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A Building Inspection System to evaluate the technical performance of existing buildings

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ABSTRACT

The technical performance assessment of a building is essential for planning maintenance actions to improve its condition and functionality. The aim of this study is to present a Building Inspection System to evaluate the technical performance of existing buildings. To do so, a questionnaire survey to identify the defects that majoritarily affect the technical performance of a building was conducted. The system was then validated in a university campus including 22 buildings. The results revealed three main applications of the proposed system: a comprehensive asset analysis, a building operating analysis and a risk analysis system.

Author keywords:
defect, anomalies, inspection system, performance, maintenance, facility management, fieldwork, diagnosis

1. INTRODUCTION

The operational phase of a building is the main contributor to the building lifecycle cost, which proves the importance of building maintenance [1,2]. Building maintenance combines actions to keep the building in appropriate condition for use [3], including technical building inspections that provide the characterization of the building pathological state [4].

The main purpose of an inspection is to obtain useful information about the technical performance of a building [5]. Technical performance describes structural, physical and well-functioning building equipment [6]. This information can be used to predict a failure and plan further maintenance actions depending on the building performance. Despite the fact that each building is unique and presents different types of defects, it is possible to detect certain patterns when evaluating a significant sample of buildings [4]. A reliable database that provides guidance to prevent and repair can be established through the systemic analysis of data collected during these inspections [4].

Currently, there is a lack of systems and customs of the evaluation of buildings in real conditions of use [7–9]. The absence of standard assessment methods of the building's pathological situation may result in misdiagnosis on the part of the inspectors [4]. The inspection should not be technically exhaustive, as well as the gathering of information in an organized way is a fundamental for a well-informed decision-making process [10]. Therefore, an objective building inspection system to assess the technical performance of existing buildings is needed.

The aim of this paper is to devise a Building Inspection System (BIS) to evaluate the technical performance of existing buildings. The defects within the building elements and systems that majoritarily affect the performance of a building were identified in a questionnaire survey. Then the proposed building inspection system was applied in a university campus comprising 22 buildings to test its validity.

2. TECHNICAL BUILDING INSPECTION

The technical performance reduces with the passage of time, in which technical inspections can be conducted to assess their state. Technical building inspections are considered mandatory by some cities and countries. Some legislation forces builders and/or owners to implement them. In Hong Kong, for instance, the mandatory building inspection scheme is designed to cover buildings aged 30 years old or above [11]. Once every ten years, it requires building owners to carry out inspection and repair works of the common parts of the buildings, such as the external walls, projections and signboards [11].

According to Chan et al. [11], Singapore, New York and Chicago have had their own building inspection schemes implemented since the 1990s. In Singapore, the target buildings requiring inspection comprise non-residential buildings up to the age of five years and residential buildings up to the age of ten years old. In contrast, no age limit is specified in both New York and Chicago [11].

In some countries, there are laws to ensure the execution of technical inspections. In France, there is a great focus on inspection, recording and processing all the inspection information [2]. Insurers often require a technical inspection to be carried out as a prerequisite for issuing an insurance policy [12]. As for Spain, there is an obligation to prepare a technical inspection report on those buildings older than 50 years. Further inspections must be made each 5 years after the first one. The technical inspection consist in a type of preventive legal maintenance, whereby the buildings are routinely subject to the review of a series of factors that affect the safety of the building and of the persons that occupy it.

Generally, the scope of technical inspection concentrates on the main building elements. Systems are mainly checked in preventive maintenance actions (Table 1).

>Insert Table 1. Building elements and systems (based on [13–15])

Building elements are the civil and architecture elements of the building. Few owners understand the need for a preventive maintenance on these elements. Maintenance activities are based on reactive actions when a problem has occurred [16]. The absence of adequate building maintenance policies, led to the current degradation of the building stock and to the early ageing of building elements [2].
On the other hand, building systems are related to the plumbing, electrical, HVAC, elevator and fire systems. Generally, these systems have its own preventive maintenance with statutory legal requirements and standards [17]. For instance, make regular legionella test, perform an inspection of boilers at regular intervals, check periodically the fire extinguishers [17,18]. Some systems can have a building automation system (BAS), which consist of a system installed that controls and monitors building services responsible for heating, cooling, ventilation, air conditioning, lighting, shading, life safety, alarm security systems [19]. Alarm events capture a defect of some device, and the information pertaining to an alarm indicates the apparent source of the problem [19].

Building defect is the term used to define a failing or shortcoming in the function, performance, statutory or user requirements of a building, and might manifest itself within the structure, fabric, services or other facilities of the affected building [20]. Defects in building elements are visually easy to detect in building inspections while, those defects in building systems do not usually have visual signs so they are more difficult to detect. Therefore, tools such as thermography can be used to detect some systems' defects like leakages in pipelines, loose and corroded connections in electrical installations [21]. Thermal cameras can also be used in buildings elements to detect energy related defects such as moisture problems, structural defects, missing or damaged thermal insulation in walls and roofs, thermal bridges and air leakages [22,23]. Although defect detection in building systems is difficult, BAS allow automatic fault detection and thus corrective maintenance can be planned. A holistic BIS should incorporate a procedure to analyze both building elements and system performance. To do so, defects in both building elements and systems should be determined.

Previous studies have focused on determining defects classification systems and defect analysis for specific building element or system, such as façade [24–26], wet areas [24], electrical and plumbing systems [13]. However, none of them propose a holistic assessment, they are incomplete and susceptible to misinterpretation, allowing for their inaccurate use, which requires an integration of a global analysis perspective [4].

3. RESEARCH APPROACH

The research approach consisted on a questionnaire survey to determine the most influential defects that affect the technical performance of buildings with a generic view. Then, based on the classification system for defects and a severity rating, a building inspection system was devised to determine the technical performance of an entire building. Inspections in a university campus comprising 22 buildings were conducted to validate the proposed inspection system.

3.1 Questionnaire Survey

In this survey, it was attempted to identify the most influential defects that affect the performance of a building. A questionnaire for an online survey was developed on the basis of existing studies and survey instruments. Prior to a full scale survey, a pilot survey was carried out with a researcher and a maintenance expert of the Universitat Politècnica de Catalunya (UPC) to test and verify the survey. The questionnaire was refined based on the pilot survey feedbacks.

The questionnaire was divided into the following sections (Appendix A):

- Section 1: Interviewee's details, including academic and professional background, and years of experience (as a Facility manager / Maintenance / Energy manager / Asset manager / Construction Manager / Designer / Consultant).
- Section 2: The second part contained several questions regarding the technical performance of construction elements and systems. A list of potential defects that might appear in each building element and system based on existing studies [10,13,22,24,26–31] was provided to interviewees (see Appendix A). Interviewees were asked to select at most 3 main defects for each building element and system and it was given the option of adding other defects they considered relevant.

3.1.1 Sampling characteristics

Facility managers were chosen to determine the most influential defects, as they have a holistic view of building management, are the responsible to conduct or manage technical inspections and their most immediately relevant activity is building diagnostics [32].

The survey was administered online, which allowed quick, easy access and systematic collection of responses. The survey was distributed in two languages, English and Spanish, so that it was accessible to international professional experts. It was distributed to associates of the International Facility Management Association (IFMA). IFMA is the main facility management association and its members are professionals with experience in asset management, maintenance, and energy management, among other

fields. One hundred and twenty industry practitioners were randomly selected then approached by email. A total of 53 valid responses were received, representing a response rate of 44.1%, which is satisfactory and suitable for this kind of analysis [33].
Of the respondents, 86.8% had a technical degree (engineer or architect) and 13.2% were technicians. To highlight the expertise of the answers, 51% of the respondents had more than 20 years of experience, 34% had between 11 and 19 years, and 15% had less than 10 years of experience. These experts had a high level of expertise in building performance, due to their professional activity. Most respondents had experience in maintenance, energy management and consultancy on FM. Additionally, some experts had experience in design and construction management.

3.2 Building Inspection System development

Based on the results of the survey, a Building Inspection System (BIS) was presented. A severity rating depending on the defects' impact on the building and its occupants [15] and according to the repair urgency [2,10,34–36] was proposed:

1. Severity 1: Low impact. Defects related to aesthetics aspects, requiring simple repair or monitor the evolution of the defect at the next inspection. A not intervention action does not imply the progression of the defect.
2. Severity 2: Moderate impact. Defects that jeopardize the function of the element/system and it is prejudicial to use and comfort, requiring a moderate/complex repair within 6 months.
3. Severity 3: Severe impact. Defects that could compromise the occupiers' health and safety, requiring an immediate intervention. Non-intervention may result in the element's collapse and may increase the element degradation.

Figure 1 illustrates three cases of severity levels on construction elements.

>Insert Figure 1. Examples of defects: Cracking on structure element with severity 3 (left), detachment/broken of façade covering with severity 2 (centre), corrosion on plumbing with severity 1 (right).

The BIS should be agile and easy to record building defects. Information technology tools can help to capture on-field data directly. A considerable amount of research has been done on the use of ICTs, and more precisely on mobile technology to assist construction industry fieldwork and improve existing process management [37].

As an example, the mobile application Pick & Go [38] can be used for tracking on-field information. The basic concept of the application is to use images as a unique entry point to capture information on-field, and to spend an initial, but limited, analysis time by adding standardized tags from a classification system to contextualize the image. The use of tags prevent ineffectiveness such as that caused by arbitrary descriptions of observed issues, inconsistent references to the same project information, or inconsistences in the fields form [27,39]. The structured way of capturing information allows the creation of a database and the generation of automatic reports (including images and their description based on the selected tags), and makes it easier to analyse the information, due to the standardized vocabulary that is used. Each image captured is associated with an XML file containing all the attached information. This information is connected to a Dropbox account, which permit access to the file to add or modify it and to prepare basic statistics.

3.2.1 Validation of the Building Inspection System

The proposed BIS was validated in a university campus comprising 22 buildings. Each building was analysed individually during one day by the same inspectors (inspectors were taken by maintenance staff of the buildings), compelling 8 hours for the inspection of each building. All inspections comprised a period of 4 months due to the availability of time to do the inspections. The mobile application Pick & Go [38] was used to collect on-field data. The tags used to categorize the defects were: type of defect (based on the questionnaire results), the affected building element/system and severity.

4 QUESTIONNAIRE SURVEY RESULTS

The questionnaire survey results are organised by construction elements (structure, façade, roofing, flooring, interior partitions, doors/windows) and systems (electrical, plumbing, HVAC, fire, elevator).

The most influential defects that affect the building regarding the structure are illustrated on Table 2. The experts selected cracking (52.8%), water problems (45.3%) and deformation/settlement (43.4%) as the defects that predominantly influence the performance of a building. Likewise, Hovde and Moser [40] highlighted the importance of monitor cracking and spalling in the structure of the building to estimate the durability of the structure. Moreover, water problems such as the moisture content in the structure was also considered critical and present a high risk of structural damages by previous study [40].

>**Insert Table 2.** Responses frequency of the most selected defects on structure and façade

In the façade, respondents (Table 2) selected water problems, cracking and detachment/broken as the defects that mainly affect the performance of a building, representing respectively 64.2%, 54.7% and 41.5% of the responses. Similarly, Rodrigues et al. [29] identified in a study the main facades anomalies consisting of water problems, cracking, detachment and problems in the surface appearance. The impact importance of these defects have been pointed out by several other studies on façade pathologies [8,41,42]. Water problems on a façade are related to penetration damp, rising damp and water ingress [27]. Excess moisture, is the most widespread and damaging cause of deterioration and decay affecting buildings [20]. Crack is one of the most common defect on a façade and detachment is related to the façade covering that might be detached or broken.

As illustrated on Table 3, the vast majority of the respondents (77.4%) considered that water problems in the roofing are the most critical for the performance of a building, such as leaks, moisture and entrapped water. Cracking (39.6%) and biological action and change (35.8%) were also considered critical. Biological action and change was also identified in previous researches as an important defect on the roof, which is associated with plants growth on the roof, birds action, gutters clogged with leaves, among others [43].

>Insert Table 3. Responses frequency of the most selected defects on roofing and flooring

The results (Table 3) shows that problems with detachment/broken of the floor covering and cracking (52.8%) are the defects that predominantly affect the building performance. Chon and Low [44] also identified that tiles delamination is one of the main defect on the floor by the action of occupants. Moreover, surface problems, such as efflorescence, uneven, hit/scratch, soiled and discoloration of the floor covering, were also considered relevant by the respondents and previous studies.

In the interior partitions (Table 4), according to other studies [44,45], 60.4% of the respondents found that cracking is the defect that mainly affects building performance. Moreover, 54.7% of the respondents selected surface problems, such as paint peeling and blister and 50.9% selected water problems, such as excess of moisture. Problems with surface appearance and water were also identified by [44].

>Insert Table 4. Responses frequency of the most selected defects on interior partitions and doors/windows

Regarding doors/windows (Table 4), the majority of the respondents (75.5%) considered that operational faulty functioning is the most critical defect for the performance of a building, which is related to a mal function of the use of the door or window. In this elements, Chong and Low [44] have identified the malfunction of the ironmongery in doors as a specific operational faulty functioning. Water problems (39.6%), such as water ingress, humidity, mould in the window frames was the second defect more selected. Then, according to [44] surface problems (37.7%), such as paint peeling, were also considered important .

Considering the electrical system, the experts considered that operational faulty functioning in the electrical fixtures (58.5%), in the electrical distribution elements (58.5%) and in the electrical supply elements (52.8%) are the defects that mainly affect the performance of a building as illustrated on Table 5. These defects cover all the electrical system in an extensive way. The well-functioning of the electrical system is so critical, that electrical problems are the ones that have a higher impact on the users health [43], therefore, the preventive maintenance of the electrical system should be verified and checked.

>Insert Table 5. Responses frequency of the most selected defects on electrical and plumbing systems

In the plumbing system, leakage in water distribution elements (pipes) was the defect selected by 59.1% of the respondents, as illustrated on Table 5. Previous studies also identified that leakage at pipe penetration and joints are critical defects in the plumbing system [13]. Moreover, operational faulty functioning of water supply elements, which is related to problems with temperature, pressure, water level, vibration, was selected by 37.7% of the respondents. Corrosion in water distribution elements was also considered relevant by 34.0% of the respondents.

The results (Table 6) shows that 54.7% of the respondents found operational faulty functioning of HVAC production elements as the most critical defect in the HVAC system, such as chiller malfunction, noisy boiler, mechanical problems, fan motor failure. Specific defects related to HVAC malfunctions were also defined by [46]. Moreover, operational faulty functioning in HVAC fixtures elements (34%), such as thermostat malfunctions, excessive noise and vibration of air unit was also considered critical. Accumulation of dirt in HVAC distribution elements (30.2%), such as in air ducts was also considered relevant.

>Insert Table 6. Responses frequency of the most selected defects on HVAC and fire systems

In the fire system, operational faulty functioning of fire fixtures, such as sprinklers, fire extinguisher, is the defect most critical selected by more than a half of the respondents (66%) as shown on Table 6. Operational faulty functioning of water supply elements (35.8%) and fire fixtures broken (34%) were also considered important. Moreover, a regular routine with respect to the fire equipment maintenance need to be established and verified [47].

In the elevator, the majority of the experts agreed that operational faulty functioning of distribution elements (77.4%) and operational faulty functioning of elevator cabin elements (67.9%) are the most critical defects (Table 7). Park and Yang [48] identified the hazards and their corresponding causes and effects of problems in elevators, which concludes that the routine maintenance of elevators should be carefully planned to mitigate the risk of accidents.

>Insert Table 7. Responses frequency of the most selected defects on elevator system

The experts were asked if they agree that these terms cover the main potential defects that might appear in a building. Nearly all experts agreed that these terms are the most important defects (92%).

5 BUILDING INSPECTION SYSTEM TO EVALUATE THE TECHNICAL PERFORMANCE OF EXISTING BUILDINGS

The Building Inspection System (BIS) to evaluate the technical performance of existing buildings consists of three main steps: (1) characterize the building to be inspected, (2) determine the defects on the building elements and systems that majoritarily affect the building performance, and (3) assess the severity and recommend maintenance actions.

5.1 Characterize the building

The first step consists on the characterization of the building to be inspected through a brief description of general and technical information of the building. The general information consists on defining: type of the building (main use), location, gross floor area, year of construction and number of floors. The technical information consist on specifying: type of foundation, type of structure, type of façade, type of roofing, type of flooring, type of HVAC system, type of hot water generation, type of electrical system.

5.2 Inspection of main building elements/systems

The technical inspection should be conducted in an objective way detecting the defects that majoritarily affect the performance of a building. Where an area or location cannot be accessed or inspected adequately, tools such as thermal cameras or laser scanning can be used to detect problems [49]. The extent of each defect should be measured using expedient methods, like photography, thermal cameras and measuring tape as reference [2]. Mobile techniques such as Pick & Go [38], can also be used to gather on-field data directly, so that will help posterior data analysis.

The inspection starts from the underground levels (if exist) to the ground floor and the upper levels. Underground levels inspection will help on analyzing potential defects in the foundations and structure. Depending on the location, direction, length and width of cracks in the structure and envelope, inspection might determine the causal factor of these cracks (settlement, structural deformation or hygrothermic problems). Settlement and hygrothermic problems may occur due to exterior conditions. Hygrothermic problems happen due to the absorption of water into porous materials that causes an increase in the volume of the material and consequently provoke cracks. Conversely, a moisture loss tends to lead to a decrease in volume and corresponding shrinkage and cracking [20]. Settlement normally occurs in the early stages of a building and may be associated with the compaction or movement of the ground beneath the foundations [20]. The occurrence of cracking in this situation is predominantly diagonal and follows the vertical and horizontal mortar joints in brickwork. Still in the underground level, the flooring should be inspected for signs of water penetration such as dampness due to humidity coming from the ground.

If located in the underground level, the technical rooms of the HVAC system, plumbing supply and the electrical branch circuit wiring should be inspected. Regarding plumbing, operational faulty functioning of water supply elements should be detected, such as equipment malfunction, temperature, pressure, water level and vibration problems. Accessible shafts may be checked to detect corrosion of pipelines. In the case of existence of water tanks for fire systems, inspectors should check them, including the condition of pumps and valves. When inspecting the HVAC system, the inspector should check the operational functioning of HVAC production elements, such as chiller malfunction, noisy boiler, mechanical problems, fan motor failure.

Then, the ground floor and subsequent floors of the building may be inspected by checking the interior partitions and flooring. The detection of cracks on interior partitions and flooring should follow the determination of the causal factors of these cracks, for instance structural movement, overloads, lack of maintenance. Signs of water penetrations on interior partitions should be inspected to determine if the origin of the problem is external (that may come from problems with insulation on the roof or façade), or internal (that may come from problems on the plumbing, such as pipe leakage). Water problems such as damp patches on internal partitions surfaces, can be derived by rain that has saturated the wall or entered the construction through cracks in façade [20]. The general condition of all surfaces and floors should be checked for surface problems, such as paint peeling, blister, uneven, hit/scratch, soiled and discoloration. The causal factor of these surface problems might be due to the age and lack of maintenance. Moreover, the flooring should be inspected for detachment/broken in the floor's finish or covering.

When inspecting interior partitions, doors and windows should be checked for operational faulty functioning, such as difficulties in opening and closing. Moreover, inspect for water problems, such as water ingress, humidity, mould in the window frames and the origin of these problems that may be due to moisture filtrations from the enclosure system itself or from the joinery joint with the wall of the façade. Surface problems on doors and windows might also be detected due to the action of exterior conditions and lack of maintenance.

Furthermore, when inspecting air conditioned rooms operational faulty functioning in fixtures elements, such as thermostat malfunctions, excessive noise and vibration of air unit, obstructed grills or diffusers should be inspected. When possible, distribution elements (ducts) should also be checked for accumulation of dirt.

In restrooms, where reasonably possible, sanitary fittings, associated taps, traps, waste pipes and valves should be visually inspected and tested by normal operation only. All exposed plumbing parts should be checked for leaking or signs of trouble or deterioration. The water distribution elements (pipes) in false ceiling can be inspected using thermography.

After that, the inspector should access the roofing to inspect for points of infiltration of rainwater and signals of biological actions such as plants, action of birds, gutters clogged with debris. These problems may occur due to exterior conditions. Moreover, ponded water may occur due to either improper drainage or sagging of the roof deck. Lichens, mosses and other biological growths can colonise outside surfaces that present mineral salts and moisture [20]. Algae may also appear where there is concentration of humidity which may cause staining to the affected surfaces. In addition, if located in the roofing, the plumbing and HVAC systems may also be checked following the previous described procedure.

Finally, the exterior condition of the façade and exterior elements such as doors and windows should be inspected. Cracks, humidity and detachment of the façade elements should be checked. Cracks in the façade covering might be caused by structural problems or thermal dilatation. Especially in the encounter with hollows, the stresses that a wall supports produce tensions deviations which may cause cracks by the corners, and consequently, cause problems in windows such as deformation of window frame and broke window glass. Moreover, cracks on corbels and balconies occur usually due to the accumulation of loads of the enclosure. The inspection should check for detachments of the façade covering that might occur due to the action of climatic agents such as water, ice, wind on materials with a certain porosity. Problems of humidity from capillarity can be detected at the beginning of the facades and are usually manifested with stains, efflorescence, erosions and even detachments.

In the case of the building systems, the preventive maintenance should be verified if it is periodically undertaken. The inspector should also verify and check if the preventive maintenance is routinely done to form an overall opinion of the condition and the need for further investigation [50].

However, a visual inspection of the electrical system can be conducted assessing its general condition and warning those aspects that attract attention, such as exposed wiring, faulty connections, double tapping of circuit breakers. Inspections of some fire system elements are related to the electrical system, such as the inspection of the automatic fire detections (smoke detectors and fire alarms). The condition of sprinklers, fire extinguishers and hydrants should be also checked. The records of the regular testing and servicing of fire alarms, emergency lighting, fire extinguishers, sprinklers, smoke vents, fire curtains or shutters, should be reviewed [50]. Any discrepancies with the fire certificate or noncompliance with fire safety regulations and building regulations should be noted [50].

The state of the elements of the elevator, if the building has it, can be checked if is operating. In the cabin, the inspector should check operating control devices, emergency signal, operation of door closing. In the elevator machine room, the pipes, wiring and ducts should be visually inspected.

5.3 Applications of the Building Inspection System

The results of the BIS can be used as a:

a) **Comprehensive asset analysis:**
Holistic construction and systems asset analysis to develop building portfolio management strategies and a preventive maintenance program to protect its assets improving expected life cycle and optimal building performance.

b) **Building operating analysis:**
Analysis of the building's operating infrastructure to determine potential deficiencies and, once identified, determine corrective maintenance actions by repairing, retrofitting or substituting them.

c) **Risk analysis system**:
Evaluation of the global performance of a building and determination of performance labels (A, B, C, etc) to be used as a performance certification. Results of these levels of performance could be used by the administration to propose mandatory building performance evaluations to assess existing buildings and propose incentives for high-performance buildings. To do so, a causal analysis of defects should be explored.

As previously mentioned, defects are not independent which makes the need for creating causal models using appropriate tools. Bayesian networks (BN) has been recognized as one of the most successful complete and consistent tool to model causal relationships with uncertain data and have been extensively used to develop decision support systems in a variety of domains [51].

As an example, figure 2 illustrates the interrelation among façade defects and the causality chain within other exterior conditions such as age of the building, material, etc. These factors increase the probability of façade detachments or humidity to arise. These detachments can also be provoked by leakages in drainpipes hanged on the façade. These leakages can be due to piping corrosion and can also affect the performance of the HVAC system. Furthermore, if preventive maintenance in systems is properly done, then the probability of getting a higher performance rank increases.

>Insert Figure 2. Example of relationship among defects and other factors.

6 BUILDING INSPECTION SYSTEM VALIDATION

6.1 Case study characteristics

The case study consisted on 22 academic buildings of Campus Nord of Universitat Politècnica de Catalunya (UPC), located in Barcelona/Spain. The buildings comprise four modules (A, B, C and D) located in the same plot orientation, but they were built in three stages. The first one (A1-2, B1, B2 C1, C2, D1, D2) by the 1886, the second one (A3, A4, B3, B4, D3, D4) by the 1990 and the last one (A5, A6, B5, B6, D5 and D6) by the 1992. All the buildings have the same type of construction solution: reinforced concrete structure, flat roofs and masonry façades. Although using the same structural and construction characteristics, HVAC systems were different. Some buildings do only have heating by radiators but in the majority of them coexist radiators, air-water systems and multi splits for both heating and air conditioning. The main uses of the buildings is related to lecture, offices and laboratory activities. Table 8 summarizes the main characteristics of the buildings.

>Insert Table 8. Main characteristics of the buildings

6.2 Comprehensive asset management

A total of 2,097 defects were detected in the inspections in the campus. An analysis of the defect data revealed that the most common defects, as noted in Table 9, were: cracking in interior partitions, surface problems in interior partitions, cracking in structural elements, water problems in interior partitions, and corrosion in plumbing system. No defect was found regarding deformation/settlement on structural elements and accumulation of dirt in distribution elements in HVAC systems. Moreover, no defects were detected in fire system and elevators. The preventive maintenance of fire system and elevators was checked and done correctly.

>Insert Table 9. Number of defects by type

Figure 3 illustrates the distribution of each type of defect by severity in a logarithmic scale to better visualize the results. The majority of defects (57.2%) were located in the interior partitions. However, those detected cracks were minor and surface problems were related to low severe painting peeling problems.

>Insert Figure 3. Frequency of the defects by element/system affected according to registered severity in a logarithmic scale.

The most severe defects in the campus although being only 17% of the total defects were located in the structure, façade and roofing. Cracks in these elements are mainly caused by under reinforcement of the concrete structure and exterior agents. These cracks do not compromise the safety of the occupants but if not treated they can become more relevant and increase the severity of other defects such as interior partition cracking and water problems.

Plumbing defects were also found to be significant (10%) and do mainly include corrosive pipes. This fact is mainly due to the exterior and exposed piping systems with deteriorated insulation.

There were not many detected defects in HVAC systems and when so they were low sever. The university campus has a computerized maintenance management system (CMMS) to monitor complaints of end users, for instance, to capture problems regarding malfunctions of heating, air conditioning terminals, etc. Moreover, a BAS controls the heating and cooling production and provides alarms that identify problems based on system thresholds. These defects are solved at the time they appear or along the year so not detected in the inspection.

Based on the results of the inspections, modifications and improvements of the campus maintenance plan were proposed.

In general, a systematically analysis and inspection on building elements is not performed in the campus. As severe problems were detected on the structure and façade of some buildings due to the aging factor, an annual technical inspection should be planned as a preventive action to detect defects on initial stages. Preventive action such as sealing joints between roofing and façades should be included in the maintenance plan together with inspections after any severe storm.

Proper insulation maintenance including a well-sealed protective metal jacketing is recommended to piping systems. Periodic inspection of insulation systems should be undertaken to identify early failure signs of pipe insulation, especially corrosion under insulation problems.

Although low severe defects were detected in interior partitions, if no preventive maintenance is carried out, these defects can end up with serious humidity problems. Therefore, periodic inspections (bimonthly) are proposed. Some surface problems in interior partitions and flooring can be treated with cleaning actions or a local repair. Preventive measures to protect interior partitions against occupants and loads, such as installing metal or rubber protections on edges of walls in locations with high human and load traffic could prevent such defects.

Furthermore, measures to prevent water problems on doors/windows must be also planned. Distortion of doors/windows is likely to occur if moisture penetrates. Therefore, a protective painting should be scheduled with the aim to prevent future problems and decay of doors/windows.

Although using a CMMS to handle end user complaints and a BAS for monitoring systems, much data such as equipment's lifespan, type of materials is still paper-based [52]. The facility management campus department should invest on digitalizing such information to automatize all maintenance processes and handle massive data that is generated from managing all campus.

6.3 Building operating analysis

To illustrate the application of the BIS to analyse building operating three examples were selected. The results of the BIS on building B6 revealed that although detecting defects on the structure, roofing, interior partitions, doors/windows, plumbing and electrical systems, all of them are low severe and do not require direct intervention. Figure 4 shows the frequency of each type of defect detected on elements/systems of building B6.

>Insert Figure 4. Frequency of defects by element/system on B6

Analysing building B4-B5 (Figure 5), cracks about 25 mm width were detected on the slab around the abacus of one pillar. This was caused by a reduced anti punching reinforcement provided in the slab. Then reinforcement of the abacus is required. Furthermore, peeled cables in the electrical systems were detected. They should be repaired due to the risk of a short-circuit and, possibly, fire. Therefore, urgent corrective action should be carried out to substitute these cables. Although B4-B5 presented problems in interior partitions, they were low sever.

>Insert Figure 5. Frequency of defects by element/system on B4-B5

Building A1-A2 presented high problems of corrosion in the plumbing system, as illustrated on Figure 6. Plumbing pipes pass by the roof and the insulation of these pipes is in many cases deteriorated. The aggressiveness of the environment (proximity to the see) and the poor insulation of pipes were the main cause of the piping corrosion. However, pipes are still operative and no substitution is necessary. Only repair of insulation is proposed to avoid the process of corrosion and prevent potential future leaks. Regarding interior partitions, the majority of the problems were related to water dripping caused by condensation. This condensation occurs mainly on the coldest areas of the inner face of exterior walls and can be prevented by correct ventilation. The persistence of condensation on interior partitions may result in the development of mould and fungus or in the formation of efflorescence or crypto-florescence phenomena. Moreover, exposed wiring was detected on an electrical board on A1-A2, which requires to be fixed promptly.

>Insert Figure 6. Frequency of defects by element/system on A1-A2

7 CONCLUSIONS

A technical inspection is the foundation of any maintenance schedule to allow the allocation of resources and devise a proper maintenance plan to keep buildings in good performance. This study presented the development of a BIS for evaluate the technical performance of existing buildings based on a classification system of defects. The defects that majoritarily affect the technical performance of a building were identified by literature review and validated by a survey with facility management experts. The inspection system implementation goes through three main steps: building characterization, detection of defects, severity assessment and recommendation.

The BIS presented in this paper can be a useful and practical method to evaluate the technical performance of existing buildings. It provides very significant information on the most relevant defects on building performance and is undeniably useful for all actors and professionals involved in this area. Through the conduction of the proposed inspection system, a holistic overview of the current technical performance of buildings can be examined due to consider all building elements and systems. The standardization of the inspections minimise subjectivity and ensures accuracy and reliability. A mobile app to help on the inspections was also presented.

The results of the inspections may support a comprehensive asset analysis by strategic preventive maintenance recommendations. Then facility managers can improve their asset portfolio management improving maintenance plans and planning preventive measures so that factors that may favour pathological phenomena do not build up. This will help to achieve a building stock of higher quality and, most probably, lower overall associated costs.

The BIS can also be used as a building operation analysis. Results of the building inspections can be used to define corrective actions to the defective elements/systems and optimize the life cycle costs of facilities. Moreover, the inspection system can be used as prenormative basis of standardized inspections for built-assets that required an officially inspection.

The BIS was validated in a university campus comprising 22 buildings. The presented case studies have come to light the need to analyse the causal factors of those defects detected in the different building elements and systems so as to determine the adequate preventive and corrective actions. To do so, experts should be responsible to make the inspections, gather related data and subjectively evaluate their causality chain. However, BN can be used to create an easy risk analysis system and facilitate not only the causality analysis of defects but also the evaluation of a global performance of a building and determination of performance labels to be used in a certification system.

Future research should be focused on determining the causal relationships between defects to predict the performance of buildings and, consequently, reduce reactive and/or urgent repairs. The establishment of the relationships among degradation factors (e.g. external environment), defects, preventive measures, etc. will provide a better understanding of the behaviour of the building in the operational phase and facilitate the understanding of how defects appear and how to avoid and treat them. This makes explicit the multiple and often complicated nature of defects in a building and provides accurate information for decision making. These results analysis might help facility managers and researchers to evaluate and take appropriate actions to improve building performance.

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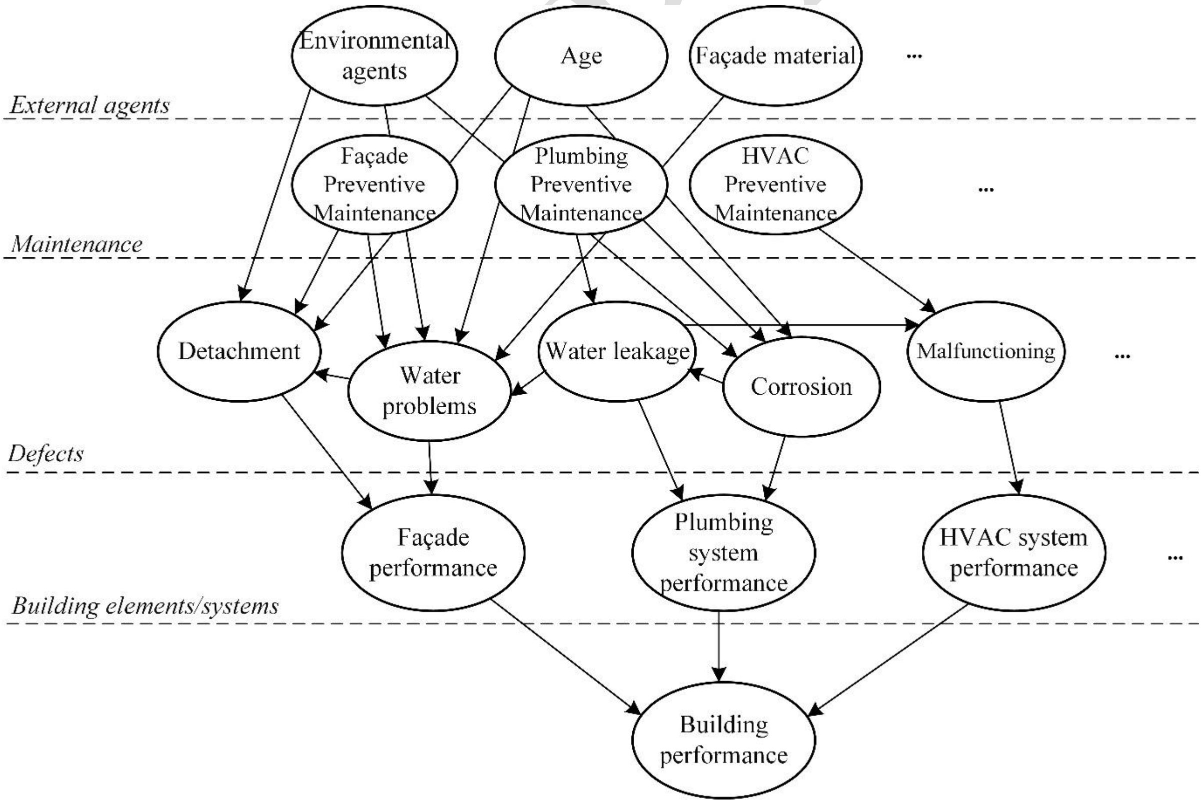
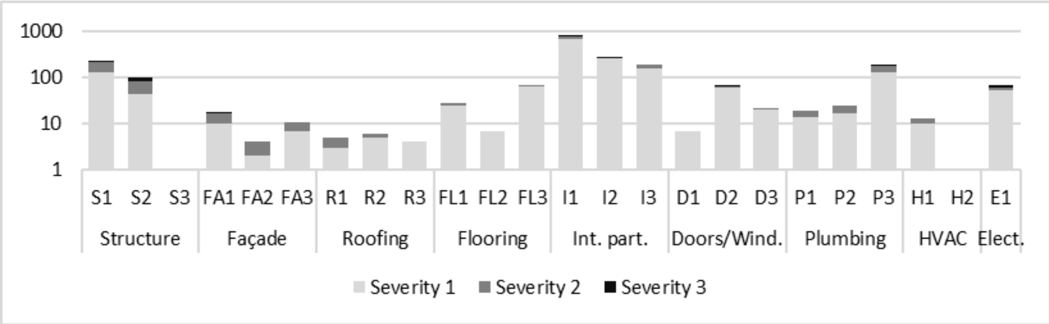
FIGURES

>Figure 1. Examples of defects: Cracking on structure element with severity 3 (left), detachment/broken of façade covering with severity 2 (centre), corrosion on plumbing with severity 1 (right).

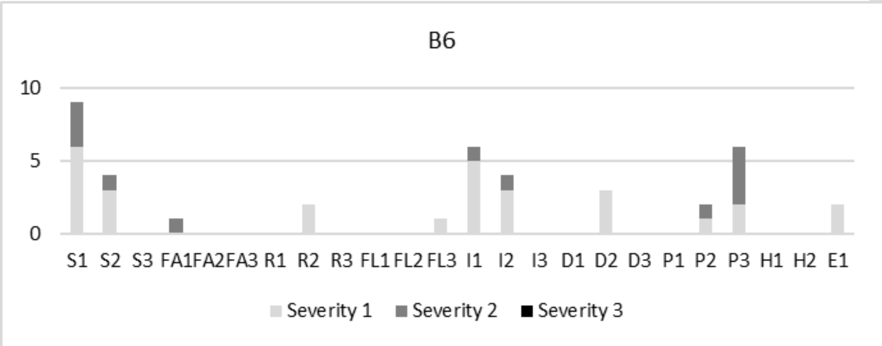
>Figure 2. Example of relationship among defects and other factors.



>Figure 3. Frequency of the defects by element/system affected according to registered severity in a logarithmic scale.



>Figure 4. Frequency of defects by element/system on B6



>Figure 5. Frequency of defects by element/system on B4-B5

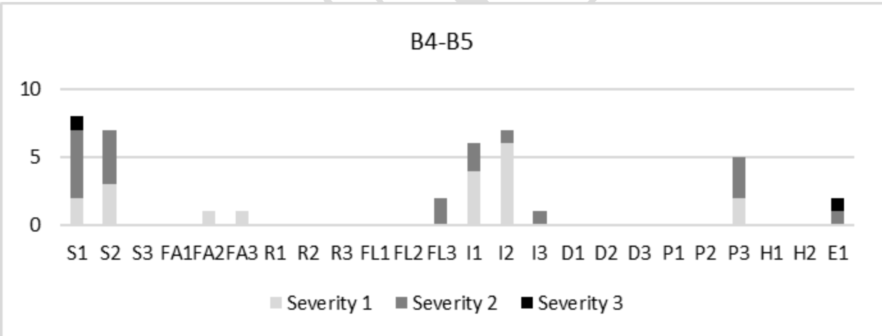
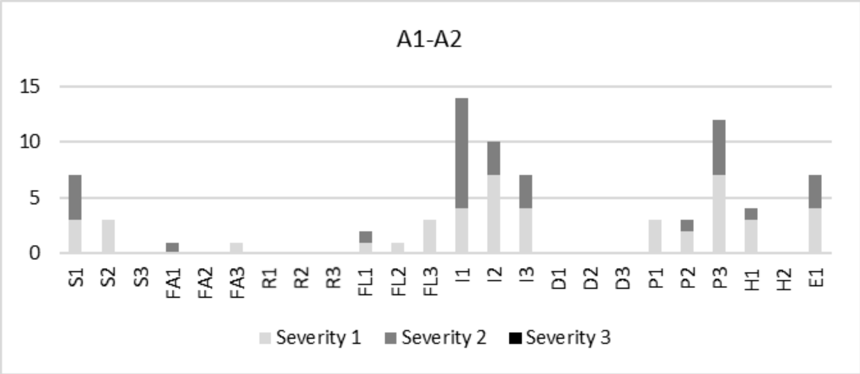


Figure 6. Frequency of defects by element/system on A1-A2



TABLES

>**Table 1.** Building elements and systems (based on [13–15])

Properties	Building elements	Building systems
Type	Structure, façade, roofing, flooring, interior partitions, doors/windows	Plumbing system, electrical system, HVAC, elevator, fire system
Maintenance	Regular cleaning and inspection	Test procedures, safety manual, operation manual, coding, warranty information
Replacement	Rare, sometimes impossible, e.g. basement	More frequent
Defects detection	Easy, usually has visible signs	Difficult, usually no visible sign
Automatic fault detection	Difficult	Easy, integrated with BAS
Effect on user	Indirect	Direct

>**Table 2.** Responses frequency of the most selected defects on structure and façade

Structure defects	Number of responses	% of the total response	Façade defects	Number of responses	% of the total response
Cracking	28	52.8	Water problems	34	64.2
Water problems	24	45.3	Cracking	29	54.7
Deformation/Settlement	23	43.4	Detachment/Broken	22	41.5