance Process. The first objective of the validation was to assess whether the framework depicts real conditions faced by the universities FM sectors. The second one was to identify potential outcomes of the implementation of a smart lighting maintenance system. The third objective was to identify technical and functional requirements to develop the proposed system. To do so, an online questionnaire with multiple-choice and open-ended questions was developed for the university experts. 14 professionals participated of this assessment. A partial view of the questionnaire on Google Forms is shown in Figure 85. Appendix J provides the complete version of the questionnaire written in Portuguese.

The document was systematized in four sections. Section 1 presents the research goals and the informed consent. Section 2 describes the questionnaire scope and raised profile information. Section 3 provides the instructions and questions for assessing the adequacy of the framework components (i.e., stages, stakeholders, ICTs). Section 4 provides the instructions and questions to identify the following aspects:

- obstacles in the traditional reactive maintenance process of luminaires;
- obstacles in the traditional reactive maintenance process of luminaires which could be minimized by the implementation of the smart lighting maintenance system prototype;
- benefits of the smart lighting maintenance system prototype to the efficiency of maintenance services;
- barriers to implement the proposed system;
- technical and functional requirements for developing the proposed system.

Figure 85: Partial view of the online questionnaire for the assessment of the Conceptual framework of BIM & IoT Assisted Predictive Maintenance Process written in Portuguese

Source: Author (2021)

c. Results

This section presents the qualitative analysis of the questionnaire's responses for the validation of the Conceptual framework of BIM & IoT Assisted Predictive Maintenance Process. Section 2 of the questionnaire provides information on the 14 respondents´ profiles. Regarding the professional background, the results show a predominance of civil engineers (50%), followed by electrical engineers (29%), architects (14%) and electrotechnical technicians (7%), whereas on the job position, most respondents are chief/coordinators (29%), designers (21%), technical supervisors (14%), and others (i.e., construction inspector, technical inspector, engineering auxiliary, and draughtsman) (36%).

In Section 3 of the questionnaire, the respondents assessed the adequacy of the framework components. Consulted whether the stages of the traditional maintenance process represented the service undertaken by their organizations, 86% replied "yes", 7% answered "no", and 7% replied "I don't see stage 8 being carried out" (EXPERTS, 2021b), and also provided suggestions and comments. One of the participants stated the diagnosis and location prior to the repair stage might not be necessary, since, in general, the user is able to inform the precise location of the fault. On the other hand, another participant described inefficiencies in the fault report that impacted service performance, and reported the lack of a systematic feedback as a problem, due to the misuse of historical information for maintenance planning:

> "Currently, in the organization I work for, the report stage is conducted through a system, in which the user registers a maintenance request and then an S.O. [Service Order] is opened. However, the user does not always know how to detail and explain in the request, what happened, and the exact problem to be solved, which creates a difficulty – the maintenance team receives the S.O., and, sometimes, wastes time in understanding what happened and locating the fault. In the S.O. registration system in the feedback stage, the only information

provided is the meeting (or not) of the demand, since no real description of what happened is provided; therefore, it can serve as a history for later monitoring."[40] (EXPERTS, 2021b)

Focusing on the fault report, one of the participants emphasized the importance of users filling a questionnaire and providing images of the issue for supporting the maintenance team in planning effective repairs. Asked if the stakeholders and communication and information management tools and interfaces of the traditional maintenance process represented the service undertaken by their organizations, 79% of the participants replied "yes", 14% replied "no", and 7% answered "partially" (because CAFM software was recent) (EXPERTS, 2021b). No suggestions for adjustments in the tools and interfaces of the traditional maintenance process were provided.

The participants were consulted on the stages of the traditional maintenance process that would potentially be impacted by the implementation of the smart lighting maintenance system and the rationale. As depicted in Table 33, the responses covered all the stages of the process. The impacts were related to the automation of activities, accuracy of information, time savings, and elimination of user participation, particularly in the stages of fault detection, report, and location.

Table 33: Stages impacted by the implementation of the Smart Lighting Maintenance System and rationale

Stage	Rationale
1. Detection	Automation: an automatic and predictive detection would trigger the repair before the problem had impacted the user
	Accuracy: the sensor would detect the problem more accurately than the user, eliminating user's bias or lack of knowledge
	Time savings
	Elimination of user participation: the user would not need to identify the problem
2. Report	Automation: the report would be automatic and autonomous
	Time savings
	Elimination of user participation: the user would not need to report the problem
3. Location	Automation: the location would be automatically identified on the map
	Accuracy: the location would be more precise
	Time savings: reduction or elimination of time for problem location
	Elimination of user participation: the user would not need to inform the problem location, which is often imprecise
4. Diagnosis	Automation: the system could apply an Artificial Intelligence algorithm to identify the problem
	Time savings: quicker diagnoses
5. Repair	Time savings: the communication between the service to be conducted and the repair would be improved
6. Check-out	Automation: the sensor would identify the performance status of the equipment
	Time savings: reduction or elimination of time for check-out
7. Delivery	Automation: the delivery stage would not be necessary, since the system is automatic
	Elimination of user participation
8. Feedback	Automation: the feedback stage would not be necessary, since the system is automatic
	Elimination of user participation: no necessity of the user signing a form to close the request

Source: Author (2021)

[40] Free translation of "Atualmente na empresa que trabalho a etapa de comunicação é feita por meio de um sistema, no qual o usuário cadastra um pedido de manutenção e em seguida é aberta uma O.S. Contudo, nem sempre o usuário sabe detalhar e explicar na sua solicitação o que ocorreu e qual é exatamente o problema para ser resolvido. Isto cria uma dificuldade, pois a equipe de manutenção recebe a O.S mas as vezes perde tempo em compreender o ocorrido e localizar a falha. Já na etapa de feedback, no sistema de registro de O.S apenas é inserido a informação se a demanda foi ou não atendida, porém não é feito uma descrição real do ocorrido para que sirva de histórico para monitoramentos posteriores."

As stated by one of the respondents, “many times the user would not even realize the lighting have been defective”[41] if user participation in the detection, report, delivery, and feedback were eliminated (EXPERTS, 2021b). Besides, the smart lighting maintenance system would avoid the duplication of requests in CAFM software, caused by more than one user reporting a same fault. However, one of the respondents highlighted the reliability of automatic information as a critical aspect to ensure an effective response and avoid disruptions.

In section 4, the participants replied to questions on the potential outcomes from the implementation of the smart lighting maintenance system prototype and functional and technical requirements for its development. Initially, they were asked to list three to five obstacles faced by their organizations in the traditional reactive maintenance process of luminaires. Table 34 shows the summary of the answers organized according to Technology, Process, and Policy themes (EXPERTS, 2021b).

Regarding Technology, the obstacles were related to the accuracy, reliability, accessibility, and availability of data and information (i.e., inaccurate fault report, duplication of requests, and ineffective communication with users). Process obstacles involved people (i.e., insufficient staff, lack of skills) and strategic, tactical, and operational issues (i.e., difficulties in managing stakeholders, insufficient material for repair), and policy ones were related to difficulties in services classification and lack of guidelines.

Table 34: Obstacles in the Traditional Reactive Maintenance Process

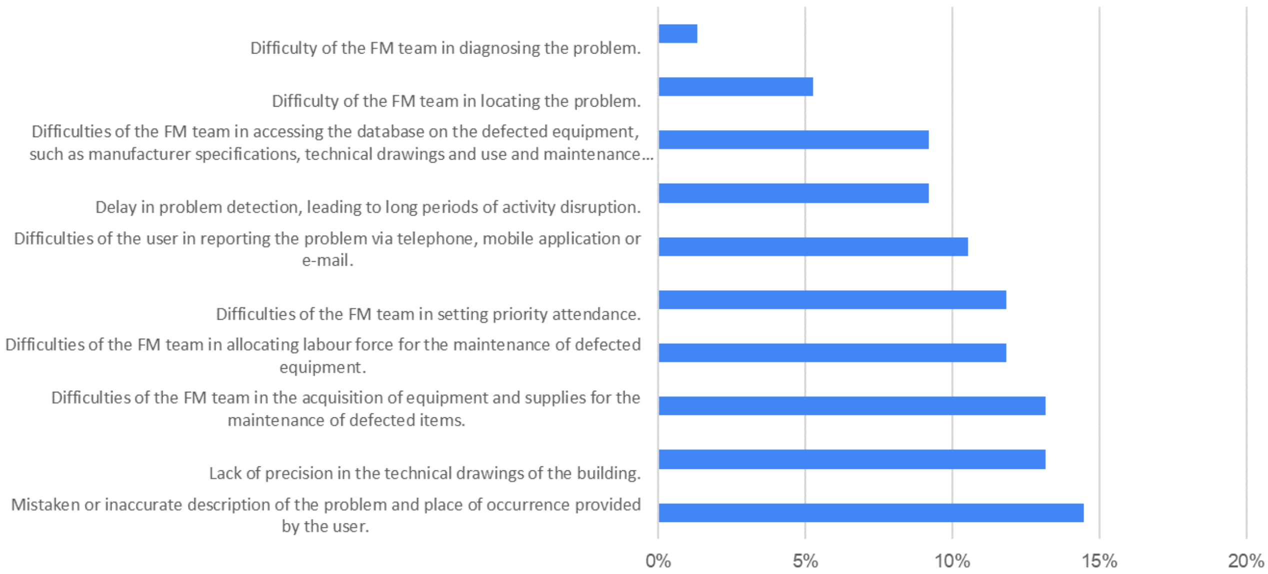
Theme	Category group	Category	Obstacles
Technology	Data and Information	Accuracy and Reliability	The late and inaccurate fault detection and report (due to omission, unavailability of time, or lack of knowledge) negatively impact on problem diagnosis and location, hence, time response
			An inaccurate description of problems hampers service provision
			Failures in communication between the requester and the maintenance sector (e.g., sending requests to the wrong sector) hamper service provision
			Duplication of requests
		Accessibility and Availability	Lack of an official on call system for maintenance on weekends, holidays and at night
			Failures in the CAFM software
			Documents and drawing of assets are not always available and updated
			Difficulties in scheduling the maintenance repair with the user, particularly in rooms with access restrictions (e.g., student bedroom)
			Lack of feedback from the user
Process	People issues	Capability	Few electricians for the service, which delays its attendance, despite the automation of the Help Desk
			Maintenance team members with insufficient skills to navigate the project documentation
	Strategic, Tactical and Operational	Leadership	Difficulties in managing many stakeholders involved in the maintenance process, from the receiving of the Service Order to the closing of the request in CAFM software
			Distribution of demands per maintenance team members
			The high dependence on the system managers hampers service provision
		Feasibility	Difficulties in planning predictive maintenance
			Insufficient material for repair in the stock
			Difficulties in controlling the stock of materials
Policy	Regulatory	Classification	Difficulties in service prioritization, mostly due to the use of the “First In First Out” (FIFO) method
		Guidelines	The lack of standardization of luminaires in the design stage hampers the acquisition of equipment for replacement

Source: Author (2021)

[41] Free translation: “(…) muitas vezes ele nem se daria conta que a iluminação esteve deficiente.”

The participants were then asked to select the obstacles observed in the traditional reactive maintenance process of luminaires from a pre-determined list. Figure 86 shows the results. "Mistaken or inaccurate description of the problem and place of occurrence provided by the user" was the most predominant obstacle (14%), followed by "Lack of precision in the technical drawings of the building" (13%), "Difficulties of the FM team in acquiring equipment and supplies for the maintenance of defected items" (13%), "Difficulties of the FM team in allocating labour force for the maintenance of defected equipment" (12%), and "Difficulties of the FM team in setting priority attendance" (12%). Other obstacles were related to problem report via telephone, mobile application, or e-mail (11%), delay in problem detection (9%), access to the database of defected equipment (9%), problem location (5%), and problem diagnosis (1%) (EXPERTS, 2021b).

Figure 86: Obstacles in the Traditional Reactive Maintenance Process of luminaires



Source: Author (2021)

The participants were asked on whether and why a smart lighting maintenance system could contribute to improving the traditional reactive maintenance process. Table 35 shows the results. All respondents agreed that the smart system can support more efficient maintenance processes (EXPERTS, 2021b). The rationale involved improvements in the service prioritization, quality of information, acquisition of material, time response, and decision-making. Nevertheless, some participants highlighted the necessity to overcome obstacles inherent to the Brazilian public sector (e. g., budget restrictions, unavailability of supplies, difficulties in team coordination, obstacles and delays in procurement caused by legal restrictions) for the obtaining of the system's benefits. As stated by one of the participants, a Return on Investment (ROI) analysis would be also necessary to support the implementation of a smart system.

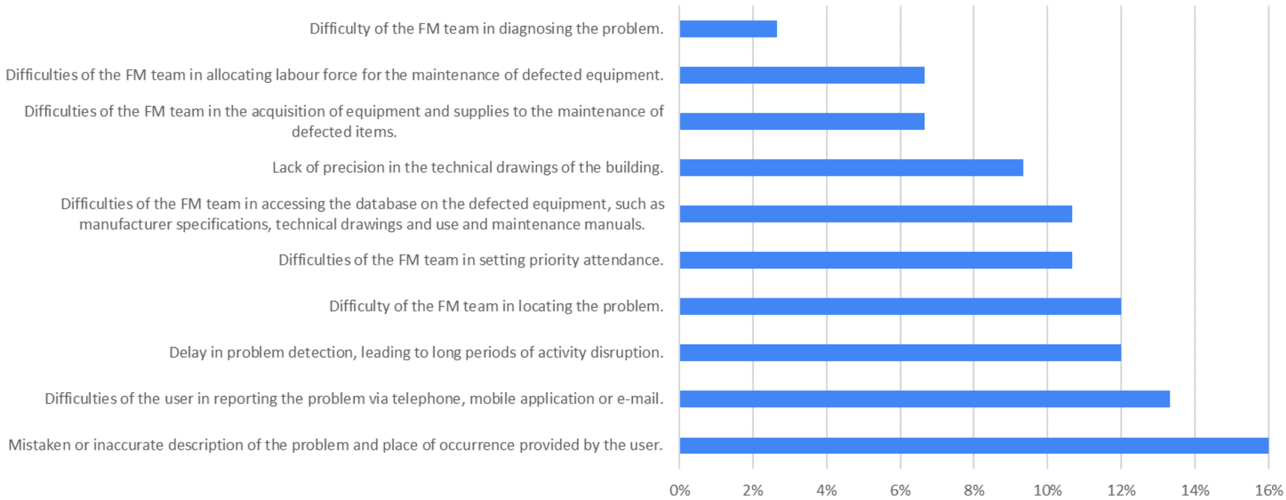
The participants were asked on the obstacles in the traditional reactive maintenance process that could be minimized through the implementation of a smart lighting maintenance system (Figure 87 shows the results). "Mistaken or inaccurate description of the problem and place of occurrence provided by the user" was the most predominant (16%), followed by "Difficulties of the user in reporting the problem via telephone, mobile application or e-mail" (13%), "Delay in problem detection, leading to long periods of activity disruption" (12%), and "Difficulty of the FM team in locating the problem" (12%). Other obstacles were related to definition of priority attendance (11%), access to the equipment database (11%), accuracy of technical drawings (9%), acquisition of supplies and equipment (7%), allocation of labour force (7%), and problem diagnosis (3%) (EXPERTS, 2021b).

Table 35: Rationale on why a Smart System improves the Traditional Reactive Maintenance Process

N	Rationale
1	"Yes, because it would optimize the time spent on each service and the setting of priorities."
2	"Yes, for prioritizing and diagnosing problems, inform the correct technical data of the location and equipment."
3	"Every autonomous monitoring system undoubtedly assists in the control of maintenance because it enables schedule of services, acquisition of materials, and planning of preventive actions over time."
4	"Yes, because it would facilitate the maintenance team in speeding up the diagnosis of a problem and accurately locating it, making maintenance faster and defining more precise priorities."
5	"It can improve the process, since it speeds up the detection of problems, their diagnosis and correction. It also eliminates bottlenecks of the traditional process, thus facilitating decision-making."
6	"Certainly yes. It can automate the process providing higher performance and agility to activities."
7	"Yes. The automation would make the process more agile and accurate in information, but it needs to be 100% reliable and functional."
8	"Yes, since some obstacles, such as delay in problem detection and mistaken description of a problem, would be eliminated."
9	"Yes. It reduces human interference and makes the process more agile and effective."
10	"Yes. I believe it can mitigate the problems reported in [question] 6.
11	"I believe so, especially in stages that demand human action for communication and decision-making. However, Brazilian public organizations would continue to have problems such as obstacles and delays in the acquisition of materials and services, due to the current legislation for bidding processes."
12	"It can potentially detect and characterize anomalies; however, it depends on other factors such as availability of supplies (composition of stock or quick means of acquisition) and team coordination for offering real benefits."
13	"Yes, because it enables the knowledge of lighting problems in advance; however, it would require data on implementation costs to check feasibility against the resources available for maintenance actions."
14	"This system would be a leap in improvements in the management of luminaires. However, significant time (years) would be necessary for public institutions to reach such a level, unless this service were removed from the responsibility of the institution's maintenance team and under that of an external company hired specifically for this type of service. The engineering teams of the public sector would therefore only manage service provision contracts."

Source: Author (2021) based on Experts (2021b)

Figure 87: Obstacles in the Traditional Reactive Maintenance Process which could be minimized through the implementation of a Smart Lighting Maintenance System



Source: Author (2021)

The participants listed three to five benefits of a smart lighting maintenance system for the efficiency of maintenance services. Table 36 shows a summary of the answers organized according to the maintenance stages (EXPERTS, 2021b). Apart from the individual benefits of each stage, the participants emphasized the contributions to the overall process, which would improve the efficiency of maintenance service providence, and trigger the adoption of BIM by the maintenance sector.

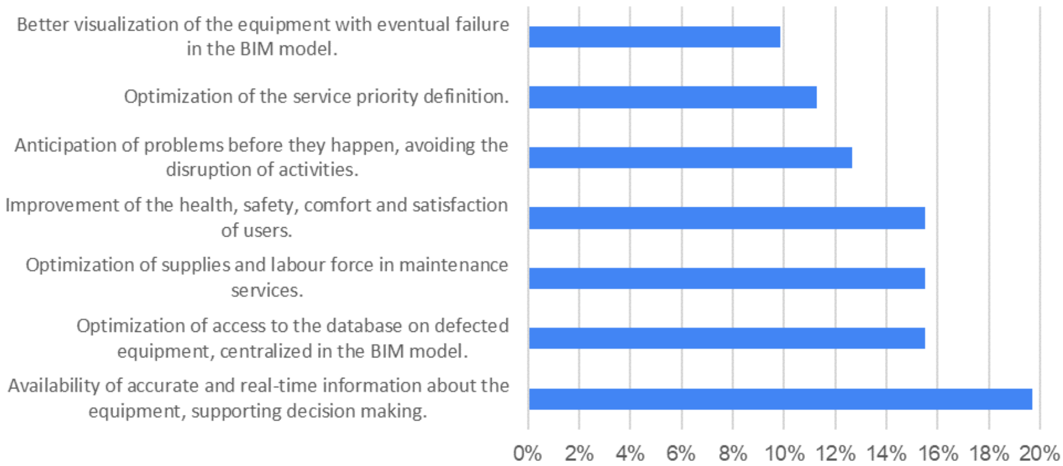
Table 36: Benefits of a Smart Lighting Maintenance System for the efficiency of maintenance services

Category	Benefits
1. Detection	Agility in problem detection, reducing or eliminating user participation
2. Report	Agility and accuracy in problem report, improving the quality of information in the CAFM system
	Agility and accuracy in service prioritization and allocation for the maintenance teams
3. Location	Agility and accuracy in problem location, facilitating field work
4. Diagnosis	Agility in problem diagnosis supported by a more accessible equipment database, reducing the necessity of local inspection
	Agility in the planning of material acquisition
5. Repair	Agility in problem repair
6. Check-out and 7. Delivery	Automation of service check-out and delivery
8. Feedback	Automation of feedback after the solution of the problem
General process management	Improvement and optimization of the overall process management through the agility in decision-making; reduction of time response and time disruption; reduction in the number of people involved in the process (e.g., user, secretary, maintenance chief)
	Triggering of the adoption of BIM by the maintenance sector

Source: Author (2021)

The participants were asked to select, from a pre-determined list, the benefits of a smart lighting maintenance system for the efficiency of maintenance services. Figure 88 shows the results. “Availability of accurate and real-time information on the equipment, supporting decision-making” was the most predominant benefit (20%), followed by “Optimization of access to the database on damaged equipment, centralized in the BIM model” (15%), “Optimization of supplies and labour force in maintenance services” (15%), and “Improvement in users’ health, safety, comfort and satisfaction (15%). Other benefits were related to prediction of failures (13%), prioritization of services (11%), and visualization of failures on BIM (10%) (EXPERTS, 2021b).

Figure 88: Benefits of a Smart Lighting Maintenance System for the efficiency of maintenance services



Source: Author (2021)

In sequence, the participants listed three to five barriers for the implementation of the system. Table 37 shows a summary of the answers organized according to Technology, Process, and Policy themes (EXPERTS, 2021b). Although technological and policy barriers were reported by the participants (i.e., difficult integration among technologies, need of standards), process-related barriers were the most emphasized. For instance, regarding people issues, the lack of specialized professionals for installation, maintenance, and operation of a smart system was described as a core barrier, and scarcity of financial resources and the bureaucracy inherent to the public sector were seen as barriers for an effective implementation of a smart system concerning strategic, tactical, and operational maintenance. The necessity of a paradigm shift towards a predictive approach was also an important barrier to be overcome.

Table 37: Barriers for the implementation of a Smart Lighting Maintenance System

Theme	Category group	Category	Barriers
Technology	Software, Hardware and Network	Interoperability	Variety of technological models and suppliers, which hampers integration among technologies
	Data and Information	Accuracy and Reliability	Lack of updated and reliable asset documentation
			Low level of digitalization
Process	People issues	Capability	Lack of a permanent training program for the maintenance team to operate the new system
			Lack of companies qualified in implementation
			Difficulties in hiring specialized professionals to maintain the equipment of the system
		Engagement	Resistance of the team members to changing established processes
	Strategic, Tactical and Operational maintenance	Leadership	Necessity of organizational and cultural changes towards a predictive approach, which involves both maintenance team and university managers
		Feasibility	Necessity to migrate to the BIM environment
			Lack of an infrastructure for sensing, communication, and processing data, including software, hardware, and network components
			High costs of acquisition and maintenance of the system, involving infrastructure (i.e., software BIM, sensors) and specialized professionals
			Scarcity of financial resources
			Difficulties in acquiring components of the system
			Bureaucracy and lack of interest from the public sector
Policy	Regulatory	Guidelines	Necessity of standardizing the system components

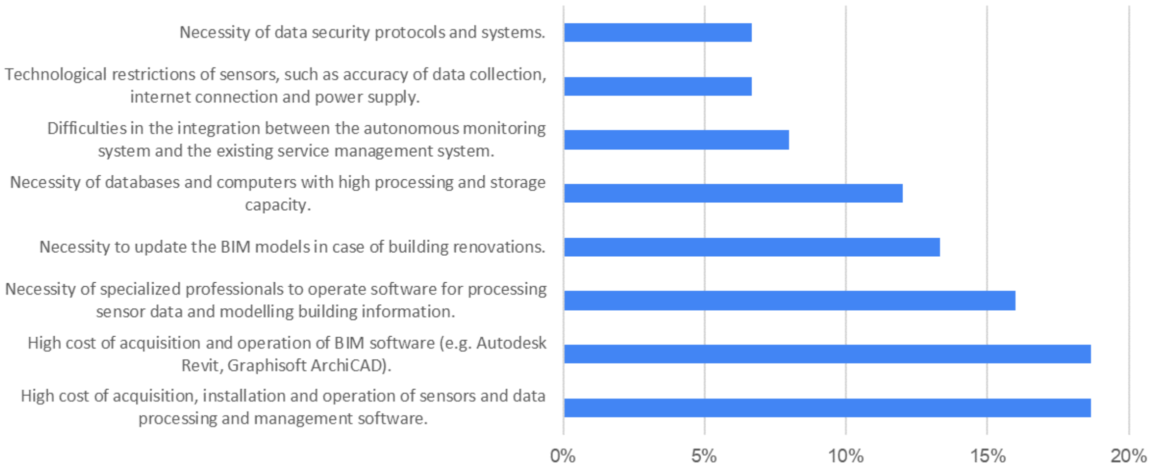
Source: Author (2021)

The participants selected the main barriers for the implementation of a smart lighting maintenance system from a pre-determined list. Figure 89 shows the results (EXPERTS, 2021b). “High costs of acquisition, installation and operation of sensors and data processing and management software” (19%) were the most predominant, followed by “High costs of acquisition and operation of BIM software” (19%), “Necessity of specialized professionals to operate software for processing sensor data and modelling building information (16%), and “Necessity to update the BIM models in case of building renovations” (13%). Other barriers were related to quality of databases and computers (12%), integration among systems (8%), technological limitations (7%), and data security issues (7%).

The participants listed three to five requirements to be considered in the development of a smart lighting maintenance system, and those related to its implementation were also provided. Table 38 shows a summary of the answers organized according to Technology and Process themes (EXPERTS, 2021b). Issues related to the abilities and design of the system were also listed and addressed both maintenance services and FM sector demands. The feasibility of implementation was conditioned to the availability of technological and human resources and the definition of priority rooms. The awareness of building users regarding the system abilities was considered relevant for its effective implementation. Such requirements supported the prototyping, as described in Section 5.2.

The participants selected, from a pre-determined list, the requirements to be considered in the development of a smart lighting maintenance system. Figure 90 shows the results (EXPERTS, 2021b).

Figure 89: Barriers for the implementation of Smart Lighting Maintenance System



Source: Author (2021)

Table 38: Requirements for the development and implementation of a Smart Lighting Maintenance System

Phase	Theme	Category group	Category	Requirements
Development	Technology	Software, Hardware and Network	Ability	Automatic detection and report of failures
				Generation of reports for supporting predictive maintenance and managerial decisions
				Information of priority of attendance of each room
				Information of data on the equipment to be maintained (e.g., manufacturer, model, etc.)
				Differentiation between emergency and non-emergency services
			Design	Use of standardized components (e.g., sensors, accessories for installation) and software that can be easily replaced and updated according to advances in technology
				Use of a device for mass storage
				Use of an open BIM platform for reducing costs
				Use of a robust system with high degree of accuracy and low likelihood of failures for ensuring the timely detection of problems
				Assurance of safety data and information
				Integration with the existing systems and facilities with no replacement of existing luminaires
				User-friendliness, due to the distinct backgrounds of the professionals
				Accessibility to all maintenance team members via smartphone
				Supply of direct and automatic tools and interfaces for de-bureaucratizing the process and improving its efficiency
				Low cost of implementation, maintenance, and operation
				Possibility to be managed by the own university
Implementation	Process	People issues	Capability	Well dimensioned and trained team for both implementation and operation of the system
			Awareness	Awareness of the building users regarding the system abilities to monitor assets and predict failures
		Strategic, Tactical and Operational FM	Feasibility	Acquisition and implementation of IT infrastructure, including software (i.e., BIM) and hardware components
	Policy	Regulatory	Guidelines	Implementation in rooms with higher number of users or safety risks (e.g., classroom, library, square, preferential pathways)

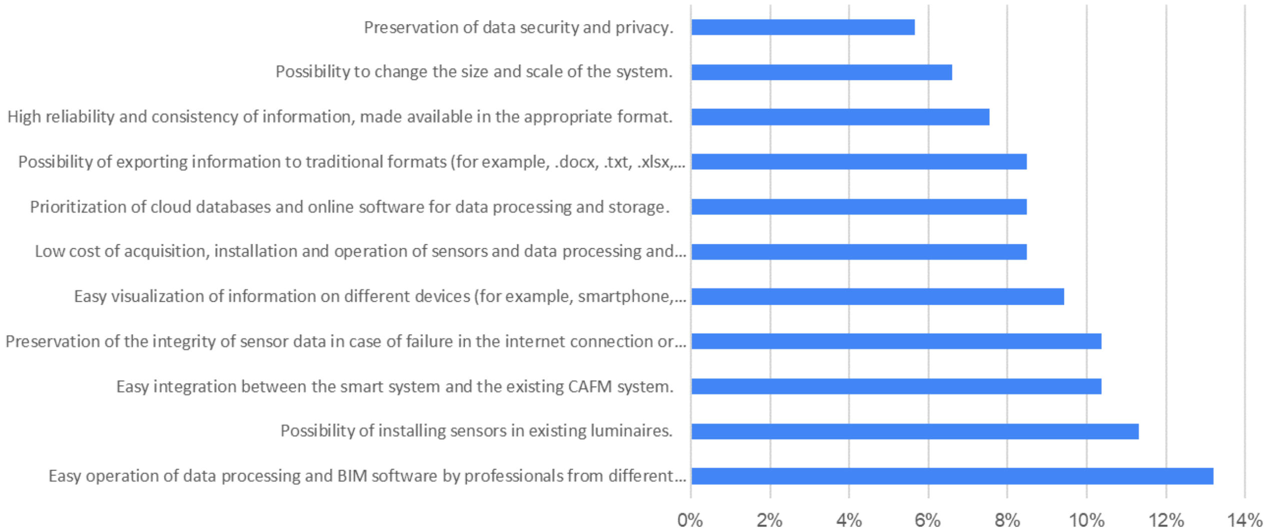
Source: Author (2021)

“Easy operation of data processing and BIM software by professionals from different technical backgrounds” (13%) was the most predominant, followed by “Possibility of installing sensors in existing luminaires” (11%), “Easy integration between the smart system and the existing CAFM system” (10%), and

"Preservation of the integrity of sensor data in case of failure in the Internet connection or power supply" (10%). Other requirements were related to information visualization (9%), implementation costs (8%), database and software types (8%), information format (8%), information quality (8%), system flexibility (7%), and data security (6%).

Finally, some participants provided additional comments on the questionnaire (EXPERTS, 2021b). The contribution of a smart lighting maintenance system to improvements in the maintenance service efficiency was highlighted not only in the context of universities, but also in residential and industrial environments. Autonomous monitoring systems were considered important tools to support an efficient management of maintenance and other services. However, according to one of the participants, some obstacles tend to remain even after the implementation of a smart system (e.g., political intervention in the prioritization of services, budget uncertainties, and delays in hiring and receiving materials and services).

Figure 90: Requirements for the development of a Smart Lighting Maintenance System



Source: Author (2021)

5.1.3. Interviews

This section addresses the online semi-structured interviews undertaken with AEC and IT professionals for the establishment of technical requirements and strategies for the prototype development. Table 39 shows a synthesis of the interviews, with details of date, professional background, job position, recording tools, and discussed topics. The first and the second interviews, conducted in June 2020 with two Architects and Urban Planners, both researchers on the BIM field, emphasized strategies to model BIM family parameters and insert real time data generated by sensors.

The third interview was undertaken in July 2021 with an electrical engineer of a public university. Focusing on lighting systems, it approached alternatives of devices to measure lighting variables, lighting performance metrics, lifecycle of lamps, and protocols for a pilot implementation. Similarly, the fourth interview, conducted in August 2020 with a mechanical engineer and researcher on architecture and building performance, focused on lighting principles, performance metrics, and protocols for a pilot implementation.

The last interview was conducted in December 2020 with the Chief of the IT Section of FM sector of the BR University. The aim was the identification of strategies towards integrating the maintenance information generated by the system prototype with the existing CAFM tools. Two members of the computer science team from LaSDPC/ICMC/USP also participated. A consent form (Appendix H) was applied to the interviewee, clarifying the research objectives, and obtaining his consent for participation. The interview was video recorded and further transcribed.

Table 39: Synthesis of online interviews with AEC and IT professionals

Date	Professional Background	Job Position	Recording tools	Topics
26/06/2020	Architect and Urban Planner	University lecturer and researcher on BIM	Written notes	Strategies to model BIM families and to integrate BIM models with external databases
29/06/2020	Architect and Urban Planner	BIM coordinator and researcher on BIM	Written notes	Strategies to insert real time data into BIM models with support of visual programming tools (e.g., Autodesk Dynamo)
06/07/2020	Electrical Engineer	Coordinator of Electrical and Mechanical Engineering of a public university	Video record	Sensor devices to measure lighting variables (i.e., current sensor, lighting sensor). Lighting performance metrics. Lifecycle of distinct lamp technologies (i.e., LED, fluorescent, incandescent, halogen, etc.) Protocol for pilot implementation, including issues related to sensor location and data collection (i.e., frequency, time)
26/08/2020	Mechanical Engineering	Researcher on environmental comfort, bioclimatic architecture and building performance	Video record	Lighting principles and performance metrics. Protocol for pilot implementation, including issues related to sensor location, data collection (i.e., frequency, time)
03/12/2020	Computer Scientist	Chief of the IT Section of FM sector BR University	Semi-structured interview (Appendix G)	Technical requirements and strategies to integrate maintenance information generated by the smart lighting maintenance system prototype with the CAFM software

Source: Author (2021)

Technical features of the existing CAFM software were identified. According to the interviewee, this system was developed in both Laravel framework and PHP, a programming language from the 2000s. The system is only used by the FM sector and its lack of flexibility hampers its integration with other university systems. In this sense, the FM sector is working on its replacement by Open-Source Ticket Request System (OTRS) in the next two years. OTRS is a commercial platform which organizes both internal and external communications of organizations involved in operations and management of services. Among its capabilities, it enables users to open a new service request (called ticket) through an e-mail message that is saved in the system, condensing all the relevant information for service management (OTRS, 2021).

Given this scenario, the challenge was to open a work request in CAFM from a notification message generated by the system prototype in case of an abnormality detection. Two strategies were drawn by the interviewee, i.e., development of a web service and creation of an e-mail notification. The first referred to the development of a proprietary middleware through a web service to introduce the notification information in the current CAFM software database. Despite the benefits of the automatic update of information, this strategy would be complex and costly (IBRAHIM et al., 2016), thus requiring efforts from the FM sector and the research team for the creation of new users in the system, organization of database structure, and implementation of the web service. The second strategy was the creation of an e-mail notification to be either manually introduced to the current CAFM, or automatically processed by the future CAFM software (i.e., OTRS). According to the participants, the development and implementation of this strategy would be quicker and simpler in comparison to the web service. The most suitable strategy was defined by the research team and is described Section 5.2.2.d.

5.2. Prototyping process development

This section presents the five steps of the Smart Lighting Maintenance System prototyping process, namely, planning, development, implementation and testing, results, and assessment, and theory generation depicted in Figure 8 in Chapter 2. The prototyping activities were coordinated by the author of this thesis and developed with the support of an IT team from LaSDPC/ICMC/USP, between July 2020 and April 2021. The interdisciplinary team was integrated by an Architect and Urban Planner (the author), a Computer Engineering graduation student, a Computer Engineer, and a Software Engineer. The collaboration was managed via online meetings, e-mail, and messaging applications across all the stages of the prototype development, due to restrictions in place for COVID-19. Project reports and presentations were monthly delivered, supporting the research development.

5.2.1. Planning

The planning stage aimed at structuring the global process and managing resources towards the research goal. Four sets of activities, namely, a. Definition of the scope, b. Establishment of requirements and assumptions for development, c. Establishment of FM BIM data requirements, and d. Outlining the experimental plan, were undertaken for planning the prototype.

a. Definition of the scope

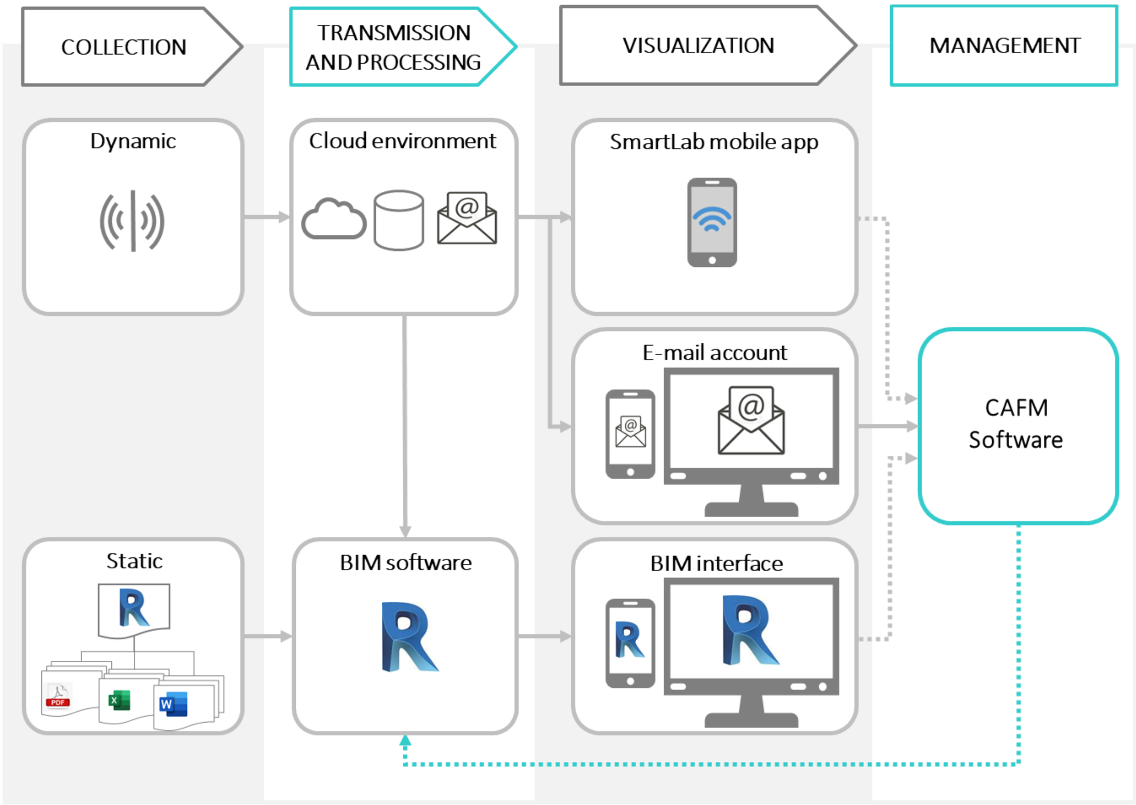
The Smart Lighting Maintenance System prototype aims to deliver accurate and anticipated lighting performance information to support university maintenance teams in decision-making. The scope of the prototype involves the following items:

- Automatic detection and report of current and potential abnormalities, generating notification messages to trigger maintenance service response.
- Automatic population of real-time information in SmartLab app and in BIM model parameters, the central database of luminaire information.
- Visualization of updated luminaire information on BIM and IoT interfaces.

A Theoretical Framework of the prototype (Figure 91) was developed to show a conceptual perspective of the system, based on the flow of luminaire data and information over the process. The SmartLab system built by LaSDPC for smart devices control (e.g. lighting, HVAC) (BUENO, 2020) was used for the development of the prototype, as detailed in Section 5.2.2. Four steps, namely, Collection, Transmission and processing, Visualization, and Management compose the framework.

Collection consists in the creation of dynamic and static data from different sources. Dynamic data regard the lighting level (V) and operating time (h) collected from sensors on the luminaire. A time-series was generated with the historical records of the luminaire performance. Static data are the permanent aspects of the lighting system (i.e., number of luminaires, model of lamp), the monitoring system (i.e., ID, type, location), and the maintenance service, all commonly stored in FM statutory documents (e.g., room plans, equipment manual, and maintenance spreadsheets). In this study, they were centralized in a BIM model developed in Autodesk Revit 2021 for maintenance purposes. The second step starts with the transmission of the generated raw data to a cloud environment. There, data is stored, processed, and analysed towards the identification of potential and current abnormalities and generation of lighting information.

Figure 91: Theoretical Framework of the Prototype



Source: Author (2021)

In the third step, the information from the cloud environment is visualized by the maintenance team on distinct interfaces, depending on the users' needs and the system's behaviour. For instance, SmartLab mobile and E-mail account focus on real-time information and notification messages, while BIM interfaces provide historical records. Finally, the fourth step is related to the management of the luminaire's performance information. The information delivered triggers maintenance service under alert or abnormal behaviour, thus minimizing the disruption of university activities.

b. Establishment of technical and functional requirements and assumptions for development

Technical and functional requirements were defined according to the findings of the questionnaires (Section 5.1.2) and the interviews (Section 5.1.3). Table 40 shows the requirements raised in the questionnaires. Mechanisms for communicating maintenance data and information generated by the prototype with the existing FM tools were discussed in Section 5.1.4 regarding the main requirement of the smart system prototype (detection and report current and potential failures). The development of a web service and the creation of an e-mail notification were the two strategies drawn by the interviewee. The second mechanism was adopted for this study, due to the reasons shown in Table 41. Assumptions were made to support the prototype development according to the target user, the technical and process-related requirements for a real prototype implementation, and the research limitations, as shown in Table 42.

Table 40: Synthesis of Prototype requirements

Category	Requirements
Ability	Automatic detection and report of failures
	Differentiation between emergency and non-emergency services
	Supply of information on the equipment to be maintained (e.g., manufacturer, model, etc.)
	Generation of reports towards supporting predictive maintenance and managerial decisions
	Information on the priority of attendance of each room
Design	Use of standardized components (e.g., sensors, accessories for installation) and software which can be easily replaced and updated according to advances in technology
	Use of device for mass storage
	Use of a robust system with high degree of accuracy and low likelihood of failures, ensuring the timely detection of problems
	Assurance of safety data and information
	Integration with the existing systems and facilities with no replacement of existing luminaires
	User-friendliness, considering the distinct backgrounds of the professionals
	Accessibility to all maintenance team members via smartphone
	Supply of direct and automatic tools and interfaces towards supporting de-bureaucratization of processes and improvements in their efficiency
	Low cost of implementation, maintenance, and operation and use of open BIM platforms to reduce costs
	Possibility to be managed by the university staff

Source: Author (2021)

Table 41: Rationale for the creation of an e-mail notification

Rationale	Description
Innovation	It addresses the broad technological innovation process faced by the organization, which considers the implementation of modern and flexible technology for all maintenance sectors, as opposed to the current PHP-based CAFM software used only by the FM sector.
Flexibility	It provides a flexible alternative to trigger maintenance processes, since the e-mail notification supports the generation of work requests either automatically, via OTRS, or manually, in the current CAFM software.
Agility	It can be developed by the research team with available time, knowledge, and technological resources, whereas the web service development would require new investments.
Validity	It can be validated by the researcher team through tests, differently from the web service, which would require the development of a quality environment unavailable in the current CAFM software.

Source: Author (2021)

Table 42: Assumptions for the development of the Smart Lighting Maintenance System Prototype

- The university maintenance sector is the target user of the prototype, although the solution must be applicable to other organizations.
- The FM sector has implemented BIM for maintenance and obtained BIM models of the university assets, including the student's accommodations.
- The maintenance team has access to the SmartLab mobile application.
- The maintenance team has the infrastructure and capabilities to manage BIM and IoT devices and software.
- The building users are aware of the system's abilities.
- The monitored student bedroom has wireless access.

Source: Author (2021)

c. Establishment of FM BIM data requirements

The establishment of FM BIM data requirements in the early stages of the design process is essential to support the development of BIM models and, accordingly, Digital Twins for FM purposes. In this work, a BIM model data structure determined the required attributes (called "parameters" in software Autodesk Revit) of the luminaire, thus supporting maintenance activities (CAVKA; STAUB-FRENCH; POTTINGER, 2015) and integration with CAFM and IoT tools. Data requirements for operation and maintenance (i.e., maintenance history, specifications of replaced component, vendor data, location ID, etc.) identified in standards and previous studies (AKCAMETE; AKINCI; GARRETT JR, 2011; BECERIK-GERBER et al., 2012; MCARTHUR, 2015; MIRARCHI et al., 2018; THE BRITISH STANDARDS INSTITUTION, 2012) supported the proposed structure. As shown in Table 43 the structure is comprised of four parameter sets, namely Room, Luminaire, Lighting Sensor, and Maintenance.

Table 43: FM BIM model data structure

Set	Parameter	Name	Description
Room	Identity Data	Room ID	STE_B1_101
		Room Name	Bedroom 101
	Dimensions	Room Length (m)	4,00
		Room Width (m)	2,80
		Room Height (m)	2,80
	Lighting	Reflexion Factor (Ceiling/Wall/Floor)	70% / 50% / 20%*
		Maintenance Factor	0,8*
		Median Illuminance on workplace (E) (lux)	300**
		Environmental Median Illuminance (E) (lux)	150**
		Number of lighting fixtures	1
Luminaire	Identity Data	Identification Code (ID)	L101
		Model	SM461V W17L169
		Manufacturer	Philips
		URL	http//:www.philips.com.eg
		Description	Surface mounted
		Material (housing)	Steel
		Installation type	Mounted
		Cost (R$)	250,00*
		Luminaire Priority Level (LPL)	LPL1
	Dimensions	Length (mm)	1685,00
		Width (mm)	171,00
		Height (mm)	85,00
		Assembling Height (m)	2,80
	Electric Data	Lamp Model	LED40S/840
		Voltage (V)	220-240 V
		Initial input power (W)	30
		Nominal lifetime (h)	25.000
		Apparent Load (VA)	21,00 VA
	Photometrics	Light loss factor	1
		Initial Luminous Flux (lm)	1350
		Initial Color Temperature (K)	6500
		Length of emission rectangle (mm)	66
		Width of emission rectangle (mm)	1135
		Light source colour	White
Lighting sensor	Dynamic Information	Performance Status	Normal / Alert / Abnormal
		% Estimated of lifetime	25%
		Link to Historical data	http://andromeda.lasdpc.icmc.usp.br:5005 /generateReport
	Identity Data	Sensor identification Code (ID)	S101
		Sensor Type	Lighting Dependent Resistor (LDR)
		Sensor Measurement Unit	Volts (V)
		Sensor Location	STE_B1_101
		Sensor assembling height (m)	2,75
Mainte-nance Service	Date record	Date of lamp Installation	07/02/2020*
		Date of last Maintenance of lamp	10/10/2019*
		Date of last Cleaning of lamp	05/04/2020*

Note: * illustrative data ** established according to ABNT (1992), considering age of the observer under 40 years, the precision of the task as an important factor, and task background reflectance between 30 and 70%.

Source: Author (2021)

The first set is related to the room parameters (i.e., identity data, dimensions, and lighting), defined according to Associação Brasileira de Normas Técnicas (1992), and the second refers to the luminaire parameters (i.e., identity data, dimensions, electric data, photometrics). Luminaire Priority Level (LPL), defined according to the Classification Matrix presented in Section 5.1.1., is one of the identity data. Other luminaire parameters were based on the BIM family of Philips LED surface mounted luminaire, model SM461V W17L169 (PHILIPS, 2019, 2021).

The third set is related to the Lighting sensor parameters (i.e., Dynamic and Identity Data), whereas the four refers to data record maintenance services (i.e., date of lamp installation, maintenance, cleaning), as proposed by Becerik-Gerber et al. (2012). Autodesk Revit 2021 software was selected as the BIM platform, since it offers the necessary modelling tools and has a free educational license. The modelling requirements also included the file format (i.e., Revit native format (.rvt) and Revit family (.rfa)), measurement units (i.e., linear meter (m) and square meter (m^2)), and Level of Detail (LOD) (i.e., LOD3 – Developed Design (according to NBS BIM Toolkit LOD definitions).

d. Outlining the experimental plan

An experimental plan was outlined to support the development, testing, and assessment of the prototype performance. It involved the definition of the monitored object and testing variables, the rationale for the luminaire performance assessment, and development of test settings and protocols.

- ### Definition of the monitored object and testing variables

A luminaire with a Light-Emitting Diode (LED) lamp was the monitored object. Its adoption was justified by its superior performance in comparison with other lights (i.e., fluorescent, incandescent) (AVELLA; SOUZA; J. L. SILVEIRA, 2015). Moreover, its lifetime of up to 50.000 hours (PHILIPS, 2018) makes it less subject to frequent replacement and maintenance interventions. Such factors are particularly relevant for the university maintenance sector, since it faces an increasing demand of services, and reduce labour force.

The lighting level (V) measured by the sensor was used to detect abnormalities in the luminaire and determine its performance status. The application of other parameters for the assessment of lighting performance (e.g. luminous intensity distribution and luminous efficacy (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2016) was not considered due to technical and time constrains of the experimental settings. In addition, operating time (h) were collected to support analyses of lighting performance over time and determination of the % expected lifetime (THE BRITISH STANDARDS INSTITUTION, 2007).

- ### Definition of the rationale for the luminaire performance assessment

Understanding the LED lifetime was essential for assessing its performance and developing a rationale for the prediction and report of failures. Equivalent to "the shortest life of the critical component" (ABNT, 2016, p. 1)[1] (commonly the LED module), the LED lifetime depends on the quality of its components, which varies according to the manufacturer. Moreover, it is influenced by environmental and usage characteristics, such as temperature and current oscillations.

According to ABNT (2013), the LED nominal lamp lifetime corresponds to the period in which the lamp provides more than 50% of the initial luminous flux for consumption applications, or more than 70% for professional applications in combination with the failure rate informed by the manufacturer. Based on this concept, three performance status, namely normal, alert, and abnormal, were set to classify lighting performance, as shown in Table 44. The failure rate was disregarded, and the luminous flux was replaced by the lighting level. A criterion was also proposed for the definition of the % expected lifetime, considering the ratio between the measured operating time and the nominal lifetime.

Table 44: Lighting performance status classification

Status	Rationale
Normal	Corresponds to lighting levels higher than or equal to 70% of the initial value;
Alert	Corresponds to lighting levels higher than or equal to 50% and lower than 70% of the initial value;
Abnormal	Corresponds to lighting levels lower than 50% of the initial value.

Source: Author (2021)

- **Development of test settings and protocols**

Ideally, the prototype would be implemented in a real context, which is a students' accommodation bedroom of the BR University. However, the restrictions from COVID-19 at the time of the experiment made the approach unfeasible. A residential bedroom was then selected as an experimental environment, since it addressed the functional and safety necessities for the study.

The prototype was implemented for assessments from March to April 2021. The researchers investigated whether it effectively collected, processed, and transmitted lighting data and information; whether the generated lighting performance information was accurate, clear, and accessible to the maintenance team; and whether the functional and technical requirements were addressed. A test protocol was then developed. Tables 45 and 46 depict the tests applied, the components, functionality criterion and purpose, activities undertaken, and performance measurement. First, tests were conducted with hardware components, focusing on their position, attachment, and connection with the existing infrastructure. Simultaneously, the software components were tested with a focus on the calibration of the sensor, data transmission and storage, data processing, and information visualization. Section 5.2.4 reports the results.

Table 45: Hardware test protocol

Component	Functionality criterion and purpose	Activities	Performance measurement
Lighting sensor module	Position: assessment of the efficacy of the sensor position to capture accurate lighting level data	Verify the existence of interferences in the sensor installed on the prototype surface	Sensor data are collected with no interference of other objects
	Attachment on the prototype: assessment of the efficacy of the adopted solutions to attach the sensor device on the prototype	Verify if Hot melt adhesive (HMA) effectively attaches the sensor devices on the prototype surface	Sensor devices are firmly and steadily attached on the prototype surface
	Connection with existing electric infrastructure: assessment of the efficacy of the developed solution to connect sensor devices to an external power supply	Verify if the solution developed with electrical sockets effectively provides power to the sensor devices	Sensor devices are correctly charged

Source: Author (2021)

A qualitative analysis of the implementation and testing results was conducted. The performance measurements depicted in Tables 45 and 46 were used for assessing the prototype ability to effectively collect, process, and transmit lighting data and information, and the accuracy, clarity, and accessibility of such information for the maintenance team. The attendance of the requirements shown in Table 40 by the prototype was also evaluated. The assessment was organized into three categories, namely, yes, no, and partially (see Table 47).

Table 46: Software test protocol

Component	Functionality criterion and purpose	Activities	Performance measurement
Sensor data collection	Calibration for data collection considering the interval and time proposed	Verify the efficacy of instantly collecting lighting level data after the luminaire has been turned on Verify the efficacy of collecting the time the luminaire is turned on and off, generating the operating time data	Calibration enables an accurate data collection
Wi-Fi transmission and online storage of sensor data	Assessment of the efficacy of sensor data transmission and storage	Verify if the sensor data have been accurately transmitted and stored across the architecture components	Data are accurately transmitted across the architecture components
Sensor data transmission and processing	Accuracy of collected data (i.e.: lighting level, operating time (turn on – turn off), and date (day/month/year) under distinct conditions of performance, energy supply, and time of day (i.e., day or night)	Verify data collection accuracy in three distinct performance statuses: - the lamp is correctly installed in the socket, representing a normal condition of use (normal status). - the lamp is correctly installed in the socket, but covered with a sheet of paper, displaying a deviant behaviour (alert status). - the lamp is removed from the socket, representing the total failure (abnormal status). The test must be undertaken at both daytime and night-time for observations of the influence of environmental conditions on the measurement.	Sensor is accurately collecting data under distinct conditions
Sensor data transmission and processing	Data processing and transmission over the IoT and BIM and platforms: assessment of the efficacy of the system (i.e., microservices, Dynamo) in interpreting data and generating notification messages	Verify if the real time data have been correctly interpreted by the microservice and generate performance information and notification messages. Verify if the data are being correctly interpreted by modifying the “if statement” rationale colours set, considering: - Normal status in black. - Alert status in orange. - Abnormal status in white.	Both data and information are accurately transmitted and interpreted by BIM and IoT platforms, generating performance information and notification messages
Information visualization	Information visualization on SmartLab mobile application and e-mail account	Open SmartLab mobile application and e-mail account and verify if the notification information is clear and complete.	Information is accurate and easily visualized on SmartLab and e-mail interfaces
	Information visualization on BIM platforms (i.e., Autodesk Revit desktop, Autodesk Revit cloud-based Viewer)	Open BIM platforms and verify if the lighting information is clear and complete.	Information is accurate and easily visualized on BIM platforms

Source: Author (2021)

Table 47: Categories for the assessment of test results

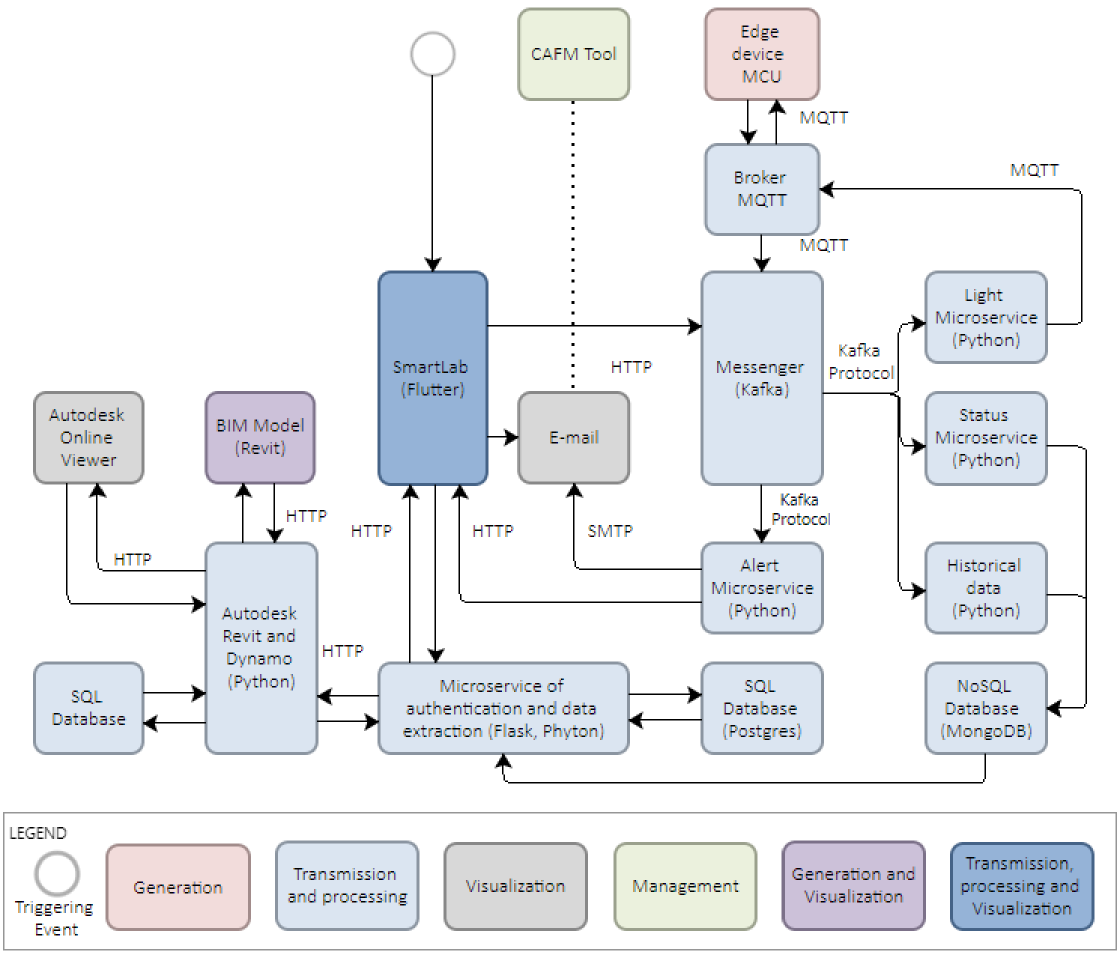
Category	Description
Yes	The performance measurement criteria or the technical or functional requirement were fully addressed by the prototype
No	The performance measurement criteria or the technical or functional requirement were not addressed by the prototype
Partially	The performance measurement criteria or the technical or functional requirement were partially addressed by the prototype

Source: Author (2021)

5.2.2. Development

This section presents the development stage activities for the construction of the physical and analytical dimensions of the prototype. Primarily, a set of models, namely, the Architecture of the prototype (Figure 92), Approach for the integration of BIM, IoT, and CAFM tools and devices (Figure 93), and Logic analysis logic of real-time data (Figure 94) were generated. The architecture represents the prototype system from the computational point of view, focusing on the relationship and data stream among hardware and software components. Following the logic of the Theoretical Framework, the components were organized into four functional groups related to data collection, transmission and processing, visualization, and management.

Figure 92: Architecture of the Prototype

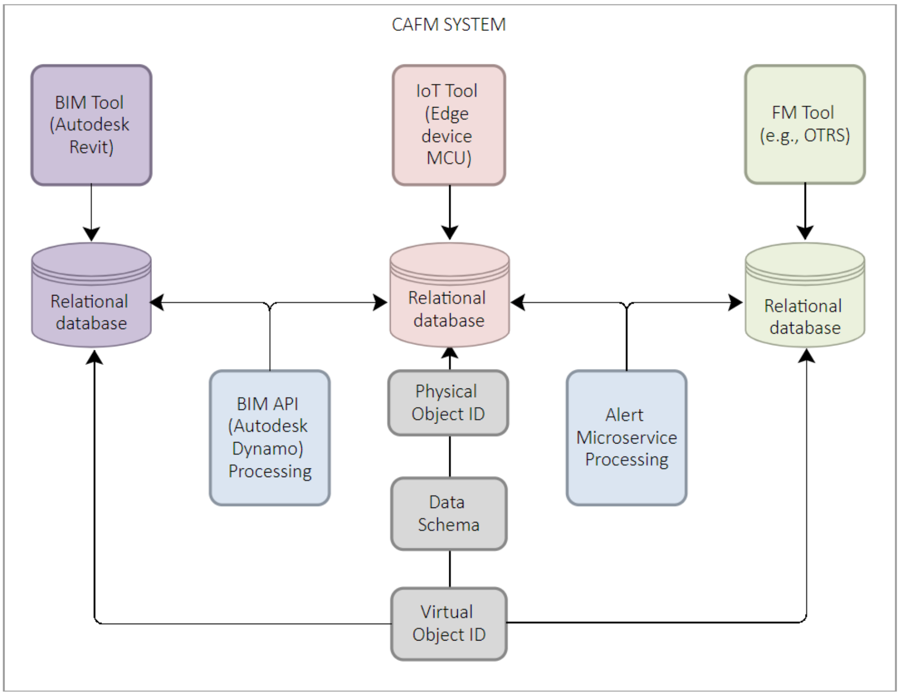


Source: Author based on Bueno (2020)

The architecture of the SmartLab prototype described by Bueno (2020) was used as reference. Commercial hardware (i.e., sensor, luminaire, lamp) and software (i.e., Revit, Dynamo) components were incorporated in the prototype for addressing the application proposed in this research. Principles of the *Microservice Architecture* structure style were adopted for the development of a resilient, scalable, and heterogeneous prototype system (BUENO, 2020). Unlike the traditional *Service Oriented Architecture* (SOA), microservices integrate small and autonomous services, enabling the use of distinct technologies for each part of the system (i.e., programming language, framework, database) and the implementation of the system according to the business needs (EUROPEAN COMISSION, 2010; NEWMAN, 2015). Such characteristics are particularly important for university FM sectors, since they promote a gradual integration of the prototype with current CAFM software and new devices. Bueno (2020) provided a detailed description of the development process of the microservices and the SmartLab application, and adjustments for this research purpose are addressed in this section.

Figure 93 displays the approach adopted for the integration of BIM, IoT, and FM tools. BIM and IoT were integrated using BIM tools' APIs and relational database, according to the proposition of Tang et al. (2019). Dynamo visual programming plugin was the bridge between Autodesk Revit and IoT database, as described in previous studies (CHANG; DZENG; WU, 2018; FINK; MATA, 2020; KENSEK; KAHN, 2013; MACHADO; RUSCHEL, 2019; MARMO et al., 2019; PIN; MEDINA; MCARTHUR, 2018; THABET; LUCAS, 2019).

Figure 93: Approach for the integration of BIM, IoT, and FM tools



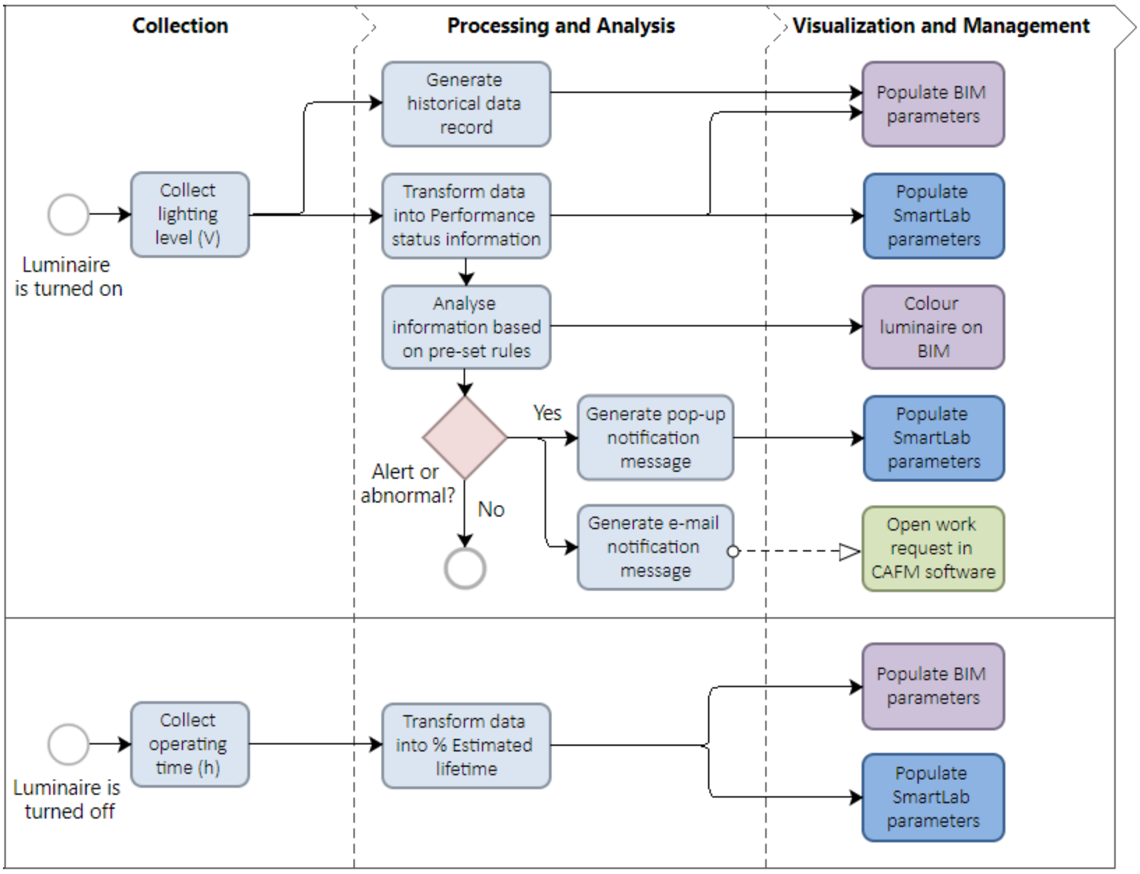
Source: Author (2021)

The IoT ecosystem and the CAFM systems were integrated through the creation of an e-mail notification to the maintenance sector triggering the opening of a work request. As discussed in Sections 5.1.3. and 5.2.1.b, the e-mail notification could play twofold roles, depending on the CAFM system adopted, for instance, as an indirect link, providing information for manual addition into the system database, or as a direct link, automatically opening a new service request.

After the establishment of the architecture components and the approach for their integration, the logic analysis aimed at the generation of relevant information from real-time data. Figure 94 depicts the logic analysis from the collection of lighting level (V) and operating time (h) data for the visualization and management of information.

The following subsections describe the decisions and activities involved in data and information collection, transmission and processing, visualization, and management.

Figure 94: Logic analysis of real-time data



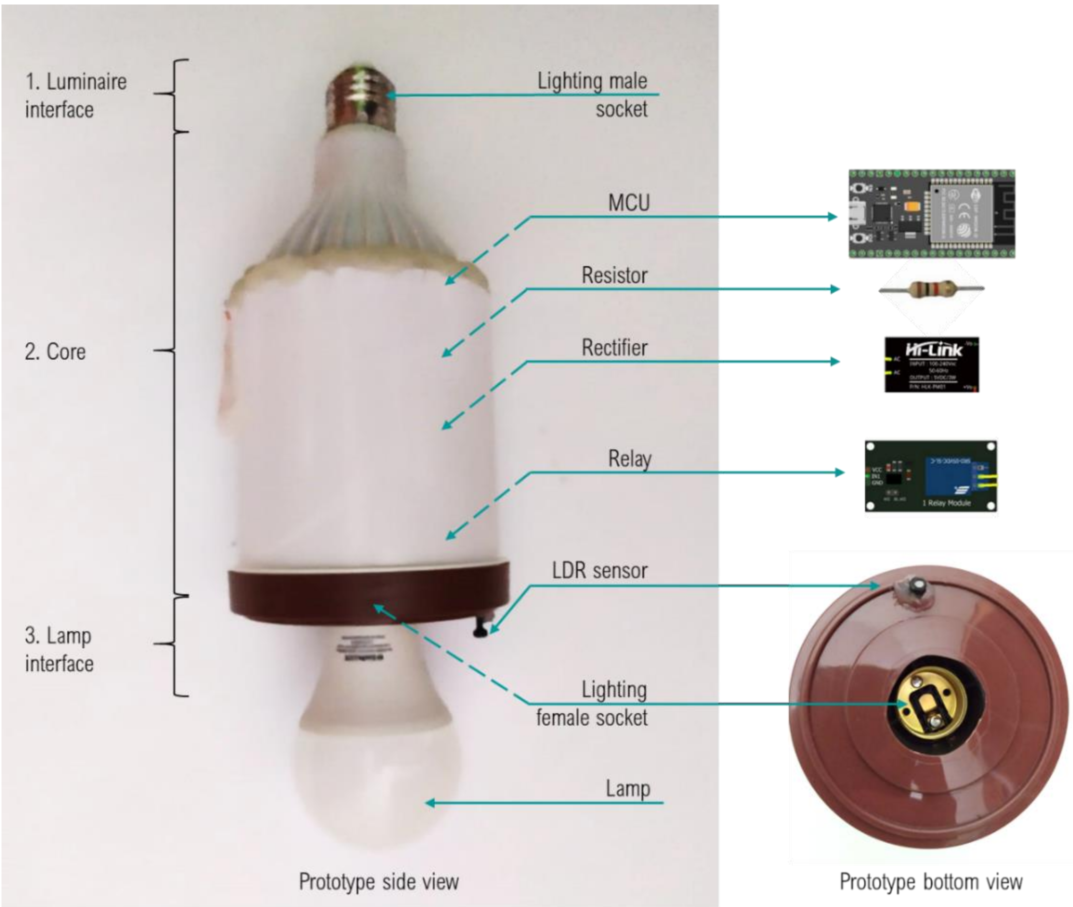
Source: Author (2021)

a. Data collection

Two main activities, namely Building the physical prototype and Development of the BIM model enabled data collection. The physical prototype was built in-house for the collection of dynamic data. The development of a customizable solution was due to budget restrictions and necessity of free access to data. The prototype was comprised of three parts, namely luminaire interface, core, and lamp interface, as shown in Figure 95.

Part 1 establishes the interface between the luminaire and the core. A lighting male socket plugged the prototype in the luminaire and provided electrical supply. Part 2 comprises the core components of the prototype (e.g., Microcontroller Unity (MCU), Lighting Dependent Resistor (LDR) sensor, resistor, rectifier, and relay). A round plastic container internally held the MCU, electronic components, and cables, and externally attached the sensor. Hot melt adhesive (HMA) attached the prototype parts, due to its versatility, low-cost, and ease of application and removal. The sensor was positioned on the edge of the bottom surface of the container. Lastly, Part 3 establishes the interface between the core and the lamp. A lighting female socket plugged the lamp.

Figure 95: Views of the physical prototype, its parts and components

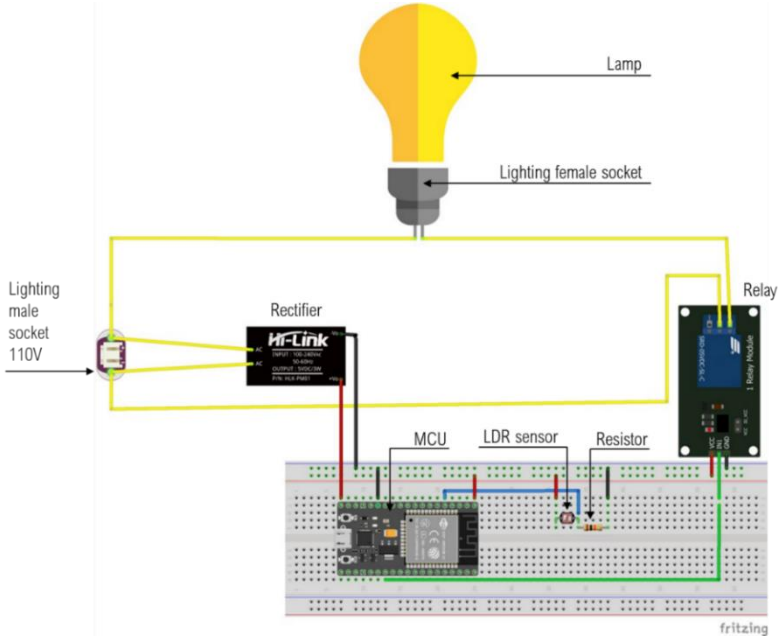


Source: Author (2021)

Figure 96 depicts the diagram of the electronic circuits of the prototype. The lighting male socket generates an alternating current (AC) for the rectifier, which supplies the lamp. The yellow lines represent the 110V voltage cables. The rectifier also converts the AC to a direct current (DC) towards supplying the MCU, the LDR sensor, and the relay. The red line represents the 5V voltage cable, and the black line denotes the ground circuit (0V). The information from the sensor is transmitted to the MCU by the cable represented in blue. Accordingly, the information from the MCU is transmitted to the relay by the cable represented in green. Depending on the voltage in the green cable, the relay connects the yellow cables, turning on-off the lamp.

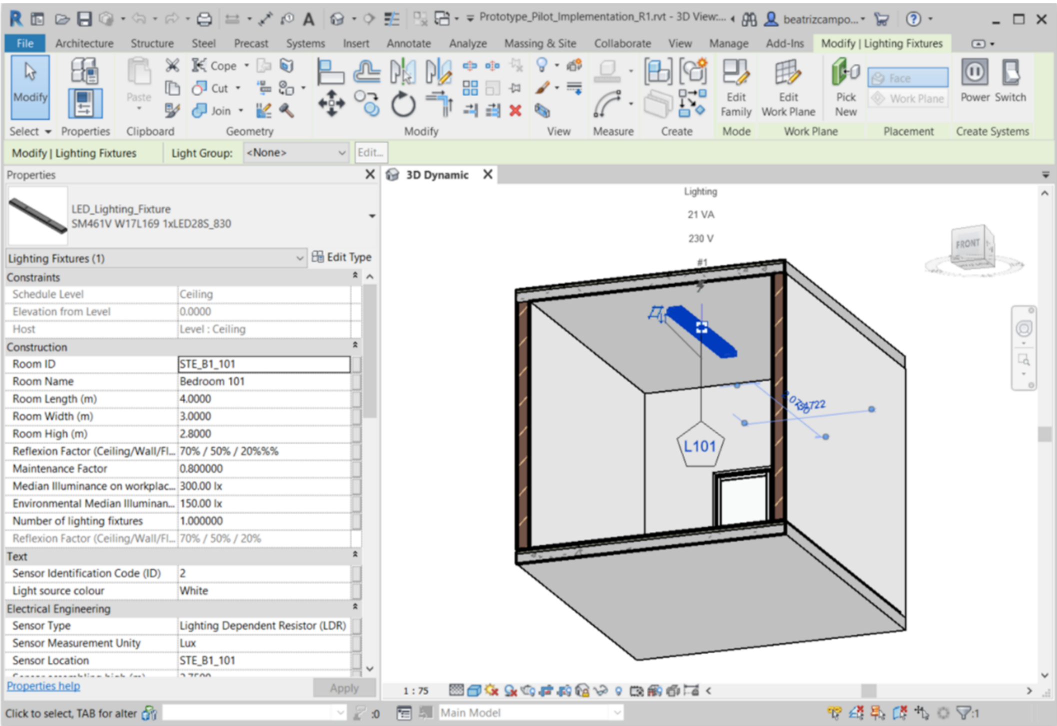
A bedroom BIM model was developed as a centralized database of dynamic and static data for maintenance purposes. This study focused on modelling essential geometric and non-geometric data for performance analyses (i.e., luminaire and sensor characteristics and basic geometry of the room), generating a more dynamic and lighter model - as recommended by the literature (AKCAMETE; AKINCI; GARRETT JR, 2010; CAVKA; STAUB-FRENCH; POTTINGER, 2015; MCARTHUR, 2015; MIRARCHI et al., 2018). The BIM model data structure shown in Table 43 was the reference for modelling in the software Autodesk Revit 2021. Figure 97 depicts a 3D view of the BIM model, highlighting luminaire parameters in the properties palette.

Figure 96: Diagram of the electronic circuits of the prototype



Source: Author (2021)

Figure 97: 3D view of the BIM model, highlighting luminaire parameters



Source: Author (2021)

b. Data transmission and processing

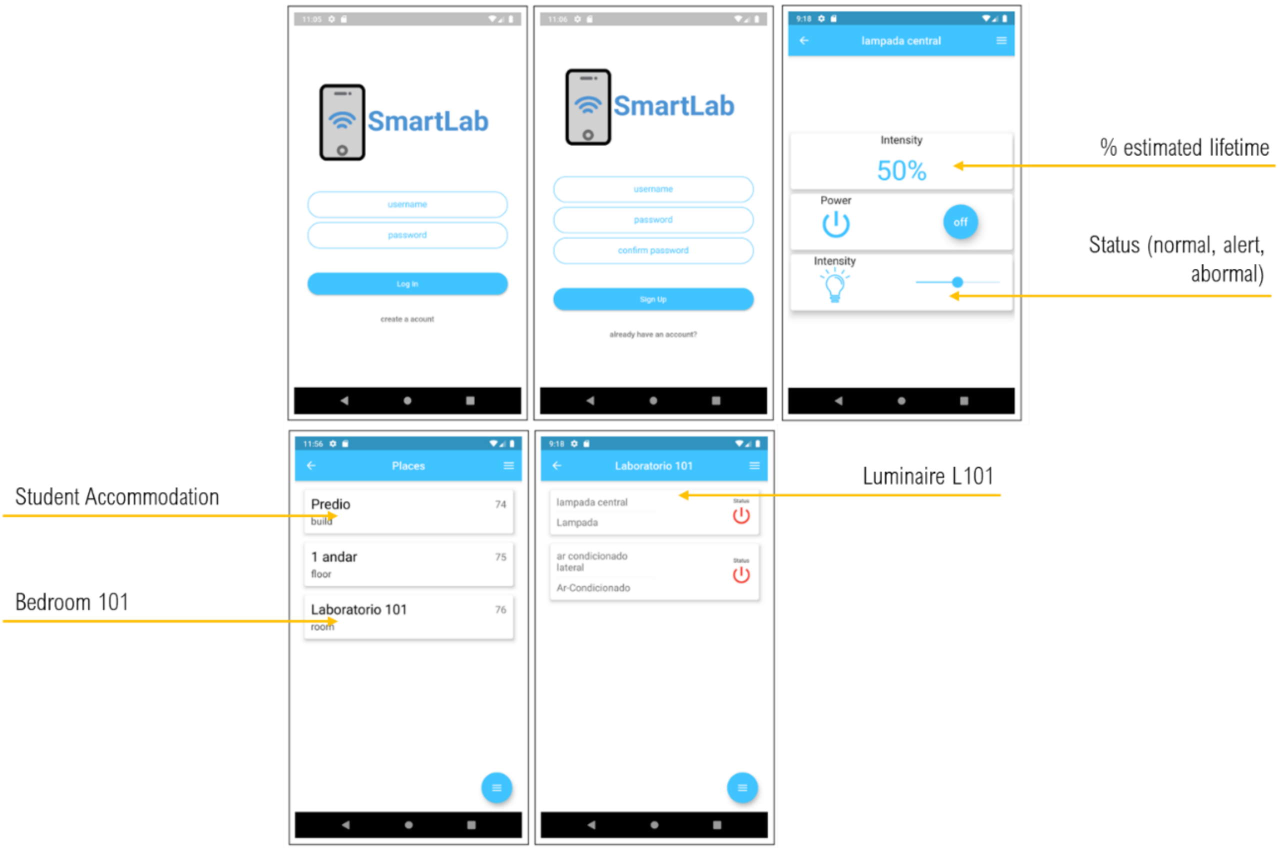
Regarding the Architecture of the prototype, adjustments in the microservices and software components were necessary to support data transmission and processing. The three activities undertaken were Update of existing microservices, Development of new microservices, and Coding Dynamo interface, as described in what follows.

- **Update of existing microservices**

Originally, two microservice groups were developed to control the luminaire and visualize its performance information. Adjustments in their data structure and type (e.g., renaming of existing fields, i.e., lighting intensity replaced by lighting status) and addition of new ones (e.g., % estimated lifetime, room name, luminaire ID, etc.) were made for the meeting of the research needs.

The first group was integrated by Microservice of authentication and data extraction and Status Microservice and connected the user and the prototype. Initially, data on the available building, floor, rooms, and devices (e.g., Students' Accommodation, 1st floor, Bedroom 1, Sensor ID S101) are requested from the Postgres database. Next, data on the last device status (i.e., on – off) and the lighting performance status (i.e., lighting level (V) and operating time (h) are requested from MongoDB database. The second group (i.e., Light Microservice) refers to the luminaire control. Figure 98 shows the interface of SmartLab mobile application for authentication and register, selection of rooms and devices, and luminaire control.

Figure 98: SmartLab interfaces for authentication and user registration, selection of rooms and devices, and luminaire control



Source: Adapted from Bueno (2020)

- **Development of new microservices**

Two new microservices, namely Alert Microservice and Historical data Microservice were built to address this research scope. The former was developed with two functionalities, i.e., analysis of lighting level data for the detection of performance abnormalities, and notification of current and potential abnormalities to the user. The "if statement" rationale for the classification of lighting performance (i.e., normal, alert, and abnormal status) was coded into the microservice, thus providing status information for user notification. In sequence, two distinct approaches were adopted to notify Abnormal and Alert statuses according to the user interface - a pop-up message was proposed for SmartLab mobile application, and an e-mail message was developed for the e-mail account.

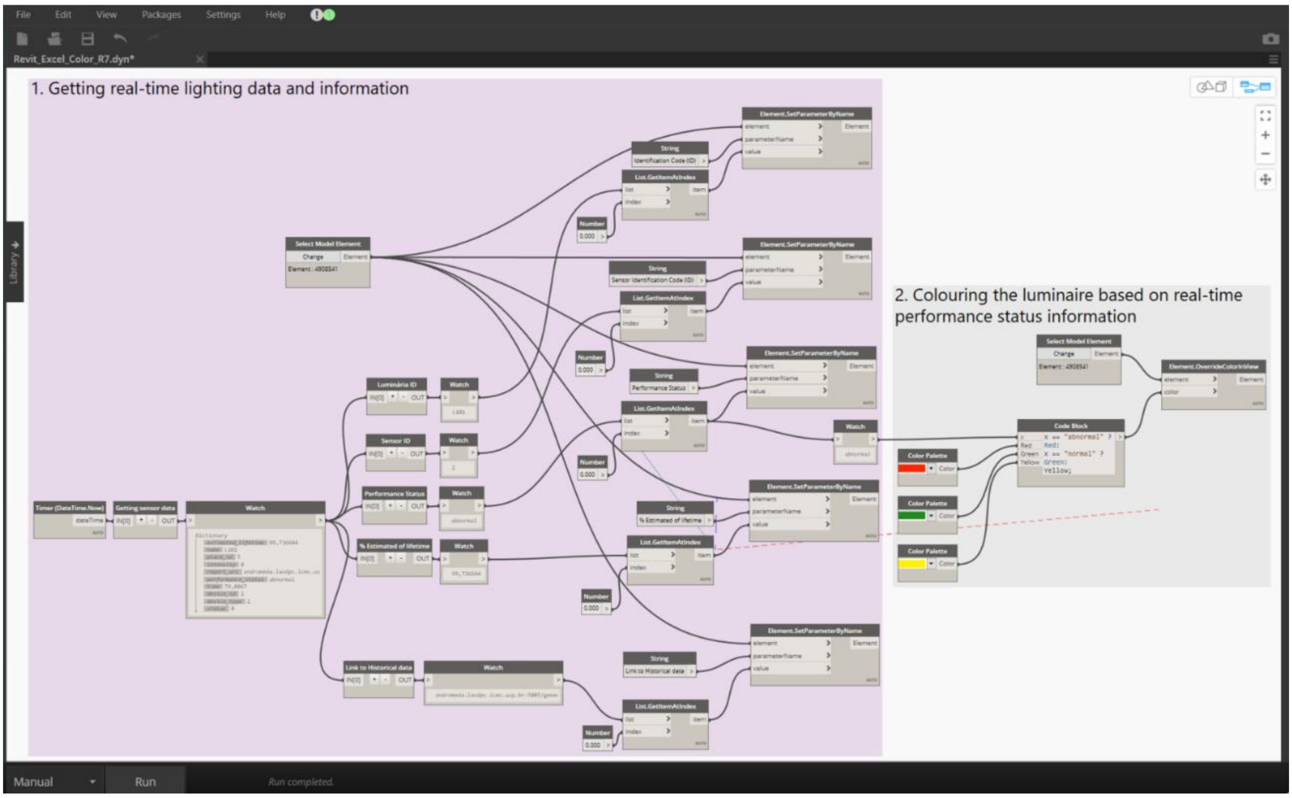
Complementary, the Historical data Microservice aimed to provide historical data records of the luminaire performance, including time frame, lighting level, and operating time. The data were delivered in a JSON file, a lightweight format for data exchange that can be either opened on a web browser (i.e., Google Chrome), or imported into a Microsoft Excel spreadsheet. The file is requested by the Microservice of authentication and data extraction for further communication with BIM model.

- **Coding Dynamo interface**

Dynamo visual programming plugin was adopted to read, process, and store lighting performance real time and historical data in Revit software environment. Commonly used in building design for parametric modelling complex structures, Dynamo is a versatile and user-friendly platform that provided the necessary tools for this prototype development. The literature reports its use for linking FM BIM model with external data (i.e., sensor measurements, Work Orders) (CHANG; DZENG; WU, 2018; FINK; MATA, 2020; KENSEK; KAHN, 2013; MARMO et al., 2019; PIN; MEDINA; MCARTHUR, 2018; THABET; LUCAS, 2019).

Figure 99 shows a broad view of the program flow, integrated by two functional groups namely 1. Getting real-time lighting data and information (i.e., Performance Status and % estimated lifetime), reading and updating it in the luminaire model parameters; and 2. Colouring the luminaire based on real-time performance status information status.

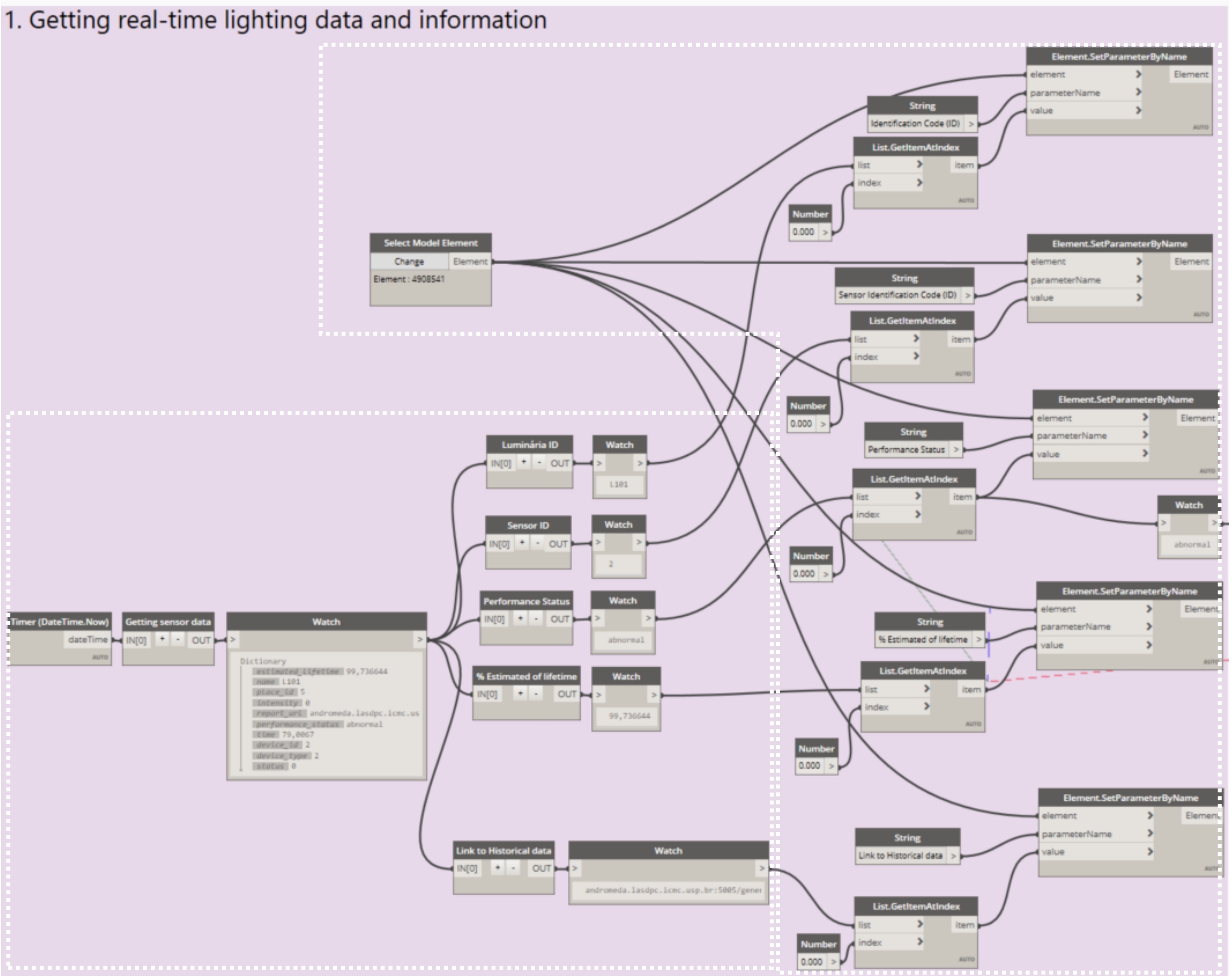
Figure 99: Dynamo program flow for real time data processing



Source: Author (2021)

In Group 1, a code imported information from the Microservice of authentication and data extraction to the BIM model (Figure 100). A set of Basic Nodes were employed to select the target element in the model and its parameters to be updated (i.e., luminaire Identification Code (ID), Sensor Identification Code (ID), Performance status, % estimated lifetime, and Link to Historical data records), and then, customized Python Nodes were created to request real time information from the microservice and populate the target parameters in the model. In Group 2, an "If" statement was coded to change the luminaire colour according to the real time performance status, as shown in Table 48 and Figure 101. The colours reproduce the universal code adopted in traffic lights, which is easily recognizable for general users, justifying its application in this study. Figure 102 depicts the BIM 3D view showing the Alert Luminaire status in yellow.

Figure 100: Dynamo program flow - Group 1



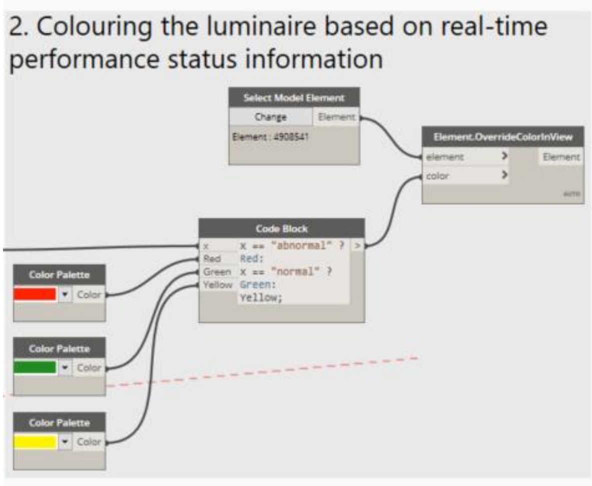
Source: Author (2021)

Table 48: Rationale for colouring the luminaire according to the lighting performance status

Status	Rationale	Colour
Normal	Corresponds to lighting levels higher than or equal to 70% of the initial value;	green
Alert	Corresponds to lighting levels higher than or equal to 50% and lower than 70% of the initial value;	yellow
Abnormal	Corresponds to lighting levels lower than 50% of the initial value.	red

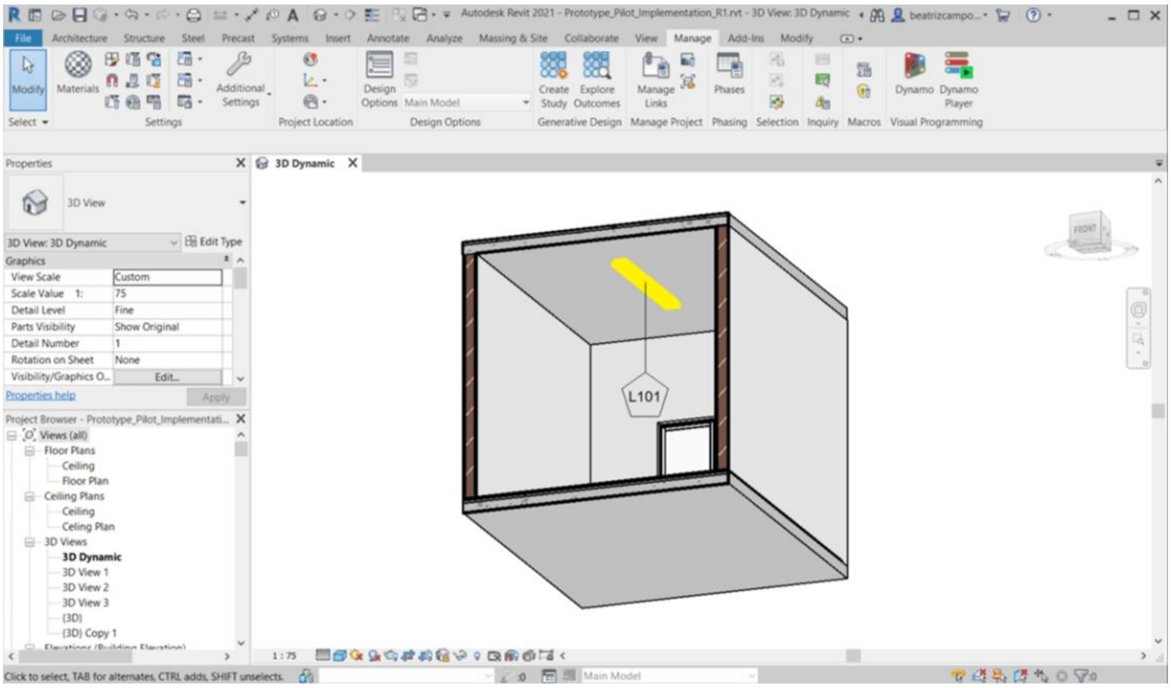
Source: Author (2021)

Figure 101: Dynamo program flow - Group 2



Source: Author (2021)

Figure 102: BIM 3D view showing the Alert Luminaire status coloured in yellow



Source: Author (2021)

c. Data visualization

The visualization of lighting performance information was supported by four interfaces, namely SmartLab mobile application, E-mail account, Autodesk Revit 2021, and Autodesk online Viewer. Each one plays a distinct role in the prototype and is applied in the maintenance process with support of specific devices, as shown in Table 49. Addressing requirements informed by the maintenance experts, various communication channels were adopted to facilitate the access to accurate information via computer, tablet, or smartphone.

SmartLab enables the maintenance team to not only control the luminaire operation, but also visualize performance status, % estimated lifetime, and notification messages (Figure 98). Similarly, the e-mail message provides a clear notification of a current or potential abnormal luminaire status. In both, the ease access to concise and text-based information, specially through smartphone or tablet, was adopted for facilitating understanding.

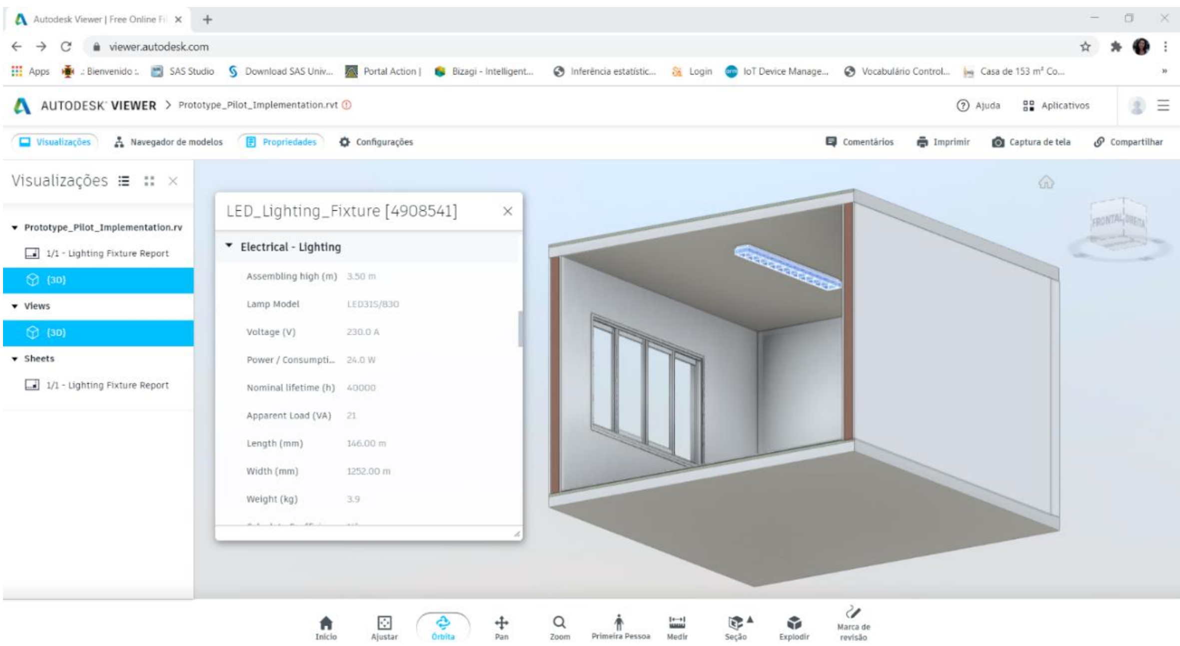
Table 49: User interfaces of the prototype system

Interface	Role	Maintenance process application	Supporting devices
SmartLab mobile application	Provide luminaire performance information and notification messages for maintenance management	Supports the maintenance team in controlling the luminaire (i.e., turn on, turn off) and detecting current and potential abnormalities through the visualization of lighting performance status and notification messages	Smartphone, tablet
E-mail account	Provide information on current and potential abnormalities in luminaire for maintenance management	Supports the maintenance team in detecting current and potential abnormalities through the visualization of notification messages and triggering opening work requests	Computer, smartphone, tablet
Autodesk Revit 2021	Provide a BIM model with detailed lighting static and dynamic information for maintenance management	As a central database, it supports the maintenance team in current and potential abnormalities detection, visualization, location, diagnosis, and repair	Computer
Autodesk online Viewer	Provide a lighter version of the BIM model for maintenance management	Supports interactions of the maintenance team with the BIM model (i.e., navigation, live sections, measurements, annotations, etc.) in a web environment, particularly relevant for field and remote works	Computer, smartphone, tablet

Source: Author (2021)

Autodesk Revit 2021 software is the most powerful platform for visualization and management of luminaire information, since it concentrates the whole BIM model database. Besides providing a range of capabilities for information management and collaboration, it is supported by Dynamo plugin, which adds real time information to the model and shows performance statuses by colour. As a central database, it supports the maintenance team in current and potential abnormalities detection, visualization, location, diagnosis, and repair. Lastly, BIM cloud Autodesk online Viewer provides a lightweight version of the BIM model accessible on a web browser from any device with an Internet connection (Figure 103). The interface enables interactions with the model, such as navigation, live sections, measurements, and annotations. However, the real data are available only on the parameter tab, since no Dynamo capabilities are provided. The visualization of luminaire information in a 3D environment and with no Revit software offers flexibility to the maintenance process, enabling team members to easily access information for field and remote works.

Figure 103: View of BIM model on Autodesk online viewer interface



Source: Author (2021)

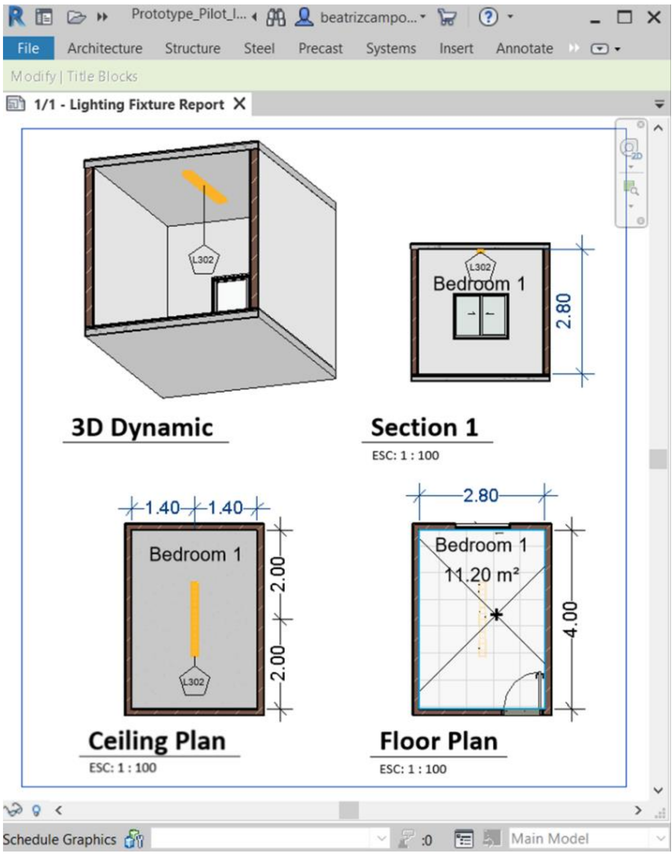
d. Data and information management

The management of the luminaire's performance information for supporting predictive maintenance service is the last step of the architecture of the prototype. The linkage between the smart lighting system and CAFM software was undertaken through the creation of an e-mail notification to the maintenance sector, which triggered the opening of a work request in CAFM. The previous section addressed the development process of the e-mail notification and its sample interface. Historical data records of the luminaire performance generated over time might significantly optimize planning activities, such as budget setting, staff sizing and allocation, and stock control, as discussed in Section 5.3.2.

5.2.3. Implementation and testing

The implementation and testing of the smart lighting maintenance system prototype in an experimental environment aimed at assessing its capabilities and identifying related limitations and potentiality. The focus was on data collection, transmission and processing, and information visualization. The information management step was not explored due to the research-related restrictions (i.e., temporal, human, technical resources) to access the current CAFM software of the BR University FM sector. The hardware and software components of the architecture were respectively implemented in physical and virtual environments. A 2,80m width, 4,00m length, and 2,80m height residential bedroom with a luminaire in the centre of the ceiling was selected for the implementation of the physical prototype. Figure 104 shows BIM model views of the experimental environment, and Figure 105 displays the physical prototype installed in the luminaire.

Figure 104: BIM model views of experimental environment: Floor plan, Ceiling plan, Section 1, and 3D Dynamic



Source: Author (2021)

The core software components of the architecture, namely middleware, microservices, and databases, were implemented in the virtual machines of the LaSDPC private cloud infrastructure, enabling the external access of the research team via host. Instabilities in the infrastructure caused delays in the implementation of microservices. BIM software was implemented in this author's personal computer, and the model was stored in OneDrive cloud-based software. Tables 45 and 46 show the test protocols (Section 5.2.1) applied for the assessment of hardware and software components efficacy.

Figure 105: Final lighting sensor

Source: Author (2021)

5.2.4. Results and assessment

This section presents the results of implementation and testing. Besides, it provides the assessment of the prototype based on the performance measurement criterion and on the technical and functional requirements set by the maintenance experts.

a. Results of implementation and testing

The results of the tests with hardware, software, and the entire system components are presented. Tests with the hardware components evaluated their position, attachment, and connection with electric infrastructure. Regarding the sensor position, a test was applied during the day and at night. It was observed that installing the sensor on the container surface led to high interference of the environmental lighting, particularly during the day. Towards mitigating it, the sensor was installed closer to the lamp, as depicted in Figure 106, thus enabling more consistent measurements. Hot melt adhesive (HMA), sued to attach the sensor, caused a partial detachment of the device, changing its original position. The problem was fixed by the addition of more HMA in specific parts of the module. Regarding connection with existing electric infrastructure, the device was continuously charged over the implementation period, proving the effectiveness of the prototype design.

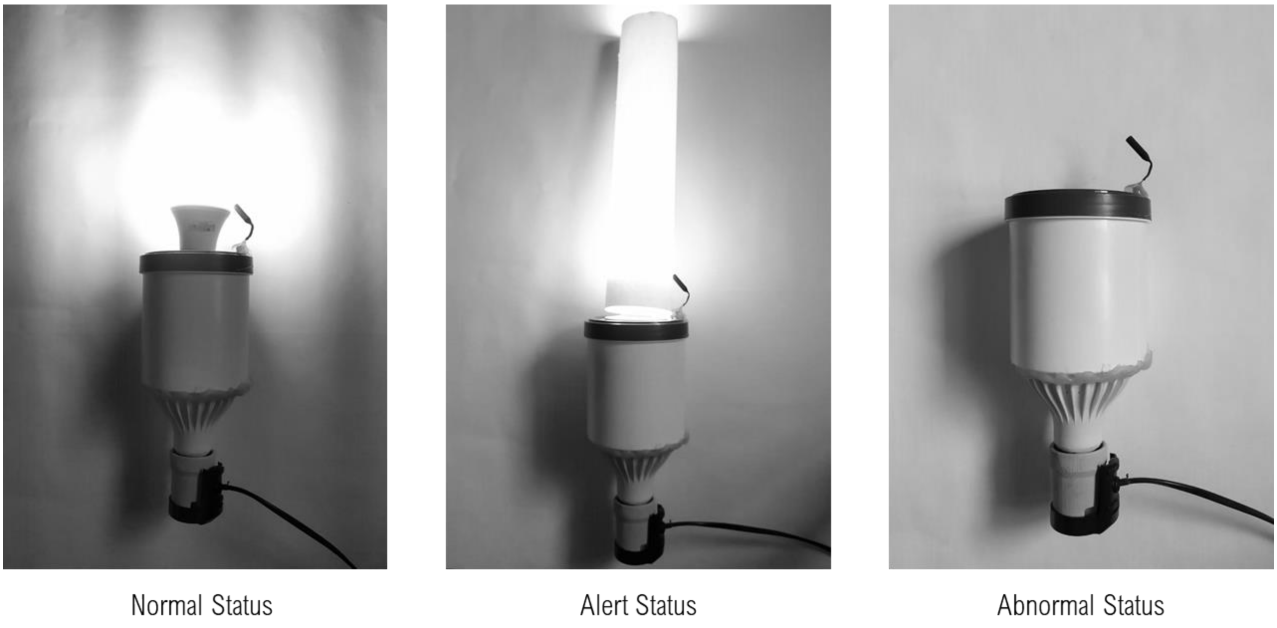
Tests with software components were then conducted according to the new position of the sensor. A series of attributes was assessed (e.g., calibration of the sensor, WI-FI transmission, online storage of sensor data, accuracy of data collection in distinct performance status, data processing and transmission over the IoT and BIM and platforms, and visualisation of information on distinct platforms). The calibration for real time data collection was the first functionality criterion evaluated. The sensor was calibrated for instantly collecting lighting level (V) data whenever the luminaire was turned on. The strategy was considered appropriate, since it covered situations in which the luminaire was used for either a few seconds, or many hours. By gathering only such essential data, the sensor avoids overloading the database, thus improving the system performance.

The system was also calibrated for collecting data on the time the luminaire was turned on and off, generating the operating time (h). The tests showed the collected data were consistently transmitted to the microservice and stored in the cloud infrastructure. The accuracy of the data collected by the sensor was assessed through the simulation of three distinct performance status, namely Normal status, demonstrated with the lamp correctly installed in the socket, Alert status, with lamp correctly installed in the socket, but covered with four sheets of white bond A4 paper, and Abnormal status, with the lamp removed from the socket. Figure 107 shows the physical interventions in the prototype for the simulation.

Figure 106: Original x New sensor positions

Source: Author (2021)

Figure 107: Simulations of three performance status: Normal, Alert, Abnormal



Source: Author (2021)

The tests were conducted during daytime and night-time for identifying the influence of environmental conditions on the measurement. Table 50 depicts the results of the night-time test. The accuracy of the data collection was observed, since the lighting performance measurements corresponded to the expected results, i.e., normal status, with 100% lighting performance, alert status, with 52,87% to 61,61% lighting performance, and abnormal status, with 0% lighting performance of the initial value. The results of the abnormal status demonstrated non-interference of external light sources.

Table 50: Nigh-time test results

Normal status			Alert status			Abnormal status		
the lamp is properly installed in the socket			the lamp is properly installed into the socket but covered with four sheets of white bond A4 paper			the lamp is removed from the socket		
Measurement	Lighting Level (V)	Lighting performance (%)	Measurement	Lighting Level (V)	Lighting performance (%)	Measurement	Lighting Level (V)	Lighting performance (%)
1	4095	100	1	2165	52,87	1	0	0
2	4095	100	2	2443	59,66	2	0	0
3	4095	100	3	2493	60,88	3	0	0
4	4095	100	4	2523	61,61	4	0	0
5	4095	100	5	2513	61,37	5	0	0
6	4095	100	6	2357	57,56	6	0	0
7	4095	100	7	2442	59,63	7	0	0
8	4095	100	8	2410	58,85	8	0	0
9	4095	100	9	2468	60,27	9	0	0
10	4095	100	10	2475	60,44	10	0	0
11	4095	100	11	2471	60,34	11	0	0
12	4095	100	12	2395	58,49	12	0	0
13	4095	100	13	2400	58,61	13	0	0
14	4095	100	14	2385	58,24	14	0	0
15	4095	100	15	2381	58,14	15	0	0
Legend								
Performance Status		Normal			Alert			Abnormal
Lighting performance		Ip ≥ 70%			50% ≤ Ip < 70%			50% < Ip

Source: Author (2021)

Table 51 shows the results of the daytime test, in which the accuracy of the data collection was partially observed. The lighting performance measurements only corresponded to the expected in normal status (with 100% lighting performance) and abnormal status (with 2,74% to 3,03% lighting performance). Although most values corresponded to the alert status, some outliers were detected. The results of the abnormal status, which registered values superior to zero, show the interference of environmental light. The tests focused on data transmission and processing over IoT and BIM tools. First, a test evaluated if the real time data were being correctly interpreted by the microservice, thus generating performance information (Figure 108) and notification messages (Figures 109, 110 and 111). As expected, the data were accurately interpreted by the system, thus ensuring correct data analysis and communication.

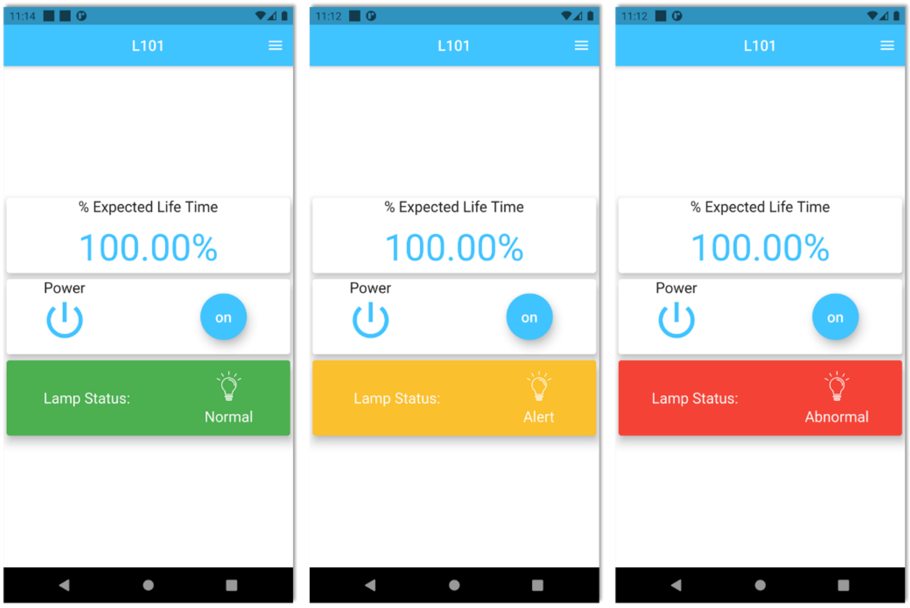
A second test assessed whether the performance information was being adequately read and interpreted by Dynamo, changing the BIM model parameters and the luminaire's colour. The colour sets were temporarily modified, considering the Normal status coloured in black, the Alert status in orange, and the Abnormal status in white. As depicted in Figure 112, the information was correctly interpreted and introduced to the model.

Table 51: Daytime test results

Normal status			Alert status			Abnormal status		
the lamp is properly installed in the socket			the lamp is properly installed into the socket but covered with four sheets of white bond A4 paper			the lamp is removed from the socket		
Measurement	Lighting Level (V)	Lighting performance (%)	Measurement	Lighting Level (V)	Lighting performance (%)	Measurement	Lighting Level (V)	Lighting performance (%)
1	4095	100	1	2825	68,99	1	116	2,83
2	4095	100	2	2885	70,45	2	115	2,81
3	4095	100	3	2111	51,55	3	124	3,03
4	4095	100	4	3015	73,63	4	115	2,81
5	4095	100	5	2512	61,34	5	119	2,91
6	4095	100	6	2523	61,61	6	114	2,78
7	4095	100	7	2652	64,76	7	119	2,91
8	4095	100	8	2761	67,42	8	112	2,74
9	4095	100	9	2285	55,80	9	114	2,78
10	4095	100	10	2672	65,25	10	119	2,91
11	4095	100	11	2652	64,76	11	112	2,74
12	4095	100	12	2853	69,67	12	113	2,76
13	4095	100	13	1719	41,98	13	113	2,76
14	4095	100	14	2946	71,94	14	112	2,74
15	4095	100	15	2597	63,42	15	112	2,74
Legend								
Performance Status		Normal			Alert			Abnormal
Lighting performance		lp ≥ 70%			50% ≤ lp < 70%			50% < lp

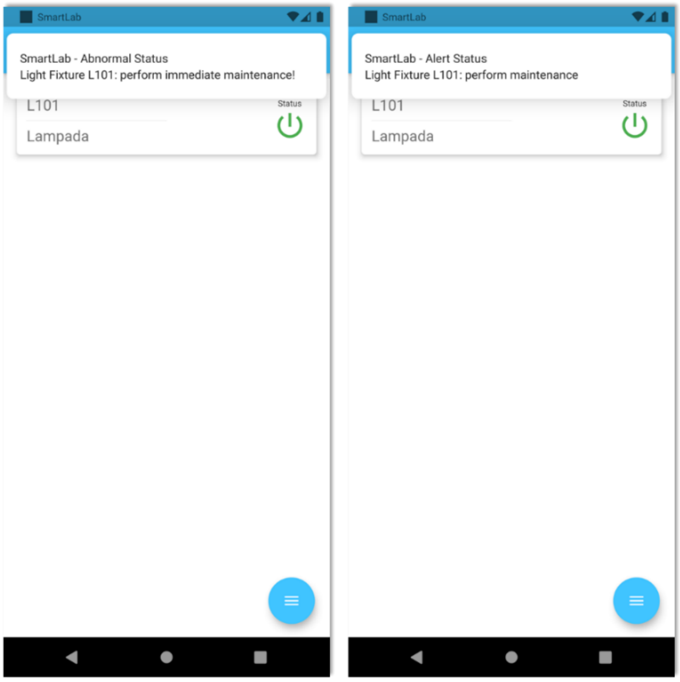
Source: Author (2021)

Figure 108: Lighting information on SmartLab interface



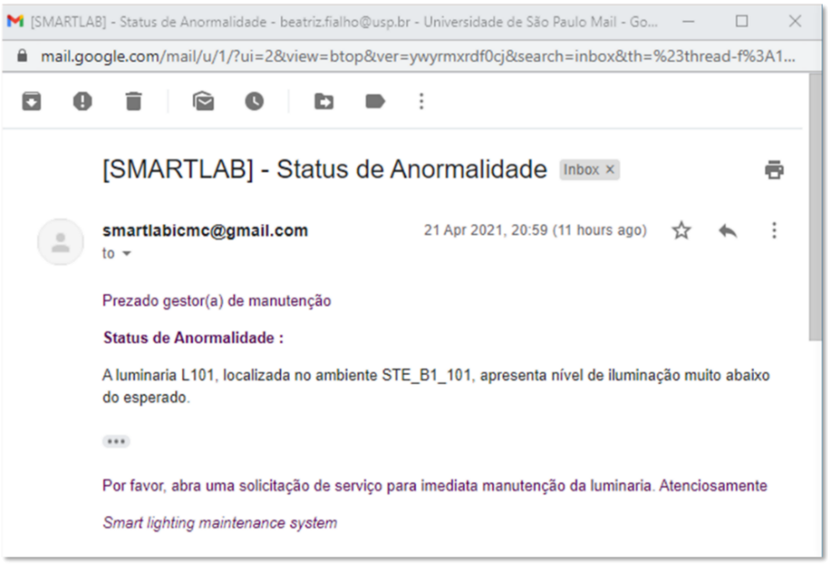
Source: Author (2021)

Figure 109: Notification messages on SmartLab interface



Source: Author (2021)

Figure 110: Notification message on abnormal status performance on the e-mail interface[42]

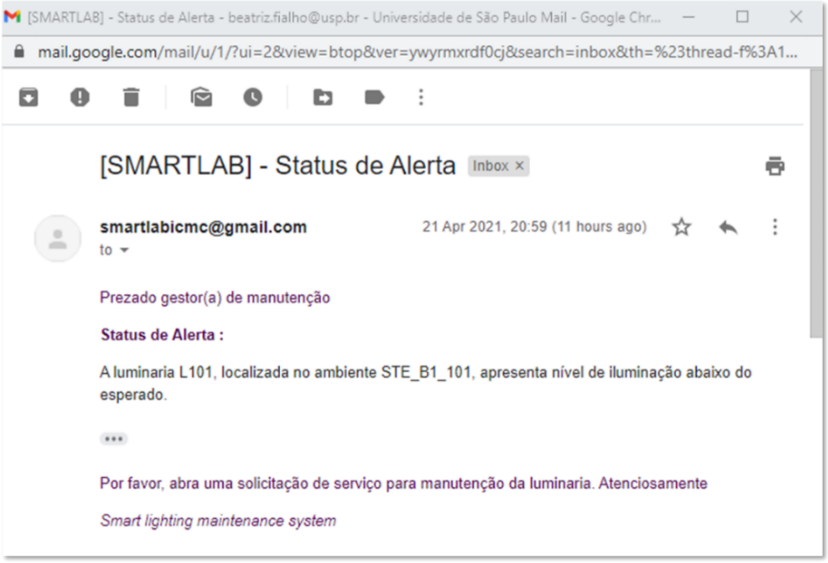


Source: Author (2021)

A test assessed the efficacy of visualizing lighting performance information on the prototype interfaces, in terms of accessibility, integrity, and clarity. The notification messages on SmartLab and E-mail interfaces addressed the requirements, providing consistent information for triggering maintenance services, as previously shown in Figures 110 and 111.

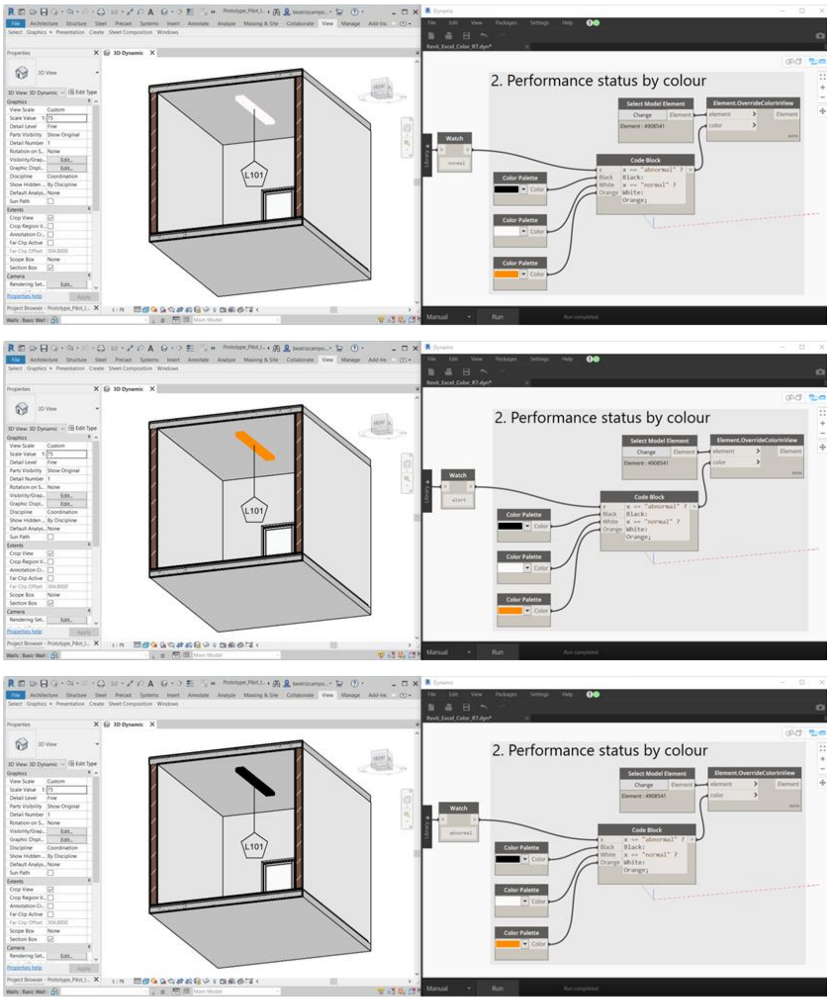
42 Free translation of the e-mail message: "Dear maintenance team member, Abnormal Status The lighting level of luminaire L101, located in room STE_B1_101, is much lower than expected. Please, open a work request for immediate maintenance repair. Kind regards, Smart lighting maintenance system."

Figure 111: Notification message on alert status performance on the e-mail interface[43]



Source: Author (2021)

Figure 112: Efficacy of Testing Autodesk Dynamo to read and interpret data

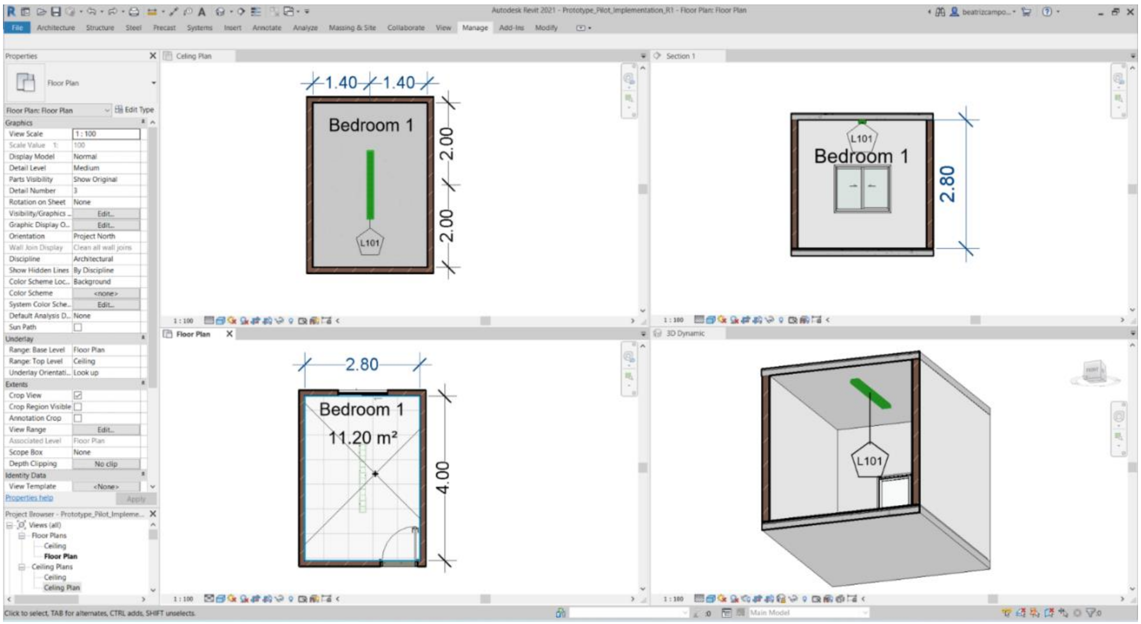


Source: Author (2021)

43 Free translation of the e-mail message: "Dear maintenance team member, Alert Status The lighting level of luminaire L101, located in room STE_B1_101, is lower than expected. Please, open a work request for maintenance repair. Kind regards, Smart lighting maintenance system."

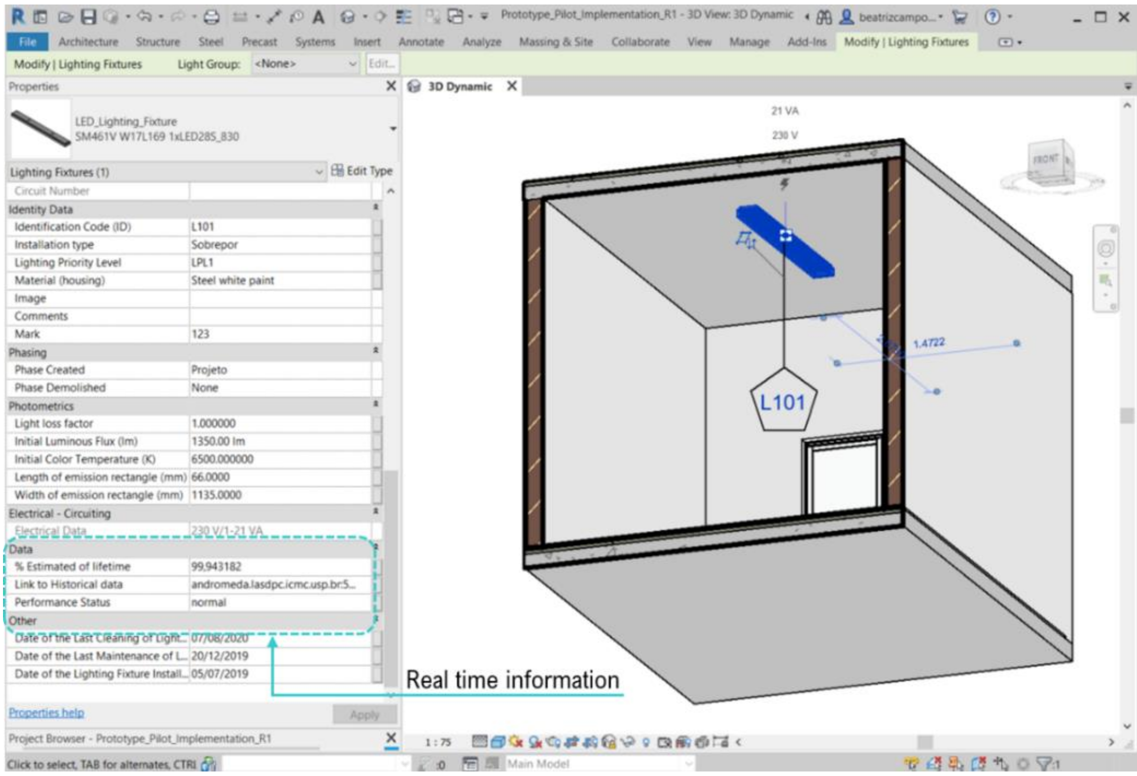
The information was effectively visualized in the BIM environment on distinct views (i.e., floor plan, ceiling plan, section plan, 3D view, etc.) (Figure 113), and in the properties palette (Figure 114). As expected, the colours were visible only in the Autodesk Revit 2021 interface, since Dynamo capabilities are not available in the Autodesk online Viewer (Figure 115). The link to the historical data spreadsheet modelled as a parameter in Revit enabled its importation and edition into a Microsoft Excel spreadsheet (Figure 116).

Figure 113: Visualization of real time information on Autodesk Revit 2D and 3D views



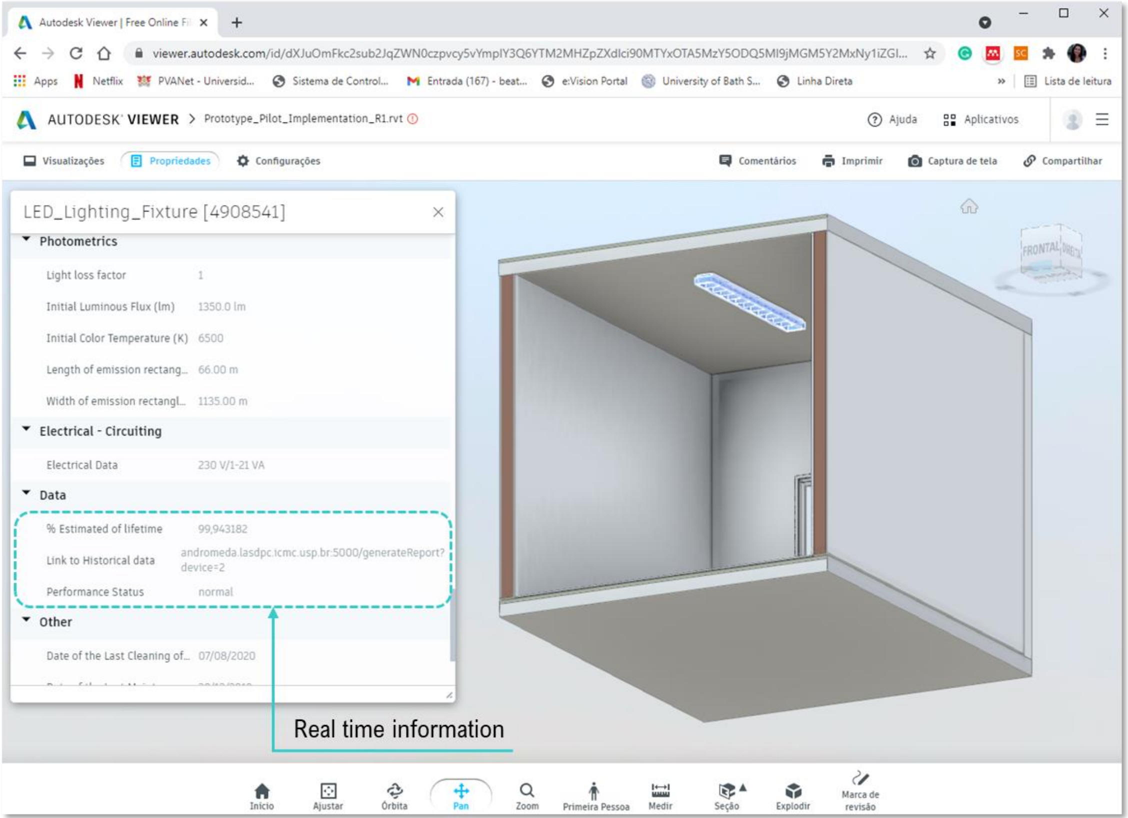
Source: Author (2021)

Figure 114: Visualization of real time information on Autodesk Revit properties pallete



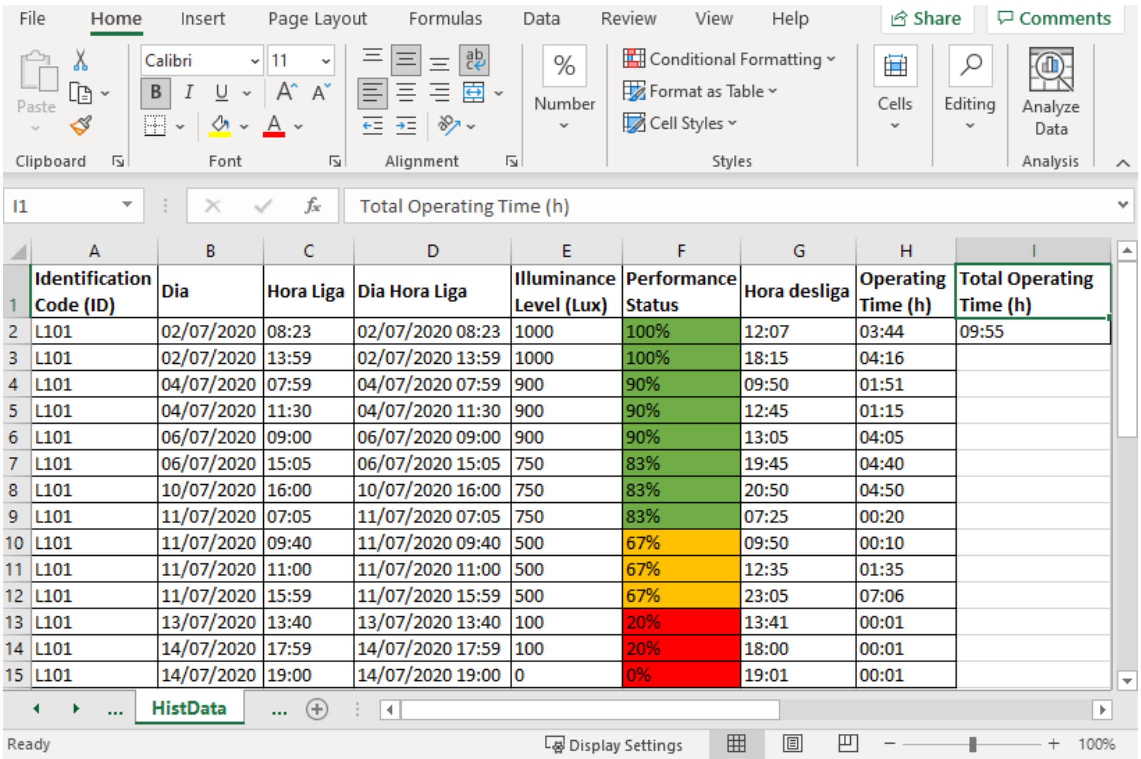
Source: Author (2021)

Figure 115: Visualization of real time information on Autodesk online Viewer interface



Source: Author (2021)

Figure 116: Example of historical data displayed in Excel spreadsheet



Identification Code (ID)	Dia	Hora Liga	Dia Hora Liga	Illuminance Level (Lux)	Performance Status	Hora desliga	Operating Time (h)	Total Operating Time (h)
L101	02/07/2020	08:23	02/07/2020 08:23	1000	100%	12:07	03:44	09:55
L101	02/07/2020	13:59	02/07/2020 13:59	1000	100%	18:15	04:16	
L101	04/07/2020	07:59	04/07/2020 07:59	900	90%	09:50	01:51	
L101	04/07/2020	11:30	04/07/2020 11:30	900	90%	12:45	01:15	
L101	06/07/2020	09:00	06/07/2020 09:00	900	90%	13:05	04:05	
L101	06/07/2020	15:05	06/07/2020 15:05	750	83%	19:45	04:40	
L101	10/07/2020	16:00	10/07/2020 16:00	750	83%	20:50	04:50	
L101	11/07/2020	07:05	11/07/2020 07:05	750	83%	07:25	00:20	
L101	11/07/2020	09:40	11/07/2020 09:40	500	67%	09:50	00:10	
L101	11/07/2020	11:00	11/07/2020 11:00	500	67%	12:35	01:35	
L101	11/07/2020	15:59	11/07/2020 15:59	500	67%	23:05	07:06	
L101	13/07/2020	13:40	13/07/2020 13:40	100	20%	13:41	00:01	
L101	14/07/2020	17:59	14/07/2020 17:59	100	20%	18:00	00:01	
L101	14/07/2020	19:00	14/07/2020 19:00	0	0%	19:01	00:01	

Source: Author (2021)

b. Assessment based on performance measurement criteria

At first, the prototype implementation and testing aimed to assess whether the prototype system effectively collected, processed, and transmitted lighting data, thus providing accurate, clear, and accessible lighting performance information to the research team. Table 52 shows the assessment of the prototype according to its sets, components, and performance measurement criteria.

Regarding the lighting sensor module, the results showed the proposed connection with the existing electric infrastructure and the calibration of the sensor were fully effective, enabling a continuous charging of the sensor and generation of data for the cloud environment. On the other hand, the original position and way of attachment on the prototype surface were partially adequate. Adjustments were made in the positioning and attachment of the sensor for avoiding environmental interference.

The efficacy of the software components was also assessed. The accuracy of the sensor in collecting data under distinct performance status was partially effective. The night-time test results (Table 50) showed the prototype accurately identified lighting performance levels in the three statuses, i.e., normal, alert, and abnormal. On the other hand, inaccuracies related to the alert status were observed at daytime (Table 51).

Table 52: Assessment of the prototype according to its sets, components, and performance measurement criteria

Set	Component	Performance measurement criterion	Assessment
Hardware	Lighting sensor module	Sensor data are collected with no interference of other objects	Partially
		Sensor devices are firmly and steadily attached to the luminaire housing	Partially
		Sensor devices are continuously charged with no oscillations	Yes
Software	Sensor data collection	Calibration enables accurate data collection	Yes
	Wi-Fi transmission and online storage of sensor data	Data are accurately transmitted across the architecture components	Yes
	Sensor data transmission and processing	Sensor is accurately collecting data under distinct conditions	Partially
		Both data and information are accurately transmitted and interpreted by BIM and IoT platforms, generating performance information and notification messages	Yes
	Information visualization	Information is accurate and easily visualized on SmartLab and e-mail interfaces	Yes
		Information is accurate and easily visualized on BIM platforms	Yes

Source: Author (2021)

The performance of the prototype components in the transmission, processing, and visualization of data and information over BIM and IoT platforms was fully effective, thus providing the necessary evidence for triggering maintenance services. The results showed the prototype accurately interpreted the data and generated performance information under the three tested performance status, i.e., normal, alert, and abnormal.

The first test revealed the microservice properly updated the % expected lifetime and luminaire performance status in SmartLab mobile app (Figure 108). Besides, it generated notification messages for SmartLab and e-mail when the luminaire showed an abnormal or alert performance status (Figures 109, 110 and 111). The second test indicated the performance information was adequately read and interpreted by Dynamo, changing the BIM model parameters and the luminaire's colour. As depicted in Figures 113 and 114, the real time information was automatically updated by running the script.

c. Assessment based on the technical and functional requirements

The prototype implementation and testing aimed to assess whether the prototype attended the technical and functional requirements provided by the maintenance experts. Table 53 displays the assessment of the prototype according to the ability and design-related requirements.

Table 53: Assessment of requirements attended by the prototype

Category	Requirements	Assessment
Ability	Automatic detection and report of failures	Yes
	Differentiation between emergency and non-emergency services	Yes
	Supply of information on the equipment to be maintained (e.g., manufacturer, model, etc.)	Yes
	Generation of reports towards supporting predictive maintenance and managerial decisions	Yes
	Information on the priority of attendance of each room	Partially
Design	Use of standardized components (e.g., sensors, accessories for installation) and software which can be easily replaced and updated according to advances in technology	Yes
	Use of device for mass storage	No
	Use of a robust system with high degree of accuracy and low likelihood of failures, ensuring the timely detection of problems	Partially
	Assurance of safety data and information	Partially
	Integration with the existing systems and facilities with no replacement of existing luminaires	Yes
	User-friendliness, considering the distinct backgrounds of the professionals	Yes
	Accessibility to all maintenance team members via smartphone	Yes
	Supply of direct and automatic tools and interfaces towards supporting de-bureaucratization of processes and improvements in their efficiency	Yes
	Low cost of implementation, maintenance, and operation and use of open BIM platforms to reduce costs	Partially
	Possibility to be managed by the university staff	Partially

Source: Author (2021)

Initially, the assessment of ability requirements was conducted and, according to Table 53, most requirements were fulfilled. The prototype automatically detected and reported current and potential failures using several BIM and IoT interfaces. Emergency and non-emergency services were differentiated through the definition of the two critical lighting performance status, namely abnormal, which demands immediate maintenance, and alert, which demands maintenance. Static and dynamic information on the equipment to be maintained (e.g., manufacturer, model, and real time lighting performance level) is centralized in the BIM model, facilitating access by the maintenance team members. Historical performance reports of the luminaires are also generated by the prototype, assisting maintenance decision-making.

Instead of providing the priority attendance of each room, the prototype informs on the Luminaire Priority Level (LPL) based on the Classification Matrix presented in Section 5.1.1. By focusing on the LPL, the prototype supports a more specific service, covering a variety of situations in which more than one type of luminaire is placed in the same room.

A series of requirements related to the prototype design was assessed. Among the fully attended requirement is the adoption of standardized components and software using solutions available on the market (i.e., LDR sensor, MCU, Revit software). Besides, the microservice architecture facilitates adjustments in parts of the prototype and the scalability of the system with no interference in its overall structure.

The integration with existing systems and facilities was fully addressed, since no interference in the current CAFM software was necessary for the development and implementation of the prototype. The solution for the integration of the prototype with the luminaire infrastructure not only enabled its power supply, but also facilitated its removal and reinstallation if necessary. Requirements related to the system prototype user-friendliness, accessibility via smartphone, and availability of tools and interfaces supporting maintenance efficiency were also attended due to the provision of relevant and objective data (i.e., Lighting level, operating time) and information (i.e., performance status, % estimated lifetime, notification messages) on intuitive and diverse interfaces (i.e., SmartLab, BIM model, e-mail).

Other requirements were partially attended. For instance, the reliability of information was affected by inaccuracies in lighting performance during daytime. The protection of data security and privacy was partially addressed through the implementation of core software components of the architecture in LaSDPC private cloud infrastructure with access restrictions. However, other components (e.g., BIM software) were implemented in local computers, with a lower level of data security. The requirement regarding mass storage was not addressed due to limitations in the hard disk adopted.

Requirements related to low cost of implementation, maintenance, and operation of the system prototype and its possibility to be managed by the university staff were partially addressed. The selection of commercial hardware components and the development of a scalable architecture aimed at reducing costs of the system over its lifecycle and facilitating its management by the organization. Although the use of commercial software (e.g., Revit) facilitates its maintenance and operation, it increases the cost of the system in comparison to open-source solutions, due the purchase of licenses and updates.

Additional costs involving, for instance, computational infrastructure for data processing and storage, specialized professionals to operate the system, and training of organization staff to manage the system, are equally relevant. Nevertheless, the assessment of such costs was not emphasized due to limitations of this research.

5.3. Discussion

This section discusses the findings for theory generation, the last step of the prototyping process. Primarily, it approaches the establishment of technical and functional requirements and the experimental plan for prototyping, the establishment of FM BIM requirements and the integration of BIM, IoT, and FM components, the generation of intelligence from raw data, and the accessibility to relevant information for decision-making. Hence, addresses the potential impacts of the system prototype on the university maintenance management and contributions to design phase. Outcomes from the Literature and SLR (Chapter 3) and the Multiple Case Study (Chapter 4) support the discussion.

5.3.1. Findings of the prototyping process

a. Establishment of technical and functional requirements and the experimental plan for prototyping

This section discusses the approach to define requirements and develop the experimental plan for the construction of the smart lighting maintenance system prototype. Such approach was based on the development and validation of the conceptual inputs with maintenance experts and interviews with AEC and

IT professionals. As discussed in Chapter 4, the thorough understanding of the needs of the FM sector and its end users and the capabilities of technological solutions are key for the effectiveness of digital transformation (JIA et al., 2019; MARMO et al., 2019).

The validation of the Conceptual framework of BIM & IoT Assisted Predictive Maintenance Process and the interviews with AEC and IT professionals supported the definition of requirements and strategies for the development of the system. The distinct professionals' backgrounds and job positions contributed to the obtaining of heterogeneous and complementary sources of evidence.

At first, requirements related to the ability (i.e., automatic detection and report of failures, information of priority of attendance) and design (i.e., use of standardized components, scalability, user-friendliness) of the system were identified, corroborating literature findings (BECERIK-GERBER et al., 2012; GHA et al., 2019; JIA et al., 2019; PÄRN; EDWARDS; SING, 2017)), and revealed maintenance experts' concerns not only with the development of a functional solution, but also with its maintenance and operation by the FM sector over time. For instance, requirements related to the easy integration of the prototype with existing tools and facilities, easy replacement and update of its components, and easy operation by professionals with several backgrounds, indicate the financial and human limitations faced by organizations.

Therefore, an experimental plan supported the development, testing, and assessment of the prototype performance, as described by Jia et al. (2019), Machado (2018), Marmo et al. (2019), Misic, Gilani and McArthur (2020), Parn, Edwards and Draper (2016), and Thabet et al. (2017). Primarily, it involved the definition of the object to be monitored, the testing variables, and the rationale for assessing luminaire performance. As described in Section 5.2.1., standards (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2013, 2016) and discussion with experts were essential for the development of a rationale on this research needs.

The complexity of developing tools and methods to measure and manage building components performance was discussed by Kulatunga, Liyanage and Amaratunga (2010) and Marmo et al. (2019), particularly of those in which performance is not easily measurable. The authors reinforced the importance of such tools and methods to support better decision-making on FM management and avoid unnecessary interventions in building facilities. Standards and guidelines are still required for assisting the development and implementation of BIM and IoT solutions to FM activities (FIALHO; CODINHOTO; FABRICIO, 2020).

Besides, the prototyping process involved the development of the Classification Matrix of Luminaire Priority Level (Section 5.1.1.), a tool for priority classification which addresses a crucial aspect of maintenance management (BARRETT; FINCH, 2014; CHANTER; SWALLOW, 2007; EXPERTS, 2021a, 2021b; FIALHO; CODINHOTO; FABRICIO, 2020; JASPERS; TEICHOLZ, 2012; MÁRQUEZ, 2007). The assessment of the matrix showed the overall effectiveness of the tool to assist universities FM teams in prioritizing lighting, which is a critical service. Its benefits are mainly related to the objective prioritization of services according to clear criteria, supporting the optimized staff and resource distributions and the structured management of outsourced services. As discussed in Chapter 4, the identification of priority assets is essential not only to improve maintenance service performance, but also to guide organizations towards digital transformation based on BIM and IoT solutions.

b. Establishment of FM BIM requirements and integration of BIM, IoT, and FM components

This section discusses the effectiveness of the adopted approach in establishing FM BIM requirements and integrating BIM, IoT, and CAFM components, addressing interoperability, a key issue for digital transformation (as discussed in Section 5.4. (ARSLAN et al., 2014; BECERIK-GERBER et al., 2012; MARMO et al., 2019; PARN; EDWARDS; DRAPER, 2016; TALAMO; BONANOMI, 2016) and corroborated by the maintenance experts (Section 5.1)).

Decisions made by the research team addressed integration issues, as demonstrated in the prototype testing (Section 5.2.4.). For instance, the development of an in-house lighting sensor module enabled the free collection and processing of data, overcoming access limitations imposed by commercial systems. Moreover, the establishment of a BIM model data structure (i.e., room ID, sensor), the adoption of interoperable programming languages (i.e., python) in Dynamo, and the use of. json as the exchange format ensured the consistency of data and information among platforms. In fact, the definition of standards and protocols and the identification of critical information were essential for integrating heterogeneous systems (MCARTHUR, 2015; PIN; MEDINA; MCARTHUR, 2018).

However, the main contribution of research is the proposition of a new architecture (LEWIS, 2012), exploring the IoT ecosystem structure attributes and its interface with BIM and IoT components. The use of a microservice architecture structure enabled a gradual and flexible integration of distinct technologies for specific functionalities (NEWMAN, 2015; TANG et al., 2019). Originally, the IoT ecosystem was designed to control the luminaire operation (i.e., turn on – turn off), identify its status (i.e., on – off), and deliver such information on SmartLab interface. Its scalable structure promoted the development of new microservices that store and process real time data and the integration with distinct BIM and FM components (i.e., Revit, Dynamo, e-mail), providing updated performance information for maintenance actions.

In fact, flexibility in the selection of BIM, IoT, and FM components is key for the legacy of the system. Teizer et al. (2017) and Mirarchi et al. (2018) recommend the use of resources available on the market (e.g., BIM software, cloud-based information management technologies, mobile devices) for new applications in the FM scenario, enabling their replacement or update. However, Kassem et al. (2015) advert about the specification of particular technologies for FM business processes due to the distinct lifetimes of technologies, which would impose frequent adaptations.

As discussed in Chapter 3, distinct mechanisms are available for integrating BIM, IoT, and FM systems, thus enabling the creation of Digital Twins Employed as a middleware, Dynamo visual programming plugin was the bridge between Autodesk Revit and IoT database, thus enabling the update of real-time and historical data and information into the BIM model parameters. The possible customization of python nodes was essential for addressing the prototype needs not covered by standardized nodes (SENA, 2019).

Some advantages of such a mechanism corroborated by the literature are easy software development by existing BIM APIs (i.e., Revit and Dynamo), requirement of less expertise in programming and IFC, easy linking of sensor data and model data, both stored in relational databases (KENSEK, 2015), and automatic update of sensor data on Revit interfaces (FINK; MATA, 2020; TANG et al., 2019). The benefits of this approach includes flexibility to integrate diverse and existing software vendors (SACKS et al., 2018), availability of a single source of information, reduction of human errors, and dynamic update of information (IBRAHIM et al., 2016). Nevertheless, the authors highlighted the mechanism would be not suitable for complex BIM models with a large number of sensors, since it requires a manual construction of virtual objects that represent physical sensors.

IoT and CAFM were integrated through the creation of an e-mail notification to the maintenance sector triggering the opening of a work request. As stated by Ibrahim et al. (2016), manual inputs of information in CAFM involve time-consuming, costly, and error prone activities, and must be avoided, particularly "for modern buildings of moderate and larger size" (SACKS et al., 2018, p. 156). However, considering the transition from traditional maintenance to a fully automated smart process, it can contribute to the service performance by eliminating the detection and reporting stages currently conducted by building users.

The use of a hybrid approach combining proprietary middleware and web services might support a better integration of BIM, IoT and FM systems. Although expensive and complex processes are involved in the development and implementation of proprietary middleware (IBRAHIM et al., 2016), the scalability of such approaches might save both costs and time in future software development and management. Besides, proprietary middleware can make BIM a dynamic database that supports applications such as "real-time model update based on IoT device readings", a two-way interaction involving information acquisition and control, "ubiquitous monitoring and crowd sourcing monitoring", and "integration with other cutting-edge technologies" (i.e., Virtual Reality, Augmented Reality, and Mixed Reality) (TANG et al., 2019).

Advances in ICTs involving new capabilities and low-cost components have been fostering innovations in the AEC industry (MANNINO; DEJACO, 2021). Nevertheless, research on BIM and IoT integration is embryonic, and new methods, web services and SOA-based design are necessary for supporting such applications (ALTOHAMI et al., 2021; TANG et al., 2019), reinforcing the relevance of this research.

c. Generation of intelligence from raw data

This section discusses the approach for the generation of relevant information from real time data towards supporting maintenance decision-making according to the assessed abilities of the prototype for data collection and analysis. It focuses on the extraction of meaningful information from raw data, reported as a challenge in the literature (CLAYTON, 2012; COLEMEN et al., 2017; LEWIS, 2012; SACKS et al., 2018):

"For example, for many years building automation systems have had the capability to collect data from equipment-level sensors and submeters and to store data on servers. In many cases the data collected from sensors and submeters (when installed) is used only for real-time monitoring and to alert building operators of an undesirable condition through an alarm. Although not currently common practice, it is possible to store the sensor and submeter data on servers and use this data to track performance and support benchmarking and troubleshooting efforts." (LEWIS, 2012, p. 239)

The collection of real time data was the first step for intelligence generation. In this study, it involved the luminaire lighting level (V) and operating time (h) collected by the lighting sensor module. As shown by the testing results (Section 5.2.4.), the components and design solutions adopted in the prototype design might have influenced the accuracy of measurements. Previous studies reported similar limitations of IoT system components, such as low precision of GIS system (MIRARCHI et al., 2018) and inaccurate location, and number of sensors to perform the measurements (CHANG; DZENG; WU, 2018; RAMPRASAD et al., 2018)). Advancements in research and development of new technologies (e.g., remote sensing technology, computing power, distributed computing, etc.) might overcome them (MANNINO; DEJACO, 2021; RASHID; LOUIS; FIAWOYIFE, 2019; SACKS et al., 2018). Besides, the costs of IoT components are gradually declining, enabling their mass distribution (INTERNATIONAL TELECOMMUNICATION UNION, 2005).

Once the real time data were available in the cloud, the following step involved data processing and analyses in IoT and BIM environments. Two complementary purposes, namely identification of potential and current abnormalities and generation of historical data were addressed. The testing results indicated the system accurately interpreted real time data, generating updated information through distinct communication channels.

In IoT environment, Alert Microservice analysed the real time data according to the pre-set criteria, generating performance status and % expected lifetime information. As discussed in Section 6.3.1., the development of methodologies that assess building performance is a key challenge in FM addressed in this study. Such information was automatically updated in SmartLab mobile app and BIM model parameters. Based on performance status, Alert Microservice generated notification messages on potential or current abnormalities via SmartLab and e-mail account.

The Historical data Microservice summarized luminaire performance data in a historical data record, which was provided in a .json file and modelled as a dynamic BIM parameter. As shown by the tests (Section 6.2.4.), a large volume of data might be generated over the luminaire lifetime - particularly in rooms where the luminaire is intensively used, hampering its accessibility, interpretation and support to decision-making (DESOGUS et al., 2017; LEWIS, 2012). According to Arslan, Riaz and Munawar (2017), changes in the traditional approaches will be necessary for the management of huge and complex data sets, conducting the sector towards the emerging paradigm of Big Data.

In BIM environment, Dynamo plugin played a twofold role for information generation. First, it populated model parameters with real time inputs (i.e., performance status, % expected lifetime information, link to historical data), enriching the model with dynamic information, and analysed the performance status based on the predefined colour set based-rule, delivering visual and straightway information on luminaire performance. In both environments, the establishment of consistent rules was essential to transform raw data into relevant information and actionable recommendations (LEWIS, 2012).

d. Accessibility to relevant information for decision-making

This section discusses accessibility to relevant information for maintenance decision-making according to the prototype abilities to support information visualization and management. As addressed in Chapter 4, the provision of reliable and effortlessly accessible information is essential for improvements in FM performance, particularly with support of BIM and IoT solutions (AKCAMETE; AKINCI; GARRETT JR, 2010; BECERIK-GERBER et al., 2012; CAVKA; STAUB-FRENCH; POTTINGER, 2015; KASSEM et al., 2015; KENSEK, 2015; LEWIS, 2012; MIRARCHI et al., 2018; PINTI et al., 2018; ZHAN et al., 2019).

The prototype effectively addressed information accessibility issues, as demonstrated in the testing step (Section 5.2.4.). Such effectiveness might be explained by the adoption of complementary interfaces for visualizing distinct tiers of information with support of specific devices and applicable to specific maintenance activities. The premise was the multiple ways for information visualization would meet the needs of the distinct stakeholders in the process.

The visualization of notification messages on SmartLab mobile app and e-mail interfaces demonstrated the prototype's ability to automatically detect and report current and potential failures, differentiating between emergency and non-emergency services. Both interfaces delivered concise and clear text-based information on the luminaire to be maintained (i.e., identification, location, and performance status level), supporting the opening of work requests in CAFM software for immediate or planned service response. SmartLab also provided clear and intuitive luminaire information (i.e., identification, location, performance status level, % estimated lifetime), facilitating the monitoring of luminaire performance in real time.

Previous studies described advantages of such user-friendly interfaces supported by mobile devices (i.e., smartphone, tablet) for BIM and IoT systems. For instance, mobile devices are currently available to most populations, thus becoming an essential tool for tradesman in field work (INTERNATIONAL TELECOMMUNICATION UNION, 2005; MIRARCHI et al., 2018). Besides, mobile apps do not require high technological expertise of end users, and, therefore, encourage collaboration among maintenance stakeholders (MIRARCHI et al., 2018) and Increase the productivity of FM staff (SACKS et al., 2018).

BIM interfaces provided clear, accurate, and updated luminaire information. The tests showed real-time performance information was effortlessly visualized on both properties palette and Autodesk Revit 2021 model views. Luminaire historical data record, modelled as a dynamic BIM parameter, was also easily downloaded and visualized in a spreadsheet. A similar approach was adopted by Chang, Dzeng, and Wu (2018), who emphasized the importance of a common platform for intuitive identification of potential problems and decision management.

The overall benefits of BIM as a central repository were discussed in Chapter 4. However, the introduction of real-time information moves BIM to a higher level (SABOL, 2012), addressing the paradigm of Digital Twin (FINK; MATA, 2020). By enabling the query of current and past status of the luminaire, the resulting digital twin might support short- to long- term maintenance response, facilitating the detection, visualization, location, diagnosis, and repair of current and potential abnormalities. Sections 5.3.2. and 5.3.3 addresses the potential impacts of the system prototype on the maintenance service performance and its contributions to the design phase.

5.3.2. Impacts of the Smart lighting maintenance system prototype on service performance

This section focuses on the potential impacts of the system prototype on university maintenance management. Once again, the BR University and the students' accommodation which supported the prototype development are the reference for inferencing. The overall optimization of maintenance process stages is explored according to the traditional reactive maintenance process model developed in Chapter 5 (Figure 84) and the expected outcomes of the BIM and IoT implementation (Chapters 3, 4, and Section 5.1.). The optimization of supporting activities towards the consolidation of a predictive maintenance approach is then explored considering the extrapolation of luminaire performance information and historical data records analysis over time.

The characterization of the traditional reactive maintenance process was the first step for the identification of potential impacts of the smart lighting system prototype implementation, as discussed in Chapter 4. Figure 117 depicts the eight stages (i.e., 1. Fault Detection, 2. Reporting and Feasibility Analysis, 3.

Location and Inspection, 4. Diagnosis and Planning, 5. Repair, 6. Check-out, 7. Delivery, and 8. Feedback and closing the request) and core activities of maintenance process under traditional and optimized scenarios, highlighting the expected benefits and impacts of a predictive approach.

As shown in Figure 117, the automatization of functions and the centralization of information in the system databases led to streamlining activities, particularly in the initial stages, and reduced stages over the predictive maintenance process. In Stage 1, the automatic detection of current and potential faults by the sensor adds value to the process. By removing the end-user participation, the system increases the accuracy and efficiency of detection, for instant, thus promptly capturing variations in building component performance that might be imperceptible or even inaccessible by humans (CHANTER; SWALLOW, 2007; EXPERTS, 2021b; UK UNIVERSITY 1, 2019c). As stated by a maintenance expert, automatic detection would avoid user's bias or lack of knowledge about the event (EXPERTS, 2021b; GUNAY et al., 2018; OUBODUN, 1996), triggering maintenance response in early days even with no the end-user's perception.

In Stage 2, the automatic report of current and potential faults and the supported feasibility analysis contribute to the optimization of activities (DESOGUS et al., 2017). Fault report is performed through notification messages via e-mail and SmartLab, thus increasing the accuracy of information and the efficiency of the activity. As a result, it eliminates the diversity of communication channels for specific users and human-related obstacles such as loss of paper forms, imprecise or late description of faulty equipment and location, and duplication of requests (ABDUL-LATEEF, 2010; AKCAMETE et al., 2011; EXPERTS, 2021b; MIRARCHI et al., 2018; PERERA; ILLANKOON; PERERA, 2016; SALLEH et al., 2016; UK UNIVERSITY 1, 2019b).

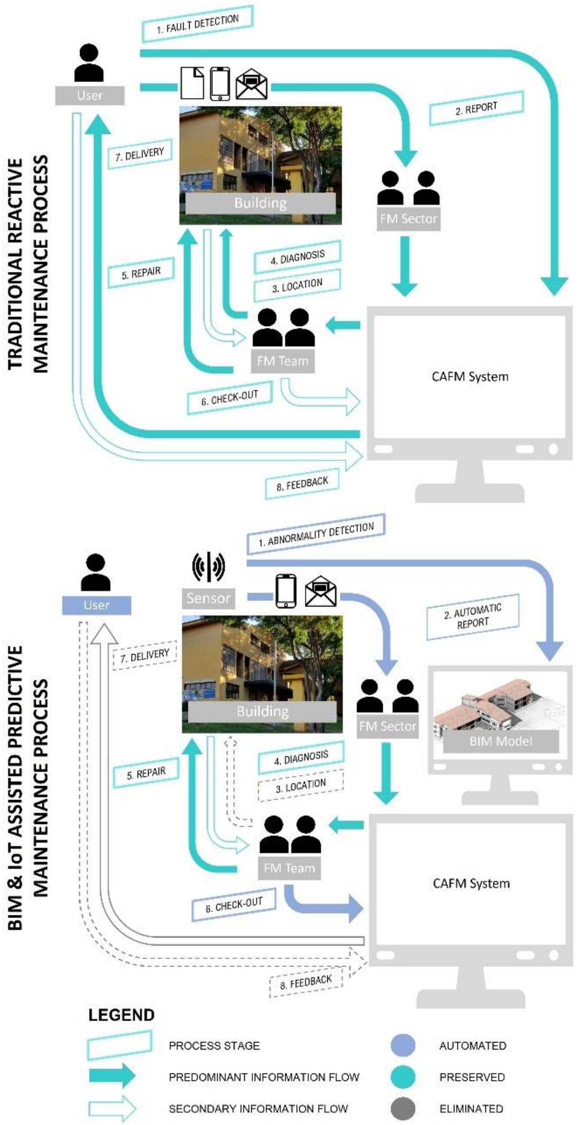
The system updates real-time information in BIM and IoT databases, providing dynamic and static luminaire information for maintenance purposes. The generation of Work Requests is also optimized, since the system prototype enables both automatic and manual input of information into CAFM, according to the functionalities of the software in place. Efficiency gains are expected even in the manual input due to the availability of updated information in BIM and IoT databases.

Considered a critical activity in the maintenance process, the prioritization of services is based on real-time luminaire performance status and Luminaire Priority Level (LPL) available in BIM and IoT databases. Such updated and standardized information supports a more agile and accurate prioritization, mitigating practices such as personal assessment (AKCAMETE; AKINCI; GARRETT JR, 2010) and the "First in First Out" method (EXPERTS, 2021a; UK UNIVERSITY 1, 2019b), and contributing to distribution of resources and maintenance staff sizing for repair (EXPERTS, 2021b).

In Stage 3, the service location is automatically provided in notification messages and BIM and IoT interfaces. Field inspections can be virtually undertaken on BIM interfaces, supporting the maintenance team in checking the position of the luminaire in the room in advance (KASSEM et al., 2015) and potential rationale for failure (UK UNIVERSITY 2, 2018). Problems caused by inaccurate descriptions of fault locations are eliminated and unnecessary visits to the field are avoided (EXPERTS, 2021b).

In Stage 4, both diagnosis and planning of repair are assisted by updated information in the system's databases. The visualization of all characteristics of the component in the BIM model facilitates the diagnosis (AKCAMETE; AKINCI; GARRETT JR, 2010) and the purchase of services or materials for repair (EXPERTS, 2021b; UK UNIVERSITY 2, 2018) and mitigates delays caused by inaccurate specification of parts to be maintained or replaced (BR UNIVERSITY, 2019a).

Figure 117: Optimization of maintenance process stages supported by the Smart Lighting System Prototype



	1. Fault Detection	**2. Reporting and Feasibility Analysis**	**3. Location and Inspection**	**4. Diagnosis and Planning**	**5. Repair**	**6. Check-out**	**7. Delivery**	**8. Feedback and closing the request**
Activities	1. Detection of a fault by the end user (i.e., student, visitor, university staff) 2. Assessment if the FM sector must solve the issue	1. Reporting a fault via distinct communication channels (i.e., phone call, e-mail, mobile app, CAFM system, personally, paper form) 2. Raising the request in CAFM System, if externally reported 3. Generation of the Work Request, based on CAFM database 4. Feasibility analysis 5. Service prioritization based on personal assessment or "First in First Out" method 6. Problem classification, based on CAFM database 7. Work Order (WO) generation 8. Raising the WO in the financial system 9. Financial approval 10. Dispatch to the in-house or outsourced electrical section 11. Tradesman allocation	1. Service location and site inspection, based on statutory and building documents 2. Damage containment, if necessary	1. Diagnosis, based on statutory and building documents 2. Assessment of service complexity and risk 3. Assessment of availability of staff and material 4. Service or material purchase, if necessary 5. Bidding process, if necessary 6. Service or material purchase order emission, if necessary 7. Service Order (SO) generation	1. Execution	1. Execution inspection 2. Fill out forms to register the service and to get approval, based on statutory and building documents 3. Execution approval 4. CAFM system informing to the end user about service end via e-mail	1. Service Delivery	1. Service attendance approval 2. Feedback and asking to close the request via phone call, e-mail or personally

	1. Abnormality Detection	**2. Automatic Reporting and Feasibility Analysis**	**3. Location and Inspection**	**4. Diagnosis and Planning**	**5. Repair**	**6. Check-out**		
Activities	*1. Automatic detection of current or potential fault*	*1. Automatic reporting of current or potential fault to the maintenance team via notification message and update of real-time information in BIM and IoT databases* *2. Automatic or optimized generation of the Work Request, based on BIM and IoT database* *3. Supported service prioritization, based on real-time luminaire performance status and Luminaire Priority Level (LPL)* *4. Automatic problem classification, based on BIM database* *5. Supported Work Order (WO) generation* 6. Raising the WO in the financial system 7. Financial approval 8. Dispatch to in-house or outsourced Electrical section 9. Supported tradesman allocation based on historical data records	*1. Automatic service location and virtual site inspection, based on BIM database* 2. Field inspection and damage containment, if necessary	*1. Supported diagnosis, based on BIM database* *2. Supported assessment of service complexity and risk, based on BIM database* *3. Assessment of availability of staff and material* *4. Supported service or material purchase, if necessary* 5. Bidding process, if necessary 6. Service or material purchase order emission, if necessary 7. Service Order (SO) generation	*1. Execution supported by accurate information*	1. Automatic execution inspection 2. Fill out forms to register the service and to get approval, based on statutory and building documents 3. Execution approval 4. Closing request		
Impacts	*Maintenance process triggered before the problem impact the end-user* *Fault detected with more accuracy, avoiding user´s bias or lack of knowledge*	*Centralization of communication between the building component and the maintenance team, supported by BIM and IoT solutions* *Avoidance of losing paper form requests, receiving inaccurate fault description and location, and duplication of requests in the CAFM system* *Agility and accuracy in service prioritization*	*Location automatically provided by the notification message and visible on BIM model, reducing the necessity of local inspection*	*Quicker diagnosis, supported by BIM database* *Agility in service allocation to the maintenance teams*	*Improving the precision about the service to be carried out*	*Optimization of check-out, due to the automatic verification of the luminaire performance status*	*Elimination of stages 7 and 8 due to the lack of participation of the end user*	
Benefits	*Improvement of service efficiency, safety and satisfaction of workers and users, and environmental sustainability*							

Source: Author (2021)

The availability of updated historical data is a powerful tool for analysing luminaire performance over time and predict future behaviour, optimizing planning activities, such as staff sizing and allocation, budget planning, and stock control (ROYAL INSTITUTE OF BRITISH ARCHITECTS; INTERNATIONAL FACILITY MANAGEMENT ASSOCIATION, 2018; SULLIVAN et al., 2010). Within a predictive approach, the FM managers could identify in advance accurate number, type, and location of damaged items automatically extracted from the smart lighting maintenance system report, optimizing the available resources. Such improvements contribute to the efficiency of service repair (Stage 5), carried out with more precision and agility. In this sense, it addresses the scarcity of electricians for the maintenance of buildings and infrastructure of the university campuses, as described by Experts (2021b).

The quality of the inventory parts could also be improved, since historical record would evidence those items underperforming. Such benchmarking data based on the behaviour of the monitored components could justify upgrades in equipment and systems, and projects of optimization and control, (AKCAMETE; AKINCI; GARRETT JR, 2010; DI GIUDA et al., 2018; LEWIS, 2012). In a long run, the historical data can provide a rich database for predicting future behaviour, particularly with support of Artificial Intelligence (AI) and Machine learning technologies (MCGLINN et al., 2017), supporting the achievement of “optimum performance throughout the life span of a facility with a minimum life cycle cost” (BECERIK-GERBER et al., 2012, p. 436).

In Stage 6, the service check-out is optimized, since the system automatically verifies the luminaire performance status after repair, facilitating the execution approval and closing the request. The Delivery (7) and Feedback and closing requests (8) stages are eliminated, since no end user’s participation is required (EXPERTS, 2021b).

The benefits of moving from a reactive to a predictive approach are expected in all organization sectors. From a maintenance management perspective, predictive maintenance promotes significant efficiency gains, reducing both time response and labour and material costs and improving the quality of services. Sullivan et al. (2010) estimated cost saving opportunities between 30 and 40% due to an efficient usage of staff resources and the reductions in overtime work, possible damage of secondary processes or equipment, and stock of spare parts (SULLIVAN et al., 2010).

Since labour costs represent about 70% of the overall maintenance services costs (ABDUL-LATEEF, 2010; OFORI; DUODU; BONNEY, 2015) and information-related activities might represent 12% of the time response (LEE; AKIN, 2009), the optimization of FM activities through BIM and IoT solutions is critical for significant savings. For instance, the time of lamp replacements is expected to be reduced by approximately a third only with support of BIM, due to the easy access to precise information within the model database (UK UNIVERSITY 2, 2018).

Improvements in safety and satisfaction of maintenance team members and university users are also expected. The automatization of functions and the centralization of information in the system databases enable the maintenance team to anticipate risks involved in field activities, reducing the likelihood of accidents or the unprotected exposition to hazardous environments. The team members can therefore focus on core activities (LEE; AKIN, 2009), such as training programs and development of standards, contributing for the efficiency of service provision. For the end-user, reduction of disruption occurrence and length can mitigate accidents in risky conditions (i.e., dark stairs or plant rooms) and the stability of activities. The reduction of user participation in bureaucratic tasks (i.e., fault report and execution approval) represents time savings for adding value activities in the university context, such as researching and studying.

Finally, a predictive approach might generate significant benefits to the environment. For instance, the replacement of a damaged component based on its current performance condition reduces the frequency of repairs and the unnecessary generation of waste. Moreover, energy savings are achieved, since the component will efficiently run during its design life (SULLIVAN et al., 2010).

On the other hand, investments in technology, process, and policy issues are required for the obtaining of such benefits. As discussed in Chapters 3 and 4 and corroborated in Section 5.1.2., the acquisition and installation of technological components are the start point for effective improvements in service provision. Additional costs must also be considered in the maintenance and operation of such components, including hire of specialized services and professionals. Nevertheless, the most important investments must be related to organizational changes, which involve the upskilling of the maintenance team and development of protocols and standards compatible with a predictive approach (ABDUL-LATEEF, 2010; AKCAMETE; AKINCI; GARRETT JR, 2010; ALI et al., 2010; JOHNSON; WYTON, 2015; LEWIS, 2012).

5.3.3. Potential contributions of the Smart lighting maintenance system prototype to the design phase

Potential contributions of the BIM and IoT-based system prototype to the design phase are discussed in this section. As addressed in Chapter 3, the effective management of information over the design process is challenging and crucial for efficient decision-making (FABRICIO, 2002; TALAMO; BONANOMI, 2016). On the one hand, the establishment of the activities, requirements, and responsibilities for information management supports the generation of consistent data structure and information containers for Procurement, Construction, Handover, and O&M (BECERIK-GERBER et al., 2012; BRILAKIS; FISCHER; FELLOW, 2019; EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY ASSOCIATIONS, 2019; INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018; KASSEM et al., 2015; SACKS et al., 2018; SALGADO, 2005; THE COMPUTER INTEGRATED CONSTRUCTION RESEARCH GROUP, 2010).

Since the design phase concentrates the most important decisions on building lifecycle, a clear understanding of the FM and end-users' needs enables the optimization of technical solutions towards more functional and sustainable assets, thus reducing operational costs and environmental impacts (BØLVIKEN; GULLBREKKEN; NYSETH, 2010; BRASIL, 2010; CEOTTO, 2008; DESOGUS et al., 2017; FABRICIO, 2002; KNOTTEN et al., 2015; MELHADO, 1994; PINTI et al., 2018; SACKS et al., 2018; SILVA; SOUZA, 2003).

On the other hand, knowledge and data generated by O&M activities can support FM teams on Building Performance Evaluations (BPEs) and Post Occupancy Evaluations (POEs) (BARRETT; FINCH, 2014; PÄRN; EDWARDS, 2017; ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2016), providing an accurate picture of buildings' spaces and components performance in use. Such a rich set of information can feedback owners and designers and improve the quality of design and procurement in future and recycling projects (CORRY et al., 2014; MCARTHUR, 2015; OTI et al., 2016; ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020); as claimed by Barrett and Finch (2014, p. 43) "performance measures provide a mechanism to both learn from the past and evaluate contemporary trends in the use of facilities of universities". The smart lighting maintenance system prototype provides current and historical data records on luminaires' performance, thus contributing towards filling this lacuna.

As discussed in Section 5.3.1.c., the extraction of intelligence from raw data involves procedures of analysis and synthesis for the delivery of relevant and intelligible information for owners and designers making decisions (CLAYTON, 2012; COLEMEN et al., 2017; INFORMATION MANAGEMENT, 2021; LEWIS, 2012; SACKS et al., 2018). Data generated by the prototype enable the assessment of the in-use performance of a luminaire or group of luminaires, thus supporting several applications. For instance, the availability of data on current luminaire's performance (i.e., illuminance levels, operating time, energy consumption, etc.) can assist the calibration of performance simulations and generate datasets for the prediction of risks and future behaviour through the application of machine learning and AI, thus supporting adjustments in design criteria and fostering the green construction practices (BECERIK-GERBER et al., 2012; ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020; SACKS et al., 2018).

The comparison between real and expected performance set at design phase can guide the specification of higher-quality components and spare parts. The assessment of the performance of technical parameters defined by the manufacturer (i.e., lifetime, illuminance, energy consumption, etc.) against the measured performance can indicate a defective or underperforming item (i.e., model or type of luminaire) and deterioration patterns (AKCAMETE; AKINCI; GARRETT JR, 2011; BECERIK-GERBER et al., 2012), providing evidence for the selection of better products in new projects. Such an assessment is particularly important for public organizations in bidding processes, in which the "technique and price" criterion is adopted for the identification of the most advantageous proposal for the contractor (BRASIL; SALGADO; LOMARDO, 2013; CAMPOS, 2010; ESTEVES, 2013).

Finally, the availability of historical data records can inform designers on specific users' needs, supporting more effective design solutions. Through a clear understanding on the way buildings are used in practice, designers can adapt, for instance, the number, type, size, and position of luminaires (KENSEK, 2015) and windows per room, thus providing a more comfortable, functional, safe, and healthy environment. Besides, the identification of the pattern of use in each room, floor, or building can indicate opportunities for energy savings through, for instance, the replacement of specific types of luminaires or the installation of motion lighting sensors. As a result, both users' satisfaction and productivity, as well as the cost-effective use of organizational resources for the management of the built environment and the business performance can be increased (SULLIVAN et al., 2010).

Since maintenance and design are usually segregated areas within organizations (ABDUL-LATEEF, 2010; CHANTER; SWALLOW, 2007; OLANREWAJU; ABDUL-AZIZ, 2015; OTI et al., 2016; TALAMO; BONANOMI, 2016), an effective interaction among Facilities Managers, owners, and designers is required for the development of an accessible, interoperable, and reliable source of BIM data, thus closing the information loop over the design process (BECERIK-GERBER et al., 2012; PÄRN; EDWARDS, 2017; PINTI et al., 2018; ROYAL INSTITUTE OF BRITISH ARCHITECTS, 2020). As discussed in Chapters 3 and 4, the effectiveness of such interactions within the BIM and IoT-based digital environment depends not only on human factors (e.g., engagement and capabilities of the stakeholders (BARRETT; FINCH, 2014; LEWIS, 2012; OFORI; DUODU; BONNEY, 2015)), but also on organizational and political aspects, such as establishment of protocols and standards for information management (EUROPEAN FEDERATION OF ENGINEERING CONSULTANCY

ASSOCIATIONS, 2019; KASSEM et al., 2015; MUNIR; KIVINIEMI; JONES, 2019) and adaptation of contracts and specifications related to BIM processes (SACKS et al., 2018).

5.4. Summary

This chapter addressed the development process of a BIM- and IoT-based smart lighting maintenance system prototype towards supporting university FM sectors in decision-making. The analysis of empirical evidence generated by online questionnaires and interviews and the prototyping process enabled the achievement of the research goals i.e., characterization of steps and decisions involved in prototyping a smart lighting maintenance system and identification of its potential impacts on maintenance management and contributions to design phase.

The prototyping process development was presented in Section 5.2. A set of activities undertaken in the planning stage structured the process and managed the available resources. First, the prototype scope was defined, and its main capabilities and steps were characterized. Requirements (i.e., technical, functional, FM BIM data) and assumptions for prototyping were established with the support of maintenance experts, AEC and IT professionals and based on previous studies, thus clarifying the end users' needs. An experimental plan was outlined, and guided the development, testing, and assessment of the prototype performance. This stage was the most challenging and time consuming due to the range of requirements raised by the maintenance experts to be addressed and the lack of guidelines for the measurement and assessment of building components performance.

The development stage involved activities for the construction of the prototype. Primarily, theoretical models defined the components of the prototype, their relationship, and the logic for real-time data analysis. The physical and analytical dimensions of the prototype, including the lighting module sensor, BIM model, microservices, and Dynamo code were then established for the collection, transmission, processing, visualization, and management of data and information. As discussed in Section 5.3.1.b., the architecture and the integration approach addressed interoperability and scalability issues, focusing on free access to sensors data, flexible and gradual integration among components, and consistency of data transmission. Besides, the establishment of clear rules for data analysis was crucial for the generation of intelligence from raw data, providing accessible and relevant information for maintenance decision-making.

In the final stages, activities for implementing, testing, and assessing the efficacy of the prototype were conducted according to the experimental plan. The assessment of testing results based on the performance metric criteria (Section 5.2.4.) revealed the prototype was mostly effective in data and information management. Considering the requirements provided by the maintenance experts, the lighting maintenance system prototype addressed most of its scope, since it automatically detected and reported current and potential failures, informed the luminaire priority level, provided historical data and information, and differentiated between emergency and non-emergency services. The major system's restriction was related to the accuracy of collected data, which might influence on information reliability. As discussed in Section 5.3.1., advances in research and development of components and design solutions must contribute to overcoming such limitations. The activities undertaken demonstrated the complexity of convergence of maintenance sector needs and technological abilities in such an interdisciplinary project.

The potential impacts of the maintenance management were identified. Primarily, the overall optimization of maintenance process stages was explored under a predictive approach and according to the traditional reactive maintenance process of the BR University. As discussed in Section 5.3.2., the automatization of functions and the centralization of information in the system databases led to streamlining activities, particularly in the early stages, and reduced stages over the predictive maintenance process. Benefits were therefore expected in all organization sectors (e.g., efficiency gains in maintenance management, improvement in safety and satisfaction of maintenance team members and university users, and reduction of environmental impacts). However, investments were identified for ensuring the efficacy of a predictive approach over time (e.g., hire of specialized services and professionals for maintaining and operating the technological components, upskilling of the maintenance team, and the development of protocols and standards).

The potential contributions of the smart lighting maintenance system prototype to the design phase were explored in Section 5.3.3. The in-use performance data generated can be used for the calibration of simulations and prediction of risks and future behaviour and the comparison between real and expected performance set in design can guide the specification of higher-quality components and spare parts. Moreover, the availability of historical data records can inform designers on specific users' needs. Such applications are relevant inputs for owners and designers and support adjustments in design criteria and solutions towards more functional and sustainable assets. Nevertheless, the achievement of those benefits depends on the development of a reliable source of BIM data by Facilities Managers, owners, and designers. In this scenario, the engagement and upskilling of professionals and organizations, the establishment of protocols and standards for information management, and the adaptation of BIM-related contracts and specifications are imperative.

6. Conclusions

This thesis addressed an investigation on the BIM and IoT implementation in maintenance services, considering their contributions to information management as a core element for efficiently delivering and maintaining assets. Although previous studies have approached individual benefits of such ICTs for AEC industry, the literature lacks scientific and empirical evidence regarding strategies, decisions and impacts of BIM and IoT for FM, particularly from the perspective of driving maintenance towards predictive actions and feeding information back to the early phases of the building design process.

The present study aimed at the development of a framework for BIM and IoT implementation in reactive maintenance services oriented to a predictive approach through the

i. characterization of critical reactive maintenance problems and scenarios and opportunities for BIM and IoT implementation;
ii. analysis and classification of BIM and IoT solutions recently applied to Facilities Management and reactive maintenance services according to the related benefits, gains, enablers and barriers; and
iii. the characterization of strategies and decisions involved in the planning, development, implementation, testing, and assessment of a BIM and IoT-based smart maintenance system and its impacts on the maintenance services and potential contributions to the design phase.

The focus was on the procedural issues involved in the application of BIM and IoT solutions to critical services. Such a phenomenon was investigated in the complex, dynamic, and innovative context of university campuses.

The research methodology developed was based on a pragmatic philosophy within the convergent parallel mixed method design. Due to the specificity of the research aim, Multiple Case Study and Prototyping were adopted as research strategies and supported by a set of methods for data generation (i.e., Documental Analysis, Semi-structured Interviews, Focus Group, and Prototype development) and analysis (i.e., Qualitative, Content, and Statistical). The adoption of multiple cases and the triangulation of theoretical and empirical sources of evidence increased the validity and significance of the findings. At the first stage, the empirical evidence generated by the Multiple Case Study characterized the problem to be addressed. A Systematic Literature Review (SLR) established a context of BIM and IoT for FM and reactive maintenance service, thus providing theoretical evidence for problem solution. Finally, such evidence supported the development of the prototyping process, showing the strategies, decisions, and outcomes involved in the problem-solving.

Both research process and methodology contributed to the body of knowledge, and the achievement of the aim and objectives raised the main contributions of the study. Regarding the characterization of critical reactive maintenance problems and scenarios and opportunities for BIM and IoT implementation (Objective i.), this thesis has clarified the circumstances in which maintenance services and FM sectors can benefit from the ICT solutions. From the Multiple Case Study, the research showed institutional aspects influence both features and scale of FM and, accordingly, the adopted performance metrics and strategies for service attendance. Considering the role of effective information management for informed FM decision-making, the thesis proposed a Conceptual framework of the traditional reactive maintenance process (Figure 15) mapping its main stages and activities and identified its bottlenecks (e.g., dependence on human communication and inefficient protocols and tools for information management), which can be overcome through BIM and IoT implementation. As discussed in Chapter 5, the framework assisted the assessment of the prototype performance and can contribute to similar investigations.

Besides, a deep understanding of technological, procedural, and policy issues involved in the implementation of BIM and IoT-based solutions in FM activities was provided by the Multiple Case Study and supported by the literature. Interoperability, flexibility, and user friendliness were requirements highlighted for making BIM and IoT software, systems, and devices suitable for FM purposes. Upskilling actions, strengthening of the relationship among FM team members, IT developers, and providers, and establishment of a clear strategy of implementation adherent to the university business goals were reinforced. The development of standards and guidelines concerned with FM services' needs also emerged as an important step for a better service provision within a digital environment.

Moreover, the investigation identified critical scenarios for reactive maintenance problems, considering characteristics of problems, buildings, and services. This is the first study that applied statistical analysis to a data sample of approximately 300.000 Work Requests. Patterns of problems (i.e., predominant site, service categories, priority levels, room types, among others), as well as building characteristics of significant influence on reactive maintenance problem occurrence and time response (i.e., size, area, age, function, etc.) raised from the comparative analysis between cases. The results were partially corroborated by the literature, evidencing both novelty of the findings and necessity of complementary investigations for validating the overall results. In this sense, the study demonstrated the availability of a large number of variables influencing reactive maintenance problems in the built environment adds complexity to the identification of root causes, which might be mitigated with reliable and accessible performance information provided by BIM and IoT-based systems.

Regarding the analysis and classification of BIM and IoT solutions recently applied to FM and reactive maintenance services (Objective ii.) conducted through the Systematic Literature Review (SLR), the thesis contribution is the Conceptual framework establishing a context of BIM and IoT for FM and reactive maintenance service and the identification of gaps and trends in the research field. Based on the four key aspects of the framework (i.e., Research approach, FM and Reactive Maintenance areas and activities, BIM and IoT solutions and devices, and Outputs of BIM and IoT implementation), the investigation has demonstrated the embryonic stage of studies on the topic and the necessity of holistic approaches for implementation supported by empirical evidence; the necessity of clarity regarding critical services and activities and impacts of BIM and IoT on FM performance; the necessity of an interoperable and robust range of technologies for the combined implementation of BIM and IoT solutions in FM activities; and the role of monitoring and management of building performance through BIM and IoT as an input for improvements in both Operation and Maintenance (O&M) and the initial design process stages. Such findings were addressed through the development of the Multiple Case Study and Prototyping development process, thus contributing towards the mitigation of the lacuna identified in knowledge.

Finally, regarding the characterization of strategies and decisions involved in the development process of a BIM and IoT-based smart maintenance system and its impacts on the maintenance services and potential contributions to the design phase (Objective iii.), the contributions of this thesis to knowledge are both methodological and conceptual, providing guidelines and insights on smart maintenance field. Primarily, a Theoretical Framework of the prototype was proposed (Figure 91) for the conceptualization of the system capabilities. Based on the prototyping research method, the development process created in this study involved activities of planning, development, implementation and testing, and assessment of the testing results supported by university maintenance experts, AEC and IT professionals. A set of protocols and theoretical models (i.e., technical and functional requirements of the prototype system, FM BIM model data structure, hardware and software test protocols, categories for the assessment of results, architecture of the prototype, approach for the integration of BIM, IoT, and FM tools, and logic analysis of real-time data) supported the prototyping process and can contribute to future research in the field.

From such an interdisciplinary and practical experience, the investigation has demonstrated the necessity of identifying a range of technical, functional, and FM BIM information requirements with the involved parts for an effective smart system implementation, facilitating communication among stakeholders and decision-making; the importance of interoperability and scalability for the development of both physical and analytical dimensions of the system, ensuring free access to data, flexible and gradual integration among components, and consistency of data transmission; and the necessity of advances in tools and methods for measuring, assessing, and analysing building components performance, extracting useful information for decision-making from raw data. In this sense, the study has evidenced the effectiveness of BIM and IoT implementation in FM activities depends not only on technological abilities of software and devices, but also on a clear definition of procedures and standards that guide steps and decisions in both organizational and industrial levels.

Moreover, the thesis has provided insights on the impacts of the smart maintenance system on maintenance management and its potential contributions to the design phase. A comparison between reactive and predictive maintenance processes revealed the automatization of functions and centralization of information enabled by a BIM and IoT-based system can optimize service provision, generating environmental and efficiency gains and improving safety and satisfaction of university users and maintenance staff. The thesis highlighted the importance of feeding back relevant performance information for owners and designers that make decisions, thus supporting adjustments in design criteria and technical solutions towards more functional and sustainable assets. Lastly, for both stages of the building design process, the investigation evidenced the necessity of investments in human and organizational resources through the engagement and upskilling of IT, FM, and design teams and development of protocols and standards for maintaining and operating the smart system and a reliable source of assets' BIM information.

Contributions to knowledge have emerged from the research methodology. In the context of FM, this is the first study that applied Qualitative, Content, and Statistical techniques for analysing evidence generated by Systematic Literature Review (SLR), Interviews, Documental Analysis, and Prototyping Development Process. The integration of such techniques enabled the exploration of evidence from both qualitative and quantitative perspectives, deeply understanding some aspects of the investigated phenomenon. For instance, the interviewees' perception on the occurrence and time response of reactive maintenance problems was partially corroborated by the inferences from the statistical analysis of Work Requests, thus raising alternative explanations for the phenomena (i.e., the size of the building might exert lower influence on problem occurrence than the function of the building). Another example is related to challenges involved in the implementation of BIM and IoT in FM activities identified in the SLR and interviews and corroborated by evidence of the prototyping process. Besides the selection and application of methods for data generation and analysis, the sequence of steps and activities in the proposed research framework (Figure 5) established a rationale for characterizing a problem, identifying potential solutions, and demonstrating problem solution. Comprised of the set of protocols and theoretical models developed over the process, the methodology can significantly contribute to future investigations.

6.1. Relevance to Research, Teaching and Practice

The findings of this thesis have enhanced the understanding of complex issues involved in the implementation of BIM and IoT solutions in the building design process with emphasis on maintenance services. The study has provided a holistic approach of the topic through the characterization of the problem, identification of potential solutions, and demonstration of problem solving, covering procedural aspects usually neglected in the literature. It has also integrated distinct knowledge fields (i.e., Architecture, Facilities Management, Computer Science) into an interdisciplinary project, converging perspectives commonly fragmented in both academia and industry. Developed in the context of Brazilian and British universities, both supported by governmental funding, the investigation addressed an agenda for an innovative, sustainable, and efficient management of buildings, mitigating the environmental impacts of AEC industry and its contributions to climate change.

The relevance of the findings encompasses research, teaching, and practice. The theoretical and empirical evidence on the process of BIM and IoT implementation in maintenance services as well as the protocols and models generated have opened up opportunities for future research. The findings from the Systematic Literature Review (SLR), Multiple Case Study, and Prototyping development addressed lacunas in the literature, enhancing the scarce knowledge on BIM, IoT, Digital Twin, FM, and maintenance combined areas. The protocols and models proposed for achieving the research objectives have also contributed to knowledge, pointing out methodological directions. Although focused on the management of building lighting systems, the principles applied to the prototype development are scalable to other systems of buildings and cities. Since digital transformation in the AEC industry is still an evolving field of investigation, such advancements can support researchers and policy makers in the development of instruments, guidelines, and standards towards Smart Maintenance and Smart Cities.

Besides, the broad approach of this research involving from the design to the Operation and Management of buildings has contributed to the teaching of Architecture and Urbanism, thus covering a subject commonly neglected in traditional design courses. The findings provide a perspective on the creation and management of buildings for real, sustainable, and complex contexts, considering the requirements and value of information supported by innovative ICT's, such as BIM and IoT, for decision-making across the building lifecycle. Furthermore, they demonstrate the expanded role of architects and engineers within the building design process, concerned not only with the quality of solutions and components in the conception of the built environment but also with its performance over time.

The application of the findings to practice is also relevant for the understanding of technological, procedural, and policy aspects involved in the implementation of BIM and IoT in the AEC industry. In the organizational level, the knowledge of the most likely scenario for the occurrence of reactive maintenance problems points out areas to be potentially improved through BIM and IoT within a predictive approach. Moreover, the understanding of requirements, challenges, and expected benefits of the implementation of smart systems provides a more realistic picture of the necessary steps and resources. For owners and FM staff, such inputs are important for justifying financial and human investments (i.e., computational components, upskilling, and development of procedures) and planning the digital transformation of services for a smarter provision. For designers, they represent an opportunity for improving design criteria and solutions in accordance with critical scenarios and the quality of BIM models for the operation and maintenance of buildings. The research findings can contribute to straightening the relation between O&M and design stages, improving decision-making over the lifecycle of a project and driving organizations towards BIM5.0.

6.2. Limitations of the Research

Some limitations were identified in this research. The first is related to the consistency of Work Request data provided by the Multiple Case Study. Although data on costs of FM and reactive maintenance services were requested to all universities' FM sectors, only the Brazilian public university provided them. As a result, both the analysis of critical reactive maintenance problems according to service costs and the measurement of potential impacts of the BIM and IoT-based system on the cost of maintenance services were limited. Similarly, only one organization, namely UK University 1 provided data on the prioritization of services, restricting the analysis of critical reactive maintenance problems based on such an essential criterion. The distinct methods adopted by each university for organizing and feeding Work Request data into Excel spreadsheets also limited the research. During the standardization and summarization of UK university data into a single spreadsheet, a significant heterogeneity of data within and between organizations was observed. As a result, the useful sample of Work Requests and the statistical data analysis techniques were reduced. In this sense, further investigations are necessary to confirm the validity of the findings.

The second limitation refers to the degree of generalization of findings from the Multiple Case Study and Protype development process. Addressing the criteria for universities selection (Table 1), the tree cases represented the context intended for this investigation. However, some findings (i.e., influence of room function on reactive maintenance time response) were not supported by the literature, thus requiring further investigations for their validation (for instance, through additional case studies, surveys with other organizations, and focus groups with experts).

Regarding prototyping, the development of the BIM and IoT-based smart lighting maintenance system was driven to a critical service identified in the case studies and supported by theoretical evidence from the literature, questionnaires, and interviews with experts. Nevertheless, the lack of consistent tools, methods, and devices for measuring building components performance and restrictions in research resources (i.e., number of variables analysed) has limited the procedures for testing and assessing the performance of the prototype and the methods for the validation of findings. In this sense, future studies involving external validation by experts are necessary for the confirmation of conclusions.

6.3. Recommendations for Further Research

Further studies are recommended in the following areas for advancements in the findings of this thesis:

- **FM and maintenance service provision**

- development of methods and tools for service priority level classification (e.g., Classification Matrix of Luminaire Priority Level);
- development of models for the prediction of maintenance costs, maintenance problem occurrence, and lighting system performance through the application of artificial intelligence and machine learning algorithms;
- investigation of the impact of environmental and behavioural variables (e.g., building constructive technology, number of users per room, length of stay) on the maintenance problem occurrence, time response, and costs;
- exploration of other methods for the analysis of Work Requests data, such as text mining analysis, aiming at the extraction of meaningful patterns and information on critical maintenance problems.

- **Implementation of BIM and IoT in FM sector**

- development of tools, methods, guidelines, and standards to support the implementation of BIM and IoT-based systems in FM sectors;
- measurement of the impact of BIM and IoT on time and costs of maintenance services through experiments and simulations.

- **Smart lighting maintenance system prototype**

- application of the prototype as a diagnostic tool for the identification of users' behaviour in specific rooms and over a given timeframe. The results can indicate patterns of use and risky scenarios, supporting the FM sector in space management and predictive maintenance and designers in improving design criteria and solutions;
- implementation of the prototype in real environments, including spaces with distinct characteristics (e.g., function, size, number of users, etc.) and exploration of other computational components (e.g., BIM software, CAFM system, sensors, AI, etc.), exchange formats (i.e., IFC, COBie), and mechanisms for the integration of BIM, IoT, and FM tools (e.g., semantic web technologies), and capabilities (e.g., provision of analytical reports), towards higher effectiveness;
- implementation of the prototype in other building systems (e.g., HVAC) for assessments of its scalability.

- **Relation between Design and O&M stages**

- investigation of the collaboration between FM and design teams, focusing on the exchange of technical and BIM information requirements, and development of a reliable source of information over design process;
- development of FM BIM data standards to support the exchange of information among devices and systems.

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APPENDICES

APPENDIX A – SEMI-STRUCTURED INTERVIEW QUESTIONNAIRE – TYPE I [44]

Department of Architecture and Civil Engineering

UNIVERSITY OF BATH

Semi-structured Interview Questionnaire

Organisation name:
Date:

This questionnaire is part of a PhD Research of the Department of Architecture and Civil Engineering of the University of Bath. It aims to characterize the Facilities Management services, particularly the reactive maintenance, carried out by your organisation focusing on the impacts that Building Information Modelling (BIM) and Internet of Things (IoT) solutions can have on the efficacy and efficiency of the FM processes. This information will be used to expand the knowledge about the application of Information Technologies (IT) to FM activities as well as to develop guidelines to the improvement of the reactive maintenance processes.

Section I – Profile Information

1) What is you gender?
   - ☐ Male ☐ Female
   - ☐ Gender Diverse (gender non-conforming and/or transgender)
2) What is your age?
   - ☐ 20-25 years ☐ 26-30 years ☐ 31-35 years ☐ 36-40 years
   - ☐ 41-45 years ☐ 46-50 years ☐ 51-55 years ☐ >56 years
3) What is your professional background?
   - ☐ Architecture ☐ Civil Engineering ☐ Electrical Engineering ☐ Mechanical Engineering
   - ☐ Other:
4) What is your current job position?
   - ☐ Facilities Manager ☐ BIM Manager ☐ Project Manager ☐ Engineer
   - ☐ Other:
5) How long have you been working at this position in this organisation?
   - ☐ <6 months ☐ 6 months to 1 year ☐ 1 year to 2,5 ☐ 2,5 to 5 years
   - ☐ 5 to 10 years ☐ 10 to 15 years ☐ >15 years

Section II - Characterization of data asset information for Facilities Management (FM) activities

Regarding the building data utilised in FM activities in your organisation

1) Which types of building data are available? (e.g. site prospections, design drawings, construction reports, maintenance records, etc.)

[44] Note: the transcriptions of the interviews were not attached to this document due to ethical issues. The material is archived with this author and can be accessed for academic purposes.

2) In which formats and extensions are the data stored? Are they fully digitised or are they still analog? (e.g. analogic – manual drawings, books, printed documents; digital – 2D drawings, 3D models)

3) Where are the data stored? (e.g. physical repositories, such as a deposit room; digital repositories as a cloud or a server, web-based Space Management System, etc.)

4) What are the systems and software supporting the FM activities? (e.g. Archibus, Rapid Access, Online helpdesk service, Building Management System (BMS), etc.)

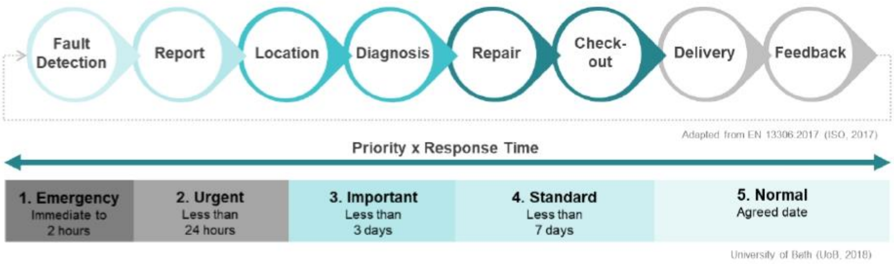
5) Who is responsible for managing data asset, including storing, updating, sharing, replacing and deleting it? Is there rework in feeding the database?

6) Who may have access to the asset database: only member of the FM sector, all member of staff, suppliers, students, external community, others? Which of them does have the permission for editing data?

7) In your opinion, what are the main difficulties for managing asset information in your organisation?

Section III – Flow of information in reactive maintenance services

Given the generic process of reactive maintenance service presented in the Figure 1:



8) How much integrated is the flow of information in the general process?

9) Which are the inputs and outputs of each stage of the process?

10) Who is responsible for entering and extracting information from each stage of the process?

11) How do users and members of staff report a fault or issue? (e.g. personally, phone call, e-mail, online helpdesk service, etc.)

12) What are the systems and software used to support the reactive maintenance process from fault detection to closure? (e.g. Archibus; Online helpdesk service, etc.)

13) In your opinion, does the efficiency of managing asset information impact the reactive maintenance service provision? Why? How?

Section IV - BIM implementation

Recently, the Department of Estates started to hire projects of buildings to be delivered in Building Information Modelling (BIM), including 3D models integrated to several documents, as example the 4 East South Building (Department of Architecture and Civil Engineering) and the School of Management. Given the specificities of BIM files, such as high size, need of integration with other documents, etc.,

14) What are the technical requirements for managing BIM models? Which software, systems and platforms had to be implemented to manage them?

15) Could you list the 3 main barriers and the 3 main enablers of BIM implementation in FM services?

Section V - IoT solutions

16) Within your organisation, is there any IoT system linked to FM and reactive maintenance in particular? For which purposes? Could you give examples of the 3 most important ones?
(e.g. barcodes, RFID, sensors, etc.)

17) In your opinion, what would be the potential impacts of the integration between BIM and IoT on the efficiency and efficacy of FM processes, in particular in reactive maintenance services?

18) Could you list the 3 main benefits and the 3 main difficulties of the BIM and IoT integration in FM and reactive maintenance in particular?

APPENDIX B - SEMI-STRUCTURED INTERVIEW QUESTIONNAIRE – TYPE II

Department of Architecture and Civil Engineering

UNIVERSITY OF BATH

Semi-structured Interview Questionnaire

Organisation name:
Date:

This questionnaire is part of a PhD Research of the Department of Architecture and Civil Engineering of the University of Bath. It aims to characterize the Facilities Management services, particularly the reactive maintenance, carried out by your organisation focusing on the impacts that Building Information Modelling (BIM) and Internet of Things (IoT) solutions can have on the efficacy and efficiency of the FM processes. This information will be used to expand the knowledge about the application of Information Technologies (IT) to FM activities as well as to develop guidelines to the improvement of the reactive maintenance processes.

Section I – Profile Information

1) What is you gender?
   - ☐ Male ☐ Female
   - ☐ Gender Diverse (gender non-conforming and/or transgender)
2) What is your age?
   - ☐ 20-25 years ☐ 26-30 years ☐ 31-35 years ☐ 36-40 years
   - ☐ 41-45 years ☐ 46-50 years ☐ 51-55 years ☐ >56 years
3) What is your professional background?
   - ☐ Architecture ☐ Civil Engineering ☐ Electrical Engineering ☐ Mechanical Engineering
   - ☐ Other:
4) What is your current job position?
   - ☐ Facilities Manager ☐ BIM Manager ☐ Project Manager ☐ Engineer
   - ☐ Other:
5) How long have you been working at this position in this organisation?
   - ☐ <6 months ☐ 6 months to 1 year ☐ 1 year to 2,5 ☐ 2,5 to 5 years
   - ☐ 5 to 10 years ☐ 10 to 15 years ☐ >15 years

Section II - Characterization of FM sector and services

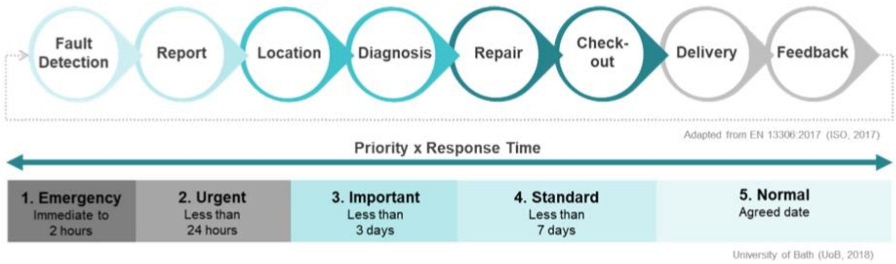
1) Which is the scope of the Department of Estates? (e.g. maintenance, operation, health and safety, etc.)

2) How is the Department of Estates structured? How is the hierarchy among its areas? (e.g. sub-departments, sectors, etc.)

11) How do the users and members of staff report a fault or issue? (e.g. personally, phone call, e-mail, online helpdesk service, etc.)

12) Is there a formal process map for reactive maintenance services?

13) In case of inexistence of a formal process map, does the generic one presented in the Figure 1 represent the real process of reactive maintenance carried out by the Department of Estates? Which aspects should be included or excluded?



Section IV - BIM implementation

14) What BIM solutions have recently been applied to reactive maintenance services? For which purposes?

15) In your opinion, has there been any impact of BIM implementation on the reactive maintenance services?

16) Do you measure the efficacy and efficiency of BIM on the reactive maintenance services? What does the measure indicate - gain or loss? By how much?

17) In your opinion, are there non-adding value activities in the process that could not have been removed even after BIM implementation? Could you give the main 3 examples?

18) What were the most benefits achieved with BIM implementation in the context of reactive maintenance?

19) Could you list the 3 main barriers and the 3 main enablers of BIM implementation in FM services?

20) What is the annual cost of implementing and using BIM for FM purposes? In your opinion, in terms of cost-benefit, why has it been worth to adopt BIM?

21) What was the business case that triggered the implementation of BIM for FM, in particular for reactive maintenance?

Section V - IoT solutions

22) Within your organisation, is there any IoT system linked to FM and reactive maintenance in particular? For which purposes? Could you give examples of the 3 most important ones? (e.g. barcodes, RFID, sensors, etc.)

23) In your opinion, what would be the potential impacts of the integration between BIM and IoT on the efficiency and efficacy of FM processes, in particular in reactive maintenance services?

24) What was the business case that triggered the implementation of BIM and IoT solutions for FM, in particular for reactive maintenance?

25) What is the annual cost of implementing and using IoT for FM purposes? In your opinion, in terms of cost-benefit, why has it been worth to adopt IoT solutions?

26) Could you list the 3 main benefits and the 3 main difficulties of the BIM and IoT integration in FM and reactive maintenance in particular?

APPENDIX C - SEMI-STRUCTURED INTERVIEW QUESTIONNAIRE – TYPE III

Department of Architecture and Civil Engineering

UNIVERSITY OF BATH

Semi-structured Interview Questionnaire

Organisation name:
Date:

This questionnaire is part of a PhD Research of the Department of Architecture and Civil Engineering of the University of Bath. It aims to characterize the Facilities Management services, particularly the reactive maintenance, carried out by your organisation focusing on the impacts that Building Information Modelling (BIM) and Internet of Things (IoT) solutions can have on the efficacy and efficiency of the FM processes. This information will be used to expand the knowledge about the application of Information Technologies (IT) to FM activities as well as to develop guidelines to the improvement of the reactive maintenance processes.

Section I – Profile Information

1) Gender
   - ☐ Male ☐ Female

2) Age
   - ☐ 20-25 years ☐ 26-30 years ☐ 31-35 years ☐ 36-40 years
   - ☐ 41-45 years ☐ 46-50 years ☐ 51-55 years ☐ >56 years

3) Professional Background
   - ☐ Architecture ☐ Civil Engineering ☐ Electrical Engineering ☐ Mechanical Engineering
   - ☐ Other:

4) Job Position
   - ☐ Facilities Manager ☐ BIM Manager ☐ Project Manager ☐ Engineer
   - ☐ Other:

5) How long have you been working at this position in this organisation?
   - ☐ <6 months ☐ 6 months to 1 year ☐ 1 year to 2,5 ☐ 2,5 to 5 years
   - ☐ 5 to 10 years ☐ 10 to 15 years ☐ >15 years

Section II - Characterization of FM sector and services

6) How the Department of Estates is structured? How is the hierarchy among its areas?
   (e.g. sub-departments, sectors, etc.)

7) Which is the scope of the Department of Estates?
   (e.g. maintenance, operation, health and safety, etc.)

8) What is the number and qualification of the FM Team professionals?

9) Roughly, what is the number and qualification of the FM professionals involved in reactive maintenance?

10) What are the systems and software used to support the reactive maintenance process from fault detection to closure?
(e.g. Archibus; Online helpdesk service, etc.)

11) How do the users and members of staff report a fault or issue?
(e.g. personally, phone call, e-mail, online helpdesk service, etc.)

12) Currently, which steps are part of the reactive maintenance process from fault detection to closure?
(e.g. fault report, diagnosis, repair, etc.)

13) What is the annual budget of the Department of Estates for FM services? Roughly, what percentage of the overall budget is used in reactive maintenance services?

14) In your opinion, which are the reactive maintenance problems that are most expensive to be fixed? List the 3 main problems.

15) In your opinion, which are the 3 most recurrent problems in reactive maintenance?

16) In your opinion, which are the 3 most disruptive problems in reactive maintenance? What kind of disruption do they cause?

Section III - BIM implementation

17) What BIM solutions have recently been applied to reactive maintenance services? For which purposes?

18) In your opinion, has there been any impact of BIM implementation on the reactive maintenance services?

19) Do you measure the efficacy and efficiency of BIM on the reactive maintenance services? What does the measure indicate - gain or loss? By how much?

20) In your opinion, are there non-adding value activities in the process that could not have been removed even after BIM implementation? Could you give the main 3 examples?

21) What were the most benefits achieved with BIM implementation in the context of reactive maintenance?

22) Could you list the 3 main barriers and the 3 main enablers of BIM implementation in FM services?

23) What is the annual cost of implementing and using BIM for FM purposes? In your opinion, in terms of cost-benefit, why has it been worth to adopt BIM?

24) What was the business case that triggered the implementation of BIM for FM, in particular for reactive maintenance?

Section IV - IoT solutions

25) Within your organisation, is there any IoT system linked to FM and reactive maintenance in particular? For which purposes? Could you give examples of the 3 most important ones? (e.g. barcodes, RFID, sensors, etc.)

26) In your opinion, what would be the potential impacts of the integration between BIM and IoT on the efficiency and efficacy of FM processes, in particular in reactive maintenance services?

27) What was the business case that triggered the implementation of BIM and IoT solutions for FM, in particular for reactive maintenance?

28) What is the annual cost of implementing and using IoT for FM purposes? In your opinion, in terms of cost-benefit, why has it been worth to adopt IoT solutions?

29) Could you list the 3 main benefits and the 3 main difficulties of the BIM and IoT integration in FM and reactive maintenance in particular?

APPENDIX D – CONSENT FORM – TYPE I

UNIVERSITY OF BATH

Department of Architecture & Civil Engineering University of Bath Claverton Down
Bath BA2 7AY
T: 01225 388388

Consent Form

Researcher: Beatriz Campos Fialho, PhD Visiting Student
(e: bcf26@bath.ac.uk beatriz.fialho@usp.br)
Supervisor: Dr Ricardo Codinhoto, Senior Lecturer, University of Bath
(e: r.codinhoto@bath.ac.uk)

Research topic: Reactive Maintenance Services
How BIM and IoT solutions can support a more efficient reactive maintenance service

Participant Information

This study is for a PhD Research which investigates the impacts of Building Information Modelling (BIM) and Internet of Things (IoT) solutions on a more efficient reactive maintenance service. The research will include a semi-structured interview (questionnaire) and organizational data collection. The aim of the questionnaire and the organizational data is to characterize the Facilities Management services, particularly the reactive maintenance, carried out by the interviewee's organisation focusing on the impacts that BIM and IoT solutions can have on the efficacy and efficiency of the FM processes. This information will be used to expand the knowledge about the application of Information Technologies (IT) to FM activities as well as to develop guidelines to the improvement of reactive maintenance processes.

Please do not hesitate to contact me for more information about the study or what the information will be used for.

I have read and understood the Participant Information and I agree to participate in this research based on the following conditions:

Yes	*No*	*Please tick the appropriate boxes*
		I agree to take part in the project
		I understand that my taking part is voluntary; I can withdraw from the project at any time and I do not have to give any reasons for why I no longer want to take part
		I agree that any data obtained during the course of this project may be utilised in any manner appropriate to this research
		I accept that the information I provide will be stored in a safe and appropriate manner and not accessible by a third-party
		I agree that a picture of me can be taken providing I cannot be identified in it
		I consent to recordings audio of myself being included in the recordings made
		I understand that the researcher will not identify me by name in any reports using information obtained from the questionnaire and organizational data, and that

		my confidentiality as a participant in this project will remain secure
		I understand and agree that my words may be quoted anonymously in presentations of the study findings e.g. in presentations or reports
		I understand that for any information regarding the research project, I can contact Dr Ricardo Codinhoto of Department of Architecture & Civil Engineering of the University of Bath
		I have read and understood the information provided to me. I have had all my questions answered satisfactorily, and I willingly t to take part in this research

I, (initials only)_____________________________________agree to participate in the questionnaire and to provide organizational data for the PhDArch thesis titled: *Towards Smart Universities' Estates: an investigation of BIM and IoT supporting reactive maintenance services* being carried out by PhDArch visiting student – Beatriz Campos Fialho of the Department of Architecture & Civil Engineering at the University of Bath.

___________________________ ___________
Researcher Date

_________________________ _________________________ ___________
Respondent's initials Signature Date

APPENDIX E – FOCUS GROUP QUESTIONNAIRE AND CONSENT FORM

Focus Group – "BR University" – Grupo de Facilities Management

Protocolo

Essa pesquisa refere-se ao uso de BIM na gestão de Facilities em Universidades. Haverá uma apresentação de 20 minutos para explicar o conceito de BIM. Seguida a apresentação, a doutoranda irá conduzir uma discussão sobre o assunto sobre o ponto de vista da equipe de Facilities da "BR University". Serão 5 perguntas a serem respondidas. Essa discussão será gravada para fins da pesquisa. Os resultados serão colocados num relatório e encaminhados aos participantes para informação, confirmação e validação das respostas.

Consentimento:

- Eu concordo em participar do focus group;
- Eu entendo que minha participação é voluntária; Posso me retirar da pesquisa a qualquer momento e não preciso apresentar motivos pelos quais não quero mais participar;
- Concordo que quaisquer dados obtidos durante o curso deste projeto possam ser utilizados de qualquer maneira apropriada para esta pesquisa;
- Aceito que as informações fornecidas sejam armazenadas de maneira segura e apropriada e não acessíveis por terceiros;
- Concordo que uma foto minha possa ser tirada, desde que não possa ser identificada nela;
- Entendo que o pesquisador não me identificará pelo nome em nenhum relatório usando as informações obtidas no focus group, e que minha confidencialidade como participante deste projeto permanecerá segura;
- Entendo e concordo que minhas palavras possam ser citadas anonimamente nas apresentações dos resultados do estudo, em publicações, relatórios, páginas da web, materiais didáticos, conferências
- Entendo que, para qualquer informação sobre o projeto de pesquisa, posso entrar em contato com a Doutoranda Beatriz Campos Fialho e com o Dr Marcio Minto Fabricio do Instituto de Arquitetura e Urbanismo da USP São Carlos ou com o Dr. Ricardo Codinhoto, do departamento de Arquitetura e Engenharia Civil da Universidade de Bath.
- Eu li e entendi as informações que me foram fornecidas. Todas as minhas perguntas foram respondidas de forma satisfatória e desejo participar dessa pesquisa.

Nome:
Cargo / Função:
Anos exercendo o cargo/função:
Profissão:
E-mail:

Questões:

1. Independentemente das possíveis dificuldades ou barreiras de implementação, quais vantagens vocês veem na adoção do BIM para o FM?
2. Dos problemas do dia a dia da gestão da manutenção do campus, liste os três problemas que na opinião de vocês se beneficiariam mais com a adoção do BIM.
3. Se "recursos" não fossem um impedimento, e vocês quisessem adotar o BIM, por onde começariam?
4. Em ordem de importância, qual documentação das disciplinas de projeto é mais utilizada para a gestão do campus?
5. Na opinião de vocês, quais são os três problemas de gestão mais críticos do campus em relação a custos, mão de obra, risco (segurança dos alunos e funcionários) e interferência nas atividades do campus?

APPENDIX F – SEMI-STRUCTURED INTERVIEW – TYPE IV

Roteiro para entrevista com profissionais de FM da "BR University"

Pesquisadora Responsável: Beatriz Campos Fialho (beatriz.fialho@usp.br; Mestre em Arquitetura e Urbanismo, Doutoranda do Instituto de Arquitetura e Urbanismo da Universidade de São Paulo – IAU/USP)

Orientador: Prof. Dr. Assoc. Márcio Minto Fabricio (marcio@sc.usp.br; IAU/USP)

Co-orientador: Prof. Dr. Ricardo Codinhoto (rc784@bath.ac.uk; University of Bath)

Instituição Sede: Instituto de Arquitetura e Urbanismo - USP (Grupo de Pesquisa Arquitec). End.: Avenida Trabalhador São-Carlense, 400 – Centro, São Carlos – SP. Tel.: (16) 3373 9279

Roteiro:

Pesquisadora esclarece o objetivo da tese e explica o Termo de Consetimento Livre Esclarecido, assinado pelo entrevistado. Em seguida, inicia as perguntas sobre os seguintes tópicos:

1. Caracterização do sistema de gestão de manutenção: identificação e funcionalidades do sistema adotado; usuários e níveis de acesso; codificação de edifícios, infraestrutura urbana, setores e serviços; alocação e acompanhamento das Solicitações e Ordens de Serviço no sistema; interface com os sistemas de segurança patrimonial e pessoal do campus e sistema financeiro do setor de FM;
2. Processos de manutenção reativa: canais de recebimento de Solicitações de Serviço; procedimentos para alocação e supervisão dos serviços entre os setores técnicos; procedimentos para execução e registro dos serviços; canais de comunicação entre membros da equipe de FM;
3. Setor e serviços de FM: suporte da equipe de TI na gestão do sistema; centros de custo para pagamento dos serviços de manutenção;
4. Fornecimento de dados sobre Solicitações de Serviços entre 12/2018 e 12/2019.

APPENDIX G - SEMI-STRUCTURED INTERVIEW – TYPE V

Roteiro para entrevista com profissionais de TI da "BR University"

Pesquisadora Responsável: Beatriz Campos Fialho (beatriz.fialho@usp.br; Mestre em Arquitetura e Urbanismo, Doutoranda do Instituto de Arquitetura e Urbanismo da Universidade de São Paulo – IAU/USP)

Orientador: Prof. Dr. Assoc. Márcio Minto Fabricio (marcio@sc.usp.br; IAU/USP)

Co-orientador: Prof. Dr. Ricardo Codinhoto (rc784@bath.ac.uk; University of Bath)

Instituição Sede: Instituto de Arquitetura e Urbanismo - USP (Grupo de Pesquisa Arquitec). End.: Avenida Trabalhador São-Carlense, 400 – Centro, São Carlos – SP. Tel.: (16) 3373 9279

Roteiro:

Pesquisadora esclarece o objetivo da tese e explica o Termo de Consetimento Livre Esclarecido, assinado pelo entrevistado. Em seguida, inicia as perguntas sobre os seguintes tópicos:

1. Procedimentos para armazenamento de dados dos edifícios e das Solicitações e Ordens de Serviços;
2. Formato e mecanismos para geração de informação pelo protótipo para integracao com o sistema de gestão de manutenção.

APPENDIX H – CONSENT FORM – TYPE II

Termo de Consentimento Livre e Esclarecido

(Participantes – Profissionais de FM da universidade)

Eu, ..., nacionalidade: ...., idade: ...., estado civil: ...., profissão: ...., endereço: .... RG: ...., fui convidado a participar de um estudo denominado **"Towards Smart Universities' Estates: an investigation of BIM and IoT supporting reactive maintenance services"**, cujo objetivo é o desenvolvimento de um método para medir os possíveis impactos de soluções BIM e IoT na eficiência dos serviços de manutenção reativa. Por meio do método proposto, a pesquisa visa fornecer dados teóricos e evidências empíricas dos impactos do BIM e da IoT na provisão de eficiência de serviço RM, apoiando as organizações a identificar em quais casos e para quais atividades valem a pena e devem ser implementadas.

A minha participação no referido estudo será através da **concessão de uma entrevista semiestruturada** à pesquisadora, onde poderei falar sobre a caracterização do setor de Facilities Management e dos serviços de manutenção reativa realizados, bem como sobre o uso de soluções BIM e IoT no atendimento aos referidos serviços. Fui informado de que a concessão da entrevista não oferece riscos conhecidos à minha saúde ou integridade física. O grau de risco envolvendo minha participação é mínimo, relacionado a um possível desconforto e cansaço ao responder aos questionários.

Fui informado que terei acesso à transcrição da entrevista e, caso queira, posso fazer eventuais correções antes que a mesma seja publicada na Tese da pesquisadora. Também me foi esclarecido que posso me recusar a participar do estudo ou retirar meu consentimento a qualquer momento, sem precisar justificar, e de que, por desejar sair da pesquisa, não sofrerei nenhuma consequência.

Fui esclarecido(a) de que os usos das informações por mim oferecidas estão submetidos às normas éticas destinadas à pesquisa envolvendo seres humanos da Comissão Nacional de Ética em Pesquisa (CONEP), segundo a Resolução nº 510 de 07 de abril de 2016 do Conselho Nacional de Saúde do Ministério da Saúde.

Rubrica do participante	Rubrica do Pesquisador

Tendo sido orientado quanto ao teor do presente estudo e compreendido a natureza e o objetivo do mesmo, manifesto meu livre consentimento em participar, estando totalmente ciente de que não haverá nenhum valor econômico, a receber ou a pagar, por minha participação, que terá a finalidade exclusiva de colaborar para o sucesso da pesquisa.

Atesto recebimento de uma via assinada deste Termo de Consentimento Livre e Esclarecido, conforme recomendações da Comissão Nacional de Ética em Pesquisa (CONEP).

( ) Concordo ou ( ) não concordo que a entrevista seja gravada, fotografada ou filmada. A pesquisadora responsável pela pesquisa é a Arq. Beatriz Campos Fialho, com supervisão do Prof. Assoc. Márcio Minto Fabricio, todos vinculados ao Instituto de Arquitetura e Urbanismo da USP, em São Carlos, e com eles poderei manter contato pelo telefone (16) 3373 9279 e do e-mail beatriz.fialho@usp.br.

Este projeto foi submetido ao Comitê de Ética em Pesquisa Envolvendo Seres Humanos da Escola de Artes, Ciências e Humanidades (EACH) da USP, disponível para contato em:

- Telefone: (11) 3091-1046
- E-mail CEP: cep-each@usp.br
- Prédio I1 | Sala T14. Rua Arlindo Bettio, 1000, Vila Guaraciaba, São Paulo/SP, CEP: 03828-000

São Carlos, _______ de __________________ de __________.

Assinatura:

____

Nome:

____

Participante da pesquisa

Assinatura:

____

Nome:

____

Pesquisador(es) responsável(responsáveis)

APPENDIX I - ONLINE QUESTIONNAIRE FOR THE ASSESSMENT OF THE CLASSIFICATION MATRIX OF LUMINAIRE PRIORITY LEVEL

Matriz de Classificação do Nível de Prioridade da Luminária

TERMO DE CONSENTIMENTO LIVRE E ESCLARECIDO

Você está sendo convidado a participar da pesquisa de Doutorado intitulada "Universidades inteligentes: contribuições e desafios de BIM e IoT para os serviços de manutenção reativa" (Towards Smart Universities' Estates: an investigation of BIM and IoT supporting reactive maintenance services), cujo objetivo é o desenvolvimento de um método para medir os possíveis impactos de soluções BIM e IoT na eficiência dos serviços de manutenção reativa. Por meio do método proposto, a pesquisa visa fornecer dados teóricos e evidências empíricas dos impactos do BIM e da IoT na provisão de eficiência de serviço RM, apoiando as organizações a identificar em quais casos e para quais atividades devem ser implementadas.

A participação no referido estudo será por meio de um questionário online, destinado a avaliar a eficácia da Matriz de Classificação do Nível de Prioridade da Luminária por profissionais da área, de modo a adequar suas características às demandas do setor.

Informamos que a participação não oferece riscos conhecidos à saúde ou integridade física dos participantes. O grau de risco envolvendo a participação é mínimo, relacionado a um possível desconforto e cansaço ao responder ao questionário. Informamos que o participante pode se recusar a participar do estudo, ou retirar seu consentimento a qualquer momento, sem precisar justificar, e de que, por desejar sair da pesquisa, não sofrerá nenhuma consequência. Esclarecemos que não haverá nenhum valor econômico a receber ou a pagar pela participação, que terá a finalidade exclusiva de colaborar para o sucesso da pesquisa.

Esclarecemos que os usos das informações oferecidas pelos participantes estão submetidos às normas éticas destinadas à pesquisa envolvendo seres humanos da Comissão Nacional de Ética em Pesquisa (CONEP), segundo a Resolução nº 510 de 07 de abril de 2016 do Conselho Nacional de Saúde do Ministério da Saúde. Informamos que a privacidade do participante será respeitada, ou seja, o nome ou qualquer outro dado ou elemento que possa, de qualquer forma, identificá-lo, serão mantidos em sigilo.

Caso aceite os termos acima, assinale a opção abaixo: “Li e estou de acordo em participar da pesquisa”.

Este projeto foi aprovado pelo Comitê de Ética em Pesquisa Envolvendo Seres Humanos da Escola de Artes, Ciências e Humanidades (EACH) da USP, disponível para contato em:
- Telefone: (11) 3091-1046
- E-mail CEP: cep-each@usp.br
- Prédio I1 | Sala T14. Rua Arlindo Bettio, 1000, Vila Guaraciaba, São Paulo/SP, CEP: 03828-000

A pesquisadora responsável pela pesquisa é a Arq. Beatriz Campos Fialho ao Instituto de Arquitetura e Urbanismo (IAU) da USP, em São Carlos, sob supervisão do Prof. Assoc. Márcio Minto Fabricio (IAU) e ao prof. Ricardo Condinhoto (University of Bath). Em caso de dúvidas, gentileza contatar a pesquisadora Beatriz Campos Fialho por telefone (19 997990597) ou e-mail (beatriz.fialho@usp.br).

Caso você queira uma cópia deste termo, clique no link:
https://1drv.ms/b/s!Aiz3pn7cOjFYhKVOZrq1yW_qd1FU4Q?e=fuUHho

*Obrigatório

1. Endereço de e-mail *

2. *

Marque todas que se aplicam.

- [ ] Li e estou de acordo em participar da pesquisa.

Escopo

A pesquisa investiga o impacto de soluções BIM e IoT (Modelagem da Informação da Construção e Internet das Coisas) na eficiência dos serviços de manutenção reativa em edifícios universitários, com enfoque no sistema de iluminação.

Um dos objetivos do estudo é desenvolver uma Matriz de Classificação do Nível de Prioridade da Luminária (NPL) para auxiliar as equipes de manutenção na identificação de luminárias críticas para as atividades universitárias e na priorização do atendimento, em caso de falhas.

Este formulário busca avaliar a eficácia da Matriz de Classificação do Nível de Prioridade da Luminária por profissionais da área, de modo a adequar suas características às demandas do setor.

Identificação

3. Nome *

4. Profissão *

Marque todas que se aplicam.

- [ ] Engenheiro(a) Eletricista
- [ ] Engenheiro(a) Civil
- [ ] Engenheiro(a) Mecânico(a)
- [ ] Administrador(a)
- [ ] Arquiteto(a)
- [ ] Técnico(a) em Eletrotécnica
- [ ] Técnico(a) em Edificações

Outro: [ ] ____________

5. Cargo / Função *

Marque todas que se aplicam.

- [ ] Coordenador(a)/Chefe
- [ ] Supervisor(a) Técnico
- [ ] Fiscal
- [ ] Projetista
- [ ] Porteiro
- [ ] Zelador

Outro: [ ] ____________________

6. Tempo de exercício do Cargo / Função *

Marque todas que se aplicam.

- [ ] Menos de 1 ano
- [ ] 1 ano a 2,5 anos
- [ ] 2,5 a 5 anos
- [ ] 5 a 10 anos
- [ ] 10 a 15 anos
- [ ] Mais de 15 anos

Outro: [ ] ____________________

Avaliação da Matriz

A Matriz de Classificação do Nível de Prioridade da Luminária (Figura 1) tem por objetivo auxiliar as equipes de manutenção na identificação de luminárias críticas para as atividades universitárias e na priorização do atendimento em caso de falhas.

Figura 1: Matriz de Classificação do Nível de Prioridade da Luminária

Classe	Variável	Grau de Importância (G.I.)				
		Muito Baixo	Baixo	Médio	Alto	Muito Alto
Ambiente	Tipologia	Esporte e Lazer	Apoio Comercial	Administrativo Residencial	Acadêmico Circulação	Pesquisa Saúde
Ambiente	Função	Piscina, Quadra de Tênis, Ginásio Depósito	Cozinha, Sanitários, Oficinas Café, Restaurante	Escritório, Sala de Reunião, Dormitório Estudantil	Biblioteca, Salas de Aula, Laboratórios de Ensino, Auditórios Corredores e Calçadas	Laboratório de Pesquisa Centro Médico, Berçário Escadas e Rampas
Sistema de iluminação	Finalidade	Iluminação Decorativa	Iluminação geral	Iluminação de trabalho	Iluminação Especial (Pesquisa, Atendimento médico)	Iluminação de Emergência e Iluminação Noturna
Ambiente	Turno predominante de uso	Manhã e Tarde	Manhã e Tarde	Integral	Noite	Noite
Ambiente	Número de usuários	Individual	Coletivo (2-10 pessoas)	Coletivo (11-50 pessoas)	Coletivo (51-100 pessoas)	Coletivo (>100 pessoas)
Sistema de iluminação	Número de luminárias	≥5	4	3	2	1

LEGENDA

Nível de Prioridade da Luminária (NPL)	NPL4	NPL3	NPL2	NPL1

Sem título

A Matriz de Classificação do Nível de Prioridade da Luminária (Figura 1) se baseia em classes e variáveis relacionadas ao Ambiente onde a luminária está instalada (tipologia, função, turno predominante de uso e número de usuários) e ao Sistema de iluminação (finalidade e número de luminárias), como detalhado abaixo:

AMBIENTE:
- Tipologia e Função:
  *Esporte e Lazer: Piscina, Quadra de Tênis, Ginásio
  *Apoio: Cozinha, Sanitários, Oficinas
  *Comercial: Café, Restaurante
  *Administrativo: Escritório, Sala de Reunião
  *Residencial: Dormitório Estudantil
  *Acadêmico: Biblioteca, Salas de Aula, Laboratórios de Ensino, Auditórios
  *Circulação: Corredores, Calçadas, Escadas e Rampas
  *Pesquisa: Laboratório de Pesquisa
  *Saúde: Centro Médico, Berçário
- Turno Predominante de uso: Manhã; Tarde; Noite; Integral.
- Número de Usuários: Individual; Coletivo (2-10 pessoas); Coletivo (11-50 pessoas); Coletivo (51-100 pessoas); Coletivo (>100 pessoas)

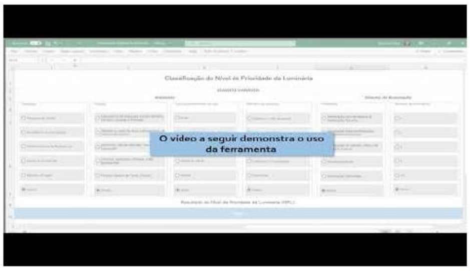
SISTEMA DE ILUMINAÇÃO
- Finalidade: Iluminação Decorativa; Iluminação geral; Iluminação de trabalho; Iluminação Especial (Pesquisa, Atendimento médico); Iluminação de Emergência e Iluminação Noturna
- Número de luminárias: 1, 2, 3, 4, >5

O Grau de Importância (G.I.) da luminária é então determinado para cada uma das variáveis: Muito Baixo, Baixo, Médio, Alto, Muito Alto.

A partir dessa classificação, foram definidos quatro Níveis de Priorização da Luminária (NPL) em ordem decrescente de prioridade:

- NPL1 (vermelho): demandas atendidas em até 2 horas;
- NPL2 (laranja): demandas atendidas em menos de 24 horas;
- NPL3 (amarelo) : demandas atendidas em até 3 dias;
- NPL4 (azul): demandas atendidas em data acordado com o usuário.

O vídeo a seguir demonstra o uso da Matriz de Classificação do Nível de Prioridade de Luminárias



http://youtube.com/watch?v=X5-Lr6Gcdoc

Com base na Figura 1 e no vídeo demonstrativo, responda as questões a seguir.

7. Na sua opinião, as variáveis relacionadas ao ambiente onde a luminária está instalada (tipologia, função, turno predominante de uso e número de usuários) são adequadas para a classificação do nível de prioridade da luminária? *

Marque todas que se aplicam.

- [ ] Sim
- [ ] Não

8. Na sua opinião, as variáveis relacionadas ao sistema de iluminação (finalidade e número de luminárias) são adequadas para a classificação do nível de prioridade da luminária? *

Marque todas que se aplicam.

- [ ] Sim
- [ ] Não

9. Você sugere a inclusão de alguma variável para a classificação do nível de prioriodade da luminária? Qual? *

____
____
____
____
____

10. Na sua opinião, o Grau de Importância (G.I.) atribuído às variáveis do ambiente e do sistema de iluminação é pertinente? *

Marque todas que se aplicam.

- [ ] Sim
- [ ] Não

11. Você sugere alguma alteração no Grau de Importância (G.I.) proposto? Qual? *

12. Na sua opinião, os Níveis de Priorização da Luminária (LPL) propostos são pertinentes? *

Marque todas que se aplicam.

- [ ] Sim
- [ ] Não

13. Você sugere alguma alteração nos Níveis de Priorização da Luminária (LPL)? Qual? *

14. Você acredita que a Matriz de Classificação do Nível de Prioridade de Luminárias proposta pode auxiliar as equipes de manutenção na identificação de luminárias críticas e na priorização do atendimento em caso de falhas? Por quê? *

15. Se desejar, faça comentários adicionais.

Obrigada pela contribuição!

APPENDIX J - ONLINE QUESTIONNAIRE FOR THE ASSESSMENT OF THE CONCEPTUAL FRAMEWORK OF BIM & IOT ASSISTED PREDICTIVE MAINTENANCE PROCESS

Protótipo de sistema BIM & IoT autônomo de monitoramento e gestão de luminárias para suporte aos serviços de manutenção

TERMO DE CONSENTIMENTO LIVRE E ESCLARECIDO

Você está sendo convidado a participar da pesquisa de Doutorado intitulada "Universidades inteligentes: contribuições e desafios de BIM e IoT para os serviços de manutenção reativa" (Towards Smart Universities' Estates: an investigation of BIM and IoT supporting reactive maintenance services), cujo objetivo é o desenvolvimento de um método para medir os possíveis impactos de soluções BIM e IoT na eficiência dos serviços de manutenção reativa. Por meio do método proposto, a pesquisa visa fornecer dados teóricos e evidências empíricas dos impactos do BIM e da IoT na provisão de eficiência de serviço RM, apoiando as organizações a identificar em quais casos e para quais atividades devem ser implementadas.

Este estudo é voltado para profissionais de Facilities Managements (FM). A participação será por meio de um questionário online, destinado a identificar requisitos funcionais e técnicos para o desenvolvimento de sistema BIM & IoT autônomo de monitoramento e gestão de luminárias para suporte aos serviços de manutenção. O sistema de iluminação foi selecionado como objeto de investigação em função da elevada demanda por manutenção identificada em Estudos de Caso realizados previamente nesta pesquisa junto a duas universidades inglesas e uma brasileira.

Informamos que a participação não oferece riscos conhecidos à saúde ou integridade física dos participantes. O grau de risco envolvendo a participação é mínimo, relacionado a um possível desconforto e cansaço ao responder ao questionário. Informamos que o participante pode se recusar a participar do estudo, ou retirar seu consentimento a qualquer momento, sem precisar justificar, e de que, por desejar sair da pesquisa, não sofrerá nenhuma consequência. Esclarecemos que não haverá nenhum valor econômico a receber ou a pagar pela participação, que terá a finalidade exclusiva de colaborar para o sucesso da pesquisa.

Esclarecemos que os usos das informações oferecidas pelos participantes estão submetidos às normas éticas destinadas à pesquisa envolvendo seres humanos da Comissão Nacional de Ética em Pesquisa (CONEP), segundo a Resolução nº 510 de 07 de abril de 2016 do Conselho Nacional de Saúde do Ministério da Saúde. Informamos que a privacidade do participante será respeitada, ou seja, o nome ou qualquer outro dado ou elemento que possa, de qualquer forma, identificá-lo, serão mantidos em sigilo.

Caso aceite os termos acima, assinale a opção abaixo: "Li e estou de acordo em participar da pesquisa".

Este projeto foi aprovado pelo Comitê de Ética em Pesquisa Envolvendo Seres Humanos da Escola de Artes, Ciências e Humanidades (EACH) da USP, disponível para contato em:
- Telefone: (11) 3091-1046
- E-mail CEP: cep-each@usp.br
- Prédio I1 | Sala T14. Rua Arlindo Bettio, 1000, Vila Guaraciaba, São Paulo/SP, CEP: 03828-000

A pesquisadora responsável pela pesquisa é a Arq. Beatriz Campos Fialho ao Instituto de Arquitetura e Urbanismo (IAU) da USP, em São Carlos, sob supervisão do Prof. Assoc. Márcio Minto Fabricio (IAU) e ao prof. Ricardo Condinhoto (University of Bath). Em caso de dúvidas, gentileza contatar a pesquisadora Beatriz Campos Fialho por telefone (19 997990597) ou e-mail (beatriz.fialho@usp.br).

Caso você queira uma cópia deste termo, clique no link:
https://1drv.ms/b/s!Aiz3pn7cOjFYhKsgp1vb8i9OiBP19Q?e=Q5YMZE

*Obrigatório

1. Endereço de e-mail *

Escopo

Esta pesquisa investiga o impacto de soluções BIM (Modelagem da Informação da Construção) e IoT (Internet das Coisas) na eficiência dos serviços de manutenção reativa em edifícios universitários, com enfoque no sistema de iluminação.

Um dos objetivos do estudo é desenvolver o protótipo de um sistema autônomo de monitoramento e gestão de luminárias para suporte aos serviços de manutenção, utilizando soluções BIM & IoT para captação, processamento e visualização de dados pertinentes ao desempenho das luminárias. Para isso, o sistema integra dados dinâmicos das luminárias gerados por sensores de luminosidade (como o índice de iluminância e o tempo de funcionamento) com dados estáticos armazenados no modelo BIM do edifício (como marca e dimensões do equipamento, data de instalação, etc.). Assim, a informação gerada pelo sistema visa antecipar eventuais falhas, orientar as equipes de FM na priorização do serviço e auxiliar os profissionais de FM no diagnóstico e atendimento do problema.

Este formulário busca identificar requisitos técnicos e funcionais para o desenvolvimento do protótipo de um sistema BIM & IoT autônomo de monitoramento e gestão de luminárias para suporte aos serviços de manutenção, adequando o sistema às demandas do setor.

Identificação

2. Nome *

3. Profissão *

Marque todas que se aplicam.

- [ ] Engenheiro(a) Eletricista
- [ ] Engenheiro(a) Civil
- [ ] Engenheiro(a) Mecânico(a)
- [ ] Administrador(a)
- [ ] Arquiteto(a)
- [ ] Técnico(a) em Eletrotécnica
- [ ] Técnico(a) em Edificações

Outro: [ ] ____________________

4. Cargo / Função *

Marque todas que se aplicam.

- [ ] Coordenador(a)/Chefe
- [ ] Supervisor(a) Técnico
- [ ] Projetista

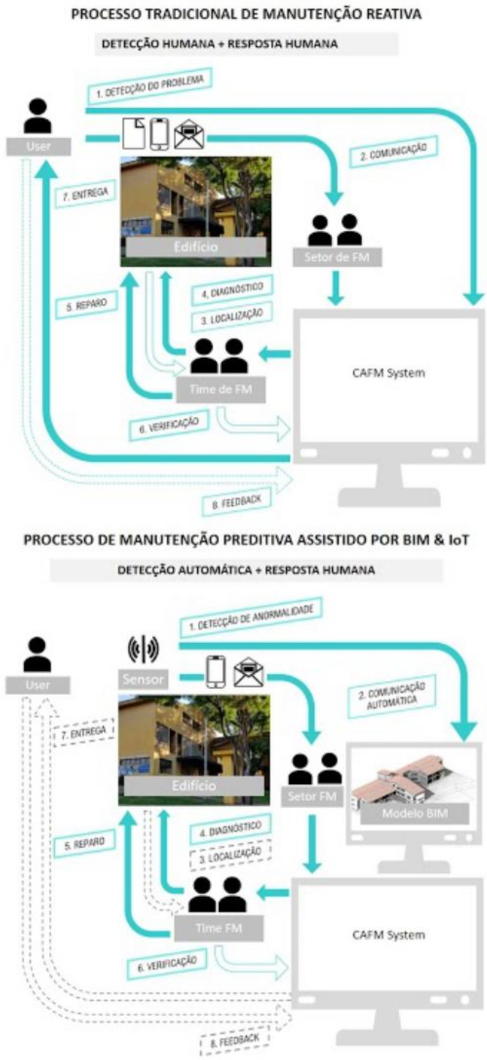
Outro: [ ] ____________________

Hipótese da pesquisa

A pesquisa parte da hipótese de que a implantação de um sistema autônomo de monitoramento luminárias baseado em soluções BIM e IoT pode aumentar a eficiência do processo de manutenção de seus equipamentos, eliminando etapas que não agregam valor e melhorando a qualidade e acessibilidade à informação. Dessa forma, o sistema auxiliaria as equipes de FM da predição de eventuais falhas e na tomada de decisão para a solução do problema, aprimorando a qualidade do serviços e ampliando a satisfação dos usuários.

A Figura 1 apresenta o Framework da Aplicação Conceitual do Processo Tradicional de Manutenção Reativa e do Processo de Manutenção Preditiva assistido por BIM & IoT por meio da implantação do sistema de monitoramento e controle de luminárias é apresentado.

Figura 1: Framework da Aplicação Conceitual do Processo Tradicional de Manutenção Reativa e do Processo de Manutenção Preditiva assistido por BIM & IoT



A Figura 1 estabelece as principais etapas do processo de manutenção baseado nas proposições da norma ISO EN 13306:2017 Maintenance - Maintenance terminology:
1. Detecção (do problema ou de anormalidade) > 2. Comunicação > 3. Localização > 4. Diagnóstico > 5. Reparo > 6. Verificação > 7. Entrega > 8. Feedback.

Além disso, informa o fluxo de informação entre agentes do processo (usuário, sensor, setor de FM) e as ferramentas e interfaces de comunicação e gestão da informação empregadas no processo de manutenção de luminárias, como: telefone, formulário e e-mail; sistema de gestão de serviços de manutenção (por exemplo, Sistema Integrado de Gerenciamento de Serviços - Argos); software de Modelagem da Informação da Construção (por exemplo, Autodesk Revit).

Conforme demonstrado na Figura 1, o processo tradicional de manutenção do sistema de iluminação de edifícios é predominantemente centrado em uma abordagem reativa, voltada para a solução de problemas após a sua ocorrência. Esse processo é caracterizado por uma grande dependência de ações humanas para detecção, comunicação, localização e registro de falhas. Embora mediado por recursos digitais, como e-mail e sistema de gestão de serviços de manutenção, a eficiência dos serviços é por vezes comprometida.

Por sua vez, o Processo de Manutenção Preditiva assistido por BIM & IoT propõe eliminar etapas que não agregam valor e melhorar a qualidade e acessibilidade à informação, antevendo problemas antes que eles aconteçam. Nesse sentido, o usuário perde a atribuição de detectar e comunicar o problema. Essa tarefa é assumida pelo sistema de autônomo de monitoramento composto pelo sensor de luminosidade, que identifica anormalidades no desempenho da luminária e as comunica em tempo real para o setor de FM e para o modelo BIM do edifício. Com base nessa informação, o setor de FM é capaz de visualizar com precisão e agilidade o status da luminária, sua localização e as especificações do equipamento, auxiliando no planejamento do setor para o reparo da luminária.

Com base no exposto, responda as questões a seguir.

5. 1. Na sua opinião, as etapas (1 a 8) do processo tradicional de manutenção representam os serviços realizados pela sua organização?

Marque todas que se aplicam.

☐ Sim
☐ Não
Outro: ☐ ____________________

6. 2. Você sugere alguma alteração nas etapas do processo tradicional de manutenção? Qual?

____
____
____
____
____

7. 3. Na sua opinião, os agentes (usuário, setor de FM e time de FM), ferramentas e interfaces (telefone, e-mail, sistema de gestão de manutenção) do processo tradicional de manutenção representam os serviços realizados pela sua organização?

Marque todas que se aplicam.

☐ Sim
☐ Não
Outro: ☐ ____________________

8. 4. Você sugere alguma alteração nos agentes, ferramentas e interfaces do processo tradicional de manutenção? Qual?

9. 5. Na sua opinião, quais etapas do processo tradicional de manutenção (1 a 8) seriam potencialmente impactadas com a implantação do sistema BIM & IoT autônomo de monitoramento e gestão de luminárias? Por quê?

Requisitos do sistema

Esta seção visa identificar requisitos técnicos e funcionais para o desenvolvimento do protótipo do sistema BIM & IoT autônomo de monitoramento e gestão de luminárias

10. 6. Com base em sua experiência, liste de três a cinco entraves observados no processo tradicional de manutenção reativa de luminárias. *

11. 7. Na sua opinião, quais entraves são observados no processo tradicional de manutenção reativa de luminárias? Marque mais de uma alternativa se desejar. *

Marque todas que se aplicam.

- [ ] Demora na detecção do problema, levando a longos períodos de interrupção de atividades.
- [ ] Dificuldades do usuário na comunicação do problema por telefone, aplicativo ou e-mail.
- [ ] Descrição equivocada ou imprecisa do problema e do local de ocorrência pelo usuário.
- [ ] Dificuldade do time de FM em localizar o problema.
- [ ] Dificuldade do time de FM em diagnosticar o problema.
- [ ] Dificuldades do time de FM no acesso à base de dados sobre o equipamento danificado, como especificações do fabricante, desenhos técnicos e manuais de uso e manutenção.
- [ ] Falta de precisão nos desenhos técnicos do edifício.
- [ ] Dificuldades do time de FM na aquisição de equipamentos e insumos para a manutenção de itens danificados.
- [ ] Dificuldades do time de FM na disponibilização de mão-de-obra para a manutenção de equipamentos danificados.
- [ ] Dificuldades do time de FM na definição de prioridade de atendimento.

12. 8. Na sua opinião, um sistema autônomo de monitoramento e gestão de luminárias baseado em soluções BIM & IoT pode contribuir para melhorias no processo tradicional de manutenção de luminárias? Por quê? *

13. 9. Na sua opinião, quais desses entraves observados no processo tradicional de manutenção reativa de luminárias poderiam ser minimizados com a implantação de um sistema autônomo de monitoramento e gestão de luminárias baseado em soluções BIM & IoT? Marque mais de uma alternativa se desejar. *

Marque todas que se aplicam.

- [ ] Demora na detecção do problema, levando a longos períodos de interrupção de atividades.
- [ ] Dificuldades do usuário na comunicação do problema por telefone, aplicativo ou e-mail.
- [ ] Descrição equivocada ou imprecisa do problema e do local de ocorrência pelo usuário.
- [ ] Dificuldade do time de FM em localizar o problema.
- [ ] Dificuldade do time de FM em diagnosticar o problema.
- [ ] Dificuldades do time de FM no acesso à base de dados sobre o equipamento danificado, como especificações do fabricante, desenhos técnicos e manuais de uso e manutenção.
- [ ] Falta de precisão nos desenhos técnicos do edifício.
- [ ] Dificuldades do time de FM na aquisição de equipamentos e insumos para a manutenção de itens danificados.
- [ ] Dificuldades do time de FM na disponibilização de mão-de-obra para a manutenção de equipamentos danificados.
- [ ] Dificuldades do time de FM na definição de prioridade de atendimento.

14. 10. Com base em sua experiência, liste de três a cinco benefícios do sistema autônomo de monitoramento e gestão de luminárias baseado em soluções BIM & IoT para a eficiência dos serviços de manutenção. *

15. 11. Na sua opinião, quais os benefícios do sistema autônomo de monitoramento e gestão de luminárias baseado em soluções BIM & IoT para a eficiência dos serviços de manutenção? Marque mais de uma alternativa se desejar. *

Marque todas que se aplicam.

- [ ] Disponibilidade de informação precisa e em tempo real sobre o equipamento, auxiliando a tomada de decisão.
- [ ] Antecipação de problemas antes que eles aconteçam, evitando a interrupção de atividades.
- [ ] Otimização do acesso à base de dados sobre o equipamento danificado, centralizada no modelo BIM do edifício.
- [ ] Melhor visualização do equipamento com eventual falha no modelo BIM.
- [ ] Otimização da definição de prioridade de atendimento.
- [ ] Otimização de insumos e mão-de-obra nos serviços de manutenção.
- [ ] Melhoria da saúde, segurança, conforto e satisfação dos usuários.

16. 12. Com base em sua experiência, liste de três a cinco barreiras para a implantação de um sistema autônomo de monitoramento e gestão de luminárias baseado em soluções BIM & IoT para a eficiência dos serviços de manutenção. *

17. 13. Na sua opinião, quais as principais barreiras para a implantação de um sistema autônomo de monitoramento e gestão de luminárias baseado em soluções BIM & IoT para suporte aos serviços de manutenção? Marque mais de uma alternativa se desejar. *

Marque todas que se aplicam.

- [ ] Alto custo de aquisição, instalação e operação de sensores e softwares de processamento e gestão de dados.
- [ ] Alto custo de aquisição e operação de software BIM (por exemplo, Autodesk Revit, Graphisoft ArchiCAD).
- [ ] Necessidade de profissionais especializados para operação dos softwares de processamento de dados dos sensores e modelagem da informação dos edifícios.
- [ ] Necessidade de atualização dos modelos BIM mediante reformas e adequações nos edifícios.
- [ ] Restrições tecnológicas dos sensores, como precisão de coleta dos dados, conexão com a internet e alimentação elétrica.
- [ ] Dificuldades na integração entre o sistema autônomo de monitoramento e o sistema de gestão de serviços existente.
- [ ] Demanda por bancos de dados e computadores com alta capacidade de processamento e armazenamento.
- [ ] Demanda por protocolos e sistemas de segurança de dados.

18. 14. Com base em sua experiência, liste de três a cinco requisitos que devem ser observados no desenvolvimento de um sistema autônomo de monitoramento e gestão de luminárias baseado em soluções BIM & IoT para suporte aos serviços de manutenção. *

19. 15. Na sua opinião, quais requisitos devem ser observados no desenvolvimento de um sistema autônomo de monitoramento e gestão de luminárias baseado em soluções BIM & IoT para suporte aos serviços de manutenção? Marque mais de uma alternativa se desejar. *

Marque todas que se aplicam.

- [ ] Baixo custo de aquisição, instalação e operação de sensores e softwares de processamento e gestão de dados.
- [ ] Facilidade de operação de softwares de processamento de dados e modelagem da informação dos edifícios por profissionais de diferentes formações técnicas.
- [ ] Facilidade na integração entre o sistema autônomo de monitoramento e o sistema de gestão de serviços existente.
- [ ] Possibilidade de alterar o tamanho e escala do sistema.
- [ ] Possibilidade de instalação de sensores em luminárias existentes.
- [ ] Elevada confiabilidade e consistência da informação, disponibilizada no formato adequado.
- [ ] Facilidade de visualização da informação em diferentes dispositivos (por exemplo, smartphone, computador, tablet, etc.) e plataformas (por exemplo, software de modelagem, aplicativo, página web, etc.).
- [ ] Priorização de bancos de dados na nuvem e softwares online para processamento e armazenamento de dados. processamento e armazenamento.
- [ ] Possibilidade de exportação de informação para formatos tradicionais (por exemplo, .docx, .txt, .xlsx, etc)
- [ ] Preservação da integridade dos dados gerados pelos sensores em caso de falha na conexão com a internet ou alimentação elétrica.
- [ ] Preservação da segurança e privacidade de dados.

20. 16. Se desejar, faça comentários adicionais.

Obrigada pela contribuição!

ANNEXES

ANNEX 1 – ARTICLE "TRENDS IN BIM AND IOT FOR REACTIVE MAINTENANCE"

Trends in BIM and IoT for Reactive Maintenance

Beatriz Campos Fialho[1], Ricardo Codinhoto[2], Márcio Minto Fabricio[1]

[1]The University of São Paulo, Institute of Architecture and Urbanism, São Carlos, Brazil

[2]The University of Bath, Department of Architecture and Civil Engineering, Bath, United Kingdom

*email: beatriz.fialho@usp.br

Abstract

It is widely acknowledged in the literature that a buildings' operational phase is directly related to the success of the business it supports. Building operation demands continuous efforts to reduce waste and operational costs while also improving service delivery. Of particular importance is the management of the Reactive Maintenance (RM) that if not managed efficiently can directly impact production lines and building user experiences, interrupting work and service provision. Building Information Modelling (BIM) and Internet of Things (IoT) solutions and devices have demonstrably delivered efficiency gains for some Facilities Management (FM) activities such as workplace management, building energy performance and post-occupancy evaluation. However, other areas, such as RM remain relatively unexplored. This research aims to identify BIM and IoT solutions applied to FM and propose a framework of BIM IoT uses assessed against associated gains, losses, enablers and barriers to implementation. A Systematic Literature Review (SLR) of journal and conference articles published between 2013 and 2018 was carried out to identify the outputs of BIM and IoT implementation for RM services. The review shows that the number of relevant articles is increasing and that there is also a lack of clarity regarding the cost-benefit of IoT. While the benefits and gains of systems are emphasized, disadvantages must be investigated. This research also revealed that there is a significant amount of uncertainty regarding guidance for the adoption of combined BIM and IoT applied to the improvement of RM services provision.

Keywords: Building Information Modelling (BIM), Internet of Things (IoT), Facilities Management (FM), Reactive Maintenance (RM)

1. Introduction

We crave efficiency in our businesses and yet fail to pay attention to the many areas that enable increased efficiency such as FM. Buildings can be too hot, too cold, too damp, or have high levels of CO2 concentration impacting staff performance. Poor maintenance can prevent the use of built assets, thus, driving staff out of offices, requiring clients to be relocated, and cancelling planned operations. The cost of fixing building problems is often a compounded of construction costs, reputational damages, service penalties and litigation costs. Firms also pay the price for not looking after facilities adequately, for not reacting quickly enough, and for not preventing problems before they occur. Although the desired alignment between business and FM has been continuously evolving as a reflection of improving information technology and communication systems effectiveness, there is still much to do. Early research such as Abel et al. (2006) and Atkin & Brooks (2009) showed that information modelling enables the coordination of FM processes that are essential for business operations while providing crucial information to facilities managers and corporate decision makers.

Building Information Modelling (BIM) is increasingly being investigated as a solution for increased efficiency in FM provision (e.g. Hosseini et al., 2018; Pärn, Edwards, & Sing, 2017; Patacas

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et al., 2016; Pin, Medina & MCarthur, 2018; Volk, Stengel, & Schultmann, 2014). There is evidence that information modelling is a powerful approach to aid facilities managers to improve building performance, to manage hard and soft operations more efficiently throughout the life cycle of buildings, and to enable circular economies. The amount of information about the real use of BIM for building operation and maintenance is growing with large public owners finally embracing and benefiting from BIM. However, much still needs to be understood. Advancements in areas such as IoT and Machine Learning has increased the number of potential uses of BIM in FM as well as the levels of efficiency that are possible to be achieved. Thus, a Systematic Literature Review (SLR) was carried out to aiming to gather and structure state-of-the-art knowledge about BIM and IoT implementation as an aid to FM. Special attention was paid to BIM and IoT for reactive maintenance (RM). From the analysis, a framework for the classification of research is proposed that identifies: research fields, FM priority areas, strategic FM operations and the benefits of and barriers to adoption. This framework should enable the establishment of a business case for BIM and IoT adoption.

2. Material and Methods

A SLR was carried out following the guidelines suggested by Gough et al. (2012). SLR generates subject context through the systematic identification, compilation, analysis and synthesis of reliable studies (Gough et al., 2012). It also ensures bias exemption (or, at least, its minimization) and increases the replicability of reviews (Morandi & Camargo, 2015). Also, it helps with establishing a picture of the transformations of a subject over a studied period while supporting decisions on future research paths and the use of research knowledge in practice. In this research, a research protocol was devised that led to the development of a conceptual framework used for data analysis. The SLR was divided into four steps, including research protocol development, searching, selection and extraction; as explained in the following sections.

3. Review Steps and findings

3.1 Systematic Review Entries

Table 1 provides an overview of the input criteria utilised as a part of the research protocol. Of twelve databases considered initially, seven were selected due to the availability of publications in the field of BIM and FM. Keywords and relevant Boolean Operators are presented in Table 1. The term "reactive maintenance" (RM) was excluded, so to broaden the search scope and to avoid the exclusion of relevant articles that use different terminology when referring to RM. Both peer-reviewed journal and conference articles were considered eligible publications. The research focused on recent innovative solutions; thus, only articles published between 2013 and 2018 were included.

Table 1: Research protocol

Item	Content
Research questions	What are the BIM and IoT solutions and devices recently applied to FM? In which areas and activities have these solutions been used? What are the main benefits, gains, enablers and barriers of this implementation?
Key objectives	To establish contextual knowledge regarding the implementation of BIM and IoT solutions on FM through the search, analysis and classification of articles and conference articles published between 2013 and 2018.
Databases	1. Scopus, 2. Technology Collection (ProQuest), 3. Science Direct (Elsevier), 4. Directory of Open Access Journals, 5. ASCE Library, 6. Compendex (Engineering Village) and 7. Web of Science (Web of Knowledge).
Keywords	("Building Information Modeling" OR "Building Information Modelling" OR BIM) ("Facilities Management" OR "Facility Management" OR FM) AND ("Internet of things" OR IoT)
Filters	Year of publication: 2013 to 2018. Type of publication: peer-reviewed journal and

	conference articles. Idiom: English, Portuguese, Spanish, Italian
Selection criteria	Inclusion criteria: articles investigating the implementation of BIM and IoT solutions in FM. Exclusion criteria: Publications that were not related to BIM and IoT for FM; outside the investigated research area; not written in the determined idioms.

In total, 273 publications were initially identified from journal articles, conference proceedings and PhD theses. After applying inclusion and exclusion criteria, 49 publications were selected for further analysis. Data was extracted through full-text review and publications classified according to title, authorship, type of publication, publication year, source (journal or conference), country, keywords, and three key areas: BIM and IoT solutions and devices, FM areas and activities, and positive and negative results obtained. Additional nine publications were excluded from the selection as they failed to meet protocol criteria. Figure 1 shows the distribution of publications per database throughout the different searching stages and the predominance of Scopus, Technology Collection, Science Direct and Compendex for the final 40 publications selected.

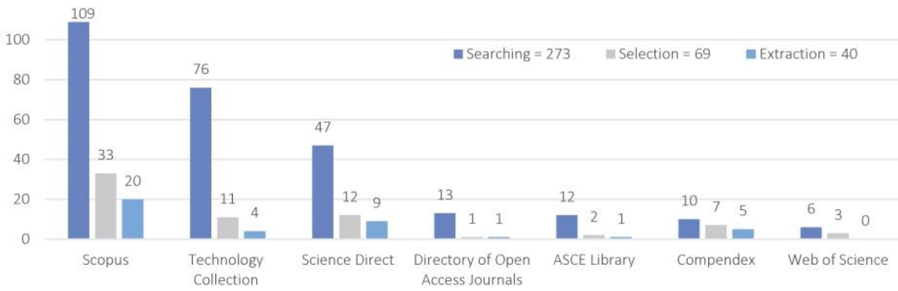
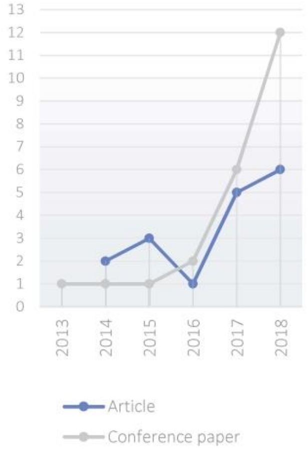


Fig. 1. Distribution of publications per database

3.2 General bibliometric analysis

The bibliometric analysis shows that 17 peer-reviewed journal articles and 23 conference articles were included and that there has been a steady increase in publications per year (Figure 2) since 2013. Figure 3 shows that contribution comes from 22 countries, thus revealing that although various countries started studying the subject, the critical mass is still embryonic (various countries with 1 or 2 publications). There is a predominance of articles (25) originated within, or with the participation of, European countries. The existence of bias is possible due to the use of English and Latin languages within the search. There is a concentration of publications in Italy (5), China (4), Taiwan (3) and the United Kingdom (3). Also, five articles spanned more than one country, evidencing a degree of international collaboration and knowledge sharing on this subject.

The distribution of publications according to where they were published shows 13 journals and 20 conferences. *Procedia Engineering, Advanced Engineering Informatics* and *Automation in Construction* have the highest concentration, accounting for approximately 47% of the articles (e.g. Costa et al., 2015; Kučera & Pitner, 2018), thus placing BIM and IoT for FM research within general engineering sources. No trend was identified for conferences, but there is a concentration of articles in events related to Automation and Robotics in Construction (5) (e.g. Chung et al., 2018; Lee et al., 2017) and IoT Technologies (3) (e.g. Pouke et al., 2018; and Ramprasad et al., 2018), which indicates that BIM and IoT for FM research refers to applied research.



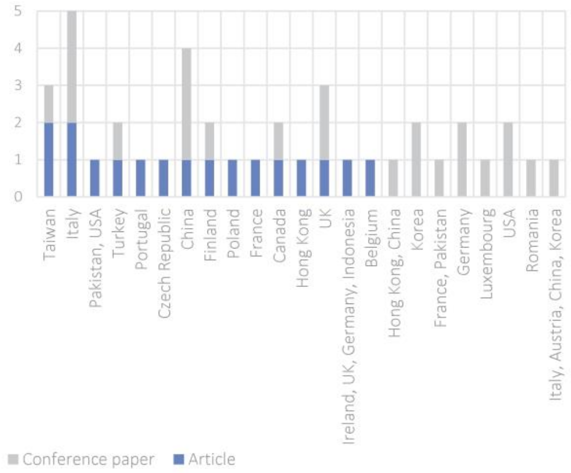


Fig. 2. Distributions of publications per year

Fig. 3. Distribution of publications per country

3.3 BIM and IoT core areas of research

With regards to core research areas, the analysed articles revealed three approaches being used for the integration of BIM and IoT for FM.

1) Process (17 entries) including the development of conceptual frameworks, methods and models for BIM-FM and IoT integration (e.g. Chen et al., 2015; Gokceli et al., 2017);

2) Technology (20 entries) including platform, software, system or tool for the integration of BIM and IoT technologies and interoperability of data related to FM (e.g. Arslan et al., 2017; Marroquin et al., 2018);

3) Theory (3 entries) including theory testing and theory generation for the integration of information and communications technology (ICT) or the description of previous applications of these technologies on BIM-FM and IoT (e.g. Araszkiewicz, 2017; Hanley & Brake, 2017).

Only articles that tested concepts through illustrative, prototype and pilot studies followed by real implementation were included in categories 1 and 2. Table 2 provides a summary of the results with examples to illustrate the three approaches. The following section covers the analysis of the 40 articles included, focusing on the technological aspects of BIM and IoT and its impact on FM and particularly on RM.

Table 2. FM BIM IoT Research core area, implementation and examples

Core area	Implementation	Example
1. Process: frameworks, methods and models for BIM and IoT integration	Illustrative, prototype or pilot implementation (9)	"A smart maintenance work process applicable to smart FM systems" (Chung et al., 2018)
	Real case implementation (6)	"A theoretical framework for digital systems integration of virtual models and smart technologies" (Mirarchi et al., 2018)
	No implementation (2)	"Realtime facility management system framework based on BIM and Web of Things" (Lee et al., 2013)

2. Technology: platforms, software, systems and tool for BIM and IoT integration	Illustrative, prototype or pilot implementation (14)	"BeDIPS - Building/environment Data-based Indoor Positioning System" (Liu et al., 2015)
	Real case implementation (6)	"3i buildings Systems - Intelligent, Interactive, and Immersive Buildings Systems" (Costa et al., 2015)
3. Theory	No implementation (3)	"Cup-of-Water theory" (Ye et al., 2018)

3.4 BIM and IoT solutions and devices for FM

With regards to IoT sensing devices, five key technologies are explicitly applied to FM activities independently or in combination. Out of 51 technologies mentioned, 73% are sensors and actuators (e.g. Dave et al., 2018; Gunduz et al., 2017), including, for example, Bluetooth Low Energy (BLE) beacons, general sensors for measuring temperature, humidity, CO2, lighting, occupancy and virtual sensors (added as an object within the 3D model of the facility); For RM, sensors are integrated into an indoor location system to identify users' position when reporting a failure (Mirarchi et al., 2018); 14% are Radio-frequency identification (RFID) tags and readers (e.g. Motamedi et al., 2016); 4% are smart cameras (e.g. Marroquin et al., 2018) and 4% are Quick Response (QR) codes used in RM for the acquisition and tracking of maintenance information (Lin et al., 2014). Finally, 5% of the articles were not sufficiently clear to fit within one of the above categories; one example is the "Smart field BIM-FM technology proposed by Chung et al. (2018) to support maintenance work on site.

Seven categories were proposed to classify solutions for BIM and the integration of data from sensing devices in FM: software application, system and network application; cloud and database solution; availability of building system; mobile application; smart devices; and associated technologies (Table 3). The results show a concentration of *Autodesk* software solutions, described in 19 publications, including 1 journal article describing the use of software for capturing and storing facility maintenance information to support RM, such as maintenance records and interface reports (Lin et al., 2014); other software solutions have been utilized less often, such as Unity software (3) and Trimble Tekla Structures (1). Building Management Systems (BMS) are present in 6 articles, followed by Building Automation Systems (BAS) in 4 publications. Nine articles applied user-friendly mobile applications, including the *Aalto Space, HereUAre* and *Nextome Noovle,* used in RM for end-users and FM staff registering and localising faults and monitoring service attendance (Mirarchi et al., 2018). Smartphones are mentioned in 10 publications within the smart device category, followed by Arduino in 3 publications. General smart devices are described in 5 articles, including webcam-enabled tablet and notebook supporting maintenance activities, such as fault location via QR code reading, visualisation of records information, monitoring service status and generation of reports (Lin et al., 2014).

Other FM associated technologies found include Blockchain for data security; Machine learning for automation of energy consumption data collection, processing and generation; photogrammetry and laser scanning associated with Geographic Information System (GIS) and Global Positioning System (GPS) for data digitalisation. Particularly applied to RM were Virtual Reality (VR) and Augmented Reality (AR) support site positioning and the visualisation of real-time facility information during maintenance inspections (Chung et al., 2018).

Table 3. FM BIM and IoT solutions

Item	Main BIM and IoT solutions and examples of publications
Software	Autodesk software (Revit, Revit Architecture, Dynamo, Green Building Studio, 3D Max, Autocad) (e.g. Lin et al. (2014); Unity Game Engine (e.g. Louis & Rashid, 2018); Trimble Tekla Structures (Costin et al., 2014)
System	Wireless Sensor Networks (WSN) (e.g. Ph.D & Ye, 2018); Integrated

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and network	Workplace Management System (IWMS) (e.g. Hanley & Brake, 2017); IoT Watson IBM (Ciribini et al., 2017); Near-field communications (NFC) (Araszkiewicz, 2017)
Cloud and database	Microsoft SQL Server (Gerrish, Ruikar, Cook, Johnson, & Philip, 2018), IoT Platform Azure (Teizer et al., 2017), MS Access database (Costin et al., 2014)
Building system	Building Management System (BMS) (Gokceli et al., 2017), Building Automation System (BAS) (Kučera & Pitner, 2018)
Mobile application	Aalto Space mobile application (Dave et al., 2018; Kubler et al., 2016), HereUAre (Liu et al., 2015), Nextome Noovle mobile apps (Mirarchi et al., 2018)
Smart devices	Smartphone (e.g. Vandecasteele et al., 2017), Arduino (e.g. Chang et al., 2018), Tablet and Notebook (e.g. Lin et al., 2014), Wearable devices (e.g. Desogus et al., 2017)
Associated Technologies	Blockchain (Ye et al., 2018), Virtual Reality (VR) and Augmented Reality (AR) (Chung et al., 2018), Machine learning (McGlinn et al., 2017), Aerial photogrammetry (Edmondson et al., 2018), Geographic Information System (GIS) (Ronzino et al., 2015), Global Positioning System (GPS) (Ph.D & Ye, 2018)

3.5 FM areas, activities and applications

Figure 4 presents the classification and occurrence of the publications according to the FM areas and activities as described by Barrett and Finch (2014). Because some publications combined more than one area and activity, the total number of occurrences is higher than the number of analysed articles. Building operations and maintenance is the most investigated FM area with 84 entries, followed by general/office services (12) and facility planning (10). With regards to FM activities, the five most relevant are: Monitoring performance (26), running and maintaining plant (18), voice and data communication (16), health and safety (12) and energy management (14) where emphasis has been placed upon predictive actions related to energy consumption optimisation rather than corrective ones.

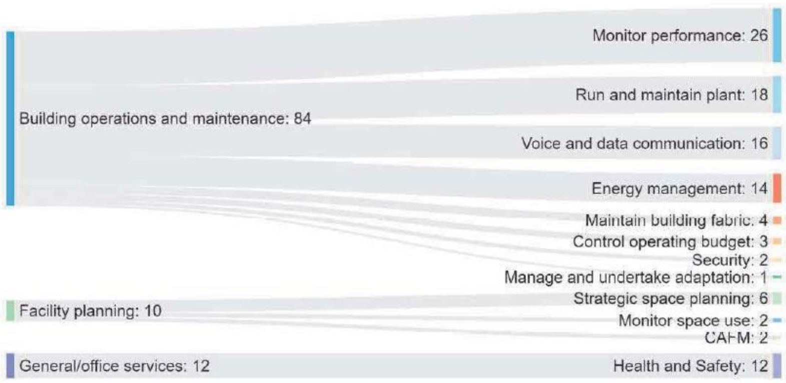

Fig. 4. Classification and occurrence of FM areas and activities

Key applications and examples found are summarised in Figure 5. These include building data management and synchronization (9) (e.g. Ramprasad et al., 2018), environmental monitoring and compliance checking (7) (e.g. Terkaj et al., 2017), energy and environmental management, monitoring and visualization (5) (e.g. Chang et al., 2018), operational and maintenance management (4) (e.g. Desogus et al., 2017) and location tracking (3) (e.g. Costin et al., 2014). Only three publications clearly describe applications relating to Maintenance Work as a process, from which two are related to Reactive Maintenance (correction, inspection and repair) (Lin et al., 2014; Mirarchi et al., 2018).

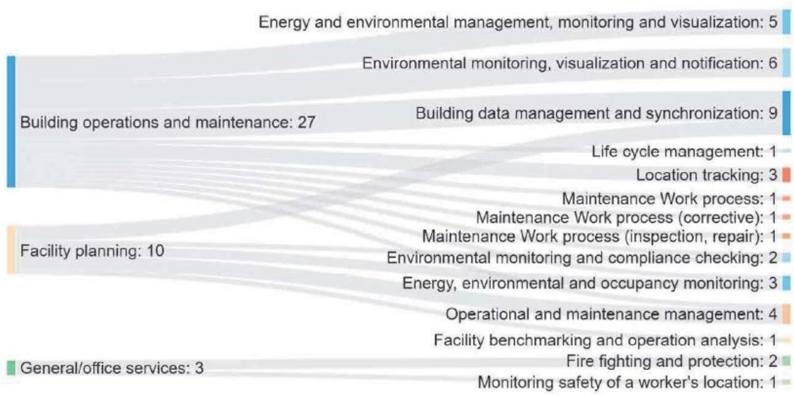

Fig. 5. Classification and occurrence of FM areas and applications of BIM and IoT

3.6 Outputs of BIM and IoT implementation for FM

Selected publications generated a total of 112 entries related to BIM and IoT implementation for FM according to its' measured and potential benefits (60), gains (32), enablers (5) and barriers (15). These were grouped into seven subcategories (Figure 6): increase or decrease of user's health & safety, comfort and satisfaction, technological issues, increase or decrease of FM efficiency, productivity and financial issues, occurrence of ethical and user privacy issues, increased or decreased environmental sustainability, enhanced (shared) building data management and asset planning, management and operation. No losses resulting from the adoption of BIM-FM and IoT were reported within the selected publications, thus revealing positive bias within the research. This aspect is depicted in Figure 6, showing that positive outputs are represented more often than negative ones. Readers must consider, however, that negative results tend not to be published due to risks associated with reputational damage as it occurs in POE studies.

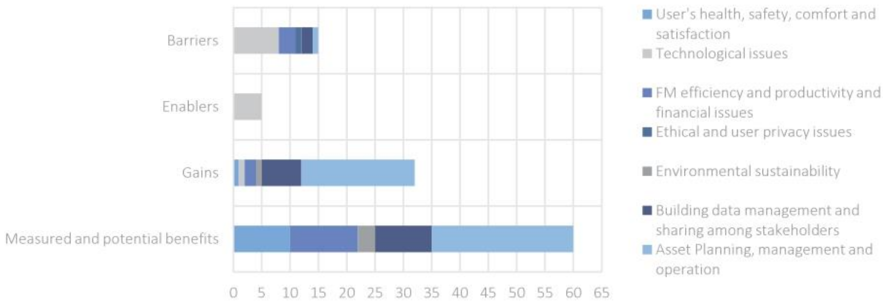

Fig. 6. Distribution of BIM and IoT implementation outputs for FM per publication

In relation to identified benefits, articles mostly describe the potential impact of the combined technologies on asset planning management and operations (25) followed by FM efficiency and productivity and financial issues (12). General examples within this category include "anticipating users' needs to support decision-making for retrofit projects" (Desogus et al., 2017); and "AEC/FM digitalisation high efficiency and security" (Ye et al., 2018), while for RM the benefits are "in facilitating FM updates and transfers in the BIM environment" (e.g. Lin et al., 2014) and "the management of the whole cycle of maintenance activities using a unique integrated system" (e.g. Mirarchi et al., 2018).

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As expected, the main gains relate to asset planning, management and operation (20) and building data management and sharing (10). For example, instant information about problems supporting facilities managers in rapid fault detection (Desogus et al., 2017); availability of "a complete management system", including historical data and current condition, enabling verifications on the behaviour of buildings (Di Giuda et al., 2018). Technology is a key enabler for BIM and IoT implementation for FM in 5 entries. For RM, Lin et al. (2014) highlight the low cost of QR code labels in comparison to RFID technologies; Ciribini et al. (2017) explore machine learning and IoT. In their research, sensors generate real-time human activity data that informs adaptive and predictive strategies embedded in BMS systems which makes automatic changes in environmental controllers (e.g. light levels and temperature control) for improved users' comfort and service attendance. Technology is also seen as the core barrier for BIM and IoT based services (8), followed by FM efficiency and productivity and financial issues (3). Examples include: "trade-offs between interoperability problems within existing sensor systems and high costs related to the development of simplified and integrated systems" (e.g. Arslan et al., 2014); the "large volume of inaccessible and incoherent information gathered through sensors" (e.g. Desogus et al., 2017). For RM, examples include reported difficulties for new user to operate the BIM model in the BIFM system; the fragility of QR code labels to external environmental pollution (Lin et al., 2014); and the limited precision of location system (Mirarchi et al., 2018).

3.7 Conceptual framework of BIM IoT implementation for FMRM

The conceptual framework presented in Figure 7 synthesises the key aspects for the investigation of BIM and IoT implementation for FM/RM. The areas within the framework are the classification of FM areas and activities; definition of an approach for BIM and IoT integration; characterisation of the structure for combining BIM and IoT solutions and devices; and identification of the outputs of BIM and IoT implementation.

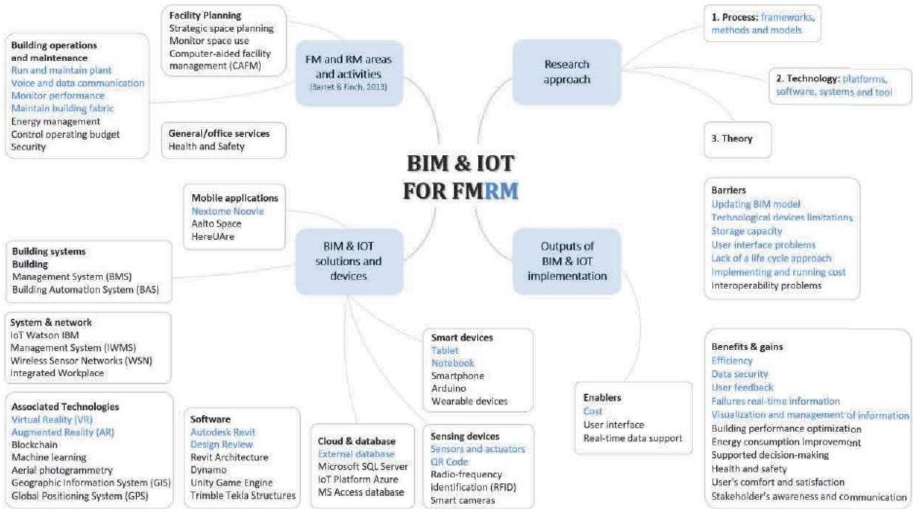

Fig. 7. Framework for BIM and IoT implementation for FMRM

4. Discussion

This work evidences the scarcity of studies in the field during the investigated period. The predominance of publications from European countries stored in three databases highlights the concentration of the topic in specific scientific environments. The prevalence of studies proposing conceptual processes and technological tools for BIM and IoT integration evidences the novelty of the

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theme and the need for advances in storing, exchanging and integrating building operation data, establishing a background for further implementation. Moreover, most of those constructs were validated through pilot implementations, highlighting, on one hand, the interest in developing applicable solutions, while on the other hand, illustrating the demand for implementations in real cases as a strategy for measuring tangible effects over the efficiency FM activities. As shown in Figure 3, although the publications were less representative between 2013 and 2016, we can observe an increasing trend after that, particularly in conference articles, which totalled twice the number of articles in 2018.

As summarised in Table 3, the solutions for building information modelling involve many components beyond sensing devices and software, which makes for even more complex BIM and IoT combined implementation. For FM activities, in general, there is a prevalence of sensors and RFID tags and readers, Autodesk software, smartphones, mobile applications and associated technologies (e.g. VR, AR). Although no trend is verified for RM in the small sample analysed, there is the potential for adapting general solutions to these activities, respecting inherent limitations highlighted by some authors (Chung et al., 2018; Lin et al., 2014; Mirarchi et al., 2018).

The predominance of publications about building operations and maintenance, particularly for monitoring building performance, managing energy consumption and voice and data communication shows that BIM and IoT based FM plays a key role in enhancing FM activities during the life cycle of a building. It provides intelligent data and solutions for enhancing the Operation and Maintenance (O&M) stage, and also to feedback and integrate designers and contractors in the early stages of the design process. However, the availability of only two RM related articles evidences the lack of studies in this area, disregarding its impact on service provision, user satisfaction and business value.

The measured and potential benefits and gains are the most significant outputs of BIM and IoT implementation for FM. In general, and for RM, the emphasis has been on the integration of building information in a centralized database, the availability of real-time updated information, the improvement of the quality and management of information among stakeholders, the fast response to faults and the performance of buildings over the lifespan. Technology is both the main enabler for BIM and IoT implementation due to its capability to process real-time information and to propose alternatives for improving user comfort and service attendance and as the main barrier as the cost and complexity of collecting, storing and exchanging interoperable building data are still major challenges. There is an evident bias towards technology-related research.

Regards to BIM/IoT/RM-based services, this article has identified different approaches to improve the communication and management of asset information. Mirarchi et al. (2018) develop a system for asset traceability, damage detection and reporting and communication of failures, based on indoor location technologies (i.e. GIS and mobile application), integrated to FM BIM models. The focus is on tracking users' position as one reference for locating the reported problems and linking this information to the BIM model. Although faults' precise location requires being interpreted by the facility manager according to other sources of information (e.g. photos, descriptions), the system provides an easy interface for users, FM staff and the supply chain actively participating in the RM process, improving the efficiency of the service. A mobile system for inspection and maintenance work was also proposed by Lin et al. (2014), integrating asset information captured through 2D barcode technology to FM BIM models. In their research, the emphasis was placed on FM staff acquiring and tracking asset information directly from the labelled elements of the building, improving the information sharing and the RM services efficiency. With distinct levels of end-user involvement, both solutions face the challenge to overcome the technological limitations and to structure the modelling, transference and update of information among IoT, FM and BIM systems, thus requiring further investigations.

Holistic approaches, covering not only the technical challenges in the FM process but also people issues and the changing business models driving FM, such as the circular economy and how we are now learning from information related to the whole life cycle of existing buildings in design of new buildings, did not appear in this systematic literature review. Although the positive outputs outweigh the negative ones, it is necessary to deeply investigate all the barriers and then propose strategies to mitigate their impact on BIM and IoT applications for FM, optimising the use of resources and seeking affordable devices and solutions for each situation. Also, it is essential to map RM processes in more detail in order to identify which services and activities can be potentially improved through BIM and IoT implementation. More research is needed to fill this gap.

5. Conclusion

Through an SLR, this work establishes a context for the implementation of BIM and IoT solutions in FM between 2013 and 2018. Addressing the research questions, BIM and IoT devices and solutions recently applied to FM, and particularly to RM, were identified, as well as the main FM areas, activities and applications. Finally, the outputs of this implementation were examined, highlighting benefits, gains and enablers rather than barriers and losses. The work indicates that RM activities represent a small field of investigation, providing a range of opportunities for new approaches and applications. The research shows that the number of articles is increasing and that there is a lack of clarity regarding the cost-benefit of BIM and IoT combined implementation. The categories and strategies for developing this work are summarised in the proposed conceptual framework which, along with the findings, contribute to understand the subject and to support future studies.

One of the limitations of this study was the difficulty of tracking publications within the databases due to the multidisciplinary nature of the subject, crossing engineering and computer science fields. Also, the focus on articles is based on secondary sources of data, providing a synthesis of previous investigations. In this respect, further research supported by empirical evidence (e.g. case studies, surveys, interviews) is recommended in order to provide metrics around costs and the impacts of BIM and IoT implementation for FM, particularly for RM. These and future studies are necessary to strengthening FM's key role in improving building life-cycle efficiency and the AEC industry.

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