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Statistical critical reactive maintenance characterisation for digital twin implementation in universities

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Received 31 March 2023
Revised 21 July 2023
Accepted 21 August 2023

Abstract

Purpose – Facilities management (FM) plays a key role in the performance of businesses to ensure the comfort of users and the sustainable use of natural resources over operation and maintenance. Nevertheless, reactive maintenance (RM) services are characterised by delays, waste and difficulties in prioritising services and identifying the root causes of failures; this is mostly caused by inefficient asset information and communication management. While linking building information modelling and the Internet of Things through a digital twin has demonstrated potential for improving FM practices, there is a lack of evidence regarding the process requirements involved in their implementation. This paper aims to address this challenge, as it is the first to statistically characterise RM services and processes to identify the most critical RM problems and scenarios for digital twin implementation. The statistical data analytics approach also constitutes a novel practical approach for a holistic analysis of RM occurrences.

Design/methodology/approach – The research strategy was based on multiple case studies, which adopted university campuses as objects for investigation. A detailed literature review of work to date and documental analysis assisted in generating data on the FM sector and RM services, where qualitative and statistical analyses were applied to approximately 300,000 individual work requests.

Findings – The work provides substantial evidence of a series of patterns across both cases that were not evidenced prior to this study: a concentration of requests within main campuses; a balanced distribution of requests per building, mechanical and electrical service categories; a predominance of low priority level services; a low rate of compliance in attending priority services; 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); a predominance of problems in student accommodation facilities, circulations and offices; and a concentration of requests related to unlisted buildings. These new patterns

This research was developed as part of the PhD of the first author. The authors would like to thank the University of São Paulo, the University of Bath and the Federal University of São Carlos for the scientific and administrative support, the participants for providing data on the FM sector and RM services, and the examiners who indirectly contributed to the research.

Funding: This research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brazil (CAPES) – Finance Code 001 and Grant No. 88881.188668/2018–01 and the Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brazil (CNPq) – Grant Process No. 308379/2021-7.

Facilities
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0263-2772
DOI 10.1108/F-03-2023-0029

form the basis for business cases where maintenance services and FM sectors can benefit from digital twins. It also provides a new methodological approach for assessing the impact of RM on businesses.

Practical implications – The findings provide new insights for owners and FM staff in determining the criticality of RM services, justifying investments and planning the digital transformation of services for a smarter provision.

Originality/value – This study represents a unique approach to FM and provides detailed evidence to identify novel RM patterns of critical service provision and activities within organisations for efficient digitalised data management over a building's lifecycle.

Keywords Facilities management, Reactive maintenance, Digital twin, BIM, IoT, University campus

Paper type Case study

Introduction

Recent and sudden changes in the world economy have exponentially raised the importance of improving the performance of assets over time. Considering the 2022 significant rise in living costs, building performance became a part of the central agenda of governments and organisations. The environmental impacts of buildings and the architecture, engineering and construction and operations 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 (IEA), 2021). Operation and maintenance (O&M) is the longest and most costly phase within the asset lifecycle, consuming roughly 80% of the full costs and resources in inefficient services (Surveyors, R.I. of C, 2015; Sullivan *et al.*, 2010).

Facilities management (FM) is the core sector within organisations responsible for boosting asset performance, user satisfaction and quality of life, and resource consumption (International Organization for Standardization, 2017; Booty, 2009). Reactive maintenance (RM), also known as corrective maintenance, figures among the FM critical services (Barrett and Finch, 2014; Sullivan *et al.*, 2010) and deals with unpredictable faults. As a result, actions towards fault repair are commonly triggered when the breakdown already impacts building users' routine, concentrating resources and efforts on service provision.

Despite their relevance, RM processes are characterised by delays and waste and difficulties in the identification of root causes of failures (Akcamete *et al.*, 2010; Perera *et al.*, 2016; Salleh *et al.*, 2016) and service prioritisation (Ensafi *et al.*, 2023; Gober, 2008; Jaspers and Teicholz, 2012; Olanrewaju and 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 and Mobley, 2001). Nevertheless, one of the main causes of inefficiencies is related to the management of asset information and communication (Lee and Akin, 2009; Pishdad-Bozorgi, 2017; Sullivan *et al.*, 2010), comprised by the complex, heterogeneous and large set of information generated during the building design process (Akcamete *et al.*, 2010; Kiviniemi and Codinhoto, 2014; Pärn *et al.*, 2017; Sacks *et al.*, 2018; Talamo and Bonanomi, 2016). Limitations involved in information management largely contribute to inefficiencies in the management of FM information (Talamo and Bonanomi, 2016; Codinhoto *et al.*, 2013b) hindering the execution of maintenance activities (Misic *et al.*, 2020; Aziz *et al.*, 2016; Akcamete *et al.*, 2010).

The recent application of building information modelling (BIM) and the Internet of Things (IoT) to FM have been showing potential for predictive and sustainable practices (Pishdad-Bozorgi, 2017). For example, the BIM and IoT integration enables the cost-effective creation of digital twins for FM, supporting not only the documentation of changes and monitoring of currence performance, but also the antecipation of failures and behaviour of buildings' systems and components (Fink and Mata, 2020; Fialho *et al.*, 2019; Grieves and Vickers, 2017).

Previous research has discussed the implementation of BIM for FM (Becerik-Gerber *et al.*, 2012; Chen *et al.*, 2018; Codinhoto *et al.*, 2013a; Edirisinghe *et al.*, 2017; Hosseini *et al.*, 2018; Kassem *et al.*, 2015; Pärn *et al.*, 2017; Pin *et al.*, 2018; Pinti *et al.*, 2018). However, only a few studies with varied types and strengths of evidence have addressed the application of BIM and IoT for RM (Chung *et al.*, 2018; Mirarchi *et al.*, 2018; Lin *et al.*, 2014) and the processes required for O&M over time (Valks *et al.*, 2021; European Federation of Engineering Consultancy Associations (EFCA) 2019; Colemen *et al.*, 2017; Lewis, 2012). Besides, a small number of studies have conducted solid investigations on the root causes of buildings failures (Abdul-Lateef, 2010; Ali *et al.*, 2010; Krstić and Mareniak, 2012; Ofori *et al.*, 2015), that could contribute for the identification of key scenarios for BIM and IoT implementation.

Thus, scientific and empirical evidence of maintenance priority areas and digitalisation steps are needed to support decision-making in the early stages of BIM and IoT-aided FM implementation (Codinhoto *et al.*, 2021; Ensafi *et al.*, 2023; Lewis, 2012). Therefore, the following research question was formulated to address this gap in practice and scientific knowledge:

RQ1. What patterns of RM benefit from BIM and IoT support?

This research aimed to characterise critical RM occurrences and explore BIM and IoT implementation scenarios. The research strategy was multiple case study research. The two cases investigated were University Campuses in the UK, and the unit of analysis was RM service orders over two years. Data analysis was based on qualitative and statistical analysis.

Background

Reactive maintenance process and challenges

RM is the most predominant and critical maintenance category in organisations, representing more than 55% of the overall breakdowns in the USA (Sullivan *et al.*, 2010). Understanding RM processes and challenges is essential to improve the performance of corrective actions and support the implementation of predictive approaches in decision-making. RM refers to items' restoration after fault recognition to ensure the functionality of the building, electric and mechanical systems (The British Standards Institute, 2017).

As an interdisciplinary area, RM entails many steps and activities to address various (and sometimes conflicting and dynamic) stakeholders' needs and expectations. The information management involved in this process is typically supported by information technology systems, such as Computer Assisted FM, Computerized Maintenance Management System and Building Management System or Building Automation System (Ghosh and Chasey, 2013; Higgins and Mobley, 2001; Park, 1994; Sullivan *et al.*, 2010). This process is captured in a traditional RM conceptual framework proposed by Fialho *et al.* (2021) based on the standard BS EN 13306 (Figure 1). The framework comprises eight stages, from fault detection to feedback.

Stage 1. *Fault detection* relates to the identification of a failure in any building of infrastructure system, equipment or fabric by an end-user or staff member (Gunay *et al.*, 2018; Oubodun, 1996). 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 (WR) is the physical or digital document used to describe the work required, thus identifying, for instance, the faulty item, the job number, the work requested and the priority level (Ensafi *et al.*, 2023; Gober, 2008; Gunay *et al.*, 2018; Márquez, 2007). Once FM staff approves the request, the service is scheduled and allocated to the maintenance staff. Subsequently, a work order (WO) is generated, providing the maintenance staff with the necessary information (i.e. material, tools and critical times) to carry out the service (Gober, 2008; Chanter and Swallow, 2007).

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). Stage 4 relates to diagnosing the problem and recognising the faulty items and the related causes with the support of statutory and asset documents. At this stage, the FM team, finance and external suppliers collectively agree on the repair plan.

Stage 5 refers to fault correction, comprising physical actions to restore the function of a faulty item. Stage 6 involves checking service completion to ensure the repaired item performs as required and authorising related payments (Chanter and Swallow, 2007). Stage 7 relates to delivering the service to the end-user or staff member and registering the attendance of the request. Finally, Stage 8 refers to requesting feedback from the client concerning service satisfaction, which is used for continuous improvements (Pin *et al.*, 2018; Royal Institute of Chartered Surveyors (RICS) and International Facility Management Association (IFMA), 2018). Once approved, the request is closed and recorded into FM databases.

The complexity of the RM process imposes challenges to the FM sector in service provision. One significant challenge is identifying the root causes of failures, which negatively impact planning service response and maintenance costs. For example, Park (1994) presents evidence that breakdowns are random and difficult to predict, thus making unavoidable the occurrence of unplanned actions. However, causes related to the performance of components can be associated with certain characteristics of the building and its operation (e.g. age, size, typology, material and number of users) (Olanrewaju and Abdul-Aziz, 2015). By using such characteristics as indicators, defects can be anticipated by monitoring real-time performance and analysis of historical data, thus enabling the identification of breakdown patterns (Bortolini and Forcada, 2020; Colemen *et al.*, 2017; Velmurugan and Dhingra, 2015; Akcamete *et al.*, 2010) and the prediction of cost repairs (Kwon *et al.*, 2020; Park *et al.*, 2019).

Precedent studies have discussed the root causes of building failure and their effects on the maintenance costs of universities assets. Stronger evidence was gathered by Krstić and Mareniak (2012), who had direct access to 12 years of maintenance data of a Croatian University relevant for the prediction of costs. Based on statistical analysis, their study has revealed that buildings' age and their area and height are important variables impacting operational and maintenance costs. The analysis of a questionnaire survey responded to by

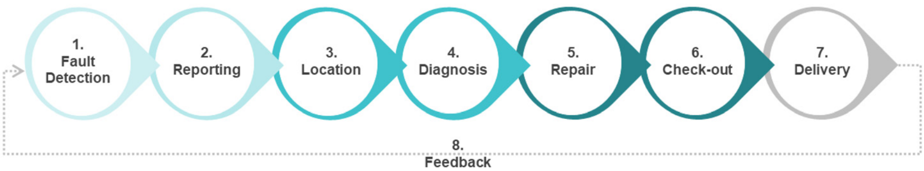

Figure 1. Conceptual framework of the traditional reactive maintenance process

Source: Courtesy of Fialho *et al.* (2021)

50 university maintenance teams conducted by Abdul-Lateef (2010) has shown that the quality of building materials and components, budget limitations, and the age of the buildings are the most significant variables influencing maintenance costs.

Other studies with varied levels of evidence strength corroborate these results for residential buildings. The ranking analysis of Malaysian housing maintenance data conducted by Ali *et al.* (2010) has shown that the expectation of tenants in relation to the property, the quality of building materials, the presence of building services (e.g. lighting, heating, plumbing, etc.), and the building age are the most influential factors affecting maintenance costs. Similarly, the analysis of quantitative data on maintenance cost of Malaysian *apartments* carried out by Salleh *et al.* (2016) has determined that building age is a significant factor influencing maintenance costs along with building material, height and area or size. The statistical analysis of Ghanaian private *house* maintenance data conducted by Ofori *et al.* (2015) has also indicated that ageing stock of buildings is among the common factors for building deterioration, along with obsolescence of buildings and environmental issues. In addition, data on *condominiums* built in Sri Lanka collected by Perera *et al.* (2016) has evidenced that building age, size, material, height and finishes are determinants to operational and maintenance costs. Investigating the root cause of a failure and its warning signs is essential to solving maintenance problems effectively, improving planning activities and reducing maintenance frequency and cost (Akcamete *et al.*, 2010; Mobley *et al.*, 2008; Márquez, 2007).

A second challenge is prioritising RM services, ensuring that the most important problems will be promptly solved (Barrett and Finch, 2014; Chanter and Swallow, 2007; Ensafi *et al.*, 2023; Jaspers and Teicholz, 2012; Márquez, 2007). Generally, a first prioritisation is informed in the WR by the fault reporter (Gober, 2008) or defined by the FM sector after receiving it (Ensafi *et al.*, 2023). This classification is based on a predefined priority code, usually developed by the FM department/division as part of a service level agreement (Chanter and Swallow, 2007). The severity of the fault is the main element of the classification, considering its current or potential consequences for end-users and the organisation's assets, according to aspects such as safety, cost and environment (British Standards Institution, 2017). Severity levels and their response time vary among organisations and depend on the typology of the building stock, the volume of requests and the availability of maintenance staff. Although predefined codes are helpful, the lack of technical knowledge or enough description of the problem for assessing fault severity can influence the reliability of the prioritisation process.

Uncertainty often leads to a second prioritisation assessment by the FM staff to plan the service delivery order. The decision on service order is also challenging due to its dependence on a series of variables, such as the repair's complexity and the availability of a record of maintenance (Akcamete *et al.*, 2010), budget, labour and material resources (Ahluwalia, 2008; Jaspers and Teicholz, 2012; Olanrewaju and Abdul-Aziz, 2015). Also important are the level of accessibility to the faulty item (Dabbs, 2008) and the impact on the organisation's activities. As Ensafi *et al.* (2023) and Gober (2008) have discussed, the lack of a systematic approach to support prioritisation leads to subjective judgement, thus impacting the delivery of critical problems.

The third and most significant challenge is the efficient management of FM information systems. Despite the potential to improve the performance of FM services, technical, procedural and policy limitations involved in information management (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.*, 2013b; Talamo and Bonanomi, 2016) contribute to wasting staff time and effort in non-value adding activities (Koskela, 1992) for generating and finding accurate information when required (Abdul-Lateef, 2010; Araszkiewicz, 2017; Codinhoto, 2013a). Consequently, the lack of reliable and centralised information about facilities' current and historical conditions obstructs maintenance and repair decision-making and wastes time for maintenance activities (Gunay *et al.*, 2018; Lee and Akin, 2009).

In summary, the literature review about RM shows that organisations still underutilise data produced by FM systems, and the technical capabilities to manage information remain unexploited. As a result, information management inefficiencies impact strategic decisions and the exploration of new business opportunities. Such limitations must be overcome so that the "building's in-use data and information can be converted into tangible business knowledge for augmenting FM performance" (Hosseini *et al.*, 2018, p. 2), thus upgrading FM to a more strategic position.

Research method

Case study was the research strategy adopted, for it is an appropriate and tested approach in the field of FM, particularly for a contemporary research problem such as using BIM and IoT to improve RM practice (Yin, 2018). Multiple cases were selected, adopting university campuses as the objects of investigation and the management of RM as the unit of analysis. Universities were chosen as they contain various types of buildings such as accommodation, catering, education and laboratories. Cases were selected based on their level of digitalisation: one case with intermediate-basic BIM-FM use (University 1 - U1) and one with extensive BIM-FM use (University 2 – U2). Each case was organised into four stages (Eisenhardt, 1989): scope and planning, entering the field, analysing data and theory generation (Figure 2). In the first stage (scope and planning), two universities from the UK were selected, representing organisations with an advanced-intermediate BIM and IoT implementation level for FM activities.

Stage 2 field activities were conducted in the UK between September 2018 and February 2019. Multiple sources of evidence were used, including a literature review that provided a common understanding of the topic of investigation (i.e. identification of building characteristics that impact problem occurrence), a documental analysis supported the characterisation of the RM services in each organisation and the identification of patterns and critical scenarios across the cases. The sources of evidence included primary data from approximately 300,000 WRs generated between 2017 and 2018 and documentation of RM plans, processes, protocols and guidelines. Subsequently (Stage 3), two analytical approaches were used for data analysis:

Firstly, a qualitative analysis was used according to the steps suggested by Miles *et al.* (2013), namely:

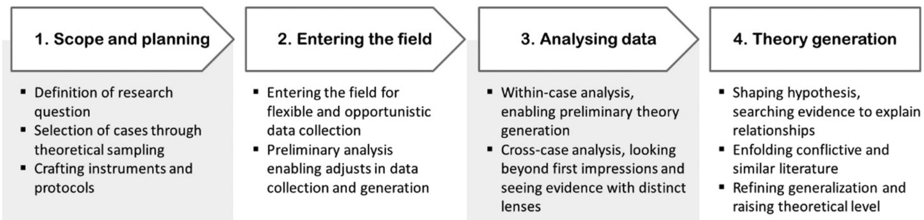

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Figure 2.
Multiple case study process

- data condensation, involving the summarisation of individual WR's files into a single Excel spreadsheet and the homogenisation of WR's categories (e.g. service category, room type and floor identification);
- data display, including the organisation of WR's condensed data into concise tables, graphs and charts, highlighting variables for analysis and their relationship; and
- data conclusion drawing and verification, thus revealing the research contributions.

Secondly, statistical analyses were conducted with WR's data from UK organisations. The application of multivariate techniques (Bryman, 2012) 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 response time (lead-time between problem reporting and service completion – Figure 3). Also, descriptive and inferential statistical approaches (Dancey and Reidy, 2006; Schuenemeyer and Drew, 2011) were used with the support of SAS Institute Inc. (SAS) University Edition software.

The sample metric variables were described and compared with the support of descriptive statistical analysis focusing on their central tendency (mode, median and mean) and dispersion (standard deviation, variance, range and coefficient of variation) (Saunders *et al.*, 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 multicollinearity analysis evaluated the relationship strength among all variables (Hair *et al.*, 2014). The descriptive stage enabled the assessment of the data validity and definition of techniques for posterior inferential analyses (Schuenemeyer and Drew, 2011).

The inferential statistical analysis measured both the degree and character of the relationship among the independent variables and their specific relationship with a single dependent variable. Partial least squares (PLS) regression (Geladi and Kowalski, 1986) was selected among other applicable analysis methods such as multiple regression, canonical

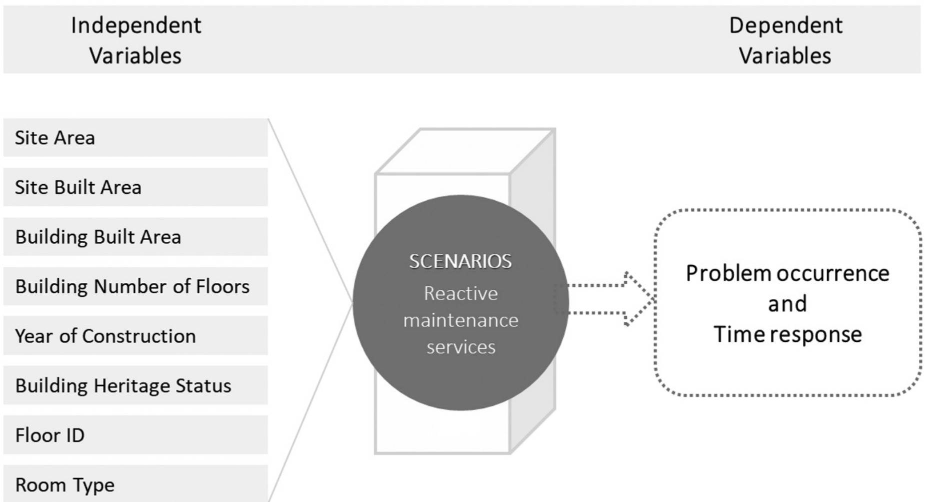

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Figure 3. Contribution of independent variables on reactive maintenance problem occurrence and response time

correlation and multiple discriminant analysis (Hair *et al.*, 2014). Primarily developed for the econometric area, PLS is currently used to develop predictive models of linear relationships among multivariate measurements (Nguyen and Rocke, 2002), thus addressing this research need. In the final stage (four), the results from the qualitative and quantitative analyses supported the discussion and interpretation of the findings.

Results and discussion

The main purpose of the WR analysis was to characterise FM requests and to identify the most critical problems within universities' infrastructure over the studied period. Criticality was based on the relationship between the severity and recurrence of problems. As presented below, the descriptive statistical analysis of WRs supported a cross-section discussion of the cases, focusing on service and building characteristics variables.

Descriptive analysis

Initially, a general approach covers the total requests focusing on the service characteristics, followed by a restricted analysis of RM requests and the related building characteristics. The WR's variables for analysis are shown in Table 1.

A comparative analysis of the distribution of all WRs per FM areas and FM groups is presented in Figures 4 and 5. 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 U1 requests and 44.55% of U2 requests and unlisted/other services sum 13.67% of U1 requests and 0.01% of U2 requests.

RM services are the most representative category for U1, with 66% of all requests; however, they represent only 21.65% of U2 requests. On the other hand, preventive maintenance sums 0.07% of U1 requests and 32.64% of U2 requests. At first, data on U1 RM corroborated the literature, which estimates its predominance among other maintenance categories (Sullivan *et al.*, 2010). However, the overall disparity among studied universities' data might be explained by applying different parameters for service classification by each FM sector or by adopting a more preventive approach by U2.

Given the general scenario, discussions about the RM area were proposed for both universities. A balanced distribution of the WRs per building, mechanical and electrical service categories was verified (Figures 6 and 7), showing the relevance of the three categories for the FM sector planning. Building services are predominant at U1 (36.95%), and mechanical services (36.31%) are predominant at U2. Since the difference between such categories is insignificant, an explanation for their recurrence is the high number of mechanical equipment (e.g. heating and lifts) and building components in the group of assets. Electrical services are the third most representative group in U1 and U2, with approximately a quarter of all requests. A plausible explanation for this result is the existence of only two main systems (lighting and power) to be maintained.

The distribution of WRs per service category and subcategory based on the service priority level was discussed only for the U1 data because U2 did not apply this classification. As shown in Figure 8, most requests were classified as Priority 5, predominantly building services, completed in a flexible time arrangement, according to the user's demands and FM staff availability. Such services include painting, furniture repair and plaster redecoration, commonly requested by the students' accommodation department.

Priorities 3 and 2 were the second and third most relevant levels (especially mechanical services involving faulty facilities such as heating systems and sanitary fitting). Problems

Group	Variable	Description
Services	FM Area	Corresponding to the FM areas proposed by Barrett and Finch (2014) (e.g. Building operations and maintenance, facility planning, real estate and building construction, general/office service)
	FM Group	Corresponding to the FM groups proposed by Barrett and Finch (2014) (e.g. Reactive maintenance, preventive maintenance, operations, fire, reprographic services and safety critical)
	Month and year	Corresponding to the month and year of service requested (e.g. September 2017, October 2018)
	Site ID	Corresponding to the name of university sites (e.g. Campus A, Site B, Site BA)
	Service category	Corresponding to the categories of services related to asset systems (i.e. building, mechanical, electrical and external areas)
	Service subcategory	Corresponding to the subcategories of services related to asset system components (e.g. door, wall, plumbing, heat/cool/vent, lighting and power)
	Priority level	Corresponding to the classification of services based on the service level agreement of the U1 into five categories, presented in descending order of importance: Priority 1 for WRs completed within two hours (on the same day); Priority 2 for WRs completed within one day; Priority 3 for WRs completed within three days; Priority 4 for WRs completed within seven days; Priority 5 for WRs completed within the time agreed with the client.
	Average time spent	Corresponding to the average time spent for service provision measured in days (e.g. 3.01 days, 9.71 days)
Building characteristics	Room type	Corresponding to the room function (e.g. bedroom, toilet, kitchen, laboratory and lecture theatre)
	Number of floors	Corresponding to the number of building levels (e.g. 1, 2 and 3)
	Floor ID	Corresponding to the identification of a building floor level (e.g. 1, 2, 3 and roof)
	Building year of construction	Corresponding to the year the building was built (e.g. 1970, 1850)
	Building heritage status	Corresponding to the building's classification according to its heritage status (i.e. listed or unlisted)
	Building built area	Corresponding to the total floor area of a building in square meters (e.g. 6.000 m^2, 3.250 m^2)

Source: Created by authors

Table 1. Work requests (WR) variables for analysis

with such services often have short- and long-term implications for the whole university community across various assets, from individual rooms (e.g. offices and student bedrooms) to common areas (e.g. library, classrooms and laboratories), which explains the significant number of requests. Priority 4 concentrates on unlisted/other and building services, followed by Priority 1, with mechanical and electrical services. The low percentage of emergency services is associated with preventive actions anticipating failures or inaccuracies in service

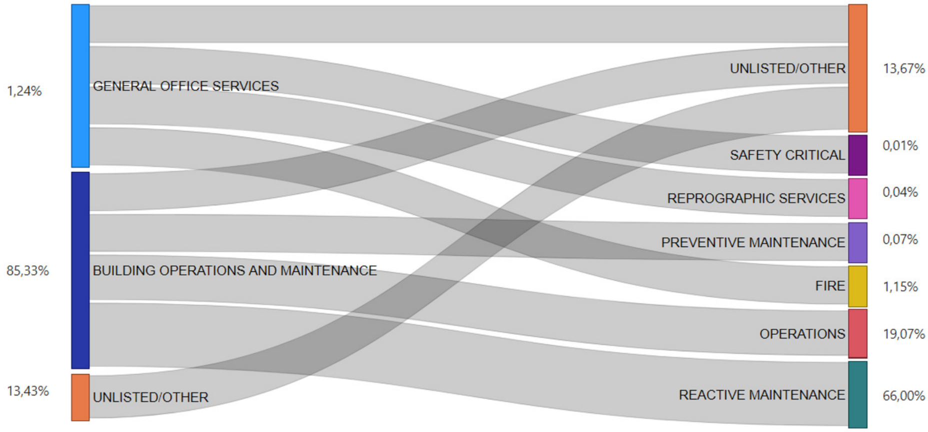

Figure 4.
U1 Distribution of work requests per FM areas and FM groups

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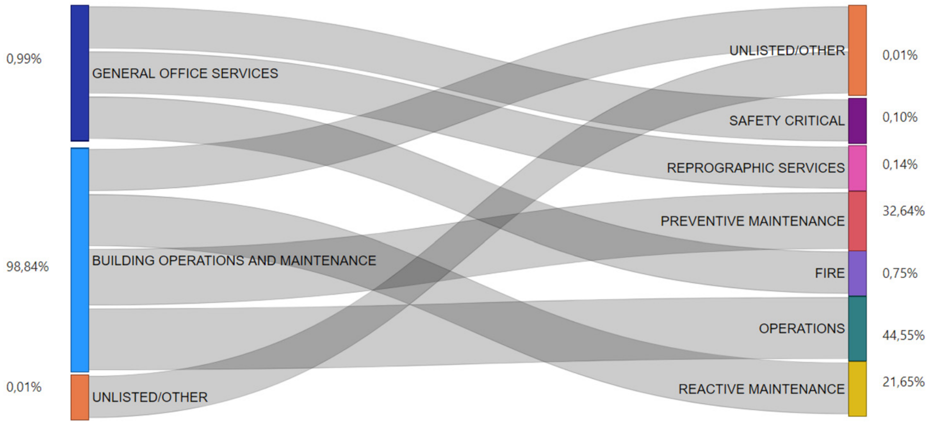

Figure 5.
U2 Distribution of work requests per FM areas and FM groups

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classification. However, Priority 1 services significantly impact personal safety and asset security, requiring special attention from the FM staff.

The classification of the priority service level of RM services provided from U1 has supported the analysis of the mean time spent for each priority level and the percentage of requests attended on time (Figure 9). The analysis shows that 100% of Priority 5 services were completed on time, while for Priorities 1, 2, 3 and 4, the percentage is about 33%. The lower compliance rate is more impactful for Priority 1 services since delays in service response can cause severe damage to property and impact the safety of users and buildings' security.

One plausible explanation for this observed phenomenon is the inaccuracy in classifying the WRs' priority level according to the description provided by the fault reporter. In many cases, the fault is more complex than initially reported, taking more time to be addressed.

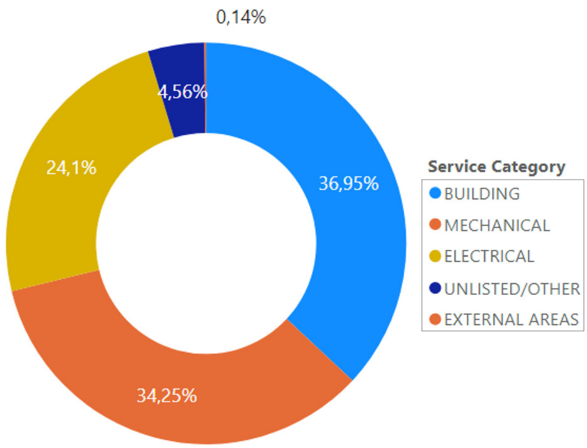

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Figure 6.
U1 Distribution of the work requests per service category

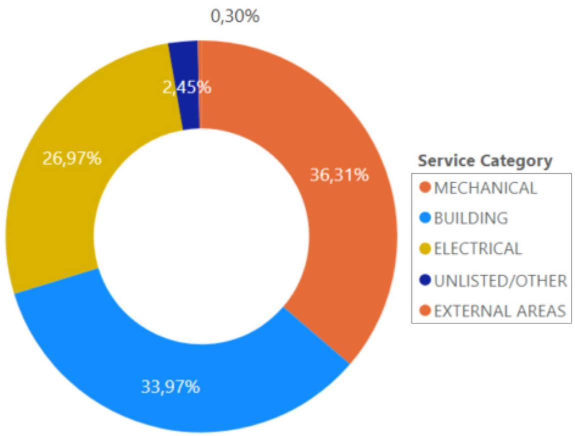

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Figure7.
U2 Distribution of the work requests per service category

Another reason is the unavailability of labour and material resources to execute the service on time. In addition, new buildings opened to users in 2018 have generated additional (snag) demands for the FM team. Therefore, inconsistencies between the service level agreement criteria and the FM sector capability for service attendance were observed. A review of standards is recommended to improve services' performance, especially critical ones and the safety and satisfaction of the university community.

The distribution of the average time spent per main service category and subcategory was analysed for both universities, supporting a comparative discussion (Figures 10 and 11). Substantial variation in the average time spent was identified for some service subcategories. For instance, for wall services, U1 spent around 416 days and U2 16 days for completion; for gas services, U1 spent about 30 days services while U2 spent five days; a

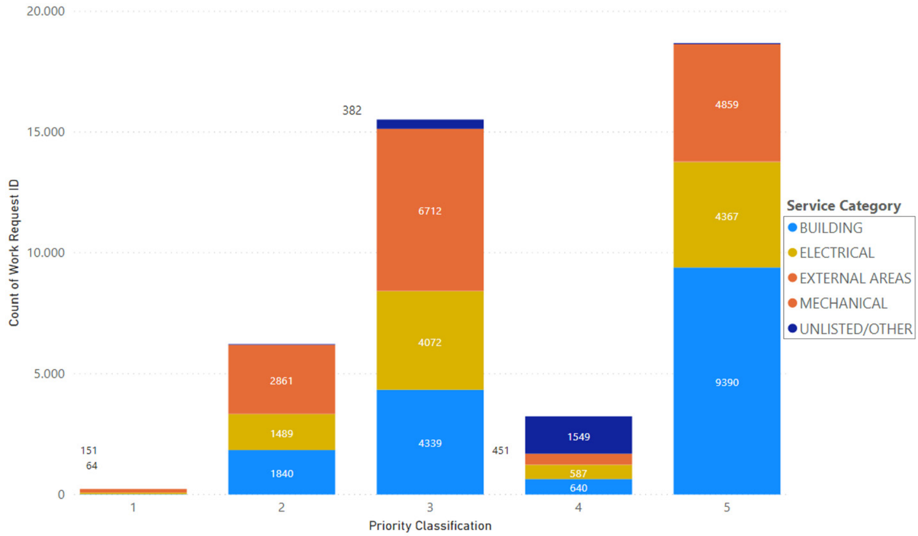

Figure 8.
U1 Distribution of reactive maintenance services category per priority level

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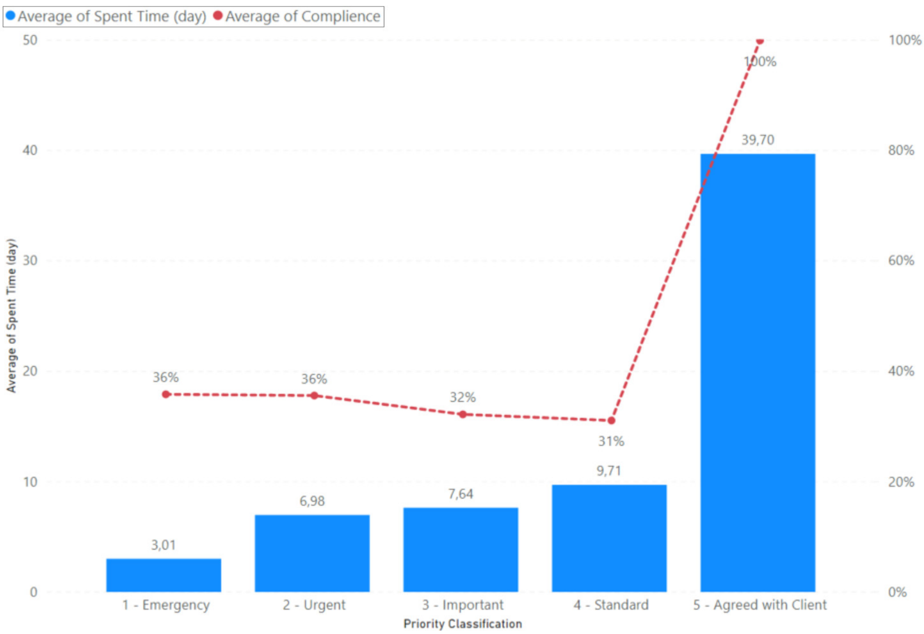

Figure 9.
U1 Average spent time for each priority service level and the percentage of compliance attendance requests attended on time

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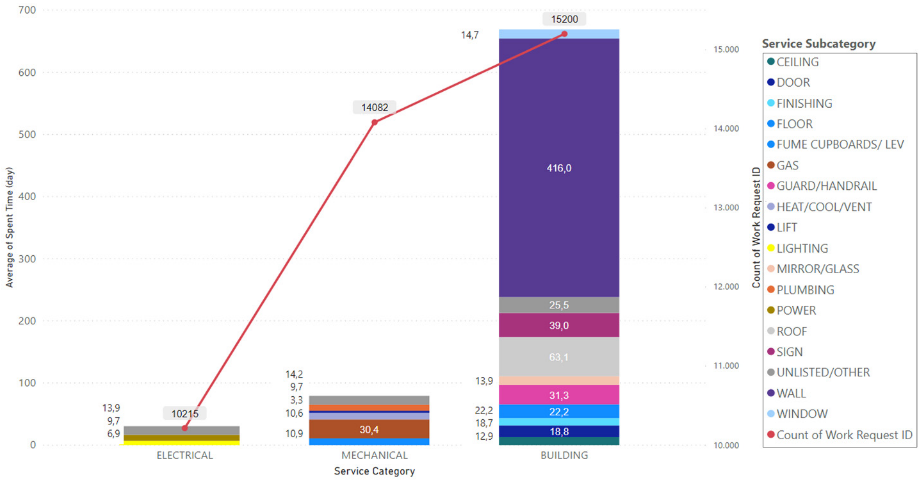

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Figure 10.
U1 Distribution of average spent time per service category and subcategory

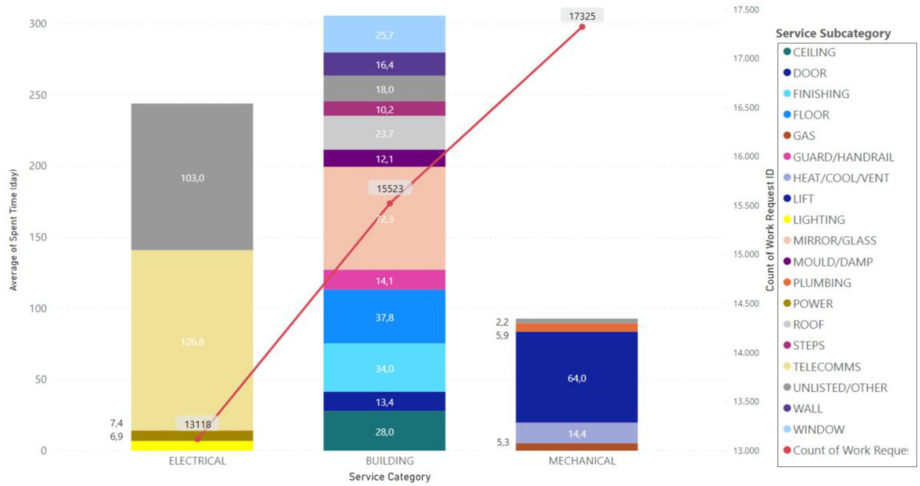

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Figure 11.
U2 Distribution of average spent time per service category and subcategory

similar average time spent was observed for electrical services in both universities, with around seven days for lighting and eight, five days for power services.

The variation in the average time spent on services was associated with the different strategies adopted by each university FM department for problem resolution, which, in turn, impact service performance; while the FM internal staff mostly provides U1 services, at U2, the O&M services are predominantly outsourced; differences in facilities and fault complexity which varied; and the criteria for service prioritisation being specific for each university, thus influencing the response time for similar problems.

The frequency of RM problem subcategories and their cumulative impact on the overall picture were previously analysed through a Pareto graph (Figures 12 and 13). 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),

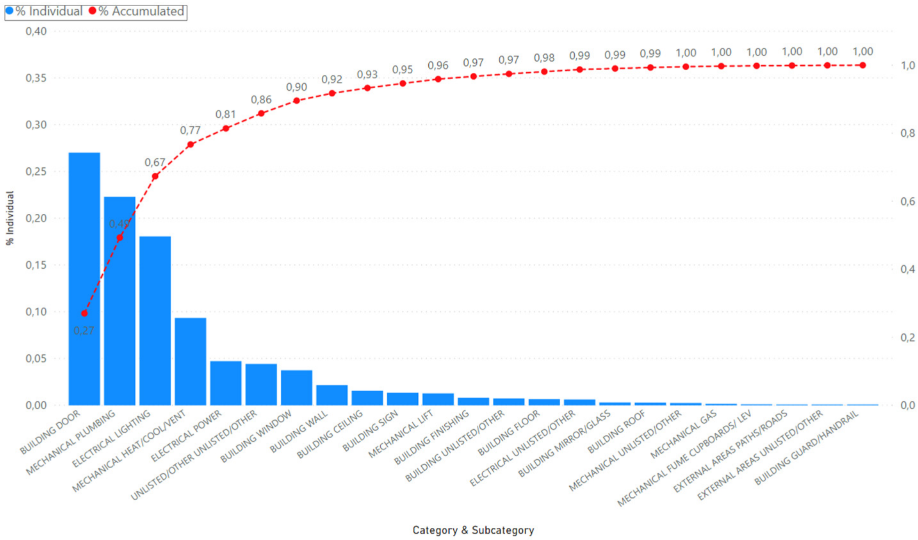


Figure 12.
U1 Pareto graph

Source: Created by authors

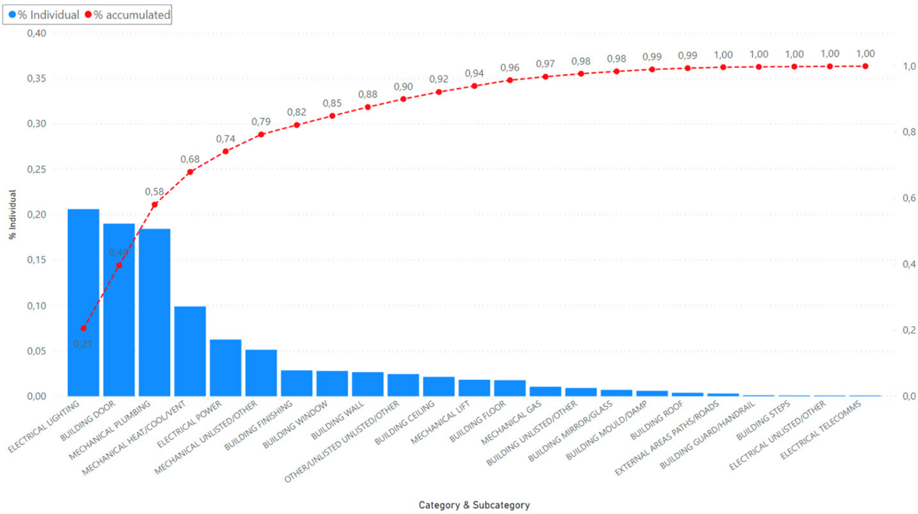
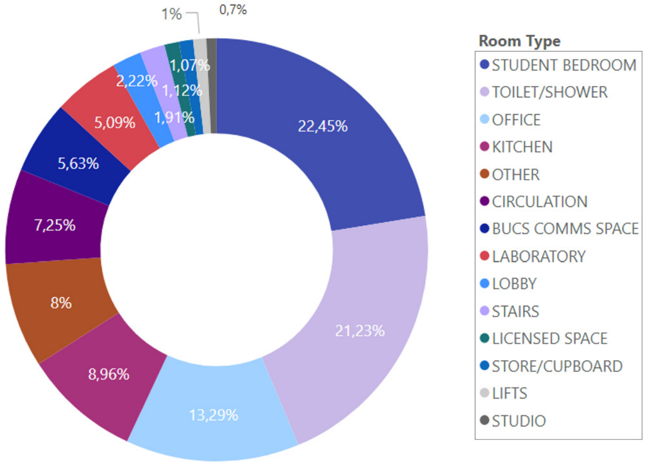


Figure 13.
U2 Pareto graph

Source: Created by authors

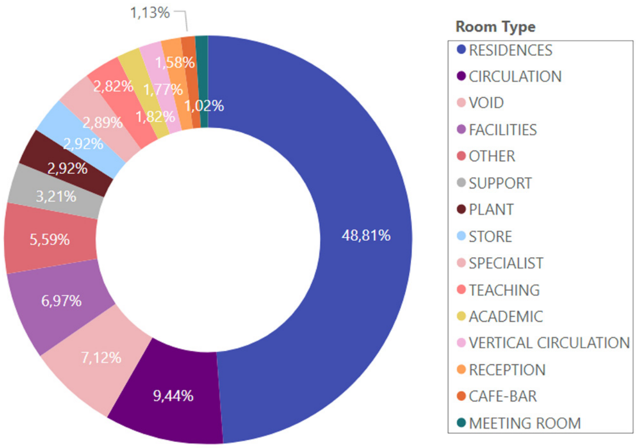
representing 81% of the whole U1 requests and 74% of the U2 requests. The results show a pattern in the frequency of RM problems despite the individual characteristics of each campus, which can be generalised to other similar organisations. Therefore, service improvement strategies must consider the highlighted problems associated with a risk assessment matrix.

Given the service's characterisation, a discussion about the RM WRs according to building characteristics variables was also proposed. The first analysed aspect is the request distribution per room type (Figures 14 and 15). At U1, the most recurrent damaged rooms are student bedrooms, toilet/shower, office, kitchen and circulation, representing



Source: Created by authors

Figure 14. U1 Distribution of work requests per room type



Source: Created by authors

Figure 15. U2 Distribution of work requests per room type

around 73% of the total requests, while at U2, residences, circulation, void, facilities, and support sum approximately 75% of the requests. However, the U2 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 WRs.

Student accommodation facilities, circulations and offices are generally predominant in both universities. The residents' intense use of their bedroom, toilet and kitchen justifies the likelihood of problems occurring and the interest in reporting faults, given the disruption caused to the students' routine. Furthermore, common spaces such as toilets, kitchens, offices, and circulations are shared by a large and diverse number of users over the day, increasing the probability of problems occurring. Besides, toilets and kitchens have complex facilities like plumbing and ventilation systems, which require maintenance more often than less complex rooms, such as meeting rooms and classrooms.

The distribution of WRs per building number of floors according to the building built area is depicted in Figures 16 and 17. At U1, a linear relationship was not observed between the number of floors or the building built area and the WRs recurrence. On the other hand, at U2, a trend for requests increasing in bigger buildings was noted. Figures 17 and 18 also highlight the (seven) buildings with more WRs in each university. Again, a predominance of residential buildings is observed, with six buildings at U1 (hosting around 1,600 students) against one administrative building and five at U2 against one administrative and one academic building.

The distribution of RM WRs according to building year of construction and heritage status was analysed (Figures 18 and 19). In general, unlisted buildings had the most WRs. However, a relationship between building age and problem occurrence was not observed. At U1, listed buildings are less representative, with fewer WRs in the studied period. Among the oldest facilities, the two residential listed buildings have a small built area (around 650 m^2 each) compared to other assets and, consequently, a smaller number of components,

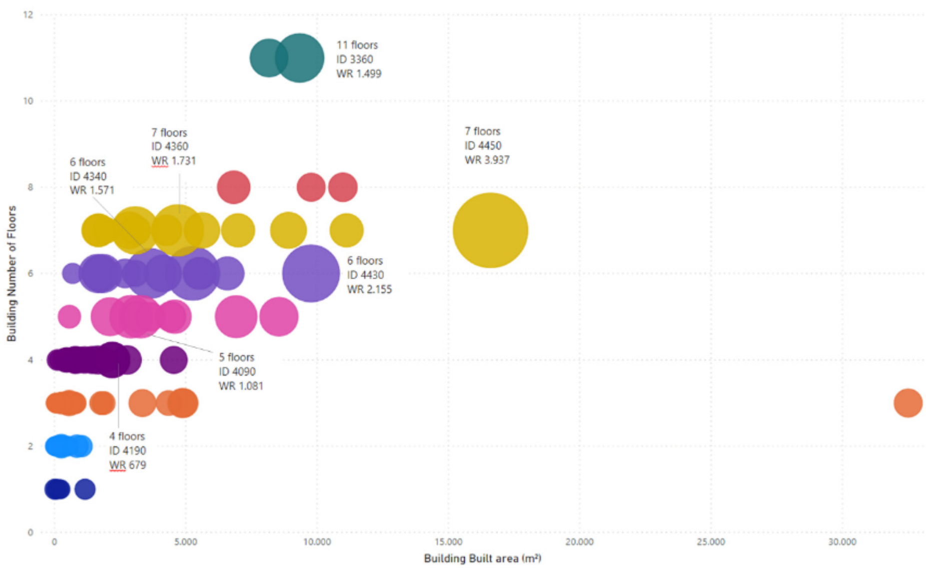


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Figure16.
U1 Distribution of work requests per building number of floors according to the building built area

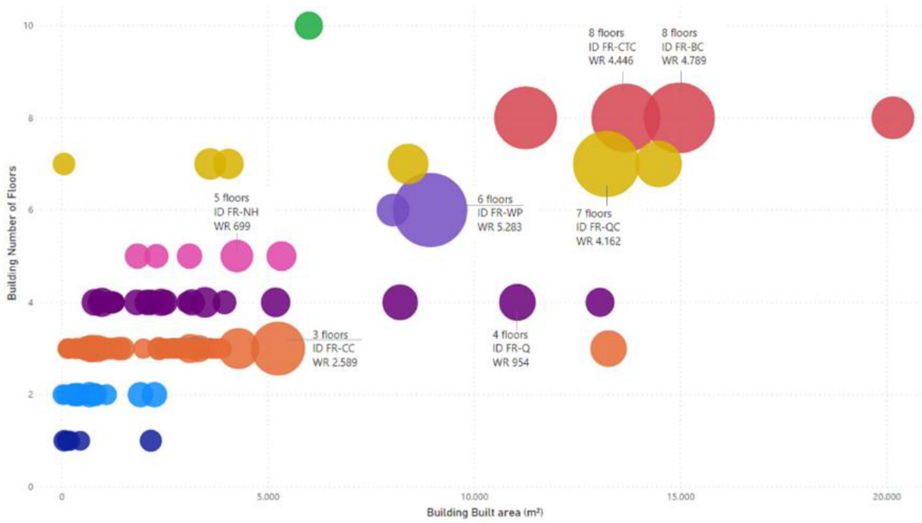

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Figure 17. U2 Distribution of work requests per building number of floors according to the building built area

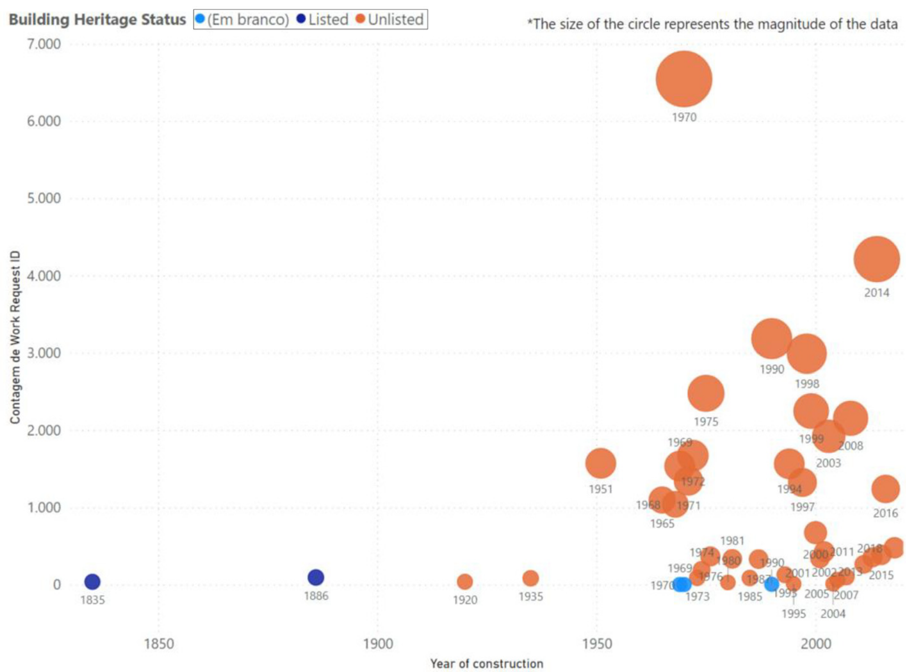

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Figure 18. U1 Distribution of work requests according to buildings' year of construction and heritage status

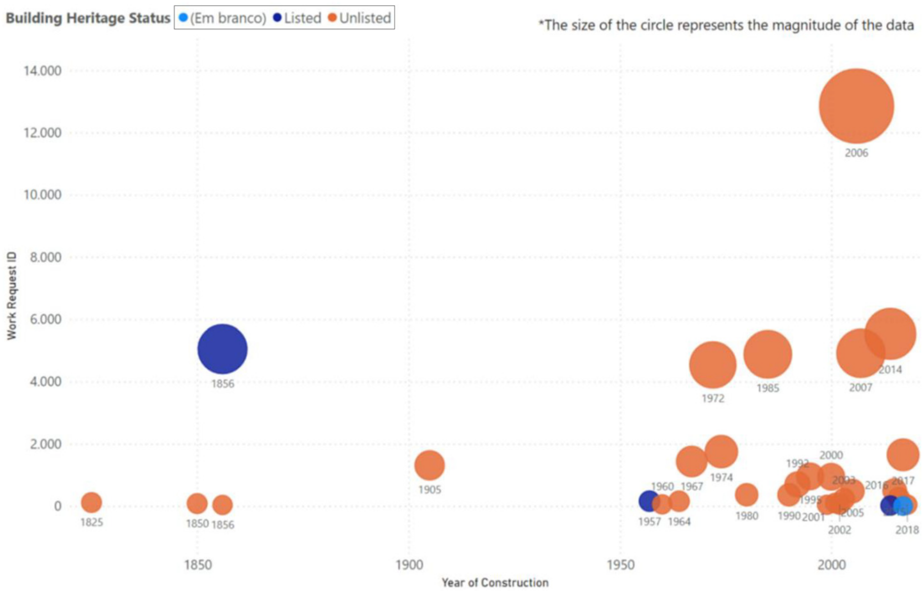

Figure 19.
U2 Distribution of work requests according to the buildings' year of construction and heritage status

Source: Created by authors

equipment and users, which explains the results. Within the unlisted cluster, buildings from the 1970s have the most WRs, including eight student accommodation buildings, five academic and research buildings, and one sports centre. These buildings, together, have approximately 50.000 m^2 of built area and are used by 750 residents daily.

Similarly, U2 unlisted buildings are the most representative in the overall WRs context, particularly those built in 2006, 2007 and 2014. The group of buildings from 2006 had 12.852 WRs, including three student accommodation buildings with circa 38.000 m^2 and 545 requests. Furthermore, 24 listed buildings also had a significant number of WRs (5.043). The three buildings with the most WRs were two student accommodations, with approximately 970 m^2 and 432 requests and 714 m^2 and 379 requests, followed by an academic building, with about 6.000 m^2 and 418 requests.

Statistical analysis

The statistical analysis of the U1 and U2 RM WRs supported identifying the degree and direction of influence of the selected building characteristics on RM problem occurrence per square meter and response time. The analytical steps taken were: firstly, only the WRs categorised as "reactive maintenance" in the FM group were selected, corresponding to 88.824 WRs. Secondly, the unit of analysis was determined aiming to cluster identical requests according to the variable's university ID, site ID, building ID, room ID, room type, floor ID, service category and service subcategory. This process resulted in 45.143 WRs. Subsequently, requests with missing building characteristics data were excluded, remaining 41.933 WRs.

Based on the above process, the dependent variables were defined, including *problem occurrence*, calculated from the number of requests per square meter, and *response time*, corresponding to the average time spent on RM service subcategories. The decision to divide the number of requests per square meter was taken to standardise the unity of analysis and avoid the bias of bigger buildings. A similar strategy was adopted by Gunay *et al.* (2018) in the investigation of heating, ventilation, and air conditioning (HVAC) WO 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 into 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 2 depicts the dependent and independent variables selected for analysis, organised according to the code, name, definition and level of measurement.

Figure 20 shows the independent variables most influencing the problem occurrence by decrescent order of importance. The variables with negative influence were

Code	Name	Definition	Level of measurement
Dependent variables (services characteristics)			
WR/m2	Occurrence	Corresponding to the number of requests per square meter (e.g. 100/m^2)	Metric
TIME	Response time	Corresponding to the average time spent on reactive maintenance service subcategories measured in days (e.g. 10.5 days)	Metric
Independent variables (building characteristics)			
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. seven)	Metric
Year_ Construction	Year of construction	Corresponding to the year the building was constructed (e.g. 1995)	Metric
Floor_ID	Floor ID	Corresponding to the floor level identification (e.g. 1, 5, roof)	Nonmetric
Room_Type	Room type	Corresponding to the functional type of room (e.g. bedroom, kitchen)	Nonmetric
Building_Heritage_Status	Building heritage status	Corresponding to the building heritage status (i.e. listed, unlisted)	Nonmetric

Source: Created by authors

Table 2. Statistics analysis variables

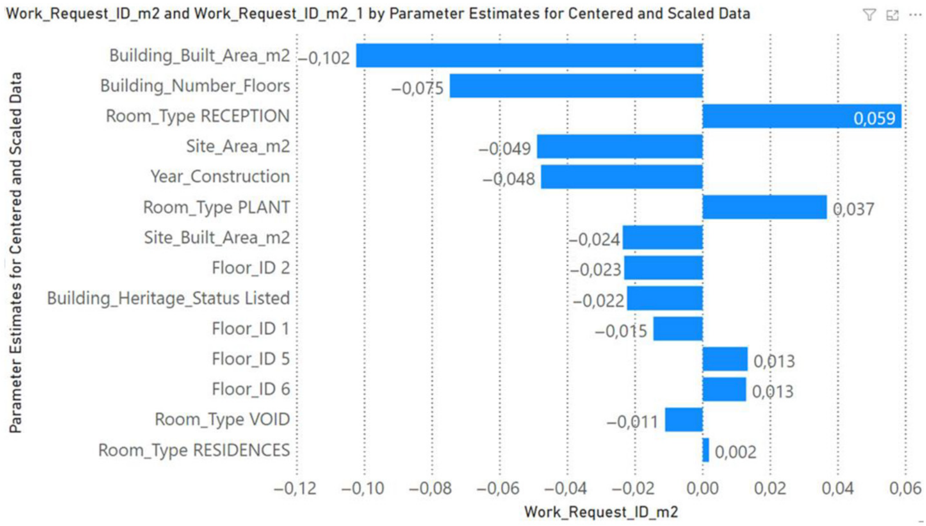

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Figure 20.
Parameter estimative of PLS analysis tested for the dependent variable WR/m^2 sorted by absolute value

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.

Regarding fault occurrence, the results show nine variables with negative influence and five 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 increasing building and site sizes contributes to reducing RM problems occurrence. Even though larger buildings and sites tend to have more complex facilities and equipment, problems are more associated with the environment's functionality than the asset size. In their study, Yacob *et al.* (2019) did not identify a significant contribution of building size to defects' occurrence, which was corroborated in this research. On the other hand, previous research has discussed the positive impact of building area and height on maintenance costs (Ali *et al.*, 2010; Krstić and Mareniak, 2012; Olanrewaju and Abdul-Aziz, 2015; Perera *et al.*, 2016; Salleh *et al.*, 2016), which could not be examined in this work.

The "Year of Construction" variable also had a negative impact, demonstrating that the older the building, the greater its fault occurrence. As previously discussed, the deterioration of building components and the necessity for technological improvements over time contribute to this result (Bortolini and Forcada, 2020; Ofori *et al.*, 2015; Talib *et al.*, 2014; Yacob *et al.*, 2019). For example, Gunay *et al.* (2018) have identified a predominance of HVAC WRs in older buildings, indicating a necessity for more maintenance efforts. Similarly, Abdul-Lateef (2010) verified that building age was one of the most influential criteria concerning university building maintenance management. In addition, some studies describe the influence of building age on maintenance costs (Abdul-Lateef, 2010; Ali *et al.*, 2010; Krstić and Mareniak, 2012; Ofori *et al.*, 2015; Perera *et al.*, 2016; Salleh *et al.*, 2016).

The negative influence of "Building Heritage Status Listed" was detected, meaning that listed buildings tend to have fewer RM problems than unlisted buildings. Although the building age has contributed to problem occurrence, the functionality of listed buildings (i.e. academic) and the number of users, have contributed to the result.

Distinct influences were observed among room category variables. Reception, Plant and Residences Room Types positively impacted service occurrence, which means that those environments tend to have more RM problems. The intense occupation for several users and the high likelihood of a failure being detected and communicated by a passer-by justifies the significance of reception. A similar condition is verified in residences, in which the permanent use of complex facilities (i.e. toilet and kitchen) and the willingness of users to report faults 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. The results are inconclusive regarding the plant and void room types 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, demonstrating that the first and second building floors do not contribute to increasing problem occurrence. The result explains the predominance of open spaces (e.g. halls, lobbies) with low complexity on the first floors. 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 was associated with the problem incidence.

The independent variables most influencing the response time are depicted in Figure 21 by descending 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,

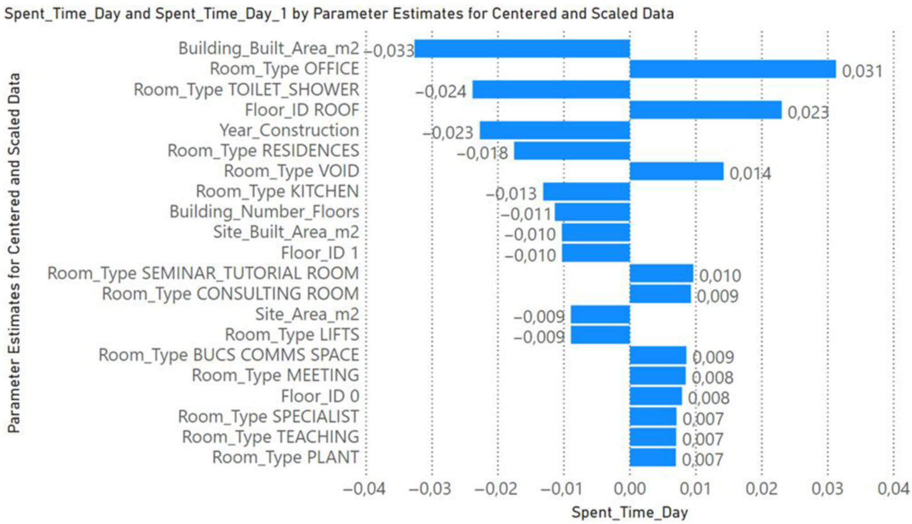

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Figure 21. Variable Importance in Projection (VIP) values of PLS analysis tested for the dependent variable TIME

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.

Concerning response time, ten variables with negative and 11 with positive influence were identified. The variables related to asset size – Building Built Area, Building Number of Floors, Site Area and Site Built Area – negatively influenced response time, which means that increasing building and site sizes contribute to reducing response time – as larger assets tend to impose difficulties in service completion. For example, finding updated information on building components and systems in FM databases, hampering service location, diagnosis and acquiring 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 variety of functionalities (e.g. teaching, administrative, residential, catering), causing a significant impact on user's safety and comfort and university activities.

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

Variables related to Room Type had a distinct impact on response time. Toilets, Showers, Residences, Kitchens and Lifts Room Types had a negative influence, meaning that fixing problems in these locations takes less time than in other rooms. Toilets, showers and kitchen facilities are essential for users' permanence in university buildings, particularly for residents, which might explain a faster response. Furthermore, the complexity of plumbing and electrical systems tends to be inferior compared to other rooms (e.g. laboratories), facilitating the diagnosis, acquisition of spare parts and repair. Considering the vertical transportation of equipment, the short response time is justified by users' safety and accessibility legal requirements in multi-storey buildings, particularly in cases involving people getting stuck in the lift. Also, specialised outsourced providers must perform lift maintenance calls according to contractual requirements.

Conversely, some room type variables have positively influenced response time, i.e. Void, Plant, Office, Seminar Tutorial Room, Teaching, Meeting, Consulting Room, Specialist and Bucs Comms Space, which means that RM services in these places take longer than in other rooms. As aforementioned, the lack of precision in classifying Void and Plant rooms imposes obstacles that prevent drawing conclusions from the results. The remaining variables refer to common spaces occupied by various users to develop administrative, academic and leisure activities. Inaccurate description of problem type and location, difficulties accessing busy spaces for problem diagnosis and the occasional necessity of interrupting activities for service repair justify prolonged response times.

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

Some limitations were identified in this research. The first relates to the consistency of the WRs data obtained. Although data on the costs of FM and RM services were requested from both universities' FM sectors, such information was not provided, thus limiting the analysis. Similarly, only one organisation (U1) provided data regarding the prioritisation of services, restricting the analysis of critical RM problems based on such an essential criterion. The distinct methods adopted by each university for organising and feeding WRs data into Excel spreadsheets also limited the research since a significant heterogeneity of data within and between organisations was observed. As a result, the useful sample of WRs and the statistical data analysis techniques were significantly reduced. Even though the volume of data analysed is large, further investigations are necessary to confirm the validity of the findings.

The second limitation refers to the degree of generalisation of findings from multiple case studies. Although the two universities are representative of the context intended for this investigation, some findings (e.g. the influence of room function on RM response time) were not supported by the literature, thus requiring further investigations for their validation (for instance, through additional cases, surveys with other organisations and focus groups with experts).

Conclusions

The analysis of empirical evidence provided by multiple case studies has provided the first detailed characterisation of FM RM services and processes to enable the identification of the most critical RM problems and scenarios for digital twin implementation through BIM and IoT.

Identifying critical scenarios for RM problems was undertaken based on the WRs' analyses, considering characteristics of problems, buildings and services. The descriptive analysis of data from the studies universities revealed a series of patterns:

- a concentration of requests within main campuses;
- a balanced distribution of requests per building, mechanical and electrical service categories;
- a predominance of low priority level services;
- a low rate of compliance in attending priority services;
- 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);
- a predominance of problems in student accommodation facilities, circulations and offices; and
- a concentration of requests in unlisted buildings.

In addition, the statistical analysis of RM requests supported the identification of building characteristics which significantly influence RM problem occurrence and response time. The variables were divided into two groups:

(1) with negative influence, meaning they do not contribute to the observed phenomenon; and

(2) with positive influence, meaning that they contribute to the observed phenomenon.

In both cases, variables related to asset size and age negatively contributed to the observed phenomenon, while variables associated with room function and location over building floors had a positive contribution.

This research is the first to apply statistical analysis to a substantial data sample of approximately 300,000 WRs. Patterns of problems (e.g. predominant site, service categories, priority levels and room types) and building characteristics of significant influence on RM problem occurrence and response time (e.g. size, area, age and function) were raised from the comparative analysis between cases. Our results partially corroborated the literature findings, evidencing both the novelty of the findings and the necessity for complementary investigations to validate the overall results.

This study is the first to demonstrate that the availability of many variables influencing RM problems in the built environment adds complexity to identifying root causes, which might be mitigated with reliable and accessible performance information provided by digital twins-based systems. Applying the findings to practice is also relevant for understanding procedural aspects involved in implementing BIM and IoT in the architecture, engineering, and construction (AEC) industry within a predictive approach. At the organisational level, the knowledge of the most likely scenario for the occurrence of RM problems may support the organisations in preventive actions forecasting failures occurrence and in planning financial, administrative and logistical requirements for their attendance.

This work can inspire new research, which can include the following areas for further advancements of the findings of this study:

- The development of models for the prediction of maintenance costs and maintenance problem occurrence through the application of artificial intelligence and machine learning algorithms;
- The 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, response time and costs;
- The exploration of other methods for analysing WRs data, such as text mining analysis, aiming at extracting meaningful patterns and information on critical maintenance problems; and
- We believe that our novel data-driven characterisation of RM can inform digitalisation strategies, which we estimate will help organisations worldwide directly save billions of $ in building maintenance costs and reduce millions of tons of CO2 emissions by converting RM problems into preventive and predictive maintenance. Therefore, more research is needed to explore the intricacies of such conversion. We are in agreement that this is such an important aspect to be investigated considering the current financial and climate emergency global context.

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