Enhancing building performance: A Bayesian network model to support Facility Management

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Summary

The performance of existing buildings is receiving increased concern all over Europe. A reason for this attention is the need to renovate the aging building stock and provide better quality of life for end users. The conservation state of buildings and the indoor environment conditions have been related to occupants' well-being, health, and productivity. At the same time, there is a need for more sustainable buildings with reduced energy consumption.

Most challenges encountered during the analysis of the performance of existing buildings are associated with the complex relationships among the causal factors involved. The performance of a building is influenced by several factors (e.g., environmental agents, occupant behavior, operation, maintenance), which also generate uncertainties when predicting it. Most previous studies that investigate methods to assess a building's performance do not consider the uncertainty and are often based on linear models. A scarce number of researches is focused on a causality analysis between the building operation and its systems, and how the building parts dynamically interact with each other.

Although different stakeholders' requirements regarding building performance coexist, few studies centered on the implications of these requirements. Previous studies tend to be highly specific on indicators related to a particular performance aspect, overlooking potential trade-offs that may occur between them. Therefore, a holistic and integrated approach to manage the performance of existing buildings has not been explored. Facility managers need an efficient approach to deal with uncertainty, to manage risks, and systematically identify, analyze, evaluate and mitigate factors that may impact the building performance.

Taking into account the aforementioned aspects, the aim of this thesis is to devise a Bayesian network (BN) model to holistically manage the operational performance of buildings and support facility management. The proposed model consists of an integrated probabilistic approach to assess the performance of existing buildings, considering three categories: safety and elements working properly, health and comfort, and energy efficiency. The model also provides an understanding of the causality chain between multiple factors and indicators regarding building performance. The understanding of the relationships between building condition, end user comfort and building energy efficiency, supports facility managers to unwind a causal explanation for the performance results in a reasoning process.

The proposed model is tested and validated using sensitivity analysis and data from existing buildings. A set of model applications are discussed, including the assessment of a building's performance holistically, the identification of causal factors, the prediction of building performance through renovation and retrofit scenarios, and the prioritization of maintenance actions. Case studies also allow to illustrate the applicability of the model for ensuring that its interactions and outcomes are feasible. Scenario analyses provide a basis for a deeper understanding of the potential responses of the model, helping facility managers to optimize operation strategies of buildings in order to enhance its performance.

The results of this thesis also include data collection methods for the inputs of the proposed BN model. A building inspection system is proposed to evaluate the technical performance of buildings, a text-mining approach is developed to analyze maintenance requests of end users, and a questionnaire is formulated to collect end-user satisfaction regarding building comfort. To conclude, this work proposes the use of Building Information Modeling (BIM) to store and access building information, which are typically disperse and not standardized in existing buildings.

Keywords: Building performance, facility management, building condition, building comfort, energy efficiency, causality analysis, probabilistic risk assessment, Bayesian networks, Building Information Modeling.

Contents

List of Acronyms

BEMS	Building Energy Management System
BIM	Building Information Modeling
BMS	Building Management System
BN	Bayesian Network
CAFM	Computer Aided Facilities Management
CEN	European Committee for Standardization
COBie	Construction Operations Building information exchange
CPTs	Conditional Probability Tables
DAG	Directed Acyclic Graph
FM	Facility Management
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
HVAC	Heating, Ventilation, and Air-Conditioning
IEQ	Indoor Environmental Quality
IFC	Industry Foundation Classes
IFMA	International Facility Management Association
ISO	International Organization for Standardization
KPI	Key Performance Indicator
MC	Markov Chain
NBIMS	National Building Information Modeling Standard
O&M	Operation and Maintenance
PAS	Publicly Available Specification
POE	Post-Occupancy Evaluation

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Chapter 1

Introduction

1.1 Introduction

This chapter provides an introduction to the thesis, which is focused on the building's performance assessment at the operational stage. This chapter states the problem, outlines the research aim and objectives, and sets out the scope of the work, its limitations and delimitations. Lastly, the structure of the dissertation is presented.

1.2 Problem statement

The operational phase of a built-asset is the main contributor to the building lifecycle cost (Kassem et al., 2014; Madureira, Flores-Colen, de Brito, & Pereira, 2017). Buildings require continuous operating expenses, including maintenance actions on a periodic basis to keep them in appropriate condition for use and to meet a minimum standard or level of performance (Grussing & Liu, 2014). If not maintained properly, buildings deteriorate over time even faster (Heo, Choudhary, & Augenbroe, 2012).

The aging and obsolescence of buildings over time lead to greater energy waste, reduced occupants' comfort and increased maintenance requests (Watt, 2007; Abisuga, Famakin, & Oshodi, 2016). It is estimated that 80% of the energy consumed throughout a building's life cycle occurs when it is occupied and in use (Menassa & Baer, 2014). This has motivated extensive research on the means to reduce the energy intensity through the promotion of control strategies, diagnostics methods and retrofits (Wang, Yan, & Xiao, 2012; Ascione, Bianco, De Masi, De'Rossi, & Vanoli, 2015; Hong, Koo, Kim, Lee, & Jeong, 2015; Azar, Nikolopoulou, & Papadopoulos, 2016).

In addition to energy management studies, occupants' comfort is another building performance aspect that has been studied extensively (Bluyssen, 2010; O'Brien & Gunay, 2014; Azar et al., 2016). As people spend more than 80% of their lives in buildings, the environmental condition of the built-asset is a key driver to occupants' well-being, health, and productivity (Dounis & Caraiscos, 2009; Frontczak & Wargocki, 2011). A vast literature can be found on assessment methods for indoor environmental quality (IEQ), occupants health and well-being, as well as related building standards and regulations such as the American Society of Heating, Refrigerating and Air-Conditions Engineers (ASHRAE) (Roulet et al., 2006; Holopainen et al., 2014; Jensen & Maslesa, 2015; Atzeri, Cappelletti, Tzempelikos, & Andrea, 2016; Ornetzeder, Wicher, & Suschek-Berger, 2016).

Improving building performance requires a comprehensive understanding and integration of various indicators related to different aspects covered above, such as building condition, energy performance and occupants' comfort (Grussing & Liu 2014; Azar et al. 2016; Thomas et al. 2016). The analysis of these indicators is an inherent part of asset and facility management, which includes a decision-making process in order to overcome the potential risks facing inefficient buildings (Lavy, Garcia, & Dixit, 2010; Bozorgi, 2015).

Despite their interdependence, these indicators have been mostly evaluated independently, overlooking potential trade-offs that can occur between them (Azar et al., 2016). A building is made up of interconnected parts and materials to form systems that perform one or more functions in an operating building (Grussing & Liu, 2014). However, most existing studies do not consider the building holistically, i.e., considering the building as a whole and thinking about how its parts dynamically interact with each other (Grussing & Liu 2014; Azar et al., 2016). Also, previous studies tend to be very specific and often linear in investigating indicators in relation to one specific performance aspect, e.g., the impact of indoor environment quality on occupants' comfort (Grussing & Liu, 2014; Holopainen et al., 2014; Azar et al., 2016). Another typical example is the assessment of the building condition neglecting the variability associated with the degradation process (Duling, Horak, & Cloete, 2008) and without establishing the implications of the building condition to other performance aspects, such as occupants' health and comfort (Abisuga et al., 2016).

While some methods are available to evaluate building performance, these studies provide complex tools, which require a large amount of time to perform an evaluation of an entire building. Moreover, they are difficult to use due to the restricted or limited availability of data, or they are not good for practical implementation due to practical inflexibility (Grussing & Liu, 2014; Ruparathna, Hewage, & Sadiq, 2017). Consequently, researchers are facing important limitations to study and optimize the performance of the built environment in a holistic approach (Azar et al., 2016).

In addition, many existing buildings face incomplete, obsolete or fragmented information which create obstacles to conduct a performance evaluation (Becerik-gerber et al., 2012; Volk et al., 2014). Most European countries present a relatively old building stock (BPIE, 2011a). These buildings often do not have as-built documentation due to lack of update (Volk et al., 2014). Operators need to manually process dispersed and unformatted information (Koch et al., 2014) from different areas such as maintenance, space and energy management. This process is laborious and inefficient (Becerik-gerber et al., 2012).

Innovative approaches are required to improve the performance of existing buildings through asset and facility management (Ruparathna et al., 2017). The definition of the interactions between performance indicators in a holistic approach, and the quantifications of the uncertainty associated with the relationships between them, can aid the management of buildings and improvement of their state of conservation, end user comfort and energy performance (Azar et al., 2016). Models should be able to include estimations of stochastic behavior, uncertainty, and provide ranges of expected outcomes given reasonable distributions of inputs (Kalz & Pfafferott, 2014). This approach must consider multiple stakeholders, use data collection methods to build the knowledge base, and provide powerful consequence analysis and visualization tools to facility managers (Grussing & Liu, 2014).

To overcome these issues, a Bayesian network (BN) is considered suitable since it consists of a relatively simple causal graphical structure for modeling cause-effect relationships of real-world problems. BNs have the ability of integrating multiple matters, interactions and outcomes, and investigating trade-offs (Pearl & Verma, 1994; Chen & Pollino, 2012). Furthermore, BNs can be used to handle uncertainty through the established probability theory, use data and knowledge from different sources, and handle missing data (Pearl & Verma, 1994). Consequently, and in this specific context, BNs can be used to create the relationships and behavior between key variables that affect building performance. Moreover, Building Information Modeling (BIM) models can be used to store and access assets and facility information to overcome the drawbacks of obsolete, scarce and not standardized information faced by existing buildings (Akcamete, Liu, Akinci, & Garrett, 2011; Lavy & Jawadekar, 2014; PAS 1192-6:2018).

1.3 Aim and Objectives

The primary aim of this thesis is to develop a Bayesian network model to holistically manage building performance and support facility management practices of existing buildings.

The objectives for this thesis are the following:

Objective 1: Identify and analyze shortcomings in the current approaches that address building performance assessment.

Objective 2: Define the most relevant performance categories, indicators and factors to assess the performance of a building.

Objective 3: Define the different sources of data for building performance assessment and where to locate such data in BIM models.

Objective 4: Devise a Bayesian network model, including the causal relationship between the identified factors and indicators to assess the performance of a building in different aspects.

Objective 5: Verify and validate the proposed Bayesian network model.

1.4 Scope of the research, limitations and delimitations

The scope of this research includes the development of a BN model to support facility management practices for enhancing building performance. The model can be applied to existing non-residential buildings, specifically the group of buildings classified by the International Building Code (2018) in: Business (e.g., offices, banks), Educational (e.g., schools, universities), and Mercantile (e.g., department stores, markets). In these types of buildings, different stakeholders are involved (e.g., owner, occupants). Moreover, facility managers are in charge of the performance management of these buildings. Particular types of non-residential buildings are not considered due to their strict requirements and characteristics, e.g., hospitals. Residential buildings are outside of this investigation. The property ownership, stakeholder relationship, use pattern, and other influencing factors of building performance are different between non-residential and residential buildings.

The proposed BN model includes the assessment of buildings in operation without evaluating if they fulfill the related regulations. For instance, old buildings might not meet new legislations about energy design strategies or ventilation requirements. Moreover, the model considers buildings that are currently in use, disregarding abandoned buildings.

The developed model is limited to the main performance indicators and factors that affect a building in three different performance categories: condition, comfort and energy. Moreover, only the main construction elements and systems that compose a building are analyzed. The inclusion of detailed parts of each construction element and system would significantly increase the extension of the research and complexity of the model.

The boundary of the model includes the analysis of indicators related to the operational performance assessment of buildings, without taking into account economic aspects.

Moreover, the model concentrates on the identification of the main factors that affect the building during the use phase, without including a detailed analysis of the causes and potential risks that may have occurred in the design and construction phases.

Expert judgment and data from existing buildings are used to conceive the model which can be refined with a larger database. For instance, data from existing buildings are collected to obtain quantitative information and define the relationships between the identified variables. The strength of these relationships can be updated once new information is available. The tool used to construct the BN model has the capability of parameter learning, which consists of automatically updating the belief about one variable when new observations are considered.

Probability distributions for the variables analyzed in the BN model are defined from different reports and databases. Typical or average levels are modeled taking into account the existing non-residential building stock in the European context. Uncertainty of these levels and the relationships between these factors are provided based on literature review and the opinion of experts on the domain. For specific purposes, adaptation of these patterns to specific contexts and purposes could be performed.

The use of BIM models as an integration repository of the data needed to assess a building performance is also proposed. Consequently, BIM models can be used to provide the data required in order to set evidences in the BN model. However, the programming tasks and technical specifications of data integration are out of the scope of this thesis.

1.5 Thesis structure

This thesis is structured in ten chapters as follows:

Chapter 1 introduces the research work, provides a background to the research problem, identifies the aim and objectives, and sets outs the scope of the work and its limitations and delimitations.

Chapter 2 presents the state of the art about building performance, risk assessment and BIM. This literature review relates the relevant studies on the subject of this work to be the basis for the model development.

Chapter 3 describes the research method, including the steps carried out in the development of the research.

Chapter 4 details the work undertaken to identify the most relevant performance categories, indicators and factors to be considered in the BN model for assessing building performance.

Chapter 5 presents the data collection methods to gather data from existing buildings. These data serve as inputs to the development of the BN model.

Chapter 6 presents the development of the BN model of building condition performance. This includes the relationships between indicators and factors affecting building condition performance.

Chapter 7 presents the development of the BN model of building comfort performance. This includes the relationships between factors affecting building comfort performance.

Chapter 8 presents the development of the BN model of building energy performance. This includes the relationships between factors affecting building energy performance.

Chapter 9 describes the integration and operational evaluation of the BN model considering the three performance categories together. A case study demonstrates the capabilities of the developed BN model and different practical applications of the model are discussed. This chapter also identifies the potential integration of the different data sources in BIM.

Chapter 10 presents the main conclusions of this thesis, including the practical and theoretical contributions. Potential future research topics are also provided.

The outline of this thesis is illustrated in Figure 1.

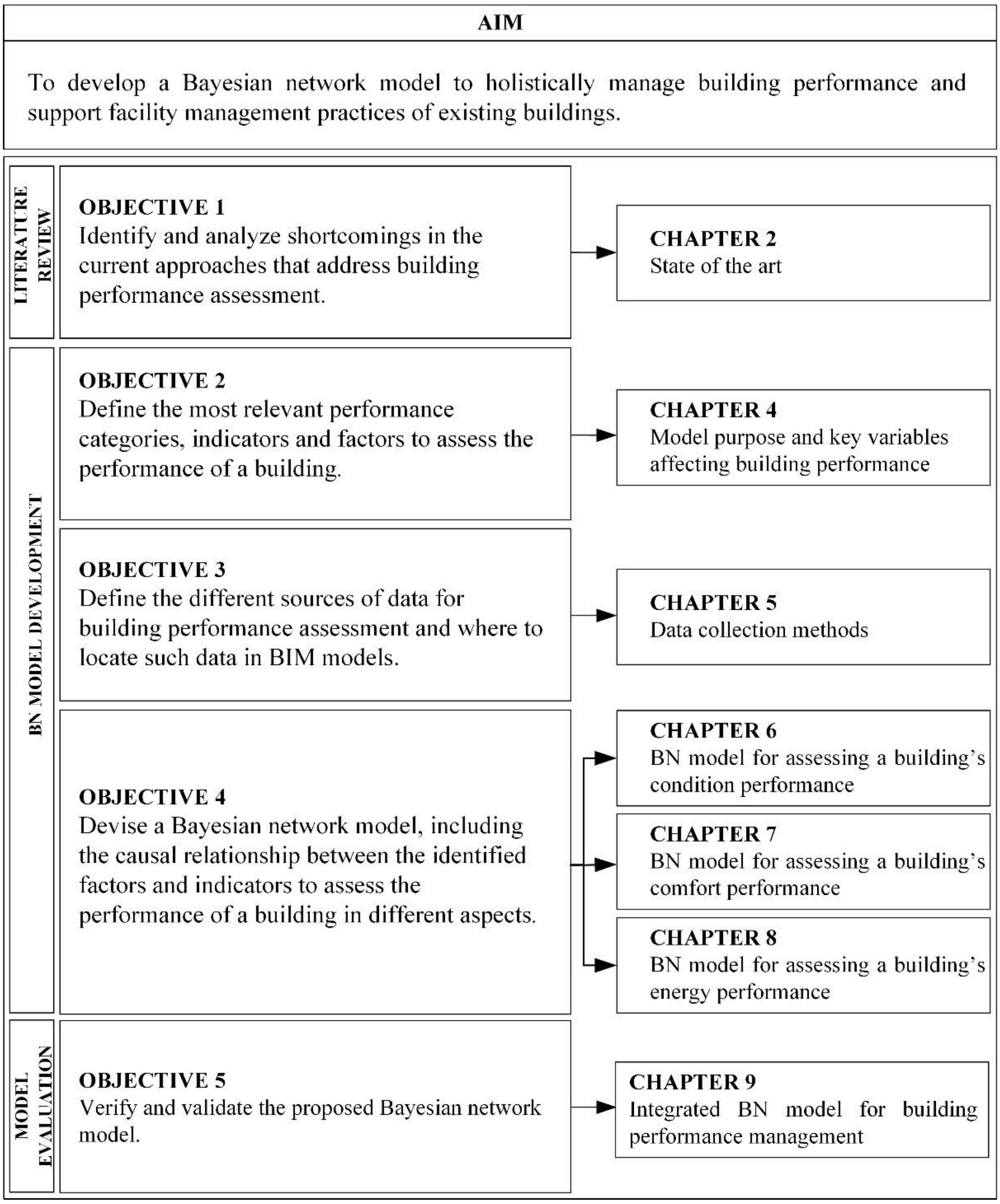


Figure 1. Thesis outline

Chapter 2

State of the art

2.1 Introduction

This chapter presents a complete literature review carried out to gather the existing knowledge within the subject of research. First, it is explained the concept of building performance, the relevance of performance to facility management, and existing evaluation methods. Then it is discussed the different requirements (interests) of stakeholders (e.g., owner, occupants) and the need for a holistic building performance assessment. The need of a risk analysis system considering uncertainty in building performance, and the most common risk assessment methods and tools are presented. Also, benefits of the implementation of causality analysis to evaluate building performance and to make decisions are discussed. Furthermore, this chapter describes the need for data integration in the operational phase and the use of BIM as a digital database. Finally, the complexity of the research subject is summarized, establishing the basis for this thesis.

2.2 Building performance

2.2.1 Building performance concept

Building performance can be described as the practice of thinking and working in terms of ends (Gibson, 1982). It is concerned with what a building is required to do, and not with prescribing how it is to be constructed (Gibson, 1982). This concept was defined by the International Council for Research and Innovation in Building and Construction (CIB), one of the groups paying special attention to the development of the ‘performance approach’. CIB started addressing the performance concept in 1970 through the working commission W60, entitled ‘The Performance Concept in Building’ (Gibson, 1982).

For Hartkopf et al. (1986), performance definition can be divided into two parts: building enclosure integrity and interior occupancy requirements. Building enclosure integrity includes protection of the buildings' visual, mechanical and physical properties from environmental degradation such as temperature, radiation, and natural disasters. The second part includes the elemental parameters of comfort: thermal, acoustic, visual, air and spatial comfort (Hartkopf et al., 1986). In addition to these two parts, the Federal Facilities Council (2002) added that a building should also provide the infrastructure (water, electricity, waste disposal systems, fire suppression) necessary to carry out activities in a safe environment.

In the 1980s the concept of sustainability gained importance, which led to an expansion of the aspects typically taken into account in assessing building performance, beyond the traditional energy efficiency, health and environmental aspects (Lützkendorf & Lorenz, 2006). The concept of building performance gained a more broad perspective and terms such as 'total building performance', 'whole life performance', 'overall performance' or 'integrated building performance' started to be used (Rudbeck, 2002; Lützkendorf & Speer, 2005). The term performance in a broad sense is related to buildings meeting the requirements of users in providing a conducive, safe, comfortable, healthy and secure indoor environment to carry out different activities, including work, study, leisure, family life, and social interactions (Bakens, Foliente, & Jasuja, 2005; Ibem, Opoko, Adeboye, & Amole, 2013).

2.2.2 Building performance and Facility Management

In the 1980s the building industry started to face pressure from government institutions, clients and increased international competition to improve building quality, construction speed and reduce costs (de Wilde, 2018). This pressure led to the emergence of the new discipline of Facilities Management (FM) (Cohen, Standeven, Bordass, & Leaman, 2001). FM is defined by the International Facility Management Association (IFMA, 2015) as "a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology" (Figure 2).

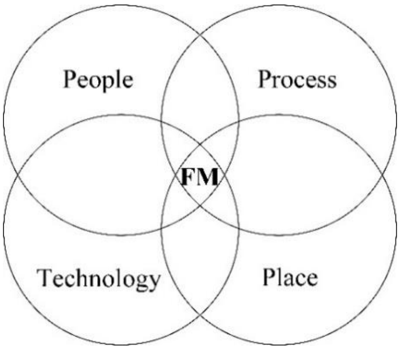


Figure 2. Facility Management (Source: IFMA, 2015)

FM needs to deal with a set of processes that can be divided into three levels: strategic, tactical and operational (CEN, 2011). The operational level, which is the focus of this work, is the primary function of FM (Chotipanich, 2004). This operational function supports the basic routine, and regular needs of an organization (CEN, 2011). An effective operational FM provides a safe and efficient working environment which is essential to the performance of any building (Chotipanich, 2004). At this level, operators monitor the building performance and report the performance gaps to the higher management (Ruparathna et al., 2017). This includes data collection through measurement of physical parameters (e.g., indoor air temperature), collection of end user perceptions (e.g., perceived level of thermal comfort), or a combination of both (Talamo & Bonanomi, 2015; Lai & Man, 2017). Figure 3 illustrates the organizational levels of FM.

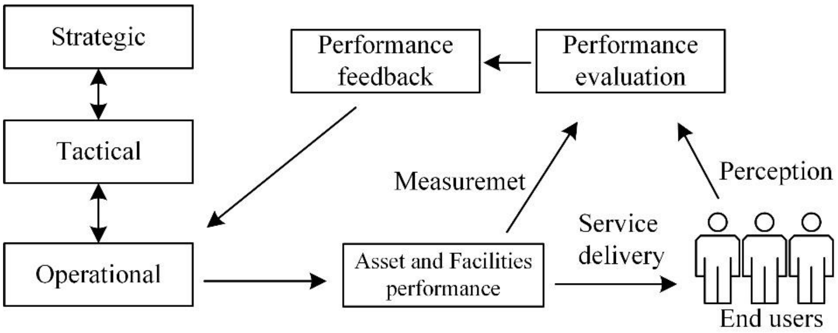


Figure 3. Organizational levels of FM (based on CEN 2011; Lai & Man 2017)

The interface between building performance and FM is illustrated in Figure 4. Of the three primary branches of building performance indicated in Figure 4, building diagnostics is the most immediately relevant to FM (Douglas, 1996). Building diagnostics regard the systematic study and evaluation of building performance through the use of performance indicators (Mwasha, Williams, & Iwaro, 2011). Many authors use the term Key Performance Indicator (KPI) as the concept of quantifying building performance (de Wilde, 2018).

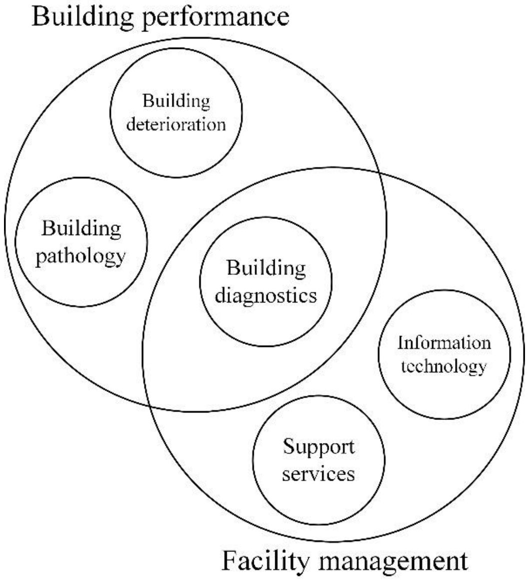


Figure 4. Building performance and FM interface (adapted from Douglas 1996)

2.2.3 Building performance evaluation methods in the O&M phase

Over the years, many approaches have been developed to evaluate performance of buildings in the operational phase. These evaluation methods include: post-occupancy evaluation (POE), building rating systems, indexes, and methods included in standards and regulations (Preiser & Vischer, 2005; Lavy, Garcia, Scinto, & Dixit, 2014; Ruparathna et al., 2017). One of oldest and most common methods for building performance assessment is POE (Jensen & Maslesa, 2015). POE is a strategic performance evaluation technique that measures performance of a building in use against specified standards from the perspective of the user (Preiser & Vischer, 2005). Different tools based on POE are EPIQR (Flourentzos, Droutsa, & Wittchen, 2000), TOBUS (Flourentzou, Genre, & Roulet, 2002), PROBE (Cohen et al., 2001), and RENO-EVALUE (Jensen & Maslesa, 2015), which focus on building diagnosis, including environmental and energy performance aspects and provide decision making for building renovation.

Around the early 2000s, with growing concerns about the natural environment, a number of rating systems emerged, specifically focused on green buildings (Preiser, Hardy, & Schramm, 2017). These rating systems cover different phases of a building's life cycle and take different environmental issues into account (Haapio & Viitaniemi, 2008). The majority of the commonly used building rating systems are credit-based systems (e.g., LEED, BREEAM, Green Star, CASBEE, BEAM) and are focused on the effectiveness of energy use, while they might also consider water, waste, material and site (Wang et al., 2012). Some of these systems are suitable for assessing different types of buildings, while some of them can only be used for assessing new buildings or office buildings (Haapio & Viitaniemi, 2008). A recent addition is the WELL standard, which specifically links building performance to human health and well-being (WELL Building Standard, 2014).

Another method for evaluating building performance is through condition index indicators, which have been mainly focused on condition assessment of building elements (Pereira, Palha, de Brito, & Silvestre, 2011; Rodrigues, Teixeira, & Cardoso, 2011; Silva, de Brito, & Gaspar, 2016). A condition index is typically defined by an equation including the identification of the most common defects of a building component, which are weighted according to their severity and repair costs (Serralheiro, de Brito, & Silva, 2017). The condition index scale for building components usually ranges from 0 to 100, where 0 represents a critical condition (failure) and 100 represents a good condition.

Several organizations were and still are involved in the development of performance-based codes, regulations and standards (Rudbeck, 2002; Lützkendorf & Speer, 2005). For example, the ASTM Standards on the Whole Building Functionality and Serviceability provide a strategic view for the evaluation of buildings using indicators of capability to assess how well a proposed design, or an occupied facility, meet the functional requirements specified by the business units, and facility occupants (Szigeti et al., 2004). Other building standards and regulations such as the American Society of Heating, Refrigerating and Air-Conditions Engineers (ASHRAE) are focused on assessment methods for environmental quality, occupants' health and well-being.

2.2.4 Stakeholder requirements and building performance categories

Stakeholder requirements are the key starting points for the exploration of how a building functions and, ultimately, performs (de Wilde, 2018). In a non-residential building, different stakeholders' requirements regarding building performance coexist. Users expect that buildings will be functional, comfortable, and safe, and will not impair their health (Federal Facilities Council, 2002). Owners focus on investment decisions related to costs. They expect that their investments will result in buildings that support their business lines or missions by enhancing workers' productivity, profits, and image, that are energy efficient, and cost-effective to build and to maintain (Council, 2002; Love, Simpson, Hill, & Standing, 2013). Facility managers are concerned with the overall functionality of the built environment and need to deal with all of these previous expectations of users and owners (Cotts et al., 2009).

All those performance requirements can be grouped into performance categories (Lützkendorf et al., 2005). There is no established theory (e.g., formal classification) for the definition of performance category at the whole building scale, but several general schemes have been developed, which are mostly linked to research networking activities initiated by the CIB (Hensen & Lamberts, 2011). Previous studies categorized building performance in: technical, functional, behavioral, aesthetic and environmental (Straub, 2003; Hovde & Moser, 2004; Preiser & Vischer, 2005; Lützkendorf & Lorenz, 2006; Yan et al., 2015).

Technical performance is related to structural, physical and other technical features and characteristics of the building (Lützkendorf et al., 2005). Buildings must provide physical protection for their occupants and assets, which includes protection from crime, vandalism, terrorism, fire, accidents, and environmental agents. The functional performance of a building describes and assesses how well use-specific activities and processes can be performed. It covers how well-suited the design of the space is for the planned use, the extent to which the design is accessible and barrier-free, and the adaptability of the building to changing user requirements and uses, among other factors (Lützkendorf et al., 2005). The correct functioning of elements is also related to the functional performance of a building (Sullivan, Pugh, Melendez, & Hunt, 2010).

Behavioral performance is related to the interaction between occupants and building systems to meet comfort and health needs, which may vastly differ due to individual perception variance and the influence of many contextual factors (Yan et al., 2015).

Another category can be identified as aesthetic properties. Aesthetic performance is associated with the building's image and appearance (Preiser & Vischer, 2005), which is related to the absence of surface defects, and the homogeneity of color and finishes (Straub, 2003).

Due to increasing concern for global sustainability, environmental performance has become more important. This category is related to evaluating the performance of buildings across a broad range of sustainable considerations and analyzing the building's features that affect the local and global environment (ALwaer & Clements-Croome, 2010).

For Douglas (1996), the categorization of building performance is to understand how well a building is satisfying specific user or functional requirements. However, to assess how well a building is behaving in the long term, the predictability of total building performance is relatively low since it depends on many variables (Douglas, 1996). Variables such as climate conditions and operational conditions of the building cause inherent uncertainties and make the accurate prediction of the building performance an arduous task (Holmes & Hacker, 2007). Therefore, increasing predictability by incorporating these uncertainties is necessary to help identifying strategies and methods to improve building performance (Douglas, Ransom, & Ransom, 2013).

2.2.5 Key factors affecting building performance

The performance of buildings is associated with various degrees of uncertainty, due to the many factors that may affect a building (Silva, Gaspar, de Brito, & Neves, 2015). A factor is a variable that influences a building performance, such as building characteristics (building age, building size, building design condition, etc.) (Kang, Lee, Hong, & Choi, 2018).

The first class of factors affecting building performance is related to design and construction errors. Error can be defined as ‘‘the failure of planned actions to achieve their desired goal, where this occurs without some unforeseeable or chance intervention’’ (Reason & Hobbs, 2003). Design errors are a problematic issue in construction and engineering projects (Lopez, Love, Edwards, & Davis, 2010). Design and execution issues affect all kinds of construction elements and systems (Pereira, de Brito, & Correia, 2014).

Moreover, buildings tend to have their performance decreased unless proper maintenance is carried out (de Wilde, Tian, & Augenbroe, 2011). According to ISO 15686-1:2011, maintenance can be defined as the “combination of all technical and associated administrative actions during service life to retain a building or its parts in a state in which it can perform their required functions”. Maintenance can prevent or rectify the deterioration of building elements and systems, thus increasing the efficiency, reliability and safety of buildings (Sullivan et al., 2010). Building maintenance can be classified in three types: corrective, preventive and predictive. The corrective maintenance regards a reactive maintenance in response to a cause of failure or breakdown (Motawa & Almarshad, 2013). Preventive maintenance is carried out by periodically undertaking routine tasks necessary to maintain component or system in a safe and efficient operating condition. More recently, another maintenance category called predictive maintenance was developed. This approach detects the system degradation and conduces maintenance on the actual condition of the facility (Sullivan et al., 2010).

Building maintenance depends on decisions involving technical building inspections and handling maintenance requests (Sullivan et al., 2010; Chen, Hou, & Wang, 2013). The former focuses on the detection of defects in construction elements and the latter on the identification of problems in building systems. The detection of building defects plays a key role on determining building performance (Watt, 1999; CIB W86, 2013). Building defects are among the most common problems that construction projects may suffer (Mills, Love, & Williams, 2009). Watt (1999) defines defect as “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”.

The operation management of the building is another key factor that have impact on the building performance. This includes the daily based operations and the use of systems to support such operations, like Building Management Systems (BMS) (Motawa & Carter, 2013). The use of BMS can help a facility manager on the identification of critical components and the probability of a problem occurring. It can also control unanticipated problems that tend to lead to higher costs for unscheduled repairs and potential loss in building occupant comfort (Levine et al., 2007). Occupancy (e.g., occupant behavior), which refer to the human presence inside buildings and their active interactions with various building system, is another key aspect with regard to building operation that affects building performance (Dong et al., 2018).

The performance of a building also depends on the environmental agents it is exposed to, which is associated with factors related to the building location and type of exterior condition (e.g., temperature, rain, humidity, pollution) (Balaras, Droutsa, Dascalaki, & Kontoyiannidis, 2005; Olanrewaju & Abdul-Aziz, 2015). For instance, a coastal area accelerates the degradation process of a building. Another example is urban pollution (Madureira et al., 2017). Variations of temperature and a high exposure to damp are the environmental actions with the highest probability to be the most unfavorable degradation conditions (Watt, 1999; Silva et al., 2015). Noteworthy, a region’s vulnerability to natural disasters (e.g., earthquakes, hurricanes, floods, landslides) is also an important factor to be considered (Watt, 1999). The risk of a natural hazard can be analyzed by considering the exposure, i.e., the average amount of natural hazards that a region is exposed to. Figure 5 illustrates a map with five levels of natural disaster risk (Kirch et al., 2017).

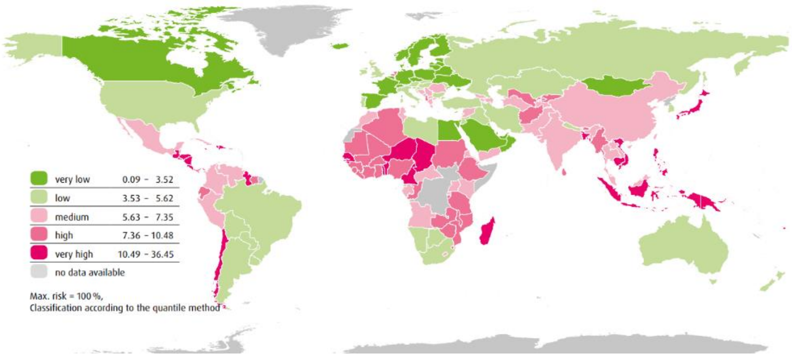


Figure 5. Level of natural disaster risk (Source: Kirch et al. 2017)

Other factors that affect building performance are related to building properties, such as the age of the building (Olanrewaju & Abdul-Aziz, 2015), building geometry (Parasonis, Keizikas, & Kalibatiene, 2012), the type of constructive solution (Balaras et al., 2005; Flores-Colen, de Brito, & Freitas, 2010), the thermal properties (Al-Homoud, 2005), and the efficiency of its equipment (e.g., type of HVAC system) (Heo et al., 2012). Building elements and systems deteriorate and their performance is reduced with the course of time (de Wilde et al., 2011). The building geometry includes characteristics of the building design, such as the shape (e.g., proportions between exterior surface and volume) (Parasonis et al., 2012), and the percentage of openings (Pino, Bustamante, Escobar, & Pino, 2012). The type of constructive solution takes into consideration the material properties and their susceptibility to deteriorate. For instance, ceramic and wood are sensitive to moisture through absorption, metals are sensitive to corrosion due to contact with other metals (galvanic series) or agents from its environment (Hermans, 1995). The thermal properties are related to the insulation of the building, which is mainly characterized by the thermal transmittance of the building envelope (i.e., façade, roof and openings) (Al-Homoud, 2005). The efficiency of the equipment (e.g., heat generating equipment) is an important factor that impact the performance of the building, which is related to the type of system adopted (Heo et al., 2012).

In summary, based on the literature review, the key factors affecting building performance can be grouped on:

- Design and construction errors
- Building operation and maintenance: maintenance policy, building management system, occupancy
- Building defects and problems
- Environmental agents: weather condition, surrounding environment, risk of natural disasters, geological conditions
- Building properties: building age, geometry, type of constructive solution, thermal properties, type of equipment, equipment efficiency.

2.2.6 Building performance under uncertainty

Previous sections explored building performance as a concept that expresses different stakeholders’ requirements and that is influenced by many factors. Buildings are complex systems, both in terms of the many systems involved and the long life cycle, which result in many disciplines with interest and interaction with the area of building performance (de Wilde, 2018). Based on the introductory discussion, buildings therefore have to be considered in various levels, which reflect the demands of their owners, occupants, and of society in general (Watt, 2007).

Building performance is also a dynamic concept as it is highly dependent on the context, loads that work on the building, control settings, occupants behavior, system aging and degradation, maintenance and refurbishment (de Wilde, 2018). This often introduces uncertainties when predicting performance (de Wilde, 2018). Uncertainty analysis has received increasing attention in the field of building performance assessment because a number of variables that influence building performance are inherently uncertain (Tian et al., 2018). Silva et al. (2016), for instance, expressed the uncertainty associated with the prediction of building elements condition, which can be related to many factors, including the possibility of errors in design, execution or use, which are not possible to identify during an inspection but compromise the building elements. Macdonald (2002) quantified uncertainties associated with energy performance, including thermo-physical properties, casual gains, and infiltration rates. Tian et al. (2018) complemented and described that uncertainties in building energy assessment are related to weather data, building envelope, HVAC system, and occupants' behavior.

Due to the uncertainty associated with the building performance, facilities managers must manage performance with appropriate tools (Hovde & Moser, 2004). Risk assessment has been recognized as a critical decision support tool in decision making (Chemweno, Pintelon, Van Horenbeek, & Muchiri, 2015). This is related to assist facility managers with a method to control risks over a building and to systematically identify, analyze, evaluate and mitigate factors that can affect building performance (Martani, 2015). In particular, risk analysis aims to reduce uncertainty by envisioning possible scenarios and making forecasts on the basis of what it is considered probable within a range of possibilities (Martani, 2015). This can be used to guide facility managers to conduct a more rational management and maintenance of the building stock, defining the most appropriate maintenance strategies, refurbishment or retrofitting actions to enhance building performance in a holistic approach (Grussing & Liu, 2014; Azar et al., 2016).

2.3 Risk assessment

2.3.1 Risk concept

Risk is traditionally defined as a combination of the probability (or likelihood) of something happen and its positive and negative consequences (Duffuaa & Ben-Daya, 2009; Weber, Medina-Oliva, Simon, & Iung, 2012). The ISO 31010:2009 defines risk assessment as “that part of risk management which provides a structured process that identifies how objectives may be affected, and analyses the risk in term of consequences and their probabilities before deciding on whether further treatment is required”. The purpose of a risk assessment is to provide evidence-based information and analysis to make informed decisions on how to mitigate particular risks and how to decide between possible options (ISO 31010:2009).

2.3.2 Risk assessment methods for building performance

In asset maintenance, well-known risk assessment techniques include the Fault Tree Analysis (FTA), Markov chains (MCs), Failure Mode and Effect Analysis (FMEA), and Bayesian Networks (BNs) (Weber et al., 2012; Chemweno et al., 2015).

Fault Tree Analysis (FTA) is a technique to build a causal model relating failure to its causes by combining events using simple and logical relationships (e.g. AND, OR, etc.) (Mohaghegh, Kazemi, & Mosleh, 2009). It can be used as a preventive or diagnostic tool (Motamedi, Hammad, & Asen, 2014). FTA has been utilized, for example, to identify potential causes of failures in HVAC systems (Motamedi, Hammad, & Asen, 2014). An FTA can identify the causes of failure and prioritize contributors to this failure. However, when multiple failures can potentially affect a component with several consequences, the model needs a representation of multiple state variables. In this context, FTA is not suitable (Weber et al., 2012). Another constraint is that FTA is limited to assessing just one top event (e.g. a major failure) (Weber et al., 2012).

A Markov chain (MC) is one of the most common methods used to assess stochastically the future condition of building components (Bocchini, Saydam, & Frangopol, 2013). For instance, Silva et al. (2015) utilized MC to analyze the degradation of façade claddings. This consist of a stochastic process, in which future chains are dependent only on the present state and are independent from any previous states (Weber et al., 2012). MC consist of an initial state distribution and a transition matrix (Bocchini et al., 2013). The transition matrix represents the probability of the process moving from state A to state B. This matrix of state transition probabilities is usually obtained from a vast amount of historical data. In fact, the quality and quantity of data is a major challenge to the applicability of MC. To explain behaviors and causalities, modeling of the system becomes complex with many variables. This requirement is the main drawback of MC, since there is a combinatory explosion in the number of states that leads to an unreadable model when real industrial systems are studied (Weber et al., 2012).

Failure Mode and Effect Analysis (FMEA) is a technique used to identify and eliminate known or potential failures, in order to enhance the reliability and safety of complex systems (Liu, Liu, & Liu, 2013). The results of the analysis can help analysts to identify and correct the failure that have a detrimental effect on the system and improve its performance. It has been applied to analyze the principal causes and effects of anomalies in building elements and to identify the relationship between the deterioration state of the analyzed elements and their performance level (Rodrigues et al., 2011). FMEA may be followed by a criticality analysis which defines the importance of each failure mode, qualitatively, semi-qualitatively, or quantitatively (ISO 31010:2009). As FMEA is essentially a scoring method, it only indicates the average performance in a single score and does not present the true diverse nature of an assessment, including human's judgment (the human's knowledge on the distribution of different risk states) (Chin, Tang, Yang, Wong, & Wang, 2009). Therefore, FMEA can only be used as a tool for an initial assessment or a rough assessment categorization tool (Chin et al., 2009).

Bayesian Networks (BN) is a type of probabilistic graphical model that provide a formalism for reasoning about partial beliefs under conditions of uncertainty (Pearl, 1991, 2000). BN is considered a powerful tool to model risks with uncertainty data and have been extensively used to develop decision support systems in a variety of domains (Nguyen, Tran & Chandrawinata, 2016; Hu et al., 2013). Although BNs have been an attractive technique to examine a range of issues in the construction industry, it is still relatively novel in this field (Nguyen et al., 2016).

BN is a combination of two different parts: graph theory and probability theory. It consists of a directed acyclic graph (DAG) and an associated set of conditional probability tables (CPTs) (Pearl, 1997). A DAG is comprised of nodes that represent random variables with a finite set of states, and the edges correspond to probabilistic causal dependence among the variables (Pearl, 1991). CPTs specify the degree of belief (expressed as probabilities) that the node will be in a particular state given the states of the parent nodes (the nodes that directly affect that node) (Pearl, 1991). The dependencies between variables in a BN can be described both qualitatively and quantitatively, and it is suitable for knowledge representation and reasoning (Holický, Marková & Sýkora, 2013).

BN are capable of representing cause-effect relationships and precisely specifying how each variable is influenced by its parents in the DAG (Pearl & Verma, 1994). They also handle uncertainty though the established probability theory. The notion of causation is related to finding a satisfactory explanation for a given set of observations, and determining the meaning of the explanation (Pearl & Verma, 1994).

Among the advantages of BNs models is the suitability for small and incomplete data sets, they are apt for utilizing data and knowledge from different sources, and handling missing data (Uusitalo, 2007; Chen & Pollino, 2012). Moreover, BNs are based on the conditional probability theory, or Bayes' theorem by Thomas Bayes (Nguyen, Tran & Chandrawinata, 2016). The Bayes' theorem is expressed as follows:

$$P(B|A)=\frac{P(A\cap B)}{P(A)}=\frac{P(A|B)P(B)}{P(A)}$$

where P(A) [or P(B)] is the probability of A (or B); P(A|B) [or P(B|A)] is the probability of A (or B) given B (or A); and P(A∩B) is the probability that both A and B occur (Nguyen, Tran & Chandrawinata, 2016). In probability theory, investigators are concerned not merely with the presence or absence of causal connections but also with the relative strengths of those connections and with ways of inferring those connections from observations (Pearl, 2000).

When two nodes are connected by an edge, the causal node is called the parent of the other node, called child node (Figure 6). Child nodes are conditionally dependent on their parent nodes (Nguyen, Tran & Chandrawinata, 2016).

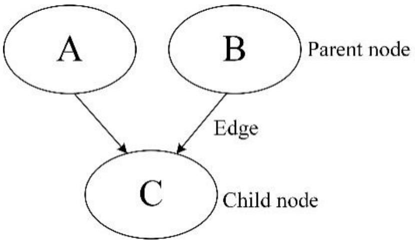


Figure 6. Example of a BN

In general, BN has a much more flexible structure than FTA (Khakzad, Khan, & Amyotte, 2011) with the advantages of multi-state variable modeling and the ability to assess several output variables in the same model (Weber et al., 2012). Moreover, the number of parameters within the conditional probabilities table is considerably lower than in an MC (Weber et al., 2012). BN allow easy computation of the joint probability distribution of all variables involved in a complex process (Celeux, Corset, Lannoy, & Ricard, 2006).

2.4 Building Information Modeling

2.4.1 BIM concept

Building Information Modeling (BIM) is a technology focused methodology that has been employed to improve the performance and productivity of an asset's design, construction, operation and maintenance processes (Love et al., 2013). The concept of BIM is defined by National BIM Standard (NBIMS-US^{TM}, 2015) as "a digital representation of physical and functional characteristics of a facility and as such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onwards”. It is worth to mention that BIM is not a software, it includes set of innovative tools, process and policies within the construction industry (Succar & Kassem, 2015).

The key idea for understanding BIM is the concept of parametric objects and its differentiation from traditional 2D objects (Eastman et al., 2008). According to Eastman et al. (2008), parametric BIM objects are defined as a geometric definition with associated data and rules which automatically modify associated geometries when inserted into a building model, or when changes are made to associated objects. Another important concept on BIM is the interoperability, which is defined as the capacity of sharing data between multiple applications over any life cycle phase of a building’s development which facilitates smooth data workflows and automation (Arayici, 2008; Eastman et al., 2008). Some initiatives have driven interoperability between software vendors such as the Industry Foundation Classes (IFC) developed by the International Alliance for Interoperability (IAI), which support the sharing and reuse of design, as-built and maintenance data on building projects.

The main applications of BIM processes and technologies include: 3D visualization of the project; fabrication/shop drawings; code reviews; cost estimations; conflict interference and collision detection (Eastman et al., 2008); visualization of quality risks in construction projects (Forcada et al., 2014); site logistics planning and construction sequencing planning (Bortolini, Shigaki & Formoso, 2015); and facilities management (Cavka, Staub-French, & Poirier, 2017; Pishdad-Bozorgi, Gao, Eastman, & Self, 2018).

Considering the implementation in the Operation and Maintenance (O&M) phase, BIM has potential benefits like as-built documentation, maintenance of warranty and service information, quality control, energy management, space management, emergency management, maintenance and retrofit planning (Irizarry, Gheisari, Williams, & Roper, 2014; Volk et al., 2014). Indeed, there is an opportunity for facilities managers to improve the current practice of FM and use BIM as a decision making tool (Carbonari, Stravoravdis, & Gausden, 2018). The best benefit of BIM application in FM is the integration of data systems over the life cycle of a facility (Teicholz, 2004).

2.4.2 BIM information for building performance assessment

In order to release BIM for FM, the first step is to identify the required data and define the desired levels of detail (LoD) (Liu & Issa, 2016). LoD defines geometric and nongeometric attribute information provided by a model component (BIMForum, 2015). This is essential for O&M personnel operate and maintain equipment and systems in buildings efficiently and effectively (Cavka et al., 2017). Standards and specifications have been developed about availability, integrity, and transfer of data and information during the operational phase of a built-asset (Re Cecconi, Maltese, & Dejaco, 2017). The Construction Operations Building information exchange (COBie) is the predominant international standard for FM to exchange general facility information as well as information about spaces, floors, zones, components, technical systems and equipment (NBIMS-US^{TM}, 2015). COBie configures an important milestone for BIM use in FM (Volk et al., 2014) because it defines specifications to exchange information enabling the information to flow from design, construction and O&M phases (NBIMS-US^{TM}, 2015). As a buildingSMART alliance project, COBie is based on IFC. The usage of non-proprietary standards like IFC enhance data exchange between different systems (Volk et al., 2014). Moreover, initiatives to structure and classify systems for the construction industry such as OmniClass, unify the information for electronic databases (OmniClass^{TM}, 2006).

Some studies on the non-geometric building information requirements for FM are found in the literature. For instance, Mayo and Issa (2012) conducted a Delphi panel of FM personnel to establish a list of building information needs. Cavka, Staub-French, and Poirier (2017) specified the information required by O&M personnel to conduct maintenance, building systems operation and monitoring, and manage assets. Pishdad-Bozorgi et al. (2018) also defined which information was imperative to the BIM model for building maintenance. Working with BIM consultants, Pishdad-Bozorgi et al. (2018) developed a required information list that specify the major assets for maintenance. Additionally, particular parameters or field of data that should be tracked for each building component were specified, including: Manufacturer, Model, Serial number, Warranty start date, Warranty expiration date, among others (Pishdad-Bozorgi et al., 2018).

A recently published standard, the PAS 1192-6:2018, suggests the use of BIM models to store and access facility information and specifies requirements for a collaborative sharing of structured health and safety (H&S) information throughout the project and asset life-cycles. H&S risks need to be identified to prioritize the elevated risks and aspects that are safety critical with the goal of providing a safer and healthier environment for end-users (PAS 1192-6:2018).

2.4.3 Applications of BIM in the O&M phase

Some existing studies propose and discuss the use of BIM in O&M phase, and benefits for FM. These studies can be categorized in the following scope of research: (1) application of standards; (2) integration of data; (3) capture and retrieval of facility information; (4) support decision making; (5) improvement of visualization.

Some studies focused on the application of standards as an important process to deliver information for FM. In this sense, the Sydney Opera House was a notable case study using BIM for FM. The project was modeled using IFC standard to specifically support FM operations required by the Sydney Opera House (Cooperative Research Centre for Construction Innovation, 2007). Information about the services, maintenance, cost and data fields for building condition indices were added to the BIM model of this project. The difficulties of modeling the existing building were identified, which included the existing inaccurate 2D CAD data, the complex structure of the building and its service systems, the disparate and independent documentation of the facility (Cooperative Research Centre for Construction Innovation, 2007).

In the same research scope, Lavy and Jawadekar (2014) described the application of BIM and COBie standard in FM for three educational projects. The same authors give recommendations to the use of COBie in the design and construction phases due to the importance for FM in terms of gathering inventory data for preventive maintenance. Patacas et al. (2015) explored how and whether IFC and COBie can deliver the data and information about assets required by facility managers within a whole life cycle perspective. The same authors explained that IFC and COBie do not satisfy all information requirements of asset register and service life planning by default.

Other studies have focused on the integration of data in the FM for specific purposes. Dong et al. (2014) proposed an information framework connecting fault detection and diagnostics and Building Energy Management System (BEMS) through the use of BIM. The purpose of this study was to integrate data from these systems to support energy performance simulation. In the same field of energy management, Ham and Golparvar-Fard (2014) proposed a connection with BIM elements and thermal properties of existing buildings materials with the aim to obtain more reliable energy performance results. Park et al. (2013) also explored data integration but with focus on defect management. The authors proposed a conceptual framework for construction defect management that integrates ontology and augmented reality with BIM.

Some studies have focused on capturing and retrieving information. Lucas, Bulbul and Thabet (2013) proposed a framework to help facility managers to manage the life cycle information in FM healthcare operations. The framework incorporates BIM to capture and store facility information for easy recall when needed during O&M phase. The system is supported with a Graphical User Interface (GUI) to allow the user to input, query, retrieve, and store information within the product model (Lucas, Bulbul & Thabet, 2013). Also with emphasis on capture information, Motawa and Almarshad (2013) proposed an integrated system to capture information and knowledge of building maintenance operations during and after maintenance is carried out to understand how a building is deteriorating and to support preventive/corrective maintenance decisions. The proposed system integrates BIM and knowledge-based techniques via a web-based application.

Regarding decision making research, Irizarry et al. (2014) proposed the integration of augmented reality and BIM to build a conceptual ambient intelligent environment, where an integrated BIM model would be used for virtually accessing operational-level information requirements of the facility. The authors also proposed the use of a mobile interface to support decision making process and provided an implementation in healthcare case study. Other authors investigated support decision making for building retrofit projects. Woo and Menassa (2014) proposed a framework for connecting BIM and energy simulation tools to define more accurate HVAC retrofit solutions. Habibi (2017) explored how BIM can support the review of results for improving building performance in terms of energy efficiency and indoor environmental quality, and make energy efficiency improvement strategies for buildings. To enhance decision making in FM, Chen et al. (2018) proposed a framework based on BIM and FM systems to provide automatic scheduling of maintenance work orders.

Regarding visualization improvement, Akcamete et al. (2011) explored the need for storing and visualizing work order information in BIM models, as a digital facility information database. The authors explained that the use of BIM can enable analysis for understanding patterns of maintenance and repair tasks in a facility, supporting proactive maintenance decisions. In order to identify problems in the facility, Akcamete et al. (2011) highlighted the need for integrating information about building context and investigating the performance history of components; correspondingly spatial clusters of maintenance and repair work for identifying reoccurring problems and potential breakdowns (Akcamete et al., 2011). Also for visualization, Motamedi, Hammad and Asen (2014) investigated the potential of knowledge-assisted BIM-based virtual analytics for visualizing possible root causes of failures. This study integrated BIM, inspection and maintenance data of Computer Maintenance Management System (CMMS) by defining relationships among the databases. Considering the same research approach, Forcada et al. (2014) investigated the use of BIM model to visualize quality risks in construction projects. The same authors provided a quantitative methodology to forecast potential quality risks into a 4D model.

In summary, all previous studies provided a case application of BIM and other technologies. These case studies vary in typology of buildings, including healthcare, educational, residential, commercial, with a great concentration of studies on a generic building (a prototype). Besides these studies, applications of BIM in the O&M phase are still under development, and the research in this area, while growing, is still at a very early stage (Cavka et al., 2017; Pishdad-Bozorgi et al., 2018). Pärn, Edwards, and Sing (2017) stated that an early integration of both geometric and semantic data would prove invaluable to the FM team during building operation, particularly with respect to monitoring building performance.

2.5 Knowledge gap

The literature review demonstrated that building performance is an inherent part of asset and FM, and is related to the achievement of the needs and requirements of different users. In addition, a building is affected by many factors (e.g., environmental agents, building properties) which create uncertainties when predicting performance. Different strategies to evaluate the performance of a building were discussed. Despite the existing contributions, commonly used performance rating systems do not provide adequate information on managing the operational performance of buildings. Moreover, most existing studies do not consider the building holistically, on how its parts dynamically interact with each other. Studies are focused on the assessment of specific building elements or systems, not exploring the relationship between factors that may affect the entire building. Also, previous work is focused on one specific performance aspect, such as occupants’ comfort or building condition.

A holistic and integrated approach is needed to provide a better management of the performance of buildings. To systematically analyze factors that can affect a building performance, literature review identified risk assessment as an essential method. Some risk assessment methods were discussed. Amongst them, BN is considered well suited for this research for the following reasons: (1) they are graphical models that can display relationships clearly and intuitively; (2) they are directional and can therefore represent cause-effect relationships; (3) they can handle uncertainty through the established theory of probability; (4) they can make predictions with incomplete data.

Incomplete, obsolete or fragmented data is also discussed in the literature review as a known problem found on existing buildings. The extra effort of obtaining information or dealing with its absence are some of the obstacles for conducting a performance evaluation. Reliable information is critical for efficient and effective building maintenance and daily operations. Literature review highlighted the potential benefits of BIM during O&M phase and empirical results from existing studies also corroborate these findings. Some recent studies on incorporating BIM into FM have shown life cycle BIM values and capabilities of providing a digital database to FM. The use of BIM as a digital database represent a great potential to support FM, regarding the enhancement of building performance. Therefore, facility managers will be able to make informed decisions regarding the building, achieving better results.

Chapter 3

Research Method

3.1 Introduction

This chapter explains the research method adopted to achieve the objectives of this thesis. The main steps of the research process is illustrated in Figure 7.

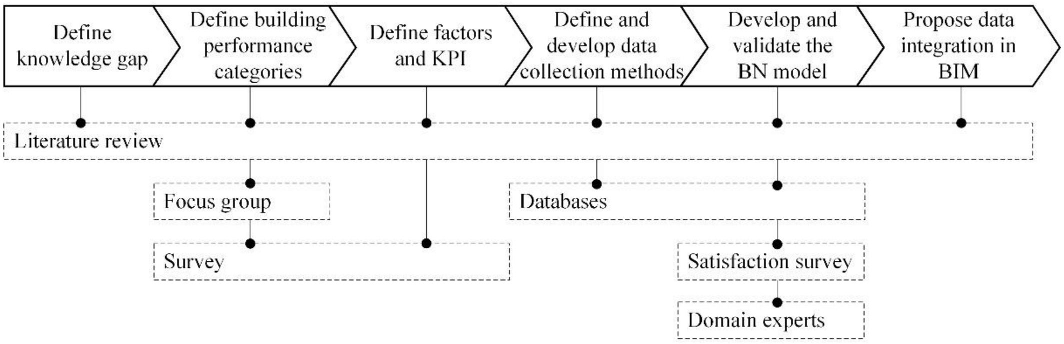


Figure 7. Research process

Chapter 2 has described the probability theory and the Bayes' theorem providing the basis for the development of a Bayesian network (BN) model. In this chapter, the detailed process to the BN model development is explained in five main steps, which are illustrated in Figure 8: (1) model purpose; (2) key variables identification; (3) model structure definition; (4) conditional probability tables (CPTs) definition; and (5) model evaluation.

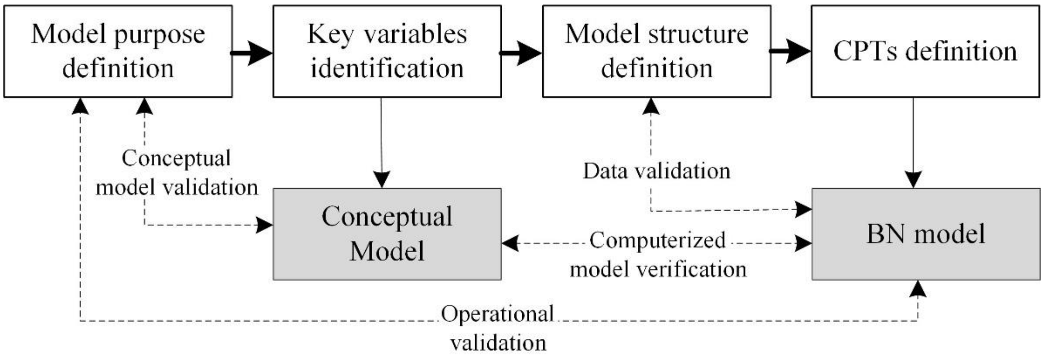


Figure 8. BN model development process

The model development involved several cycles of analysis, implementation, and verification to refine the model. The evaluation is divided in conceptual model validation, data validation, computerized model verification, and operational validation (Sargent, 2013). Therefore, several versions of a model are developed prior to obtaining a satisfactory valid model.

The most common BN modeling tools used by the scientific community were explored to construct the BN model. Although Netica (https://www.norsys.com) and Hugin (https://www.hugin.com) are the most recurrent tools in the literature, the dynamic discretization technology used in AgenaRisk (https://www.agenarisk.com) is more powerful than the discretization algorithm included in either Netica or Hugin (Perez-Minana, 2016). The main drawback of Hugin is the limitation on the types of links that can be created between discrete and continuous nodes. Regarding SMILE/Genie (https://www.bayesfusion.com), only discrete nodes are allowed, and any node's CPT must be completely specified, unless sufficient data is available, enabling the tool to learn the network from the data. Neither OpenBUGS (http://www.openbugs.net) nor any of the R packages include a Graphical User Interface (GUI) that ease the modeling process.

Furthermore, only two of the tools evaluated provide the functionality to break the network into smaller components and propagate information across network components: Hugin and AgenaRisk (Perez-Minana, 2016). Another point evaluated is the construction of appropriate CPTs with minimal use of expert elicitation. The AgenaRisk tool includes a special type of node (rank node), which simplifies the definition of CPTs for a large class of commonly occurring nodes (Fenton, Neil, & Caballero, 2007). Considering all the advantages and drawbacks of the BN tools, AgenaRisk was selected for its power, versatile capabilities, and user friendly interface.

3.2 Model purpose definition

Prior to the construction of the BN, the purpose of the model needs to be established by gathering and understanding the existing knowledge of the subject under analysis. This process entails identifying the most relevant performance categories to assess a building's performance in a conceptual model. Experts' feedback may help identifying key variables or processes in the conceptual model, particularly if the model is used as a management tool (Langseth & Portinale, 2007; Chen & Pollino, 2012).

The proposed model supports facility managers on building performance management, thus their participation in the model development is particularly relevant. The detailed description of the methods to define the main performance categories to assess a building's performance is presented in Chapter 4.

3.3 Key variables identification

The second step of the BN modeling process is the identification of key variables influencing the model purpose. Variables consist of factors that affect building performance, and indicators to quantify the performance. In the BN model, each variable is represented as a node. Interviews with one or more domain experts are typically required in order to identify all of the important variables required to meet the core objective for the BN model (Constantinou, Fenton, & Neil, 2016). Existing knowledge should be synthesized into a conceptual model (i.e., influence diagram) to provide a visual summary of how the variables are linked to each other (Chen & Pollino, 2012).

All nodes in the model must affect (or be affected by) the final output. If this is not the case, the node can be removed (Chen & Pollino, 2012). The inclusion of insignificant variables can increase the complexity of the network, reduce the model outputs' sensitivity to important variables, and require extra time and effort, without adding any value to the overall model (Chen & Pollino, 2012). The identification of key variables is applied repeatedly until the least number of variables is obtained. In other words, until the key variables are not influenced by any other factors that are considered of interest to be included in the model (Chakraborty, Mengersen, Fidge, Ma, & Lassen, 2016).

Empirical evidence about the key variables identified need to be collected for legitimate inference of cause-effect relationships between them (Pearl, 2000). Based on the evidence gathered, possible relationships between the key variables can be understood and inferences can be drawn. This is essential for the construction of the model structure in the following steps. Therefore, different data collection methods may be required, such as registers, questionnaires, interviews, and direct observation. To ensure the accuracy, quality and integrity of the data, data collection methods must be defined.

Chapter 5 presents data collection methods to gather empirical evidence about the key variables that influence a building performance.

3.4 Model structure definition

There are three typical approaches for constructing a BN model: automatically, manually, or a combination of both (Fenton & Neil, 2012). The first approach involves learning the BN structure on the basis of historical data (Nguyen et al., 2016). In this approach, a BN software defines the location and direction of links between the variables based on the data available. Structural learning may be useful for modeling poorly understood systems, or those which are difficult to characterize (Chen & Pollino, 2012). However, the learning process requires a large amount of data and is highly sensitive to the settings chosen by the user (e.g., number of states, significance level) (Chen & Pollino, 2012). Moreover, the independence structure may not satisfy a faithfulness condition (Fenton & Neil, 2012). Some studies claim that a BN structure learned purely from data may fail to capture the underlying dependency structure required in situations where not all variables are captured by historical data (Fenton & Neil, 2012; Constantinou et al., 2016).

The second approach, which is practical in most engineering areas, is constructed based on the knowledge and experience from expert subject matters (Nguyen et al., 2016). According to Constantinou, Fenton and Neil (2016), the definition of the BN structure in collaboration with domain experts is a reliable method which considers the information that is really needed to model.

The third approach is the combination of (limited) data and expert judgment (Zhou, Fenton, & Neil, 2014). In this approach, the BN structure is constructed by identifying the causal relation between the variables based both on the data available and expert judgment (Chen & Pollino, 2012). A panel of experts can provide a feedback of the causal relations constructed by data, which may be helpful to identify key variables or processes that were overlooked and fix potential errors of the model.

For large complex systems, the model structure should be divided into modular subnetworks (or subnets) that represent smaller component models (Fenton & Neil, 2012). The component models are called object-oriented BNs (OOBNs), because they have some of the properties associated with object-oriented modeling (Fenton & Neil, 2012). OOBNs are particularly suitable for systems containing repetitive or hierarchical structures (Chen & Pollino, 2012). Moreover, it is often easier to conceptualize complex systems in terms of smaller, interlinked components, which is particularly relevant to multidisciplinary problems (Chen & Pollino, 2012).

As this research includes different building performance categories, the model structure definition is divided into subnets. The process to construct the model structure is explained in detail in the chapters describing each of the subnets: Chapters 6, 7 and 8.

3.5 Conditional probability tables definition

The conditional probability tables (CPTs) represent the conditional probability distribution for each node (Hu et al., 2013). Each variable identified during the second step is defined as a node in the BN model and its states need to be specified. A node may have binary states such as "Yes" and "No", or may have multiple states such as "High", "Medium" and "Low" (Chakraborty et al., 2016). The states of the nodes depend on the type, which can be discrete (e.g., labeled, Boolean, discrete real, ranked) or continuous (Fenton & Neil, 2012). The states for each node can be identified based on available data and expert opinion (Chakraborty et al., 2016). To keep the size of the CPTs manageable, it is recommended to have the smallest number of states possible in each node.

The approach to obtain conditional probabilities include (Chen & Pollino, 2012):

- Databases, from field monitoring or laboratory studies;
- Process equations, derived from peer-reviewed studies or models;
- Datasets, derived from models;
- Information elicited from experts or stakeholders.

When using databases, the data must represent how the node is modified according to the state changes of the parent nodes. Each of these data samples is referred to as a case. Accordingly, the accuracy of the conditional probabilities increases with a larger number of cases.

If no appropriate databases or models are available, then expert judgment can be used to estimate CPTs, which is based on past observation, knowledge and experience (Chen & Pollino, 2012). Expert judgment can be used to provide an initial estimate of the probabilities (i.e., prior probabilities), which are then updated using the available observed data.

Furthermore, if the number of parents of a node is too large, then approximation methods may be used to complete the CPTs. One of these methods regards the ordering of the marginal probabilities and obtaining a set of weights that represent the relative importance of each of the parent nodes. These weights can be calculated from the data, but can also be specified using other information such as ancillary reports, published literature or expert judgment (Chakraborty et al., 2016).

For each subnet, different approaches are used to derive the CPTs. The process to obtain them is described in detail in the chapters describing each of the subnets: Chapters 6, 7 and 8.

3.6 Model evaluation

The objective of a model evaluation is to ensure that the model's interactions and outcomes are feasible (Chen & Pollino, 2012). Generally, there are two methods for evaluating a model: verification and validation (Sargent, 2013). Validation is the assurance that a product, service, or system meets the needs of the customer and other identified stakeholders (Engel, 2010). Verification is demonstration that the model is transformed from a problem formulation into a model specification with sufficient accuracy (Balci, 1997).

Four steps to evaluate the BN model are investigated based on Sargent (2013), as shown in Figure 9: (1) conceptual model validation, (2) data validation, (3) computerized model verification, and (4) operational validation.

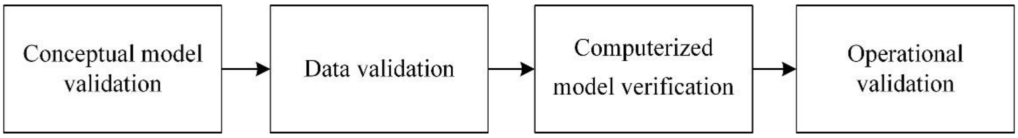


Figure 9. Model evaluation process

The first step includes the conceptual methodology validation, which is focused on the analysis of objectives, assumptions and outputs of the model, and on checking the accuracy of transforming the problem formulation into a model specification (Sargent, 2013). The model should be developed for a specific purpose and its validity checked with respect to that purpose (Sargent, 2013).

The second step is data validation, which consists of assessing the model behavior with the use of accurate and consistent data. Ideally, the accuracy of the model should be tested with empirical data. Data independent from the used to parameterize the model should be used for testing. The simplest form of such Cross-Validation is to randomly split the dataset into two parts, one for training, and the other for testing (e.g., 80%/20%) (Chen & Pollino, 2012). In the absence of data, a common technique for validating a BN is based on expert opinion. This process consists of simply asking experts whether they agree with the model structure, discretization, and parameterization (Pitchforth & Mengersen, 2013).

The third step deals with the computerized model verification by assessing the behavior of the parts or the whole model by applying different scenarios (i.e., combinations of inputs) and examining whether the resulting probabilities are reasonable and logical (Chen & Pollino, 2012). The scenarios are used for understanding the impacts of any change in the model (Chakraborty et al., 2016). Another form of quantitative evaluation is a sensitivity analysis. This analysis ranks the variables in order of their importance relative to the variable of interest, typically the final output (Chen & Pollino, 2012). The analysis results may provide a better understanding of the most significant factors in a decision scenario and can be used to verify whether the model's response has the expected behavior (Chakraborty et al., 2016). Moreover, existing methods and models can be used to verify the BN model output and compare if the proposed BN model behaves as expected (Sargent, 2013).

Finally, the last step includes operational validation, which is concerned with the conduction of case studies to demonstrate the operational use and outputs of the model.

As the BN model is divided into subnets, the evaluation is conducted for each subnet individually first, in Chapters 6, 7 and 8. The entire BN model is then evaluated considering the operational validity of the subnets together in Chapter 9.

Chapter 4

Model purpose and key variables affecting building performance

4.1 Introduction

This chapter presents the work undertaken to define the purpose of the model and the key variables that affect building performance. It includes the identification of the main performance categories and their relationships in a conceptual model.

4.2 Methodological proposal

To define the purpose of the BN model, a literature review was conducted to identify existing studies on building performance. In a second phase, a focus group with experts was conducted to understand and define the most important building performance categories to assess the performance of non-residential buildings. The third phase consisted of validating the results obtained from the focus group, by conducting a questionnaire survey and identifying the key variables that affect these performance categories. These variables comprise of factors (e.g., building age, geometry) and indicators to assess building performance. The final step included the development of a conceptual model that illustrates the relationship between the performance categories, indicators and factors.

4.2.1 Focus group

The research process used to conduct the focus group was based on Krueger and Casey (2009). The focus group technique is defined as a carefully planned series of discussions to learn what people think about a specific area of interest in a permissive, non-threatening environment (Krueger & Casey, 2009). Furthermore, interactions among participants may yield important data and the sense of belonging to a group may increase participants' sense of cohesiveness (Morgan, 1988).

The focus group meeting followed a schedule divided into topics. To establish a sense of belonging to the group, in the *opening question* participants were asked to explain their current role within their organization and their experience in FM. Then, the *introductory question* was an easy question to answer, designed to get everyone talking. Thus, the experts were asked to present their company's main building management concerns.

In the next step, *key questions* were proposed and participants were asked to brainstorm and suggest the categories they considered important when evaluating the performance of a building. Furthermore, as an *end question*, the experts were asked to write on a post-it note the 5 most important categories, based on their experiences. The experts were then put into groups of four to present their selection, to discuss and to reach an agreement on the most important areas. After this activity, a representative from each group was invited to present the results of their discussion to the whole group, and to explain why they had selected the categories.

The meeting lasted approximately two hours and was kept open using phrases such as "could you give me an example", "tell me more about it". Continuous effort was made to break any barriers that may have existed between the moderator and the participants. An assistant moderator took notes during the focus group, to support the digital transcription process, maintain validity and safeguard in case the digital recorder failed.

Sampling characteristics

Facility managers were chosen to define the building performance categories, as they have a holistic view of the building. Generally, facility managers communicate with all stakeholders of a building. For instance, they need to follow the owner's rules, manage end user complaints, and periodically undertake end user satisfaction surveys (Pärn & Edwards, 2017). For that purpose, facility managers have a general, objective view of the interests of all stakeholders while owners' or end users' perceptions of performance are influenced by the "forgiving factors" of surrounding conditions (Adrian Leaman & Bordass, 2007) or economic interests.

The experts who were invited to join the focus groups were selected on the basis of experience. The criteria required the experts with at least 5 years of working experience in FM and currently working in any non-residential building. The selection priority was given to the managers with more than 20 years of experience (Level I), followed by 10–20 years of work experience (Level II), and 5–10 years of work experience (Level III) (based on

Zhang et al., 2014). Experience in academic research and availability were also taken into account. Generally, individuals' judgment tends to become increasingly sophisticated and stable with the accrual of educational and work experience (Zhang et al. 2014). Although the participants were selected for their knowledge of the topic to be discussed, some heterogeneity was also considered, to encourage active discussion and contrasting opinions (Wibeck, Dahlgren, & Öberg, 2007; Krueger & Casey, 2009). Therefore, experts from different companies with experience in different types of buildings were taken into account during the selection.

Participants were formally invited to take part in the focus group via e-mail, in which the purpose of the group was explained. A total of twelve experts participated. Seven of the participants had over 20 years of experience in FM consulting and maintenance activities, two had between 10 and 20 years of experience, and three had between 5 and 10. Table 1 summarizes the participants' details. The experts included industrial engineers (8), an architect (1), quantity surveyors (2), and a technical engineer (1).

Table 1. Focus group participants' positions and level of work experience

Participant	Level of work experience	Position
1	I (more than 20)	FM consultant and director of an FM company
2		FM consultant at a company with experience in European projects and government administration
3		Head of the maintenance department on a public university campus
4		Coordinator of a maintenance department at a public university
5		Head of a maintenance department at a government building
6		Head of a department in a private foundation in the construction sector with experience in government administration
7		Project management consultant with experience in international projects and integrated project delivery
8	II (between 10 and 20)	Deputy head of a maintenance department on a public university campus
9		FM consultant at an international company
10	III (between 5 and 10)	FM at a company with experience in government administration
11		FM on a private university campus
12		FM consultant at an FM company

4.2.2 Questionnaire survey

A questionnaire survey was developed to validate the focus group results. The survey also validated the key factors to be consider in the O&M phase of a non-residential building. A copy of the survey is available on the Appendix A. Prior to a full-scale survey, a pilot survey was carried out with a researcher and a maintenance expert from the Universitat Politècnica de Catalunya (UPC) to test and verify the survey. The questionnaire was refined based on the feedback from the pilot survey.

The questionnaire was divided into the following sections:

i. Section 1: Respondent's details, including academic and professional background, and years of experience (as a facility manager, maintenance manager, energy manager, asset manager, construction manager, designer or consultant).
ii. Section 2: Validation of the results of the focus group about the building performance categories. The survey asked the experts to evaluate if the categories defined by the literature review and the focus group were the most significant to evaluate building performance. The Likert scale was 1-5, where 5 was "highly significant". An open ended question was included to give comments and add other categories they personally found relevant.
iii. Section 3: Definition of factors that most affect the performance of a building identified by literature review. The survey asked the experts to rate if the factors obtained from the literature review cover the most relevant factors affecting building performance. An open ended question was included to give comments and add other factors they personally found relevant.
iv. Section 4: The second part contained several questions regarding the technical performance of construction elements and systems. A list of potential defects that may appear in each building element and system based on existing studies (Chew & De Silva, 2004; Walter et al., 2005; Das & Chew, 2011; Rodrigues et al., 2011; Macarulla et al., 2013; Pereira et al., 2013; Chai et al., 2014; Fox et al., 2014; Gaspar et al., 2016; Serralheiro et al., 2017) was provided to the respondents. They were asked to select at most three main defects for each building element and system, and were given the option of adding defects they considered relevant to the list of possibilities.

Sampling characteristics

The survey was administered online, which allowed quick, easy access and a systematic collection of responses. The survey was available in two languages, English and Spanish, so that it was accessible to international experts. It was distributed to associates of the 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. A list of 120 industry practitioners were randomly selected and contacted 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 (Fellows & Liu, 2015).

Most 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 consulting on FM. Additionally, some of the experts had experience in design and construction management.

4.3 Building performance categories identification

In Chapter 2, the most relevant performance categories for building performance assessment were discussed. The literature results were used as a basis for the focus group discussions. The results of this focus group have been published in Frontiers of Engineering Management journal (Bortolini & Forcada, 2018b).

The results of the focus group revealed that the main categories to assess building performance are related to safety and user satisfaction rather than aesthetics. Regarding safety, all experts agreed that it was essential to meet regulations (as a threshold), so building regulations should not be taken for granted. Consequently, prevention of occupational risks was considered the most relevant category of building performance, which is related to the correct functioning of all elements and systems of the building.

Regarding building appearance, the results revealed that aesthetic aspects are relatively unimportant. In comparison with previous studies, aesthetics was valued, but was considered the least important category in a hierarchy of performance levels (Preiser & Vischer, 2005).

In addition, they considered user satisfaction an essential aspect to take into consideration. All experts believed that health and comfort aspects, such as air quality, were the main priority. Furthermore, space management based on users' needs was considered an essential aspect of performance, as was the level of cleanliness of a building. The experts also discussed the importance of assessing energy consumption considering the resources and costs (e.g., electricity, gas).

The experts declared that “forgiveness factors” should be considered in assessments of end users’ satisfaction. End users accept different performance levels depending on whether the building is private or public, which is related to the resources that are available for the building (e.g., human, technological, financial). Generally, buildings managed by the government are restricted by budget limits and conditioned by political issues, consequently the quality of services provided by public buildings is different from that of private buildings (Alonso, Clifton, & Díaz-Fuentes, 2015). However, experts considered that the general building performance categories are the same for both public and private buildings.

When joined in groups, although different terminology was used, based on the type of buildings they had experience with, all experts agreed on the same categories to define building performance: safety and assets working properly, health and comfort, space functionality, cleanliness, and energy efficiency.

When analyzing the survey results, most experts (83% of the respondents) agreed that the categories selected by the focus group were the most important to consider when assessing building performance. However, the results of the survey revealed that cleanliness was considered a minor area that should be incorporated when evaluating the space quality.

The questionnaire results suggested including space flexibility within space functionality. Other suggestions were related to the functionality of the building, i.e., that the building should provide the required features so that its users can satisfy their requirements or needs. Although the literature review suggested that there is a distinction between technical and functional performance (Lützkendorf et al., 2005), the results indicated that these two categories can be analyzed together.

Differently of previous studies (Lützkendorf et al., 2005; Preiser & Vischer, 2005), the results suggested that two levels of building functionality should be considered: asset level and space level. In the first level, the concern is to assess whether all building elements and systems are working properly, to guarantee the functionality and safety of the building. The second level is mainly related to the layout of the space and how people interact with it. For instance, if there are spaces for performing work activities.

The analysis of the literature review, the conclusions of the focus group and the results of the survey revealed that the main performance categories to assess the operational performance of a building can be limited to:

- Safety and Assets working properly: the physical condition of the building and the correct operational functioning of its elements and systems, including fire safety, structure, strength, stability, and weather tightness (Lützkendorf et al., 2005; Sullivan et al., 2010; Preiser et al., 2017);
- Health and Comfort: the building indoor conditions creating healthy and comfortable environments (i.e., air, thermal, acoustic, and light quality) and satisfaction of building users (Preiser & Vischer, 2005; Bluyssen, Aries, & van Dommelen, 2011);
- Space functionality: the availability of space to perform the required activities of occupants, including the needs of building users, ergonomic comfort, handicap access, and functional serving (Preiser et al., 2017);
- Energy performance: the total building energy use and the control of the growth in energy consumption by using energy more efficiently and consequently reducing the environmental impacts of the building (Escrivá-Escrivá, Álvarez-Bel, & Peñalvo-López, 2011; Preiser et al., 2017).

4.4 Key variables identification

4.4.1 Key factors identification

In Chapter 2, the key factors that influence on the performance of a building were presented. These factors were identified via literature review and included: design and construction errors; building operation and maintenance; building defects and problems; environmental agents; and building properties (Watt, 1999; Al-Homoud, 2005; Balaras et al., 2005; Flores-Colen et al., 2010; Lopez et al., 2010; de Wilde et al., 2011; Parasonis et al., 2012; Heo et al., 2012; CIB W86, 2013; Olanrewaju & Abdul-Aziz, 2015; Kirch et al., 2017; Madureira et al., 2017). The questionnaire survey validated the relevance of these factors.

The results of the questionnaire survey revealed that the majority of the experts (86.8%) found the defined exterior conditions (e.g., weather condition, surrounding environment, natural disasters, geological conditions) suitable to define the environmental agents that affect a building's performance. Some experts suggested the inclusion of human and urban environmental conditions, such as buildings near schools, façades opening onto public spaces, and buildings in deprived city areas are more prone to deterioration. This concept was considered relevant to incorporate in the surrounding environment agents.

Most of the experts (73.5%) agreed that the type of constructive solution and the age were the most important factors affecting building performance. Additionally, some experts suggested that renovations over the years or any kind of refurbishment should be included, and, therefore, change the element's age. The type of constructive solution is regarded to the materials of each building element. For instance, concrete and steel are one of the most common construction materials for building structure. The type of equipment is related to the designed system. For instance, a ventilation system may be natural, forced or mixed. Depending on the characteristics of the building, exterior conditions and the defined ventilation type, the air distribution within the building can vary and may impact building performance.

Regarding the building defects, the survey results indicated the main defects in each construction element and system, i.e., structure, façade, roofing, flooring, interior partitions and doors/windows, electrical, plumbing, HVAC, fire and elevator. The results were published in Journal of Performance of Constructed Facilities (Bortolini & Forcada, 2018a).

The main defects affecting the building structure are described in 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 (2004) highlighted the importance of monitoring cracking and spalling in the structure of a building, in order to estimate the durability of the structure. Moreover, water problems such as the moisture content in the structure were also considered critical, presenting a high risk of structural damage, according to a previous study (Hovde & Moser 2004).

Table 2**.** Response frequency of the main defects selected in the 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

In the façade, respondents 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 (Table 2). Similarly, Rodrigues et al. (2011) identified the main anomalies in façades as water problems, cracking, detachment, and problems in the surface appearance. The impact of these defects have been pointed out by several other studies on façade pathologies (Gaspar & Brito, 2008; Vieira, Silva, Sousa, de Brito, & Gaspar, 2015; Silva et al., 2016). Water problems in a façade are related to penetration damp (e.g., dampness from driving rain, leaking gutters, roof defects, defective seals of windows), rising damp (e.g., moisture rising by capillarity from the ground), and water ingress (Macarulla et al., 2013). Excess moisture is the most widespread and damaging cause of deterioration and decay affecting buildings (Watt, 1999). Cracking is one of the most common defects on a façade, and detachment is related to the façade covering that might be detached or broken.

As described in Table 3, most of the respondents (77.4%) considered that water problems in the roofing are the most critical to the performance of a building, including 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 research as a major defect on the roof, which is associated with plant growth, the action of birds, and gutters clogged with leaves, among others (Abisuga et al., 2016).

Table 3**.** Response frequency of the main defects selected in the roofing and flooring

Roofing defects	Number of responses	% of the total response	Flooring defects	Number of responses	% of the total response
Water problems	41	77.4	Detachment/Broken	28	52.8
Cracking	21	39.6	Cracking	28	52.8
Biological action and change	19	35.8	Surface problems	21	39.6

The results show that problems with detachment/broken of the floor covering and cracking (52.8%) are the defects that predominantly affect building performance (Table 3). Chong and Low (2006) also identified tile delamination as one of the main defects on the floor due to the action of occupants. Moreover, surface problems were also considered relevant by the respondents and in previous studies, such as efflorescence, unevenness, knocks/scratches, soiled areas and discoloration of the floor covering.

In the interior partitions (Table 4), in accordance with other studies (Chong & Low, 2006; Pereira et al., 2011), 60.3% of respondents found that cracking is the main defect that affects building performance. Moreover, 54.7% of the respondents selected surface problems, such as paint peeling and blistering, and 50.9% selected water problems, such as excess of moisture. Problems with surface appearance and water were also identified by (Chong & Low, 2006).

Table 4**.** Response frequency of the main defects selected in the interior partitions and doors/windows

Interior partitions defects	Number of responses	% of the total response	Doors/windows defects	Number of responses	% of the total response
Cracking	32	60.3	Faulty operation	40	75.5
Surface problems	29	54.7	Water problems	21	39.6
Water problems	27	50.9	Surface problems	20	37.7

Regarding doors/windows (Table 4), most respondents (75.5%) considered that faulty operation is the most critical defect for the performance of a building, and is related to malfunction in the use of doors or windows. In these elements, Chong and Low (2006) identified malfunction of the ironmongery in doors as a specific kind of faulty operation. Water problems (39.6%), such as water ingress, humidity and mold in the window frames were the second most frequently selected defect. In accordance with (Chong & Low 2006), surface problems (37.7%), such as paint peeling, are also considered important.

Considering the electrical system, the experts considered that faulty operation of electrical fixtures (58.5%), electrical distribution elements (58.5%) and electrical supply elements (52.8%) are the defects that most affect the performance of a building, as illustrated in Table 5. These defects cover all the electrical system extensively. The smooth functioning of the electrical system is critical, as electrical problems have a greater impact on users' health (Abisuga et al., 2016). Therefore, preventive maintenance of the electrical system should be verified and checked.

Table 5**.** Response frequency of the main defects selected in the electrical and plumbing systems

Electrical defects	Number of responses	% of the total response	Plumbing defects	Number of responses	% of the total response
Faulty operation of electrical fixtures	31	58.5	Leakage in water distribution elements	26	49.1
Faulty operation of electrical distribution elements	31	58.5	Operational faulty functioning of water supply elements	21	37.7
Faulty operation of electrical supply elements	28	52.8	Corrosion in water distribution elements	18	34.0

In the plumbing system, leakage in water distribution elements (pipes) was the defect selected by 49.1% of the respondents, as illustrated in Table 5. Previous studies also identified that leakage at pipe penetration and joints are critical defects in the plumbing system (Das & Chew, 2011). Moreover, faulty operation of water supply elements, which is related to problems with temperature, pressure, water level and vibration, was selected by 39.6% 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 considered that faulty operation of HVAC production elements is the most critical defect in the HVAC system. These faults include chiller malfunction, noisy boiler, mechanical problems and fan motor failure. Specific defects related to HVAC malfunctions were also defined by (Motamedi et al., 2014). Moreover, faulty operation in HVAC fixture elements (34.0%), such as thermostat malfunctions, excessive noise and vibration of an air unit, was also considered critical. Accumulation of dirt in HVAC distribution elements (30.2%), for example in air ducts, was also considered relevant.

Table 6**.** Response frequency of the main defects selected in the HVAC and fire systems

HVAC defects	Number of responses	% of the total response	Fire defects	Number of responses	% of the total response
Faulty operation of HVAC production elements	29	54.7	Faulty operation of fire fixtures	35	66.0
Faulty operation of HVAC fixtures elements	18	34.0	Faulty operation of water supply elements	19	35.8
Accumulation of dirt in HVAC distribution elements	16	30.2	Broken fire fixtures	18	34.0

In the fire system, faulty operation of fire fixtures, such as sprinklers and fire extinguishers, is the most critical defect and was selected by more than half of the respondents (66.0%), as shown in Table 6. Faulty operation of water supply elements (35.8%) and broken fire fixtures (34.0%) were also considered important. Moreover, a regular routine with respect to fire equipment maintenance needs to be established and verified (Bromann, 2010).

Regarding elevators, most of the experts agreed that faulty operation of distribution elements (77.4%) and faulty operation of elevator cabin elements (67.9%) are the most critical defects (Table 7). Park and Yang (2010) identified hazards and the corresponding causes and effects of problems in elevators. They concluded that routine maintenance of elevators should be carefully planned to mitigate the risk of accidents.

Table 7**.** Response frequency of the main defects selected in the elevator system

Defect	Number of responses	% of the total response
Faulty operation of distribution elements	41	77.4

Faulty operation of elevator cabin elements	36	67.9
Broken elevator cabin parts	20	37.7

The experts were asked if they agreed 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%). Cronbach’s alpha for the survey results on defects was 0.846, which indicates good internal consistency of the data.

In summary, the general factors to consider when assessing building performance are shown in Table 9.

Table 8. General factors affecting building performance

Factors	Example
Design & Construction errors	• Inadequate HVAC sizing • Wrong execution • others
Environmental agents	• Weather condition • Surrounding environment • Risk of natural disasters • Geological conditions
Building properties	• Building age • Building geometry (e.g., building shape, % of openings) • Thermal properties (e.g., envelope insulation) • Type of constructive solution (e.g., type of structure: concrete, steel, others) • Type of system (e.g., ventilation system type: natural, forced, mixed) • others
Building operation and maintenance	• Maintenance policy adopted (e.g., corrective, preventive, predictive) • Building management systems • Occupancy density • others
Building defects and problems	• Cracking • Faulty operation • others

4.4.2 Key Performance Indicators identification

Literature review and discussions with industry leaders were used to define the indicators within each performance category to evaluate building performance. An important aspect indicated by the literature review was the simplicity and meaningfulness of the indicators, in order to allow benchmarking (Kumar, Galar, Parida, Stenström, & Berges, 2013). The establishment of benchmarks allows the comparison with other facilities, and aids management in decision-making (Lavy et al., 2010).

Safety and Assets working properly

The KPIs for safety and assets working properly comprise the defects detected in each building element or system. For example, if we consider the façade of a building, the indicator to evaluate the performance of the façade should consider all its defects (e.g., cracks, erosion, water ingress, efflorescence) and their severity (Gaspar & de Brito, 2008). The severity should take into account the repair costs and the likelihood of causing other defects, and express the impact of the defect on the service or the end user (Serralheiro et al., 2017).

Another method to quantify the condition of building system is the analysis of incidents and complaints reported by users and building managers (Goins & Moezzi, 2013). The number of complaints and the severity of the reported problems are therefore one way to quantify this indicator.

Health and comfort

Regarding health and comfort, relative humidity together with temperature has been claimed as one of the main parameters related to thermal quality (Atzeri et al., 2016). Thermal quality is the indicator that measures the indoor thermal conditions that have a potential impact on the satisfaction of users (ISO 21929-1:2011). Moreover, air quality, light quality, noise and workplace pollution correspond mostly to the health and comfort of users (Roulet et al., 2006; Ornetzeder et al., 2016). Air quality is mainly linked with the lack of discomfort due to odor and sensory irritation (Frontczak & Wargocki, 2011). Light quality is the indicator that measures the occupant comfort with natural and artificial illumination (Frontczak & Wargocki, 2011). Acoustic quality is defined as a state of contentment with acoustic conditions (Catalina & Iordache, 2012). And space quality comprises the adequacy of space to fulfil the required function of the building (Lavy et al., 2014).

Building occupants are the best source of information on needs and comfort requirements (Frontczak et al., 2012). Therefore, the indicators about building comfort should be obtained by questionnaire surveys that rank a set of criteria in levels of user satisfaction (Au-Yong, Ali, & Ahmad, 2014).

After a carefully literature review analysis, space functionality was included in health and comfort category. This refinement was undertaken since the evaluation of spaces can be conducted in the same level as comfort indicators (e.g., thermal quality) by means of satisfaction surveys (Frontczak et al., 2012). Regarding whether it is ergonomic and accessible, there should be a periodic survey of regular users to gather information about ergonomic hazards in the workplace and complaints about accessibility.

Energy efficiency

Indicators related to energy efficiency include the energy performance of each building system: heating, cooling, ventilation, hot water, and lighting systems (Borgstein, Lamberts, & Hensen, 2016). The routinely management and operation of the building systems is an important aspect when evaluating energy performance indicators (Gul & Patidar, 2015; Hellwig, 2015). This is related to the facility control systems, such as the use of BMS and BEMS. Moreover, the efficiency of the equipment of each system and characteristics of the building are significant factors to take into account. For instance, the efficiency of the installed lights and the daylighting utilization can save energy by reducing the usage time of electric lighting (Pati, Park, & Augenbroe, 2006). The energy performance indicators are generally defined by square meter and per year (kWh/m^2.year), and the results should be compared with a reference building at the national or regional level (EN15217:2007).

In summary, the general indicators to consider when assessing building performance are illustrated in Table 9.

Table 9. General indicators for assessing building performance

Performance category	Indicators
Safety and Assets working properly	• Building elements condition (structure, façade, roof, interior partitions, floor, doors/windows) • Building systems condition (HVAC, electrical, plumbing, fire, elevator)
Health and Comfort performance category	• Thermal quality • Air quality • Light quality • Acoustic quality • Space adequacy
Energy efficiency performance category	• HVAC energy performance • Lighting energy performance • Hot water energy performance

4.5 Relationships among performance categories: Conceptual model

The understanding of the relationships between the three main performance categories is an essential task for the assessment of the building performance. Interactions among health and comfort of occupants, the energy efficiency and condition of the building elements and systems can be used to guide a way to achieve a comfortable, healthy and energy-efficient building (Roulet et al., 2006; Grussing & Liu, 2014; Abisuga et al., 2016; Fox, Goodhew, & de Wilde, 2016).

Essentially, there is a need to understand how the performance loss or failure of one building element affects the performance of other elements, and systems and building as a whole (Grussing & Liu, 2014). For instance, some construction elements not working properly may provoke other problems in the building (e.g., cracks in the façade may cause water infiltrations). Moreover, depending on the condition of the building envelope, higher thermal loads would be required to reach interior comfort temperature, provoking higher electricity consumption and thus reducing the energy performance of the building. This can be associated to energy related building defects such as ventilation losses, moisture related defects, and service faults (Fox et al., 2016). The effect of deterioration on building systems also affect the end users (Grussing & Liu, 2014). Poorly maintained indoor environments have been linked to discomfort and health problems experienced by users (Abisuga et al., 2016).

The results of the literature review, focus group and questionnaire were used to establish a conceptual model as a starting point for the construction of the BN model. Figure 10 illustrates a holistic causal model among KPIs within categories, and factors. The term “holistic” refers to the fact that the model supports the consideration of the interdependencies among various indicators and factors.

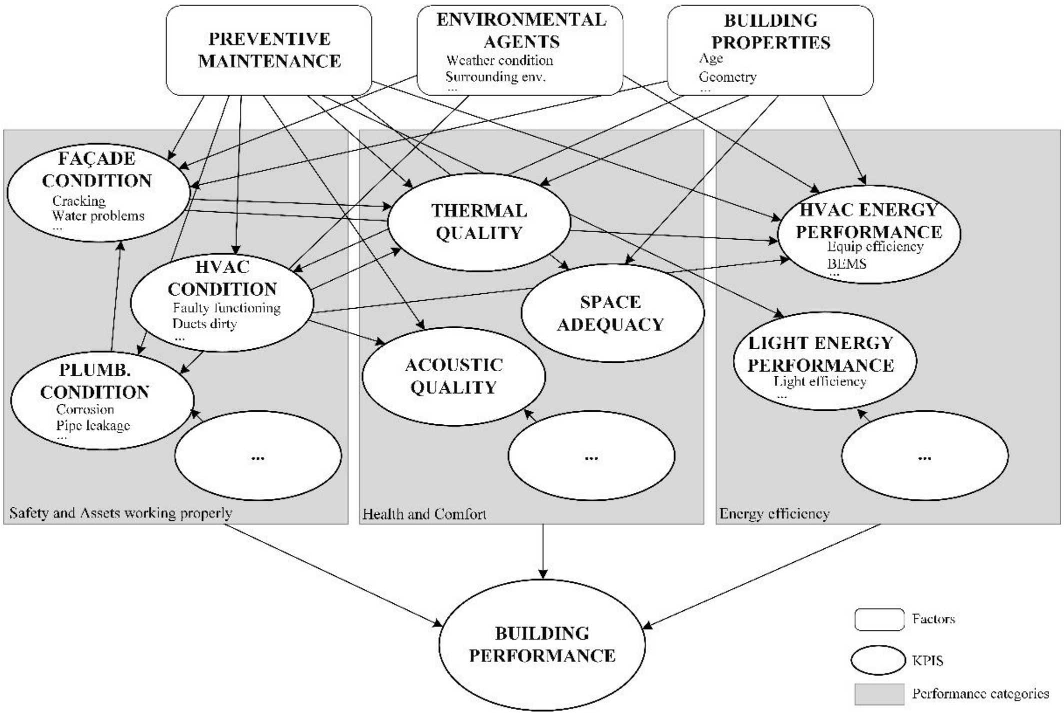


Figure 10. Holistic building performance causal model

Figure 10 presents the causal effect among KPIs within each performance category. For instance, a malfunction in a drain pipe hanging on the façade may trigger another problem on the façade (e.g., cracks). Moreover, the causal effect among KPIs and different performance categories is also represented. For example, thermal quality, as a health and comfort KPI, is influenced by the condition of the façade and the HVAC system.

Furthermore, the causal effect between KPIs and factors was also established. Environmental agents and building properties affect the KPIs related to all categories. For instance, the environmental exposure of a building may accelerate the degradation of the façade. Preventive maintenance can also be a factor of delay in the degradation of building elements and systems.

Through the definition of the main performance indicators and factors and their relationships, experts can understand the causality chain that exist when analyzing multiple factors that affect building performance holistically. This definition makes explicit the multiple and often complicated nature of buildings and provides a more rational analysis of building performance.

Chapter 5

Data collection methods

5.1 Introduction

Obtaining information about existing buildings is a complex task. Existing buildings often lack as-built documentation, resulting in incomplete or obsolete information (Volk et al., 2014). Moreover, even when the information is available, it is dispersed among different databases and unformatted (Koch et al., 2014).

In the Chapter 4, three categories were defined as the most relevant to assess the performance of an existing building: safety and assets working properly, health and comfort and energy efficiency. For each performance category, key variables were also identified. As a result of the literature review, focus group and survey analysis (Bortolini & Forcada, 2018b; Bortolini & Forcada, 2018c), three main sources to obtain information about these variables were defined:

- FM/operators: these variables include those that can be measured by extracting from databases, such as the Computerized Maintenance Management System (CMMS), sensors connected to Building Management Systems (BMS) that report malfunctioning, and data collected from building inspections.
- Regular users: these variables are related to complaints about comfort or malfunctioning of elements reported through a call desk or intranet applications linked with CMMS. The end user notices a problem and may complain, for example, if the HVAC system is not working properly. Satisfaction questionnaires are also typically used to obtain variables related to users' comfort.
- Sporadic users: these variables are obtained from questionnaires that mainly use satisfaction ratings about comfort-related aspects.

Figure 11 illustrates the relationships between the variables within each category, the sources of information, and the tools used to get these variables.

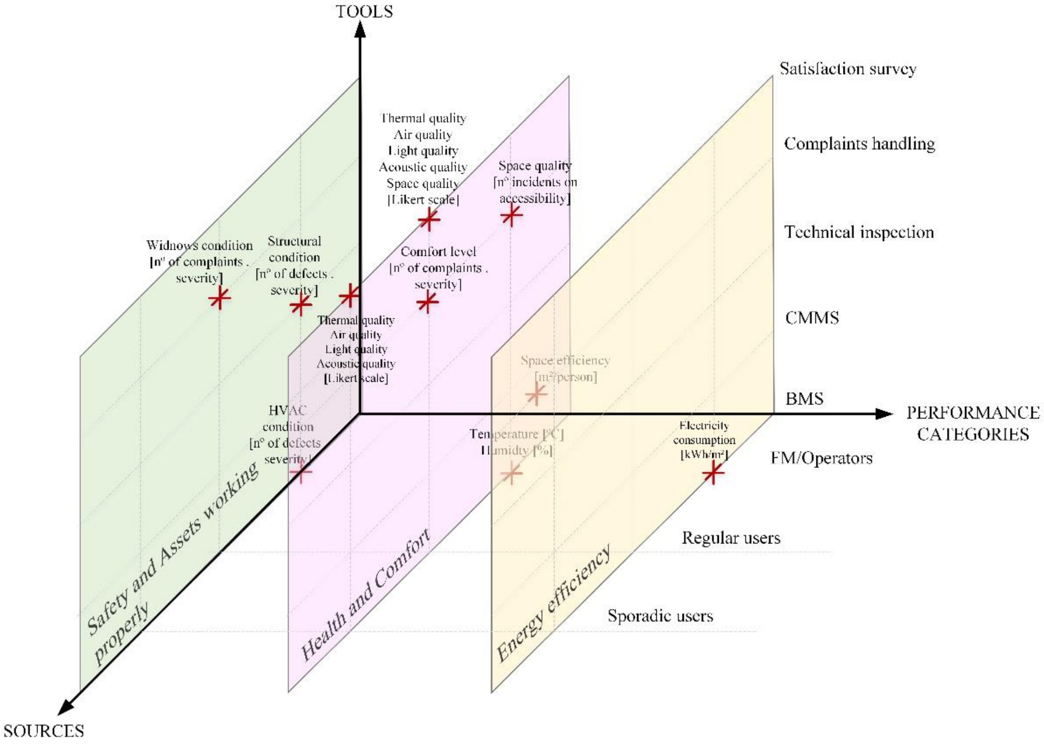


Figure 11. Building performance categories, sources and tools

Figure 11 also presents examples of variables for each performance category. For instance, in the energy performance category, FM/Operators manage BMS tools to get information about the electricity consumption (kWh/m2). The health and comfort category can be evaluated in a subjective and objective way. On one hand, regular and sporadic users can complete satisfaction surveys to report their satisfaction in terms of thermal, air, light, acoustic, and space quality (Likert scale). On the other hand, FM/Operators can evaluate objectively the same category by monitoring the temperature (ºC) and humidity (%) by sensors connected to BMS, and by using lux and sound level meters for measurement of light and acoustic quality, respectively. The category regarding safety and assets working properly can be evaluated by detecting defects during technical inspections conducted by FM/Operators and alarms monitored by BMS. This indicator can also be measured by the number of complaints reported by regular users within each building element or system.

This chapter presents the different sources and tools to collect data regarding these variables. This description is divided by the three main performance categories identified in Chapter 4. Notice that the data collected for a performance category may also be useful for another category. For instance, the condition of some construction elements are required to assess the building condition performance as well as the energy performance. Moreover, general characteristics of the building are necessary for all the three performance categories.

5.2 General building data collection

As a starting point, unstructured interviews with facility managers may be used to gather relevant information about buildings and the current practices in FM. This includes practices in condition assessment of buildings, maintenance policies adopted (corrective, preventive, and predictive), and existing tools employed to manage the built-assets. The interviews may be followed by checking existing documentations about the buildings under analysis. Usually, the documents include 2D drawings, spreadsheets, bar charts, and field reports that are typically handed over from the design and the construction phases, available as text based and maintained as handwritten record papers (Chen et al., 2013; Koch et al., 2014; Motamedi et al., 2014).

Moreover, a forensic walkthrough of the building may be conducted, reviewing building documentation. This visual observation is limited to the accessible areas of the building and may also involve an evaluation of the building surroundings, such as proximity to vegetation, traffic, industrial area or seaside (Flores-Colen, de Brito & de Freitas, 2008). 2D imaging technologies, including imaging (digital cameras) and video imaging (video recorders), are techniques that can be used to support the visual observation (Taneja et al., 2011). The information obtained may also include pictures to characterize the general properties of the building such as type of façade, type of windows, type of interior partitions, etc.

If available, information can also be obtained from a CMMS. A CMMS contains a wide range of information on building maintenance, providing managers and technicians various reports related to maintenance and repair issues, and access to information about equipment, warranty information, and maintenance polices (Duffuaa & Ben-Daya, 2009; Motamedi et al., 2014). The historical tracking of all work orders generated in CMMS also regards information about renovations conducted in the building.

Moreover, Computer Aided Facilities Management (CAFM) systems can be used to gather information about occupancy density and space management. A CAFM system is similar to a CMMS, but with an expanded functionality that includes several facility activities that may not be covered by a CMMS. These are some of the added functionalities of CAFM systems: room booking, resource scheduling, stock control, purchase ordering, health, and safety management (Best, Langston, & de Valence, 2003).

5.3 Building condition data collection

The category regarding safety and assets working properly is related to the assessment of the building condition performance. Generally, technical inspections are focused on the main building elements (civil and architectural elements of the building), rather than building systems (plumbing, electrical, HVAC, elevator and fire systems). Table 10 compares the differences in building elements and systems. In general, defects in building elements are visually easy to detect in building inspections, while defects in building systems do not usually have clear visual signs, so they are harder to detect (Das & Chew, 2011; Douglas et al., 2013).

Table 10**.** Comparison between Building elements and systems (based on Das & Chew, 2011; East et al., 2012; Douglas et al., 2013)

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
Defect detection	Easy, usually has visible signs	Difficult, usually has no visible sign
Automatic fault detection	Difficult	Easy, integrated with building automation system (BAS)
Effect on user	Indirect	Direct

Data about the condition of systems may be collected from FM systems. Some buildings may have a building automation system (BAS), which consists of an installed system that controls and monitors building services responsible for heating, cooling, ventilation, air conditioning, lighting, solar control devices, life safety and alarm security systems (Domingues, Carreira, Vieira, & Kastner, 2015). Moreover, CMMS are typically used as a system to support the maintenance operation of a facility, including the management of maintenance requests.

Two methods to collect data about the building condition, taking into account the division of the building in elements and systems were developed:

- A building inspection system to evaluate the condition of construction elements
- A text-mining approach to evaluate the condition of building systems.

5.3.1 Building Inspection System

A Building Inspection System (BIS) was created to standardize the data collection about the technical performance of existing buildings. The BIS was published in Journal of Performance of Constructed Facilities (Bortolini & Forcada, 2018a).

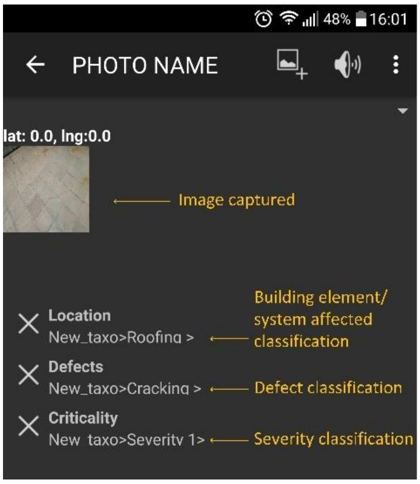
The BIS to evaluate the technical performance of existing buildings consists of three main steps: (1) characterize the building to be inspected, (2) determine the defects and their causes in building elements and systems that mainly affect the building performance, and (3) assess severity and recommend maintenance actions. The proposed BIS is based on the survey results described in the previous chapter and a literature review.

Characterize the building

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

Inspection of main building elements/systems

The technical inspection should be conducted in an objective way to detect the defects that mainly affect a building's performance. Mobile techniques such as Pick & Go (Macarulla, Forcada, Casals, & Kubicki, 2012) are proposed to gather on-field data directly, which helps in the subsequent data analysis. Figure 12 provides a screenshot of the mobile application with an image of a detected defect, and its categorization with tags describing the affected building element or system, the defect type, and the severity. Voice annotations that transcribe comments using speech recognition software and graphical annotation such as arrows or rectangles can also be added to the captured images. 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 (Taneja et al., 2011). The extent of each defect should be measured using expedient methods, such as photography, thermal cameras and a measuring tape as a reference (Madureira et al., 2017).



lat: 0.0, lng:0.0

Image captured

Location
New_taxo>Roofing >

Building element/ system affected classification

Defects
New_taxo>Cracking >

Defect classification

Criticality
New_taxo>Severity 1>

Severity classification

Figure 12. Screenshot of the mobile application to capture on-field data

The procedure for inspecting the main building elements/systems is organized as follows: (1) underground, (2) ground floor and subsequent floors, (3) technical rooms, and (4) external areas.

Underground

The inspection starts from underground levels (if they exist), and moves to the ground floor and upper levels. The inspection of underground levels helps in the analysis of potential defects in the foundations and structure. The survey results found cracks, water problems, and deformation/settlement to be the main defects in the structure. Depending on the location, direction, length and width of cracks in the structure and envelope, the inspection might determine the causal factor of these cracks (settlement, structural deformation or hygrothermal problems). Settlement and hygrothermal problems may be due to exterior conditions (Douglas et al., 2013). Hygrothermal problems can be caused by the absorption of water into porous materials, which causes an increase in the volume of the material and consequently provokes cracks. Conversely, moisture loss tends to lead to a decrease in volume and corresponding shrinkage and cracking (Watt, 1999). Settlement is one of the main problems in the structure (ACI 562-13:2017), normally occurs in the early stages of a building, and may be associated with the compaction or movement of the ground beneath the foundations (Watt, 1999). The occurrence of cracking in this situation is predominantly diagonal and follows the vertical and horizontal mortar joints in brickwork.

Still at underground level, the flooring should be inspected for signs of water penetration such as dampness, due to humidity coming from the ground (Douglas et al., 2013).

Ground floor and subsequent floors

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 determine the causal factors of these cracks, for instance structural movement, overload or lack of maintenance (Pereira et al., 2011). Signs of water penetration on interior partitions is one of the main defects encountered in the survey analysis. The inspection should determine if the origin of the water problem is external (which could be due to problems with insulation on the roof or façade), or internal (which may come from problems with the plumbing, such as pipe leakage). Water problems such as damp patches on internal partition surfaces can be due to rain that has saturated the wall or entered the construction through cracks in the façade (Watt, 1999). The general condition of all surfaces and floors should be checked for surface problems, such as paint peeling, blistering, unevenness, knocks/scratches, soiled areas and discoloration. The reason for these surface problems might be age and lack of maintenance (Chong & Low, 2006).

When interior partitions are inspected, doors and windows should be checked for faulty operation, such as difficulties in opening and closing. Moreover, the inspection should focus on water problems, such as water ingress, humidity and mold in the window frames, and the origin of these problems, which may be moisture filtration from the enclosure system itself or from the joinery joint with the wall of the façade (Douglas et al., 2013). Surface problems on doors and windows might also be detected due to the action of exterior conditions and lack of maintenance (Santos, Vicente, de Brito, Flores-Colen, & Castelo, 2017).

Furthermore, when inspecting air-conditioned rooms, survey results highlighted the need to detect faulty operation in fixture 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, when 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 ceilings can be inspected using thermography (Fox, Coley, Goodhew, & de Wilde, 2014).

Technical rooms

The technical rooms for HVAC production, plumbing supply and the electrical branch circuit wiring should be inspected. Regarding plumbing, the survey results revealed that faulty operation of water supply elements, such as equipment malfunction, water level, and vibration problems, are very relevant. Accessible shafts may be checked to detect corrosion of pipes (Douglas et al., 2013). If there are water tanks for fire systems, inspectors should check them, as well as the condition of pumps and valves. The survey results also pointed out that when inspecting the HVAC system, faulty operation of HVAC production elements should be checked, such as chiller malfunction, noisy boiler, mechanical problems, and fan motor failure (Motamedi et al., 2014).

A visual inspection of the electrical system can be conducted to assess its general condition and identify aspects that attract attention, such as exposed wiring, faulty connections and double tapping of circuit breakers. Inspections of some fire system elements, such as automatic fire detection systems (smoke detectors and fire alarms), are related to the electrical system. The condition of sprinklers, fire extinguishers and hydrants should also be checked. Records on the regular testing and servicing of fire alarms, emergency lighting, fire extinguishers, sprinklers, smoke vents, fire curtains or shutters should be reviewed (RICS, 2010). Any discrepancies with the fire certificate or noncompliance with fire safety regulations and building regulations should be noted (RICS, 2010).

The state of the elevator’s elements, if the building has one, can be checked if it is operating. In the cabin, the inspector should check operating control devices, the emergency signal, and the door closing operation (Park & Yang, 2010). In the elevator machine room, the pipes, wiring and ducts should be visually inspected.

Moreover, inspectors should verify that preventive maintenance is performed routinely to form an overall opinion of the condition of building systems and the need for further investigation (RICS, 2010).

External areas

Subsequently, the inspector should access the roofing to inspect for points of infiltration of rainwater and signals of biological impact such as plants, the action of birds, and gutters clogged with debris. These problems may be due to exterior conditions (e.g., temperature, solar radiation, wind) and lack of maintenance (CIB, 2013). Moreover, ponded water may occur due to either improper drainage or sagging of the roof deck due to design and construction errors (CIB, 2013). Based on the survey results, biological action and change is a very relevant defect that can be detected on roofs. Lichens, mosses and other biological growth can colonise outside surfaces when mineral salts and moisture are present (Watt, 1999). Algae may also appear where there is a concentration of humidity, which may cause staining of the affected surfaces. In addition, if located in the roofing, the plumbing and HVAC systems may be checked following the procedure described above.

Finally, the exterior condition of the façade and exterior elements such as doors and windows should be inspected. As shown by the survey results, cracks, humidity and detachment of façade elements should be noted. Cracks in the façade covering might be caused by structural problems or thermal dilatation (CIB, 2013). Especially in the encounter with hollows, the stresses that a wall supports produce tension deviations, which may cause cracks by the corners, and consequently, cause problems in windows such as deformation of the window frame and broken window glass. The inspection should check for detachment of the façade covering that might occur due to the action of climate factors such as water, ice and wind on materials with a certain porosity (CIB, 2013). Problems of humidity from capillarity can be detected at the beginning of the facades and are usually evident as stains, efflorescence, erosions and even detachments (Macarulla et al., 2013).

Severity

The severity is used during the inspection, to evaluate each defect detected. For that, a severity rating depending on the impact of the defect on the building and its occupants (Douglas et al., 2013) and according to the urgency of the repair (Gaspar & de Brito, 2008; Neto & de Brito, 2012; Pereira, de Brito, & Correia, 2013; Silva, Coelho, de Brito, Silvestre, & Pereira, 2017; Madureira et al., 2017) was proposed:

- Low severity: Low impact. Defects related to aesthetic aspects, requiring simple repair or monitoring the evolution of the defect at the next inspection. Non-intervention does not affect the progression of the defect.
- Medium severity: Moderate impact. Defects that jeopardize the function of the element/system and interfere with use and comfort, and require a moderate/complex repair within 6 months.
- High severity: Severe impact. Defects that could compromise the occupiers' health and safety, and require an immediate intervention. Non-intervention may result in the element's collapse and increase its degradation.

Magnitude

The magnitude is used after the inspection, to quantify the influence of each defect into the whole condition of the element/system. This is done because the same defect can be detected in different parts of a specific element (e.g., north, south, west and east façades). Therefore, the magnitude provides the global impact of these defects on the element (e.g., whole façade). The magnitude of each defect for each building should be undertaken considering the following equation:

$$\text{Magnitude} = \frac{(\text{№ of defects S1 x 1})+(\text{№ of defects S2 x 3})+(\text{№ of defects S3 x 5})}{\text{A}}$$

Where, *S1* are defects with low impact, *S2* are defects with moderate impact, and *S3* are defects with severe impact. *A* is the area of the element under analysis. For the defects in the façade, roof and floor, the square meters of these elements should be analyzed. For the defects in the structure and interior partitions, the building volume should be considered. For the defects in the doors/windows, the square meters of these openings should be analyzed.

5.3.2 Text-mining approach to analyze maintenance requests

The condition of building systems are difficult to evaluate and punctual inspections might give a wrong evaluation of the system condition. Another source of valuable information to analyze building systems consists of maintenance requests (complaints). These maintenance requests are a form of feedback to the building operators (Goins & Moezzi, 2013). Given that maintenance requests represent a perception that a feature or element of the building is underperforming (e.g., malfunctioning of some equipment), they relate directly to the building performance.

Generally maintenance requests are managed and stored in CMMS (Becerik-Gerber, Jazizadeh, Li, & Calis, 2011). A CMMS contains descriptions of end users maintenance requests, but the details are often recorded inconsistently by different operators or some details can simply be missing (Federspiel, 2001; Gunay, Shen, & Yang, 2018). Thus, although a CMMS database contains invaluable textual data to evaluate a building system, it is challenging to carry out analytics upon these databases (Hale, Arno, & Briggs, 1999).

With the development of text mining algorithms that allow the extraction of information from datasets, it may be possible to find indications of the condition of building systems. Therefore, in order to analyze systematically the maintenance requests from CMMS, a text mining approach is applied. Text mining consists of the process of extracting usable information from large quantities of textual data (Witten & Frank, 2011).

First, all the maintenance requests should be extracted from the CMMS, creating a dataset in a *.csv* format, for example. Using scripts of *Python* programming language in a text editor (such as Notepad++), all punctuation marks and spaces need to removed, so only individual words are considered. The dataset is then encoded into a standard format (e.g., UTF-8) to ensure the correct removal of diacritical marks, reducing the complexity of dealing with a multilingual dataset. Finally, all words are converted to lower-case, therefore the letter case is not differentiated (e.g., Doors and doors are considered the same word).

To classify the maintenance requests, the most frequent words of each problem type category are found using the *MapReduce algorithm* (Dean & Ghemawat, 2008). The most frequent words are then used to define a set of keywords for each category. For instance, the components of each element or system (e.g., windows, boiler, chiller, light, pipes) are the most frequent words used to classify the problem type in a category. To classify the problem, adjectives that describe the characteristics of the elements and systems (temperature, hot, cold, burnt) and the action needed to address the request (e.g., clean, check, inspect) are used. A stemming algorithm is employed to obtain the root words associated with each problem and then maximize word finding (e.g., window instead of windows). Then, the requests not labelled in any category and the ones mislabeled are reviewed and assigned with the correct category manually, improving the set of keywords.

The next step is to define the keywords that represent each problem type for each category. The most important defects for each construction element and system defined by the Building Inspection System (see Section 5.3.1) are used in this step. The same process for obtaining the most frequent words using the *MapReduce algorithm* is employed (e.g., cracking, leakage, stain). Then, root words for each defect type are established using the stemming algorithm (e.g., crack instead of cracking).

Severity

After the classification of the problem types, they are classified in three levels of severity (1, 2, 3), in which 3 is the most severe. The most frequent words related to severity 3 are the ones that the end user or the FM team use when an immediate repair or action is required (e.g., urgent, safety, emergency, alarm, fire). The words related to severity 1 are the ones that the end user or the FM team use when a repair or action can be postponed and planned (e.g., have a look, change, verify, clean, paint). The requests not classified in any of the previous categories are defined as severity 2.

The next step is the creation of a dictionary in *Python*. For each building, a key is created to count the number of maintenance requests with a given set of characteristics in the dataset.

Magnitude

The assessment of the magnitude is to quantify the influence of the problem type into the whole condition of the system. For instance, all the problems detected in electrical fixtures (e.g., lights and plugs) are evaluated to obtain the global impact of these problems considering the electrical fixtures as a whole.

The magnitude of each problem type should be undertaken using the same approach used for the magnitude of defects detected in the BIS (described in Section 5.3.1.3), but taking into account the maintenance requests:

$$\text{Magnitude} = \frac{(\text{№ of problems S1 x 1})+(\text{№ of problems S2 x 3})+(\text{№ of problems S3 x 5})}{\text{A}}$$

where *S1* are problems with low impact, *S2* are problems with moderate impact, and *S3* are problems with severe impact. *A* is the area of the building under analysis. For the problems in elevators, *A* is refers to the number of elevators in the building.

5.4 Building comfort data collection

The health and comfort category is related to the assessment of the building comfort performance. A survey was developed to obtain comfort metrics about occupants' satisfaction. If data from monitoring systems is available (e.g., sensors), it may also be gathered as an input to assess the comfort performance.

5.4.1 Satisfaction survey

Satisfaction survey is the most frequently used tool to assess end users' comfort (Au-Yong et al., 2014). Many companies conduct surveys to evaluate the conditions of the workspaces and the satisfaction of the users, considering various aspects of the environment quality. This evaluation process is not performed in all companies, therefore a questionnaire was developed as a template for gathering comfort and health aspects, in order to aid the companies to apply this important process. The full questionnaire is available in the Appendix B. This questionnaire contains terms about academic buildings as an example, but it can be easily adapted to other building typologies.

Two types of questionnaires were created: one for regular users and another to sporadic users. The questionnaires differ only on sections 2 and 3, where personal questions were asked to regular users about their workplaces:

- Section 1. Respondents' details, including gender and age.
- Section 2. For regular users: workplace location (building group and building name) and workplace characteristics, including years of working in the same workplace and availability of personal control adjustments (curtain, windows, ventilation, thermostat, and others). For sporadic users: building group and most frequently used building (campus and building name) and years of working in the same building.

- Section 3. The survey asks regular users to rate their satisfaction in relation to some aspects of their workplaces, including: thermal sensation in winter and summer, air quality in winter and summer, light quality, cleanliness, space adequacy, and acoustic quality. The survey uses a 5-point scale to rate occupants' satisfaction ranging from "very satisfied" (5) to "very dissatisfied" (1), with a neutral midpoint (3). The survey also asks the reasons for dissatisfaction given the predefined options, and a text entry box for the respondents to add other reasons.
- Section 4. The survey asks regular and sporadic users to rate their satisfaction in relation to some aspects of the common spaces of the building that they use most (e.g., classrooms, corridors, conference rooms, restrooms and dining rooms), including: thermal sensation in winter and summer, air quality in winter and summer, light quality, cleanliness, space adequacy, and acoustic quality.
- Section 5. The survey asks regular and sporadic users to rate their satisfaction in relation to the building's accessibility, and their general satisfaction with the building. Regarding the building condition, possible reasons for dissatisfaction are predefined, and a text entry box is provided to add other reasons. An open-ended question is also included, allowing respondents to comment on what they personally found relevant.

5.5 Building energy data collection

The energy efficiency category is related to the assessment of the building energy performance. Data about energy management in buildings can be collected from Building Management Systems (BMS) and Building Energy Management Systems (BEMS). BMS monitor and control building performance and mechanical equipment such as heating, ventilating and air-conditioning systems. BMS can store, integrate and analyze complex datasets from multiple data sources to help in the generation of energy efficiency reports, which should be accessible to energy managers and relevant stakeholders (Motawa & Carter, 2013). Different formats can be analyzed through the data stored on BMS, depending on the different decisions, e.g., the data maybe organized on monthly/hourly basis, for the subset of buildings in a certain site, for a certain zone of a building (Motawa & Carter, 2013). With energy meters and temperature, occupancy and lighting sensors connected to a BMS, faults may be detected manually or automated fault detection software can be used to avoid energy waste (Levine et al., 2007).

BEMS are tools for diagnosing, monitoring and generating actions to assets particularly related to energy services and consumption in a building (Elmualim & Pelumi-Johnson, 2009). BEMS control and monitor systems, such as lighting and HVAC, in order to specifically address energy use. The BS EN 15232:2016 standard presents a series of classes – A to D – representing different control levels for the energy performance in non-residential buildings. For savings to be estimated on an existing building or system, its current controls need to be rated against the classification system in this standard.

5.6 Conclusions

The holistic management of buildings is a multi-domain problem which consider maintenance, comfort, energy management, and others. In order to holistically manage the performance of a building, it is important to use knowledge from different sources.

In this chapter, data collection methods were described and developed to gather information about the main variables affecting building performance. This information is related to the three performance categories defined in Chapter 4. Detailed methods were discussed separately. A building inspection system to collect defects on building elements and systems was proposed. As still there is no method to analyze problems in building system in the literature, a text-mining approach to analyze maintenance requests was developed. Moreover, a satisfaction questionnaire was proposed to collect data about comfort of end users.

Chapter 6

Bayesian network model for assessing a building’s condition performance

6.1 Introduction

This chapter describes the work conducted to develop the subnet related to the first building performance category, which is the safety and assets working properly, as defined in Chapter 4. This chapter develops a BN model that provide an effective way of assessing the condition performance of existing buildings. The model also provides an understanding of the causality chain between multiple factors that affect building condition and help optimize inspection and maintenance plans.

6.2 Condition performance assessment methods

Several authors (Gaspar & Brito, 2008; Silva, de Brito, & Gaspar, 2011; Galbusera, de Brito, & Silva, 2014; Chai, de Brito, Gaspar, & Silva, 2015; Serralheiro et al., 2017) have developed degradation functions to express the loss of performance of building elements. These indexes consist of functions that include the sum of the number of defects detected in an inspection, weighted according to their severity and repair costs (Serralheiro et al., 2017). This method is easy to apply and understand and can be implemented rapidly (Silva et al., 2015). However, condition indexes have been developed for specific elements such as façades (Chew & De Silva, 2004; Sulakatko et al., 2014; Serralheiro et al., 2017), but none of them focus on the building as a whole. Moreover, they neglect the variability associated with the degradation process (Duling et al., 2008).

The understanding that the degradation process is a stochastic phenomenon involving large variation and uncertainties (Vieira et al., 2015) has motivated studies on the use of new methods. Recent studies have applied methods to predict the service life of building elements, such as neural networks (Dias, Silva, Chai, Gaspar, & de Brito, 2014), Markov chain (Silva et al., 2015), and fuzzy systems (Vieira et al., 2015).

These studies have made a valuable contribution, but none of them propose a holistic assessment, that is, an approach that emphasizes the functional relationships between the various building parts and the entire building. Moreover, most existing studies tend to be linear: they investigate only one cause of a problem, and do not predict further implications of these problems for other elements. A causality analysis of all the elements and systems in a building and a consideration of how its parts dynamically interact with each other has not been explored yet. Although previous studies identified causes of defects and emphasized the complexity of the systems in which they are generated, there is a lack of research quantifying the causal effect of defects in the operation and maintenance stage related to the theory of causation.

To bridge this gap, a probabilistic approach can be taken to building condition assessment (Coles, 2001). Unlike deterministic models, BN can model the condition of building elements and systems as a probabilistic process, providing the most probable condition level of performance of the building under analysis using probability distributions and dependence structures over a set of random variables.

6.3 Methodology

In Chapter 3, the general steps to construct a BN model were described. To build the BN model for building condition performance, a detailed description about these steps are explained in the following subsections and illustrated in Figure 13.

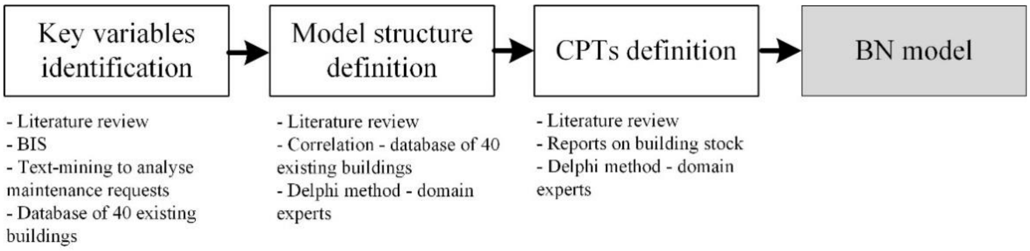


Figure 13. Main steps to build the BN model for building condition performance

6.3.1 Key variables identification

The most influential variables in a building's condition performance were identified by a literature review. This included the definition of the factors and indicators affecting building condition. Then, the BIS and the text-mining approach described in Chapter 5 were used to collect data about defects and maintenance requests of 40 existing buildings.

6.3.2 Model structure definition

The definition of the BN model structure was divided into three main steps:

i. First, a literature review was conducted to analyze the relationships (cause-effect) of key variables that affect a building's condition performance.

ii. Second, a Pearson's parametric correlation test (Gravetter & Wallnau, 2014) was undertaken to reinforce and check the previously defined relationships. Although correlation is not causation (Fenton & Neil, 2012), this analysis can help to reinforce the relationships established by the literature. The statistical tests were conducted with a database of forty existing buildings using the Statistical Package for the Social Sciences (SPSS) for Windows (version 24.00). A value of exactly +1 indicates a perfect positive fit, a value close to zero indicates no correlation, and a value of exactly -1 indicates a perfect negative fit (Gravetter & Wallnau, 2014). This approach meant that variables could be identified with significant correlations at the 95 and 99% confidence intervals.

iii. Third, to check and improve the model structure, an adaptation of the Delphi method (Wright & Rowe, 1999) was conducted. The Delphi method consists of a procedure to obtain the most reliable consensus of opinion of a group of experts (Wright & Rowe, 1999). For this, nine experts in the field of building performance and facility management were interviewed. All interviewees had over 10 years of experience in FM consulting and maintenance activities, while three of them were also specialists in energy management. The interviews lasted between an hour and an hour and a half and the experts were asked to review the model by adding, changing, erasing, and weighting the existing causal factors and relationships, if necessary. Consultation with the experts was formalized through a questionnaire survey (Appendix C). As in many cases where the Delphi method is used to elicit expert opinion, some intermediate nodes were added, and missing relationships were established in the final version of the network to increase the model's content validity. An anonymous summary of the experts' input was given to the other experts. Participants were encouraged to review the anonymous opinion of the other experts and consider revising their previous response. The goal during this process was to decrease the variability of responses and achieve consensus. The model was then refined after rounds of questions with feedback and consensus between the experts.

6.3.3 Conditional probability tables definition

The CPTs of each node of the model were defined by two main steps:

i. First, literature review and reports on the European building stock (e.g., BPIE, 2011; EU Building Stock Observatory, 2018) were consulted to define the pattern (i.e., probability distribution) of some nodes;
ii. Second, for nodes that had no available data, information was elicited from domain experts. Experts were asked to provide the most likely values for some variables under consideration. They had to identify the importance of the relationships between nodes and their uncertainty on the CPTs. This information was used to define statistical distribution expressions.

Some nodes were defined as Boolean and have binary states such as “Yes” and “No”. Others were defined as ranked nodes. Due to the underlying numerical scale of the ranked nodes, numerical statistical distribution expressions can be defined. The truncated Normal distribution (TNormal) is especially useful for defining numerical statistical distributions as expressions (Fenton & Neil, 2012). Unlike the regular Normal distribution, TNormal has finite end-points that go from 0 to 1 in equal intervals. Like the Normal distribution, TNormal is characterized by two parameters: mean and variance. The variance parameter reflects the influence of parent nodes’ uncertainties. As the variance rises, the distribution gets closer to uniform. This enables a variety of distribution shapes to be modelled. In the simplest case, the parameter mean is determined as a weighted mean of the parent nodes with the following expression:

$$WMEAN = \frac{\Sigma i{=}1 \ldots n\ wiXi}{n}$$

where $wi \geq 0$ are weights, and n is number of parent nodes. In AgenaRisk, the syntax of the function is:

wmean (w1, parent1, w2, parent2,..., wN, parentN)

Indeed, this distribution is sufficiently flexible that it has been proven to generate satisfactory CPTs for almost all BN fragments involving a ranked node with ranked parents (Fenton & Neil, 2012).

6.3.4 Model evaluation

The model evaluation consisted in three steps:

i. Data validation: four existing buildings were selected to analyze different scenarios using forward and backward propagation to then refine the strength of the relationships between the nodes and make the model more accurate. Forward propagation implies the propagation of an observed variable and measures its impact on the target variable (Pearl, 1991). If there is enough evidence that an observation occurs, then the observation can be entered into the model, and the probabilities of all unobserved variables can be updated. Backward propagation is another useful feature of BN. In backward propagation, an observation is made for a specific variable, and then the BN calculates the marginal probabilities of unobserved variables by propagating the impact of the observed variable through the network in a backward fashion (Pearl, 1991).
ii. Computerized model verification: as the proposed model is a novel approach to assess building condition performance, only some parts of the network could be verified with existing methods. Therefore, one of the most cited methods found in the literature, and described in (Silva et al., 2016), was used to compare the results and verify if the BN model behaves as expected. Then, a sensitivity analysis was undertaken to understand the most significant factors in the model and to verify whether the model response conforms to expectations. Sensitivity analysis is a useful way to check the validity of a BN model, and reveals diagrammatically which nodes have the greatest impact on any selected (target) node (Fenton & Neil, 2012).
iii. Operational validation: a case study was used to verify the model. The model verification was conducted by assessing the behavior of parts of the model under different scenarios: to make predictions, find out causal factors of known variables, and conduct what-if scenarios to make decisions.

6.4 BN model structure

In Chapter 4, the general factors that affect a building performance were defined. Defects in building elements and problems in building systems are considered key aspects to evaluate building condition performance. The most relevant defects for each element and system were also defined in Chapter 4 and published in Journal of Performance of Constructed Facilities (Bortolini & Forcada, 2018a). These defects/problems are caused by several factors including: age, type of material, design and construction errors, environmental conditions, and a lack of preventive maintenance (Watt, 1999; Chong & Low, 2006; Gaspar & Brito, 2008; Pereira et al., 2011; Vieira et al., 2015; Silva et al., 2016).

The relationships between a defect and the main causes are illustrated in Figure 14.

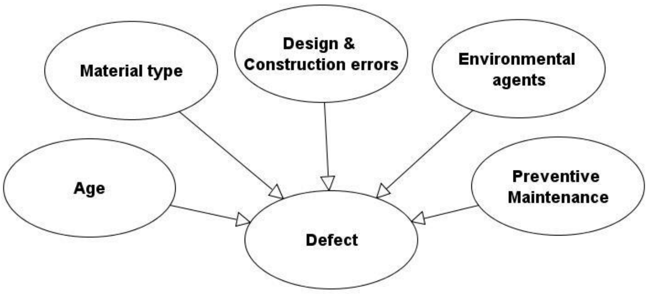


Figure 14. Main causes of defects

A defect is not usually an outcome of a single cause, but rather occurs when several interrelated causes combine (Love, Edwards, Irani, & Walker, 2009). The causes of a defect can vary in terms of the number (i.e., frequency) of pathways they take part in and the impact (i.e., magnitude) of the contribution they make to the formation of these pathways (Aljassmi & Han, 2013). This guided insights into the theory of causality of rework defects described in Love, Edwards and Smith (2015). Causality governs the relationship between events, and its formalization enables a system to be constructed that has a set of observable causal variables (Goodman, Ullman, & Tenenbaum, 2001).

Although previous studies identified defect causes and emphasized the complexity of systems in which they are generated, research quantifying the causal-effect of defects in the O&M phase related to the theory of causality is lacking.

Lewis (1973) asserted that one event causes another if there is a causal chain leading from the first to the second. For instance, the deterioration of a specific building element can cause direct/indirect effects on the performance of surrounding elements (Hermans, 1995). An example is corrosion of an element that decreases the performance of the affected component, but can also put strain on other components. A case of indirect deterioration is the expansion of a component, which might not influence the performance of the expanded component, but can cause cracking of surrounding components (Hermans, 1995). Therefore, the identification of the most influential causes of defects relating to a theory of causation is an important task to address.

Experts' opinions together with a database on 40 academic buildings were used to reinforce the relationships between element defects and causal factors of system problems in the O&M phase.

6.4.1 Database description

The database covered 40 academic buildings located in two campuses of the Universitat Politècnica de Catalunya (UPC), Spain.

In Campus Nord (CN), twenty-two buildings were selected. The buildings comprise four modules (A, B, C and D) located in the same plot orientation, but built in three stages. The first module (A1-A2, B1, B2 C1, C2, D1, D2) was completed by 1886, the second one (A3, A4, B3, B4, D3, D4) by 1990, and the last one (A5, A6, B5, B6, D5 and D6) by 1992. All the buildings have the same type of construction solution: a reinforced concrete structure, flat roofs and masonry façades. Although all have the same structural and construction characteristics, the HVAC systems are different. Some buildings only have heating by radiators, but most have a combination of radiators, air-water systems and multi splits for both heating and air conditioning. The main uses of the buildings are for classroom, office and laboratory activities. Table 11 summarizes the main characteristics of these buildings.

Table 11. Main characteristics of the buildings from Campus Nord

Name of the building	Main use	Year of construction	Gross floor area (m^2)	Number of floors
CN-A1-A2	Lectures	1990	7,886	5
CN-A3	Lectures	1991	3,783	5
CN-A4	Lectures	1991	3,795	5
CN-A5	Lectures	1992	3,886	5
CN-A6	Lectures	1992	4,216	5
CN-B1	Offices	1989	2,867	5
CN-B2	Others (Library)	1990	1,318	5
CN-B3	Administrative	1993	2,263	7
CN-B4-B5	Offices	1994	5,919	7
CN-B6	Offices	1995	2,337	7
CN-C1	Offices	1986	4,895	5
CN-C2	Offices	1989	2,124	5
CN-C3	Laboratories	1993	4,755	7
CN-C4	Common spaces	1995	4,790	5
CN-C5	Offices	1994	5,280	7
CN-C6	Offices	1995	4,753	5
CN-D1	Laboratories	1986	5,208	5
CN-D2	Offices	1989	2,971	5
CN-D3	Offices	1989	2,969	5
CN-D4	Laboratories	1990	3,049	5

CN-D5	Offices	1991	3,011	5
CN-D6	Offices	1993	3,048	5

In Campus Terrassa (TR), eighteen buildings were selected. The buildings are not unified as in Campus Nord, they are spread in different city blocks. The age of the buildings vary, the newest building was constructed in 2011 and the oldest one was constructed in the beginning of the XX century. The oldest buildings have passed through rehabilitation from 1993 to 1995. They were designed only with heating system, and multi-splits were incorporated along the years. The newest buildings have air-water systems for both heating and air conditioning. Table 12 summarizes the main characteristics of these buildings.

Table 12. Main characteristics of the buildings from Campus Terrassa

Name of the building	Main use	Year of construction / Rehabilitation	Gross floor area (m^2)	Number of floors
TR-1	Lectures	1904/1995	9,429	3
TR-2	Lectures	1904/1994	2,940	3
TR-3	Lectures	1904/1993	2,577	2
TR-4	Lectures	1960/1997	7,626	5
TR-45	Lectures	1960/2002	3,143	5
TR-5	Lectures	1960/1995	11,492	5
TR-6	Offices	1998	2,344	4
TR-7	Laboratories	1960	2,624	4
TR-8	Lectures	1992	6,446	4
TR-9	Library	1996	2,393	2
TR10	Offices	1996	2,218	4
TR11	Lectures	1997	2,779	4
TR-12	Laboratories	2001	3,198	6
TR-14	Laboratories	2011	7,378	5
TR-30	Offices	1945/1994	1,350	1
TR-31	Hall of residence	1994	4,698	5
TR-32	Lectures	2009	4,535	4

6.4.1.1 Defects on building elements

The proposed Building Inspection System (BIS) (described on section 5.3.1) was applied in the twenty-two building from Campus Nord. A total of 1,974 defects were collected during the inspections on the campus. An analysis of the defect data revealed that the most common defects, as noted in Table 13, were: cracking in interior partitions, surface problems in interior partitions, cracking in structural elements, water problems in interior partitions, and corrosion in the plumbing system. No defect was found relating to deformation/settlement of structural elements.

Table 13. Results of the building inspection in Campus Nord buildings: number of defects by type

Element/system	Defect type	Number of defects	%
Structure	Cracking	217	10.99
	Water problems	99	5.02
	Deformation/Settlement	0	0.00
Façade	Water problems	18	0.91
	Cracking	4	0.20
	Detachment/Broken	11	0.56
Roofing	Water problems	5	0.25
	Cracking	6	0.30
	Biological action and change	4	0.20
Flooring	Detachment/Broken	27	1.37
	Cracking	7	0.35
	Surface problems	70	3.55
Interior partitions	Cracking	775	39.26
	Surface problems	268	13.58
	Water problems	194	9.83
Doors/Windows	Operational faulty functioning	7	0.35
	Water problems	63	3.19
	Surface problems	22	1.11
Plumbing	Corrosion	177	8.97
	Total	1,974	100

Figure 15 shows that root causes of most defects in the campus were: age (54%), external agents (26%) and use and maintenance (15%).

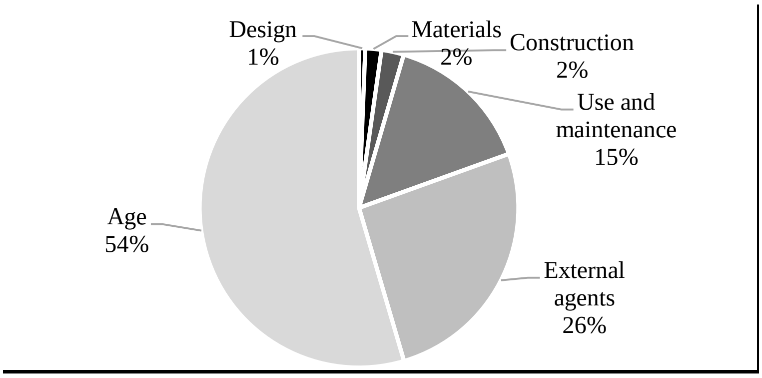


Figure 15. Results of the building inspection in Campus Nord buildings: causes of defects

Figure 16 illustrates the distribution of each type of defect by severity on a logarithmic scale to better visualize the results. Most defects (62.67%) were in the interior partitions. However, the cracks that were detected were minor, and surface problems were related to low severity painting and peeling problems.

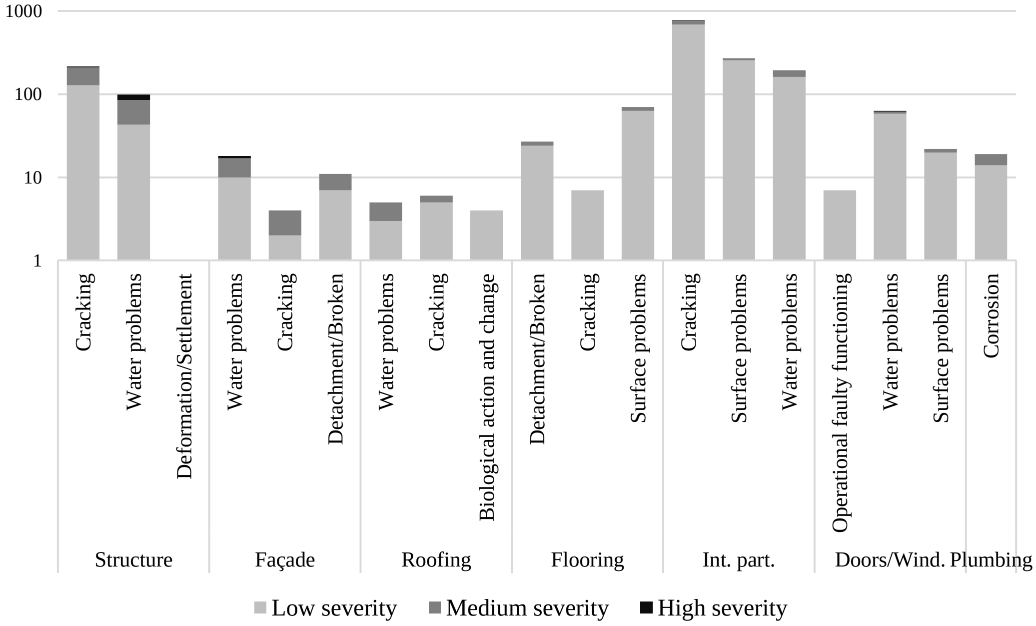


Figure 16. Results of the building inspection in Campus Nord buildings: number of defects by type according to registered severity on a logarithmic scale

The most severe defects in the campus only accounted for 17% of the total defects. They were 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 they are 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 mainly included corroded pipes. This is mainly due to exterior and exposed piping systems with deteriorated insulation.

The magnitude of each defect was also assessed as described in the BIS (section 5.3.1). The ranges used to define the magnitude of each defect are described in Table 14. The results are available in Appendix D.

Table 14. Ranges to determine the magnitude of each defect

Ranges	Magnitude	Building elements
<0.24	Low	Structure, Façade, Roofing, Flooring, Interior partitions (in a 100 plant square meter)
from 0.25 to 0.49	Medium	
>0.5	High	
<0.009	Low	Doors and Windows
from 0.01 to 0.099	Medium	
>0.1	High	

6.4.1.2 Problems in building systems

The proposed text-mining approach (described in Section 5.3.2) was applied in 40 buildings from the two UPC campuses.

The database comprises a collection of 5,373 maintenance requests submitted to the UPC Campus Facilities department between January 2015 and July 2017 (2.5 years). All requests were submitted either by the end users or the FM team through an intranet application linked to a CMMS. The information gathered was limited to the information provided by the requester (name, e-mail), date, description of the problem, problem type category (predefined labels) and the location of the room/building. The problem type categories that were analyzed included: HVAC maintenance, electricity maintenance, plumbing maintenance, fire system maintenance and elevators maintenance.

Figure 17 illustrates the most frequent terms within the maintenance requests using the *MapReduce algorithm* (Dean & Ghemawat, 2008). The size of the terms in the word-cloud represents its relative frequency in the database.

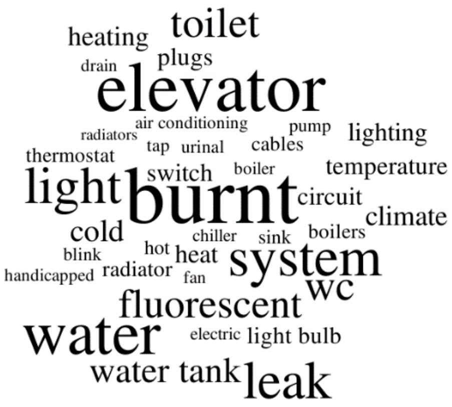


Figure 17. Results of the maintenance requests in both UPC campuses: word-cloud of the most frequent terms

Table 15 presents the number of maintenance requests by type of problem. Operational problems with electrical fixtures and HVAC fixtures were the most frequent within the maintenance requests, with 36.91% and 28.33%, respectively. Complaints about hot and cold are typically the most frequently problem type reported by occupants (Federspiel, 2001). As expected, problems in fire system and electrical supply were not relevant as the preventive maintenance is compulsory for these building systems by legislation.

Table 15. Results of the analysis of problems in systems by type

Element/system	Problem type	Number of maintenance requests	%
Electrical system	Operational fixtures problems	1,983	36.91
	Operational distribution problems	202	3.76
	Operational supply problems	79	1.47
Plumbing system	Leakage on fixtures	517	9.62
	Operational supply problems	220	4.09
HVAC system	Operational production problems	354	6.59
	Operational fixtures problems	1,522	28.33
Fire system	Electrical operational fixtures problems	60	1.12
Elevator	Operational mechanical problems	370	6.89
	Operational electrical problems	66	1.23
	Total	5,373	100

After the classification of the maintenance requests by problem type, they were classified in three levels of severity. The terms to classify the maintenance requests in low severity included those regular actions about maintenance activities that could be planned for a reasonable period of time, such as check, adjust, clean, among others. The words for the classification of the maintenance requests as high severity included those that require an urgent action, and are related to safety of end users. Figure 18 illustrates the most frequent terms within the maintenance requests for classifying them in low and high severity.

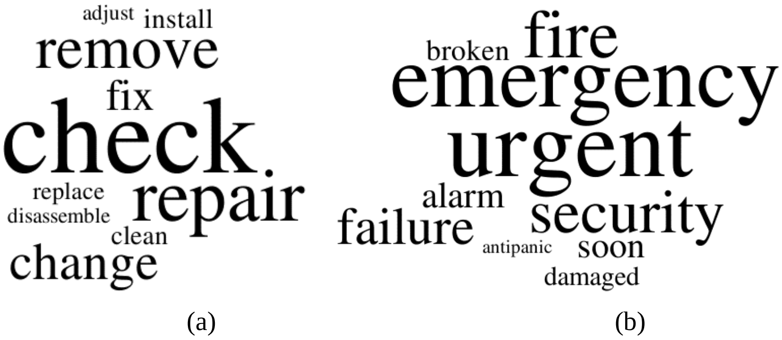


Figure 18. Word-cloud of the most frequent terms: (a) low severity and (b) high severity

Figure 19 illustrates the distribution of each problem type by severity. Most problems were in the electrical system. However, the maintenance requests submitted were minor, such as burnt lights that needed to be replaced. Problems in the HVAC system were also minor and moderate, such as unresponsive thermostats.

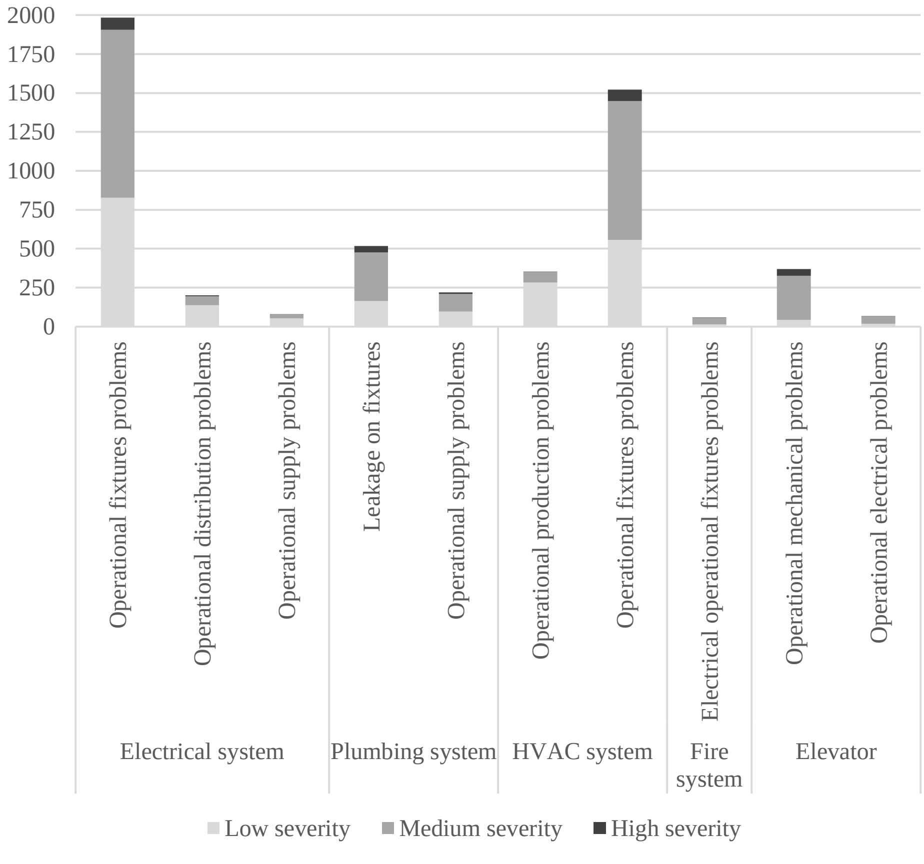


Figure 19. Results of the analysis of the maintenance requests by affected system and problem severity

The magnitude of each problem type for each building was also assessed as described in the text-mining approach (see Section 5.3.2). For each system, with the exception of elevators, a 100 plant square meter was defined. The ranges used to define the magnitude are presented in Table 16. The different problem types in each building and their magnitude are available in Appendix E.

Table 16. Ranges to determine the magnitude of each problem type

Ranges	Magnitude	Building elements
<0.30	Low	Problems in the HVAC production, plumbing and electrical supply and distribution
from 0.31 to 0.50	Medium	
>0.51	High	
<1.0	Low	Problems in the HVAC and electrical fixtures
from 1.1 to 2.0	Medium	
>2.1	High	
<0.10	Low	Problems in the fire system
from 0.11 to 0.20	Medium	
>0.21	High	
<3.0	Low	Problems in the elevator
from 3.1 to 10.0	Medium	
>10.1	High	

6.4.2 Analysis of correlation between variables

An analysis of correlation among the variables (defects and problems) were developed. Those variables with a high correlation coefficient are shown in Table 17.

Table 17. Correlation results between defects and problems

Defects and problems		Correlation coefficient
Structure – cracking	Interior partitions – surface problems	0.663**
Façade – water problems	Interior partitions – surface problems	0.523**
Doors/windows – water problems	Doors/windows - surface problems	0.547**
Structure – cracking	Façade – detachment	0.483*

Façade – water problems	Roof – biological action	0.441^{*}
Interior partitions – water problems	Interior partitions – surface problems	0.463^{*}
Roof – biological action and change	Structure – cracking	0.425^{*}
Electrical – operational distribution problems	Electrical – operational fixtures problems	0.714^{**}
Electrical – operational distribution problems	HVAC – operational fixtures problems	0.762^{**}
Electrical – operational supply problems	Electrical – operational fixtures problems	0.534^{**}
Electrical – operational supply problems	Plumbing – operational supply problems	0.529^{**}
Electrical – operational supply problems	HVAC – operational production problems	0.719^{**}
Plumbing – operational supply problems	HVAC – operational production problems	0.892^{**}

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

The building inspection database also incorporated the causes of the detected defects. Therefore, the correlation analysis between the defects and their causal factors was also analyzed. The defects and their causal factors with high correlation coefficient are shown in Table 18.

Table 18. Correlation results between defects and causes

Cause	Defect	Correlation coefficient
Design and Construction errors	Façade - cracking	$0,933^{**}$
	Façade - detachment	$0,949^{**}$
	Structure – water problems	$0,974^{**}$
	Plumbing - corrosion	$0,973^{**}$
	HVAC – operational fixtures problems	$0,929^{**}$
	Electrical – operational fixtures problems	$0,963^{**}$
	Interior partitions – surface problems	$0,965^{**}$
	Interior partitions – water problems	$0,958^{**}$
	Floor – surface problems	$0,968^{**}$
	Doors/Windows – water problems	$0,926^{**}$
	Doors/Windows – operational problems	$0,953^{**}$
Environmental agents	Façade - water problems	$0,873^{**}$
	Façade - cracking	$0,712^{**}$
	Façade - detachment	$0,869^{**}$
	Structure - water problems	$0,668^{**}$

	Structure - cracking	0,836**
	Roof - water problems	0,912**
	Plumbing - corrosion	0,981**
	Doors/Windows - water problems	0,955**
	Doors/Windows - surface problems	0,866**
Age	Façade - surface problems	0,949**
	Structure - cracking	0,986**
	Roof - water problems	0,882**
	Plumbing - corrosion	0,971**
	Plumbing - leakage	0,933**
	Interior partitions - surface problems	0,951**
	Floor - detachment	0,958**
	Floor – surface problems	0,982**
	Doors/Windows – operational problems	0,820**

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

6.4.3 Delphi method results

To check and refine the relationships among variables, interviews were undertaken with domain experts using an adaptation of the Delphi method. Nine FM experts were interviewed between June and July 2018. Experts were asked to analyze the model and validate, add, change, or erase the existing causal factors and relationships, if necessary. In general, experts agreed with the proposed relationships and made minor modifications such as the inclusion of a node describing the number of floors in a building to define the varying importance of the elevator condition in buildings that have less or more than three floors. Experts also suggested incorporating the shade factor and occupancy density as factors that contribute to some defects in the floor and interior partitions.

The relationship between occupancy density and mechanical problems with elevators was also incorporated. Human behavior could also influence the use of elevators, which is a challenging factor to measure since it is influenced by cultural, social, and personal factors. Notwithstanding the difficulty in represent human behavior in buildings, the proposed BN model incorporated this issue as an uncertainty. For elements on which human behavior has a certain impact, the uncertainty in the condition assessment was increased.

6.4.4 Directed acyclic graph for building condition performance

The relationships among defects/problem types and causes identified in the literature and reinforced in the correlation analysis and by domain experts were used to define the model structure. To aid the execution of the model, the façade, roof, and door and window condition nodes were combined in the *Envelope condition* node. Moreover, the interior partition and flooring condition nodes were joined in the *Interior elements condition* node. Building systems were also grouped in *Electrical systems condition* and *Plumbing systems condition*. All the building elements were joined in the *Civil and architecture elements condition* node, while all the building systems were joined in the *MEP (mechanical, electrical and plumbing) elements condition* node. As a result, hierarchical levels can be identified in the DAG for building condition performance, as illustrated in Figure 20.

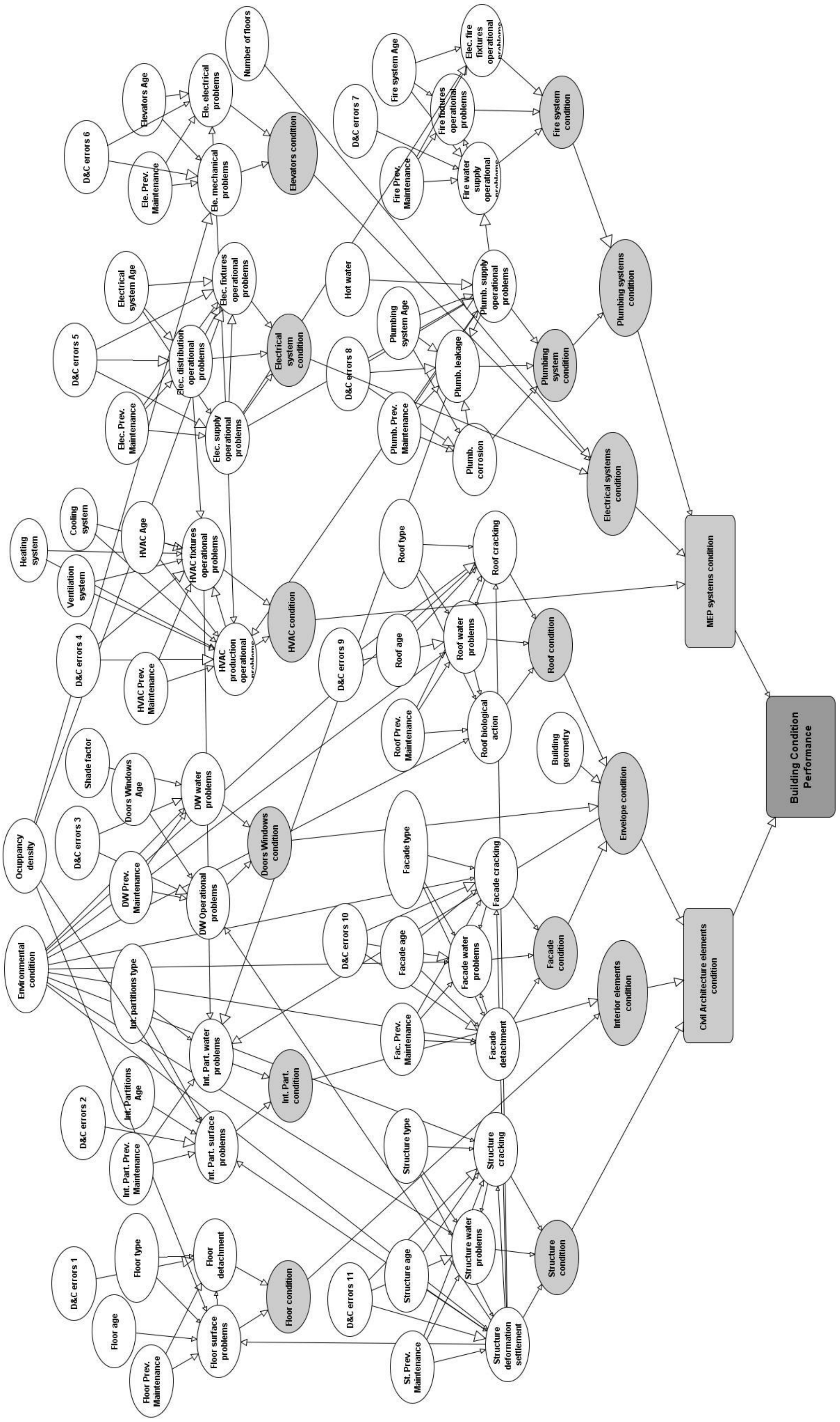


Figure 20. BN model for building condition performance

6.5 CPTs definition

The diversity in typology within the non-residential sector is vast. This sector is more complex and heterogeneous than the residential sector (BPIE, 2011a). Moreover, differences between countries are more pronounced, which makes the definition of the pattern of variables more challenging (BPIE, 2011a). Therefore, generic types of building elements and systems were defined for offices and academic buildings since they present similar usage patterns and correspond to the second and third biggest categories of non-residential buildings according to the Buildings Performance Institute Europe (BPIE). In this research, the CPTs were defined as generically as possible for the model to be applied in the European context. However, probability distributions for some variables can be adapted to a specific context (region/country).

The levels of uncertainty involved in variables for assessing building condition performance lead to the definition of discrete, uniform, or normal probability distributions depending on the input parameters (Rodríguez, Andrés, Muñoz, López, & Zhang, 2013). For instance, if there are large uncertainties about a particular input parameter, this is modelled using the uniform distribution function. The opposite case would be to define input parameter uncertainty by the normal distribution.

In this study, TNormal is used to define the probability distribution for most cases. As previously described, TNormal is an appropriate distribution, since it provides flexibility to generate a variety of distribution shapes when the mean (μ) and variance (σ^2) are defined (Fenton & Neil, 2012).

For variables related to building properties (*Age* and *Element types*), European Reports on non-residential building stock (BPIE, 2011a; Schimschar et al., 2011) were consulted to gather information about the most common ranges of building age and to define distribution functions. The age depends on the building element/system. When a refurbishment or replacement is conducted on a specific element of the building, refinement of the age should be considered. Non-residential buildings in most EU countries are generally older than 30 years, while for some countries such as Cyprus, Spain, and Ireland the share of new buildings (built after 2000) is significant (BPIE, 2011a). Notwithstanding the existence of high variability in the age of existing building stock, variables related to the age of construction elements and systems were defined with a high uncertainty (variance) (Table 19). No databases were found on the most common element types, so this information was obtained by experts (Table 20).

Table 19. CPTs for age and elements' types

Node name	ID	Type of node	States	CPT			Source
				Expression	Mean (μ)	Variance (σ^2)	
Structure age Floors age Int. partitions age	StAg FlAg InAg	Ranked	< 10 years 10 to 30 years > 30 years	TNormal	0.7	0.3	Literature (BPIE 2011); (Schimschar et al. 2011) + Experts
Façade age Roof age D&W age Electrical syst. Elevator age	FaAg RoAg DWAg EsAg ElAg	Ranked	< 10 years 10 to 20 years > 20 years	TNormal	0.7	0.3	
HVAC age Plumb. age Fire system age	HVAg PsAg FrAg	Ranked	< 3 years 3 to 10 years > 10 years	TNormal	0.7	0.3	

Table 20. CPTs for elements' types

Node name	ID	Type of node	States	CPT	Source
Structure type	StTy	Labelled	Concrete Masonry Steel Others	0.6 0.2 0.1 0.1	Experts
Façade type	FaTy	Labelled	Conc. panels or Masonry Metal panels Glazed Others	0.5 0.2 0.15 0.05	
Roof type	RoTy	Labelled	Flat concrete Flat metal panels Slopped Others	0.3 0.3 0.3 0.1	
Floor type	FlTy	Labelled	Continuous Discontinuous Others	0.2 0.6 0.2	
Interior partitions type	ItTy	Labelled	Masonry walls Light partition walls Others	0.475 0.475 0.05	

Existing literature was consulted to define the variables related to *Design & construction errors* for each building element and system. Forcada, Macarulla, and Love (2013) and Forcada et al. (2016) determined that defects that appear during the operational phase of buildings are very low in the structure, while defects in finishing such as surface cracks are relatively high. Contractors focus their quality control on structural defects that can have major consequences. Therefore, important defects caused by design and construction errors are primarily reduced and/or eliminated prior to handover (Forcada et al., 2016). The results of Forcada, Macarulla, and Love (2013) and Forcada et al. (2016) were used to define appropriate distribution functions for *Design & construction errors (D&C)*. Experts with experience in design and construction were also consulted to check the distributions.

Table 21. CPTs for Design & construction errors nodes

Node name	ID	Type of node	States	CPT	Source		Source
				Expression	Mean (μ)	Variance (σ^2)	
D&C in elec. system D&C in fire system D&C in elevator D&C in structure	D&C5 D&C6 D&C7 D&C11	Ranked	Low / Medium / High	TNormal	0.1	0.1	Literature (Fprcada, Macarulla, & Love, 2013); (Forcada et al., 2016) + Experts
D&C in Roof D&C in Façade	D&C9 D&C10	Ranked	Low / Medium / High	TNormal	0.2	0.1	
D&C in Floor D&C in Inter. Part. D&C in plumb. system	D&C1 D&C2 D&C8	Ranked	Low / Medium / High	TNormal	0.5	0.1	
D&C in Door/Windows	D&C3	Ranked	Low / Medium / High	TNormal	0.3	0.1	
D&C in HVAC system	D&C4	Ranked	Low / Medium / High	TNormal	0.7	0.1	

The adoption rate of *Preventive maintenance* practices in existing buildings is relatively low in building elements. Few owners understand the need for preventive maintenance of these elements, therefore, most maintenance activities are based on reactive actions when a problem has occurred (Lee & Akin, 2011; Bortolini & Forcada, 2018a). In contrast, building systems have their own preventive maintenance program, with statutory legal requirements and standards (RICS, 2009). For instance, regular legionella tests must be carried out, as well as inspections of boilers at regular intervals, and periodic checks of fire extinguishers (RICS, 2009; Sullivan et al., 2010). The node for *Preventive maintenance* was defined as Boolean (*Yes/No*) (Table 22). Experts were also consulted to gather opinions about the probability distributions and refine the results.

Table 22. CPTs for preventive maintenance nodes

Node name	ID	Type of node	States	CPT	Source
Structure Preven. Maintenance	StPrMa	Boolean	Yes No	0.1 0.9	Literature (Lee & Akin, 2011); (RICS, 2009); (Sullivan et al., 2010) + Experts
Plumbing Preven. Maintenance Preven. Maintenance HVAC	PlPrMa HVPrMa	Boolean	Yes No	0.8 0.2	
Fire system Preven. Maintenance	FiPrMa	Boolean	Yes No	0.99 0.01	
Electrical Preven. Maintenance Elevator Preven. Maintenance	EsPrMa ElePrMa	Boolean	Yes No	0.9 0.1	
Façade Preven. Maintenance Roof Preven. Maintenance D&W Preven. Maintenance	FaPrMa RoPrMa DWPrMa	Boolean	Yes No	0.3 0.7	
Floor Preven. Maintenance Int. partitions Preven. Maintenance	FlPrMa InPrMa	Boolean	Yes No	0.5 0.5	

Table 23 presents the Boolean and labelled nodes. When no data is available, the same probabilities are assigned to the different types.

Table 23. CPTs for the Boolean and labelled nodes of the condition performance model

Node name	ID	Type of node	States	CPT	Source
Cooling system	CoolingS	Boolean	Yes No	0.7 0.3	Experts
Heating system	HeatS	Boolean	Yes No	0.7 0.3	
Ventilation system	VentS	Boolean	Natural Forced	0.7 0.3	
Building geometry	BuGeo	Labelled	F << R F < R	0.2 0.2	

			F = R F > R F >> R	0.2 0.2 0.2	
Number of floors	Nfloors	Labelled	<3 floors / >3 floors	0.5 0.5	
Occupancy density	OccuDens	Labelled	Low Medium High	0.333 0.333 0.333	
Shade factor	ShFac	Labelled	<30% 30 to 75% >75%		

The *Environmental condition* variable was defined on a five-point scale ranging from very favorable to very unfavorable (Table 24). The following expression was defined to obtain the state of the environmental condition, based on (Kirch et al., 2017; Madureira et al., 2017):

$$Environmental\ condition = (2N + S + W + G)/5$$

Where:

- *N* is the probability of the region of the building suffer from natural disasters (from 1 to 5, according to Figure 5);
- *S* is the surrounding environment (1 – Rural area, 2 – Urban area, 3 – Urban area (near poor zones, schools), 4 – Industrial area, 5 – Coastal area);
- *W* is the weather condition (1 – Smooth changes of temperature, 2 - Moderate changes of temperature, humidity and moderate wind speed, 3 – Moderate temperature, high humidity and wind speed, 4 – High temperature, humidity and wind speed, 5 - High variation of temperature, snow);
- *G* is the geological condition (1 - Areas lacking soil layers of clay and/or silt, firm ground areas, 2 - Areas with soil layer of clay and/or silt, slope inclination is less than 1:10, 3 - Areas with soil layer of clay and/or silt, slope inclination exceeds 1:10, 4 - Areas with soil layer of fine sand, 5 – Swamp).

Table 24. CPTs for environmental condition node

Node name	ID	Type of node	States	CPT			Source
				Expression	Mean (μ)	Variance (σ^2)	

Environmental condition	EnvCond	Ranked	Very Unfavorable Unfavorable Moderate Favorable Very Favorable	TNormal	0.3	0.5	Literature (Kirch et al., 2017); Madureira et al., 2017)

As an example, Figure 21 presents how the CPTs were defined for the nodes considering the *Façade condition.* Box (a) (Figure 21) illustrates the probability distributions for the main causes of defects. The CPTs for *Environmental condition, Design & construction errors, Façade age, Façade preventive maintenance,* and *Façade type* were defined based on European building stock reports and existing literature (BPIE, 2011; Lee & Akin, 2011; Schimschar et al., 2011; Forcada et al., 2013; Kirch et al., 2017; Madureira et al., 2017; Bortolini & Forcada, 2018a). These distributions represent generic characteristics for European non-residential building stock. Once information about a specific situation is known, these probability distributions can be updated to include new evidence.

The CPTs for *Environmental condition* is defined as the probability distribution function:

$$\sim\text{TNORM}\ (\mu=0.3,\ \sigma^2=0.5)$$

The CPTs for *Design & construction errors* in the façade is defined as the probability distribution function:

$$\sim\text{TNORM}\ (\mu=0.2,\ \sigma^2=0.1)$$

The CPTs for *Façade age* is defined as the probability distribution function:

$$\sim\text{TNORM}\ (\mu=0.7,\ \sigma^2=0.3)$$

The box (b) (Figure 21) presents the probability of occurrence of each defect in function of the previous causes. The probability distributions for façade defects (detachment, water problems, and cracking) are conditioned by the *Façade type* and *Preventive maintenance*. Experts stated that if *Preventive maintenance* is *Yes,* the probability of defects on the façade is reduced by 50%. However, the most important variable is *Design & construction errors*, as illustrated in the weighted mean expression for façade detachment:

$$\sim\text{TNORM}\ (\mu=\text{wmean}(5.0,\text{DesConEr10},2.0,\text{EnviAg},1.0,\text{FaAg}),\ \sigma^2=0.01)$$

If information about the defects is known (identified in a technical inspection), evidence can be entered to find out the most probable causes.

The three main defects affecting the façade were then considered in a weighted mean expression to obtain the CPTs for the *Façade condition*. Water problems is the defect with the highest impact on the façade condition, followed by detachment and cracks:

$$\sim\text{TNORM}\ (\mu=\text{wmean}(5.0,\text{FaWa},4.0,\text{FaDe},\ 3.0,\text{FaCr}),\ \sigma^2=0.001)$$

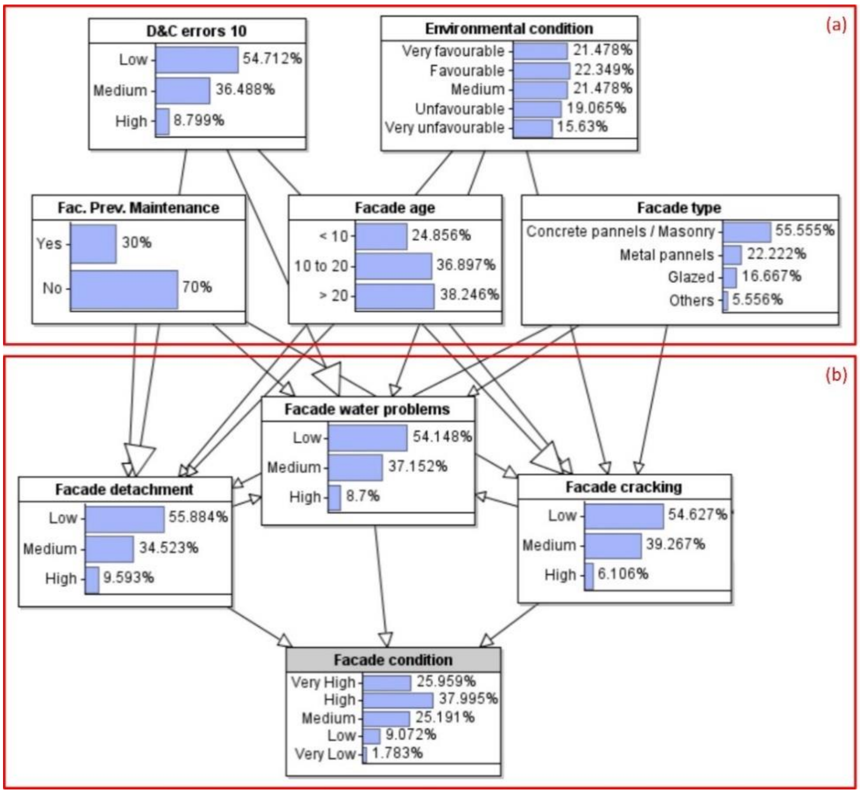


Figure 21. Risk graphs for façade condition

The CPTs for each defect and problem type were obtained from literature and correlation results found with the databases of defects and problems. The importance of each defect/problem on the final building element/system condition and the probability distribution functions of each building element/system were obtained from (Chong & Low, 2006; Gaspar & Brito, 2008; Pereira et al., 2011; Das & Chew, 2011; Rodrigues et al., 2011; Douglas et al., 2013; Silva et al., 2016; Madureira et al., 2017; Santos, Vicente, Brito, & Castelo, 2017) together with the results of the Delphi interviews. Table 25 presents the CPTs for the condition of elements and systems and the entire building.

Table 25. CPTs for the ranked nodes of the condition performance model

Node name	ID	Type of node	States	CPT			Source
				Expression	Mean (μ)	Variance (σ²)	

Structure condition	StCo	Ranked	Very High to Very Low	TNormal	wmean(5.0,StDe,3.0,StWa,2.0,StCr)	0.001	Literature (Hovde & Moser, 2004) + experts
Façade condition	FaCo	Ranked	Very High to Very Low	TNormal	wmean(4.0,FaDe,5.0,FaWa,3.0,FaCr)	0.001	Literature (Rodrigues et al., 2011); (Gaspar et al., 2008); (Silva et al., 2016)+ experts
Roof condition	RoCo	Ranked	Very High to Very Low	TNormal	wmean(4.0,RoBi,5.0,RoWa,2.0,RoCr)	0.001	Literature (Abisuga et al., 2016) + experts
Plumbing condition	PluCo	Ranked	Very High to Very Low	TNormal	wmean(3.0,PlCo,3.0,PlLe,5.0,PlOp)	0.001	Literature (Das & Chew, 2011) + experts
Fire system condition	FiCo	Ranked	Very High to Very Low	TNormal	wmean(5.0,FWOp,5.0,FFOp,5.0,EFFOp)	0.001	Literature (Bromann, 2010) + experts
Elevators condition	EleCo	Ranked	Very High to Very Low	TNormal	wmean(3.0,EMp,3.0,EElp)	0.001	Literature (Park et al., 2010) + experts
Electrical system condition	EsCo	Ranked	Very High to Very Low	TNormal	wmean(5.0,ESOp,1.0,EDOp,4.0,EFOp)	0.001	Literature (Das & Chew, 2011) + experts
HVAC condition	HVCo	Ranked	Very High to Very Low	TNormal	wmean(5.0,HVPOp,4.0,HVFOp)	0.001	Literature (Motamedi et al., 2014) + experts
Doors/Windows condition	DWCo	Ranked	Very High to Very Low	TNormal	wmean(4.0,DWOp,3.0,DWWa)	0.001	Literature (Santos et al., 2017); (Chong & Low, 2006) + experts
Interior partitions condition	InCo	Ranked	Very High to Very Low	TNormal	wmean(2.0,InSf,3.0,InWa)	0.001	Literature (Chong & Low, 2006); (Pereira et al., 2011) + experts
Floor condition	FlCo	Ranked	Very High to Very Low	TNormal	wmean(2.0,FlSf,3.0,FlDe)	0.001	Literature (Chong & Low, 2006) + experts
Envelope condition	EnCo	Ranked	Very High to Very Low	TNormal - Partitioned expression - Building geometry	wmean(FaCo,RoCo,DWCo)	0.01	Literature (Rodrigues et al., 2011); (Madureira et al., 2017); (Branco et al., 2005) + experts
Interior elements condition	IECon	Ranked	Very High to Very Low	TNormal	wmean(1.0,InCo,1.0,FlCo)	0.01	Literature (Shohet, 2003); (Branco et al., 2008) + experts

Plumbing systems condition	PLSCon	Ranked	Very High to Very Low	TNormal	wmean(4.0,PluCo,5.0,FiCo)	0.01	Literature (Shohet, 2003); (Branco et al., 2008) + experts
Electrical systems condition	ElecSCon	Ranked	Very High to Very Low	Tnormal - Partitioned expression - Number of floors	wmean(2.0,EleCo,4.0,EsCo)	0.01	Literature (Shohet, 2003); (Branco et al., 2008) + experts
Civil / Architecture elements condition	CACo	Ranked	Very High to Very Low	TNormal	wmean(5.0,StCo,4.0,EnCo,2.0,IECon)	0.01	Literature (Shohet, 2003); (Branco et al., 2008)+ experts
MEP systems condition	MEPCo	Ranked	Very High to Very Low	TNormal	wmean(5.0,PLSCon,4.0,HVCo,5.0,ElectricalCon)	0.01	Literature (Shohet, 2003); (Branco et al., 2008) + experts
Building Condition Performance	BCP	Ranked	Very High to Very Low	TNormal	wmean(3.0,CACo,5.0,MEPCon)	0.1	Literature (Shohet, 2003); (Branco et al., 2008) + experts

6.6 Data validation

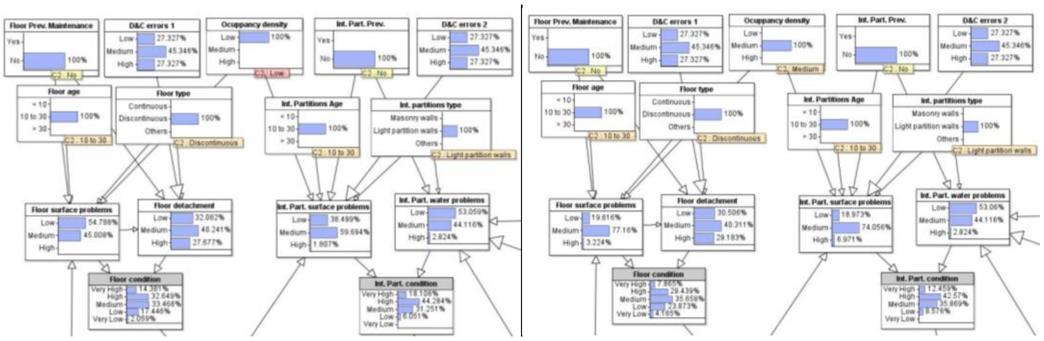
The model was validated by evaluating the parts of the model that experts were concerned about. Four Campus Nord buildings were used for that purpose. The building characteristics, the results of the technical inspection, and the maintenance requests over a year were used to check the model behavior when some scenarios were set.

For instance, the importance of occupation was validated in two buildings with the same characteristics but with different magnitude of defects identified in the technical inspections (Table 26).

Table 26. Building characteristics and inspection about interior partitions

Building	Age	Interior partition type	Building volume (m^3)	Interior partitions water problems (magnitude)	Interior partitions surface problems (magnitude)
CN-D3	1989	Light partitions	7,126	Low	High
CN-C2	1989	Light partitions	8,910	Low	Low

For this scenario, the occupancy density variable was found to be relevant when analyzing the magnitude of surface interior partitions (Figure 22). Building CN-C2 had a lower occupancy density (5.9 m^2/person) if compared with building CN-D3 (4.4 m^2/person). Therefore, the high level of defects in surface interior partitions in building D3 could be associated with the occupancy density. The same occurred with the surface problems on the floor.



(a) (b)

Figure 22. Risk graphs for occupancy density and surface defects: (a) building CN-C2 and (b) building CN-D3

Another scenario evaluated the incidence of the shade factor on door/window water problems. Two buildings with the same general characteristics obtained different technical inspection results for exterior doors/windows (Table 27).

Table 27. Scenario 1. Building characteristics and inspection about doors/windows

Building	Age	Openings surface (m^2)	Doors/Windows water problems (magnitude)	Doors/Windows operational problems (magnitude)
CN-D3	1989	397	Low	Low
CN-B2	1990	132	High	Low

The shade factor was found to be decisive when the magnitude of water problems on doors and windows was evaluated. The shade factor of building CN-D3 is higher (45%) if compared with CN-B2 (0%). Figure 23 illustrates an example of the solar protection that was adopted. Solar protection screens windows from the actions of environmental agents, such as wind and rain.

(a) (b)

Figure 23. Risk graphs for shade factor and water problems: (a) building CN-D3 and (b) building CN-B2

6.7 Model verification

6.7.1 Verification of the model results

As stated in the introduction of this chapter, a holistic assessment method to obtain the global condition of a building and consider the relationships between causal factors has not been explored yet. Therefore, only small parts of the proposed BN model can be verified with existing methods.

To verify a part of the BN model, a common method encountered in the literature was applied. This method has been applied to assess the condition of different building elements, predominantly elements of the building envelope. The method for assessing the condition of façades described by (Silva et al., 2016; Serralheiro et al., 2017) was conducted to compare the results with the BN model. This method is based on the assessment of the physical and visual degradation of the building components, translated by degradation levels (Serralheiro et al., 2017). Moreover, this method expresses the global degradation with a numerical index and consists of the following expression:

$$Sw = \frac{\sum(An \text{ x } kn \text{ x } ka,n)}{\text{A x} \sum(kmax)}$$

where *Sw* represents the severity of element degradation as a percentage, *An* is the area of the element affected by the defect *n*, *kn* is a multiplying factor as a function of its degradation level, *ka,n* is a weighting coefficient corresponding to the relative importance of each defect (repair cost or risk), *kmax* is the sum of the weighting constants corresponding to the highest level of degradation, and *A* is the total area of the element.

TR-5 building was used to verify the façade condition. Results of the inspection data of TR-5 are described in Table 28. The values for *kn* and *ka,n* were obtained from (Gaspar & de Brito, 2008). The result obtained for the degradation condition of the façade was *Sw* = 10%. This means that the façade condition is rated as level B (in a 5 point scale) according with the method described in (Serralheiro et al., 2017), which means a good performance.

Table 28. Technical information about TR-5 building

	m^2	*kn*	*kan*	*kmax*
Total façade area	4,929.04	-	-	-
Water problems (area affected)	1,478.71	2	0.6	3
Detachment (area affected)	492.90	2	2	4
Cracking (area affected)	985.80	2	1	4

The evidence about the inspection results data was then used as input to the BN model to check if the results are similar to the ones obtained by the existing method. Table 29 illustrates the results for the façade condition. The obtained results show a similar condition classification level as obtained in the existing method. The façade condition has 78.21% of probability of being *High*.

Table 29. Validation of façade condition results

	Very Low	Low	Medium	High	Very High
Façade condition	0.00	0.00	5.58	78.21	16.21

The most relevant fact is that the proposed BN model contrasts to the classical model (degradation function) by using probability distributions, providing the most probable level of condition state of a building element instead of an absolute value. Moreover, the factors that affect an element interact in a non-linear way and the BN model accommodates causal explanations and the variability associated with the degradation process. The BN model helps to derive an explanation for the observed result. Therefore, the BN model has a higher accuracy as it shows the relationships between defects and gives the most probable causes for the phenomena.

6.7.2 Sensitivity analysis

A sensitivity analysis was carried out to verify the BN model. From a purely visual perspective, the length of the bars can be thought of as the measure of the impact of that node on the building condition performance (target node). The probability of building condition performance being Very High is 23.5%, as illustrated in the tornado graph in Figure 24. The formal interpretation is that the probability of building condition performance being Very High given the results of the parent nodes goes from 17.7% (when the structure condition is Very Low) to 26.8% (when the structure condition is Very High). The impact of Floor condition on the building condition performance is limited to a narrow range, from 22.4% to 24.3%. As expected, it can be concluded that the probability of a building being in good condition is more sensitive to the changes in the states of structure condition and fire system condition and less sensitive to changes in floor condition and interior partitions condition. From a safety perspective, the results are coherent since the most important elements for building safety are related to structural elements, and the least important are associated with interior finishing.

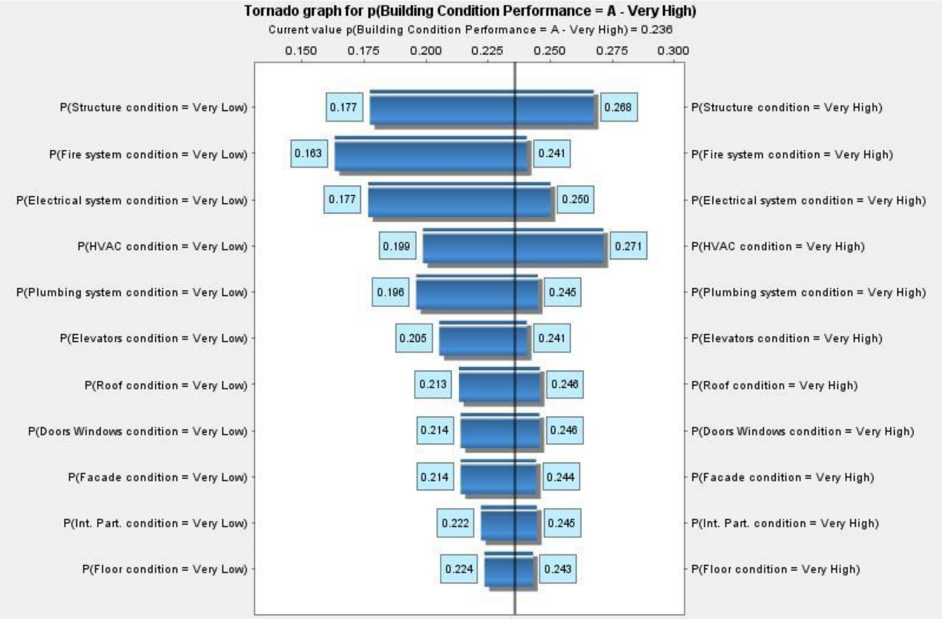


Figure 24. Tornado graph to analyze the sensitivity of building condition performance (Very High = 23.5%)

A sensitivity analysis was also conducted for the envelope condition. Figure 25 illustrates the impact of eight variables when the envelope condition is Very High. Clearly, roof biological action and roof cracking have the greatest and lowest impact on the envelope condition, respectively. The formal interpretation is that the probability of envelope condition performance being Very High given the results of the parent nodes rises from 5.7% (when roof biological action is Low) to 25.5% (when roof biological action is High). The results suggest that enhancing the condition of the Envelope has a greater impact when roof biological defects and façade water problems are corrected.

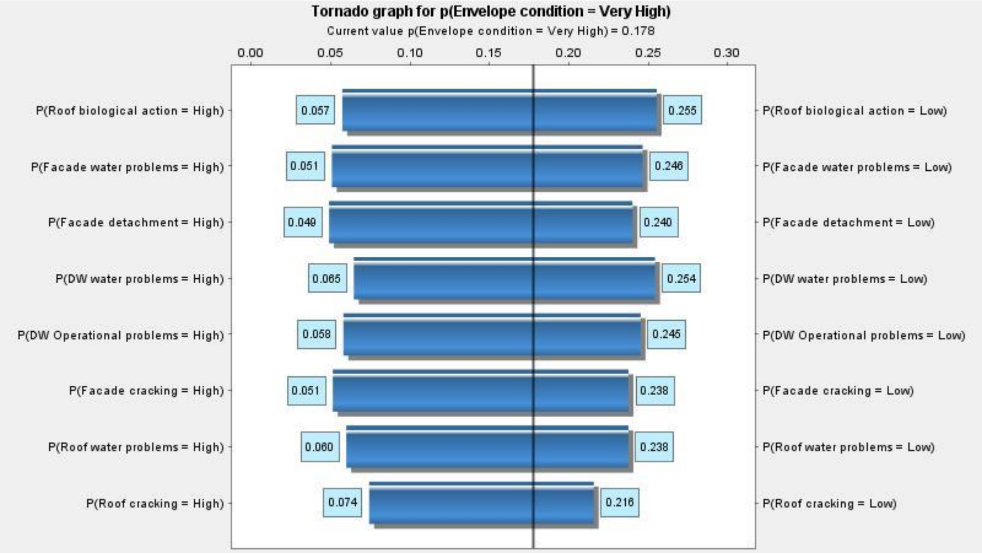


Figure 25. Tornado graph to analyze the sensitivity of envelope condition (Very High = 17.8%)

A sensitivity analysis can also be undertaken to evaluate the causes of occurrence of a specific defect. For instance, Figure 26 illustrates the tornado graph for the analysis of the probability of façade cracking being High. It can be concluded that the most probable causes for façade cracking being High is related to design & construction errors and structure deformation, and least sensitive to preventive maintenance. In contrast to problems in building systems, defects in building elements are least sensitive to preventive maintenance and more sensitive to the construction quality.

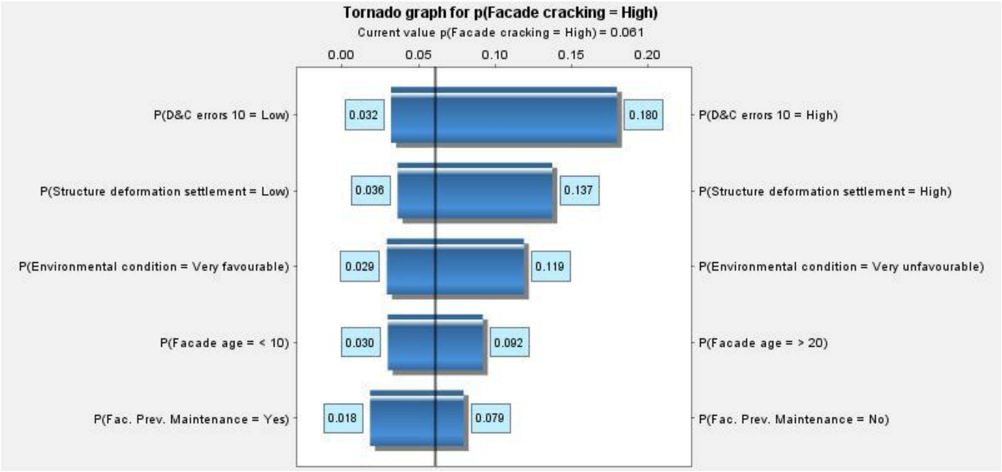


Figure 26. Tornado graph to analyze the sensitivity of façade cracking (Low = 67.7%)

6.7.3 Case study - building condition scenarios

To evaluate the applicability of the proposed model, the CN-C2 building was selected. This building was constructed in 1989, it has 2,124 square meters and five floors. A technical inspection was conducted in March 2017 to detect defects in building elements. An analysis of the maintenance requests during 2016 was also conducted to evaluate the building systems.

A forward propagation analysis was conducted for building elements and systems that could not be inspected, such as the structure and doors and windows. When evidence for structure age, structure type, and preventive maintenance had been established, a forward propagation was conducted to obtain the probabilities of defects in the structure (water problems, deformation, and cracking) and the structure condition (Figure 27). The information about design and construction errors in this building was unknown, so no evidence was established for that node.

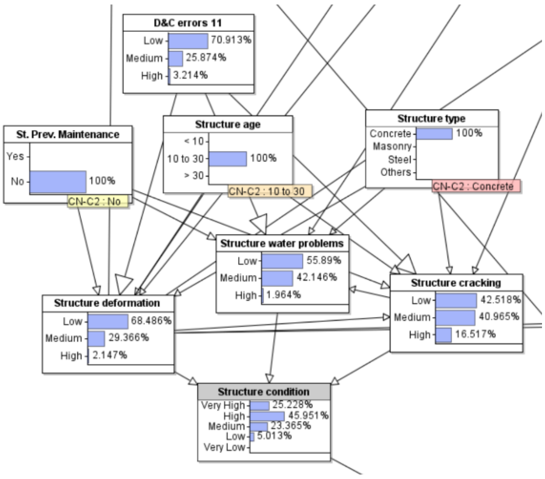


Figure 27. Evidence for structure condition

The results of the building condition performance revealed that the building had 29.30% High condition performance (Table 30).

Table 30. Condition performance results for the case study

Indicator	Performance Level				
	Very Low	Low	Medium	High	Very High
Building condition performance	**6.39**	**14.89**	**24.77**	**29.30**	**24.65**
Civil and Architecture elements condition	**0.00**	**1.00**	**15.12**	**50.10**	**33.78**
Structure condition	0.54	5.43	24.14	45.36	24.53
Envelope condition	0.00	0.08	5.08	43.52	51.32
Façade condition	0.00	0.00	0.00	33.32	66.68
Roof condition	0.00	4.87	75.23	19.90	0.00
Doors/windows condition	0.00	0.00	0.08	35.91	64.01
Interior partitions condition	0.00	0.00	0.08	36.84	63.08
Floor condition	0.00	0.00	0.08	36.84	63.08
MEP systems condition	**0.04**	**2.38**	**29.79**	**53.67**	**14.12**
HVAC condition	0.00	0.55	34.34	57.07	8.04
Plumbing condition	0.00	10.26	79.49	10.25	0.00
Elevator condition	0.00	0.00	2.80	47.19	50.01
Electrical system condition	0.00	0.00	12.32	75.36	12.32
Fire system condition	0.00	0.00	0.03	33.42	66.55

The most degraded element of this building is the roof. Table 30 shows a probability of 75.23% for the state of roof condition being Medium.

To evaluate possible rehabilitation of the roof, a what-if scenario was defined to conduct a backward propagation analysis. An observation was made by setting the age to a lower level (<10), preventive maintenance (Yes) and the type of roof (flat concrete). This scenario led to a reduction of probability of roof defects, and consequently, improved the condition state of the roof (57.54% Very High). The condition state of the envelope performance was consequently improved under such a scenario (58.79% Very High), as shown in Table 31.

Table 31. Roof and Envelope condition prediction after rehabilitation

Indicator	Performance Level				
	Very Low	Low	Medium	High	Very High
Roof condition	0.00	0.04	2.60	39.82	57.54
Envelope condition	0.00	0.04	3.37	37.80	58.79

6.8 Conclusions

The assessment of building condition performance involves the analysis of multiple variables under uncertainty. It is difficult to use traditional methods to quantify and assess building condition from such uncertainty variables. Therefore, this chapter presented the development of a novel BN model to evaluate the condition performance of existing buildings.

This model included a comprehensive, structured, robust hierarchical model for causal factors affecting building condition. The capability of the proposed model is demonstrated by applying it to a real building. The results derived from the case study demonstrated the model's ability to accurately quantify the probability of having different states of condition during the operation phase of a built asset. The outcome of the BN model will help building owners and facility managers to determine where attention should be focused and where maintenance actions should first be carried out to improve the condition performance of a specific building.

This model can be used to conduct more rational management and maintenance of the building stock. Facility managers can investigate the performance improvement achieved by different maintenance strategies, thus enabling improved decision-making. These results are fundamental in the context of insurance policies and in the definition of building maintenance plans. Different what-if scenarios can be analyzed, providing insights for decision makers as to how the probability of the condition of a building varies under different scenarios. By performing inference analysis, a facility manager can evaluate the condition of elements and systems and compare different buildings.

Chapter 7

Bayesian network model for assessing a building's comfort performance

7.1 Introduction

This chapter describes the work conducted to develop the subnet related to the second building performance category defined in Chapter 4, regarding the health and comfort building performance. This chapter presents the development of a BN model that provides an effective way to assess the comfort performance of existing buildings. The model also provides an understanding of the causality chain between multiple factors that affect building comfort and can support decision-making on renovation strategies to enhance comfort in existing buildings.

7.2 Building comfort assessment methods

There is growing interest in healthy, well-performing buildings because people spend more than 90% of their time indoors (Frontczak & Wargocki, 2011; Jensen & Maslesa, 2015). The need for building renovation is receiving increased attention in European countries. One reason for this is an ageing building stock and a need to upgrade buildings to improve the quality of life (Jensen, Maslesa, Berg, & Thuesen, 2018). There is evidence that indoor conditions have far-reaching implications for occupants' satisfaction, health, and productivity (Frontczak & Wargocki, 2011; Li, Froese, & Brager, 2018). Broadly, the definition of occupants' satisfaction is related to comfort in terms of indoor environmental quality (IEQ) or comfort in terms of the space (Frontczak et al., 2012).

Occupants' comfort can be defined by indoor conditions, which are influenced by several variables, such as the building envelope (e.g., insulation and infiltration), building systems (e.g., HVAC and lighting), and occupants' behavior (Catalina & Iordache, 2012; Abisuga et al., 2016). Improper operation or failure of the HVAC system may lead to poor ventilation, which in turn can cause a range of health problems and a condition called sick-building syndrome (Rostron, 2008; Au-Yong et al., 2014). Problems in the walls, such as dampness, were also found to be relevant in an analysis of occupants' comfort (Abisuga et al., 2016). However, the link between the condition of the building envelope, the condition of services, and how occupants perceive control has not yet become a major focus of research (Hellwig, 2015).

Numerous studies have developed methods and tools to assess the satisfaction of the users of a building, taking into account the indoor environment and which conditions are considered comfortable (Frontczak & Wargocki, 2011). Post-occupancy evaluation (POE) is a common technique used to measure building performance from the perspective of the user (Preiser & Vischer, 2005). POE surveys are typically interested in assessing occupants' comfort and productivity, and the more sophisticated ones can also conduct physical measurements of IEQ (Li et al., 2018). Standards based on IEQ factors have been developed to define the acceptable ranges of comfort (e.g., ASHRAE). Indicators such as ventilation rate or CO_2 concentration, temperature, and lighting intensity, are the most frequently used in guidelines and standards (Bluyssen, 2010). Even though the requirements of these standards are met, not all building occupants are satisfied by the same conditions (Bluyssen, 2010; Frontczak & Wargocki, 2011). The perceived comfort is strongly influenced by several personal, social, and building factors (Bluyssen et al., 2011). This is the main cause of building performance uncertainty (O'Brien & Gunay, 2014). Occupants' control of the indoor climate and moreover the perceived effect of their intervention (i.e. control action) strongly influence occupant satisfaction with thermal indoor conditions (Wagner, Gossauer, Moosmann, Gropp, & Leonhart, 2007).

Comfort assessments methods are typically based on deterministic models, such as regression models that use large database values obtained from simulations or experimental measurements (Wagner et al., 2007; Catalina & Iordache, 2012; Agha-Hossein, El-Jouzi, Elmualim, Ellis, & Williams, 2013). The problem with deterministic models is that they do not consider the effect of variability in factors that influence indoor environmental condition, such as the building microclimate, building properties, and usage patterns (Van Gelder, Janssen, & Roels, 2014; Chen, Augenbroe, Wang, & Song, 2017). Comfort is much more than the average of perceived indoor air quality, noise, lighting, and thermal comfort responses (Bluyssen et al., 2011). The relationships between several personal and building factors are complex and their uncertainty needs to be accounted for to effectively assess building comfort (Bluyssen et al., 2011; Chen et al., 2017). To close this gap, a probabilistic approach to assessing building comfort can be used. Unlike traditional models, Bayesian networks (BNs) can model building comfort as a probabilistic process, to give the most probable performance level of a building using probability distributions. Some initiatives regarding the use of BN to analyze end user satisfaction have been examined in the literature. For instance, Salini and Kenett (2009) applied BN to analyze customer satisfaction about electronic products and related services. Chakraborty et al. (2016) applied BN in the context of customer satisfaction related to public transport. However, the use of BN to model comfort building performance has not been investigated yet.

7.3 Methodology

In Chapter 3, the general steps to construct a BN model were described. To build the BN model for building comfort performance, a detailed description about these steps is provided in the following subsections and illustrated in Figure 28. For brevity, similar steps described in Section 6.3 are not repeated here.

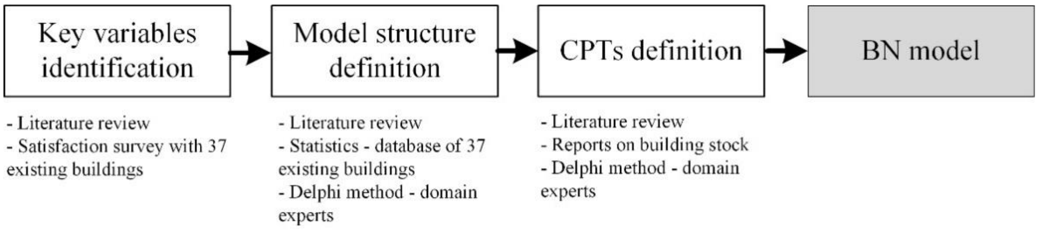


Figure 28. Main steps to build the BN model for building comfort performance

7.3.1 Key variables identification

The key variables affecting building comfort performance were identified by a literature review. This included the definition of the factors and indicators affecting building comfort. Then, the satisfaction survey described in Chapter 5 was conducted in two UPC campuses (Terrassa and Campus Nord) including 37 buildings. The survey was administered online, which allowed quick, easy access and systematic collection of responses. The survey was distributed in two languages, Spanish and Catalan, so that it was accessible to all the students, professors and administrative people.

7.3.2 Model structure definition

The definition of the BN model structure was divided into three main steps:

i. First, a literature review was conducted to analyze the relationships (cause-effect) of key variables that affect a building's comfort performance.

ii. Second, satisfaction survey results were statistically analyzed using the SPSS for Windows (version 24.00).
iii. Third, similar to the process described in the methodology of the previous chapter, an adaptation of the Delphi method (Wright & Rowe, 1999) was conducted using a questionnaire survey (see Appendix C). Nine experts with more than 10 year of experience in the field of building performance and FM were interviewed. Experts were consulted to check and improve the model structure, which implicate on adding intermediate nodes or establishing missing relationships.

7.3.3 Conditional probability tables definition

The CPTs of each node of the model were defined by a similar process as described in the methodology of the previous chapter (Section 6.3):

i. First, literature review was conducted to define the pattern (i.e., probability distribution) of some nodes.
ii. Second, for the nodes in which no data was available, information was elicited from domain experts.

For most of the cases, the nodes were defined as ranked type. The TNormal was also used to determine the distribution expressions.

7.3.4 Model evaluation

The model evaluation consisted in three steps:

i. Data validation: two existing buildings were selected to make analysis of different scenarios using forward and backward propagation for then compare the model with the results of the satisfaction survey. The strength of the relationships between the nodes was refined to make the model more accurate.
ii. Computerized model verification: a sensitivity analysis was undertaken to understand the most significant factors in the model and to verify whether the model response conforms to expectations.
iii. Operational validation: a case study was used to verify the model. The model verification was conducted by assessing the behavior of parts of the model under different scenarios: to make predictions, find out causal factors of known variables, and conduct what-if scenarios to make decisions.

7.4 BN model structure

Occupant’s comfort in non-residential buildings is influenced by many factors related to the IEQ (thermal, visual, acoustic environment, and air quality) and the space (Frontczak & Wargocki, 2011; Frontczak et al., 2012). A literature review was conducted to identify the main factors affecting each IEQ factor and space.

For thermal quality, studies revealed that factors other than indoor air temperature play an essential role, including the climate, the characteristics of the building, and its services (Hua, Göçer, & Göçer, 2014). It was found that people indoors felt warmer in winter than in summer, even though the indoor temperature was lower in the winter (Oseland, 1994). The type of HVAC system also plays a role in thermal comfort. Radiant systems, for instance, can provide higher comfort levels for indoor temperature (Karmann, Schiavon, Graham, Raftery, & Bauman, 2017). Furthermore, occupants with thermal adaptive opportunities present high levels of comfort (Kim & de Dear, 2012). This includes control options such as operable windows and thermostats. Thermal characteristics such as envelope insulation is particularly relevant for buildings that rely on thermal passive strategies (Catalina & Iordache, 2012). In this sense, an envelope with a low thermal transmittance (U-value) can help extend the periods of thermal comfort without reliance on mechanical air-conditioning (Al-Homoud, 2005). The condition of the envelope is also identified as a contributing factor to the performance of the building envelope. The main defects in the façade, roof, and doors/windows are obtained from Bortolini and Forcada (2018a).

Good indoor air quality is related to the ventilation rate (Bluyssen, 2010). In this context, criteria/threshold values for ventilation rate are recommended by regulations. For instance, the Spanish regulation Royal Decree 1027/2007 (RITE, 2007) provides the minimum fresh (outdoor) air rates based on occupancy and type of use. For high indoor air quality, a minimum of 12.5 l/person should be adopted for ventilating office and academic buildings. Moreover, the type of ventilation system adopted in a building can influence the occupants’ comfort perception. Generally, naturally ventilated buildings have higher rates of comfort than air-conditioned buildings (Rostron, 2008). The occupants can open windows and so they can vary the indoor environment to some extent. However, natural ventilation is dependent on weather conditions (e.g., temperature, humidity, and wind speed) (Chilton et al., 2012), and might not be adequate in environments with extreme temperature (e.g., extreme cold or extreme heat). Therefore, the most comfortable type of ventilation should be conditioned to the exterior environmental condition. For buildings with mechanical ventilation, the condition of the HVAC system is an important factor, as its improper operation may lead to poor ventilation causing health problems and discomfort (Rostron, 2008; Au-Yong et al., 2014).

For light quality, the impact of daylighting can be considered quantitatively through the window-wall-ratio (WWR). There is a strong preference for daylight in workplaces, which is closely associated with the belief that daylight is better for health (Galasiu & Veitch, 2006). However, occupants of buildings with a high WWR (e.g., a glazed façade) may have lower perceived control (Hellwig, 2015). Pino et al. (2012) demonstrated that lower WWRs with solar protection can achieve better daylight performance than larger WWRs, due to prevention of glare. Window shading is a key element in controlling glare and overheating, both of which affect the occupants' well-being (Galasiu & Veitch, 2006).

For acoustic quality, physical parameters are linked with the quality of the sound environment, which includes exterior and interior sound insulation of walls. Jensen, Arens, and Zagreus (2005) demonstrated that the main reasons for dissatisfaction are almost the same in all types of offices, and that people are mostly dissatisfied with hearing other people talking on telephones, private conversations being overheard, and the sound of people talking in surrounding offices. Equipment noise is another source of acoustic discomfort reported in some studies (Leaman & Bordass, 2001). Acoustic attenuators used in mechanical ventilation systems can prevent noise from air systems. In addition, buildings with natural ventilation might lead to discomfort due to outside noises.

Regarding space adequacy, occupant satisfaction is influenced by space characteristics including size, aesthetic appearance, furniture, and cleanliness (Frontczak et al., 2012; Bortolini & Forcada, 2018b). Ergonomic furniture and enclosed rooms for meetings and collaborative work are examples of factors that help ensure users' functional comfort at work (Vischer, 2008).

Design errors might be factors that cause occupants' discomfort with air, thermal, and light quality (Roulet et al., 2006). Error can be defined as ''the failure of planned actions to achieve their desired goal, where this occurs without some unforeseeable or chance intervention'' (Reason & Hobbs, 2003). The wrong dimensioning of room conditioning systems or failure to design appropriate daylight controls are some design errors that affect building comfort performance.

7.4.1 Database description

Building occupants are the best source of information on needs and comfort requirements (Frontczak et al., 2012). Therefore, to understand and check the relationships stated in the literature, a satisfaction survey was conducted in two UPC campuses with 37 buildings.

Regular and sporadic users of the two campuses were contacted by email in October 2017. A total of 1,001 valid responses were received, of which 29.07% were regular users (professors and administrative staff) and 70.93% were sporadic users (students).

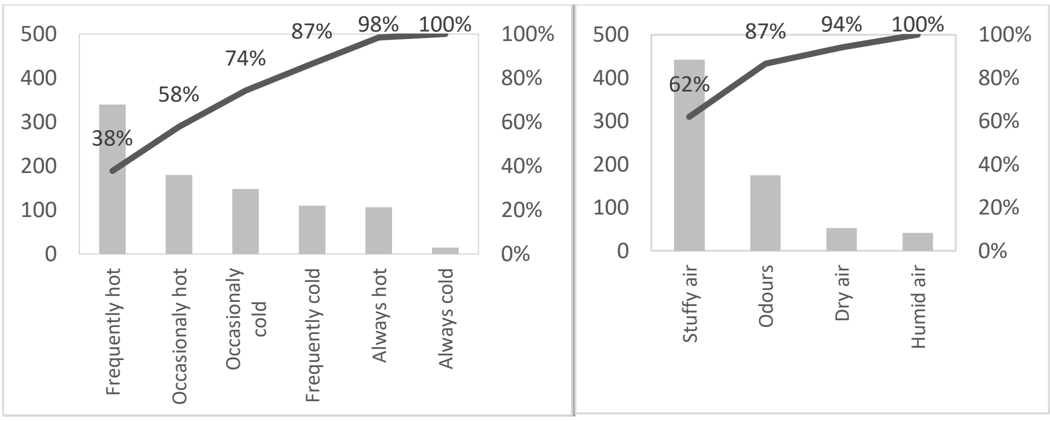
Considering both campuses, 35.86% of the respondents who were regular users were women and 64.14% were men. A total of 24.71% of respondents who were sporadic users were women and 75.29% were men. The average age of respondents who were regular users was 48.71 years, with a standard deviation of 10.04. The average age of respondents who were sporadic users was 21.38 years with a standard deviation of 3.66. Most of the regular users (72.06%) had worked in the same workplace for over 5 years. Most of the sporadic users (66.90%) had studied in the same building for a period between 1 and 5 years.

7.4.2 Analysis of comfort causal factors

Users were asked to report reasons for their dissatisfaction, and 698 out of the 1,001 participants responded with at least one cause of dissatisfaction. “Frequently hot” was noted as the greatest source of occupant dissatisfaction in the summer. Two reasons were given for this problem in the summer season, when the cooling system is on. The first is that in some cases, thermostats were shared by the next-door office, and therefore the indoor environment of one individual’s workspace was controlled by the next-door occupant’s thermal perception and attitude. This situation caused a perceived lack of personal control. The other cause was related to design errors. The low thermal insulation of the buildings together with high temperatures in summer, requires a cooling system to acclimatize the rooms. Even though these buildings require a cooling system, some have only been designed with a heating system. Therefore, occupants experience greater discomfort in summer. In the case of the winter season, many occupants stated that they were “frequently cold”, which is associated with the fact that they could not control the temperature.

“Stuffy air” was the most frequent reason given for air quality discomfort. Most of the buildings only have natural ventilation. This suggests that passive ventilation strategies (e.g., cross ventilation) might not be enough to renovate the spaces in these buildings. Indeed, most of these buildings were constructed before the introduction of legislation that make the adoption of forced or mixed ventilation for non-residential buildings compulsory in Spain (RITE, 2007).

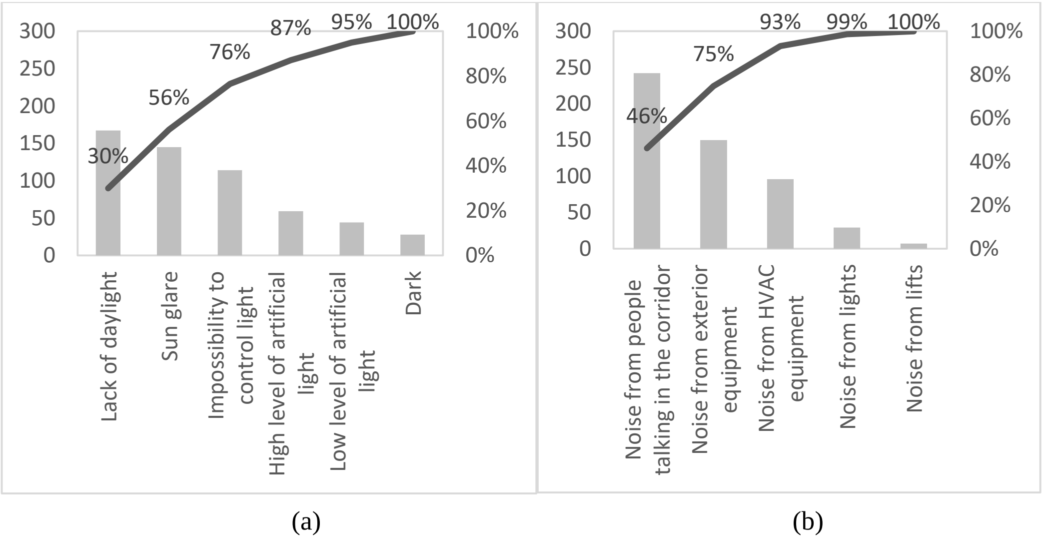
In the Pareto diagram in Figure 29, the causes of dissatisfaction with thermal and air quality accounting for more than 80% were identified as the most significant.



(a) (b)

Figure 29. Causes of dissatisfaction frequency: (a) thermal quality and (b) air quality

The survey results revealed that issues related to glazing and shading, such as “sun glare”, “lack of daylight”, and “impossibility to control light”, were cited as reasons for light quality discomfort. “Noise from HVAC equipment”, “noise from exterior equipment”, and “noise from people talking in the corridor” were the top three reported causes of acoustic quality discomfort. These problems were mainly associated with the low interior and exterior acoustic insulation of the walls. The causes of dissatisfaction with light and acoustic quality accounting for more than 80% of responses were identified as the most significant in the Pareto diagram (Figure 30).



(a) (b)

Figure 30. Causes of dissatisfaction frequency: (a) light quality and (b) acoustic quality

Regarding space adequacy, “furniture ergonomics”, “lack of flexibility”, and “inadequate space distribution” were the three most frequent reasons for dissatisfaction selected by the respondents. The causes of dissatisfaction with space adequacy accounting for more than 80% of responses were identified as the most significant in the Pareto diagram (Figure 31).

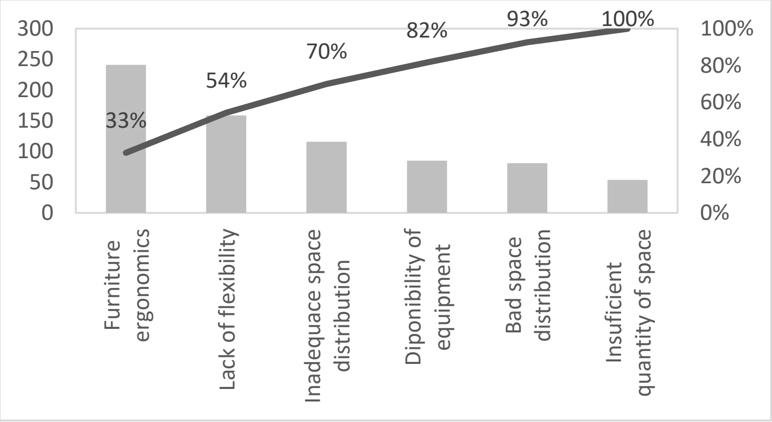


Figure 31. Causes of dissatisfaction frequency: space adequacy

7.4.3 Delphi method results

To check and refine the relationships, interviews were undertaken with domain experts using an adaptation of the Delphi method. Nine experts were interviewed between June and July 2018. Experts were asked to analyze the model and validate, add, change, or erase the existing causal factors and relationships, if necessary. In general, experts agreed with the proposed relationships and helped define the classification of HVAC systems in relation to occupants' comfort. Experts also suggested the incorporation of accessibility as a contributing factor in the category of space adequacy.

7.4.4 Directed acyclic graph for building comfort performance

The relationships identified in the literature within the statistical results for the causes of discomfort and reinforced by the domain experts were used to define the model structure. The DAG for building comfort performance is illustrated in Figure 32.

Figure 32. BN model for building comfort performance

7.5 CPTs definition

Survey results, the literature review, and experts' opinions were used to define the CPTs of each node of the BN model. The CPTs were defined as generically as possible for the model to be applied in the European context. However, probability distributions for some variables can be adapted to a specific context (region/country).

The CPTs for the *Envelope condition* and the *HVAC condition* is the same as presented in the BN condition performance model in the previous chapter. For *Envelope insulation*, the European Building Stock Observatory database (2018) was consulted to get the most common thermal transmittance (U-value) values for façade, roof and window. The average U-value for non-residential buildings is 1.1 W/m².K, 0.83 W/m².K, and 3.17 W/m².K for façade, roof and windows, respectively (EU Building Stock Observatory, 2018). Moreover, there is a certain uncertainty for U-values, as defined by Bordbari, Seifi, and Rastegar (2018), who defined probability distribution functions for uncertain parameters. These values were adapted to a TNormal distribution, as illustrated in Table 32.

The building geometry (proportions of windows, wall, and roof) influences the thermal resistance of the building envelope (Parasonis et al., 2012). Therefore, the envelope insulation node is conditioned to the building geometry and the WWR. The WWR is defined as the ratio of the glazed area with respect to the total area of the envelope (Pino et al., 2012). Based on the work conducted by (Pino et al., 2012; Alibaba, 2016), some ranges for WWR were defined, as shown in Table 32. The envelope performance node depends on the infiltration rate, which is influenced by age, construction quality, building use, and weather conditions (Macdonald, 2002). The envelope condition node refers in this case to defects that can cause infiltration such as cracks, leaks, and openings problems (Sadineni, Madala, & Boehm, 2011).

Table 32. CPTs for envelope insulation nodes

Node name	ID	Type of node	States	CPT			Source
				Expression	Mean (μ)	Variance (σ^2)	
Façade insulation	FacIns	Ranked	High (< 0.2 W/m^2.K) Medium (0.2 to 1.2 W/m^2.K) Low (> 1.2 W/m^2.K)	TNormal	0.5	0.1	Literature (Bordbari et al., 2018); (Parasonis et al., 2012); (EUBD, 2017)
Window Glazing	WinGla	Ranked	High (< 0.2 W/m^2.K) Medium (0.2 to 4 W/m^2.K) Low(> 4 W/m^2.K)	TNormal	0.9	0.1	
Roof insulation	RoofIns	Ranked	High (< 0.2 W/m^2.K) Medium (0.2 to 1.2 W/m^2.K) Low (> 1.2 W/m^2.K)	TNormal	0.5	0.1	
Window Wall Ratio	WWR	Ranked	Low (< 10%) Medium (10 - 40%) High (> 40%)	TNormal	0.5	0.5	Literature (Pino et al., 2012); (Alibaba, 2016)
Envelope insulation	EnvInsl	Ranked	Very High High Medium Low Very Low	TNormal – partitioned expression – WWR + building geometry	wmean(WinGla FacIns, RoofIns)	0.001	Literature (Bordbari et al., 2018) + Experts

Envelope performance	EnPErf	Ranked	Very High High Medium Low Very Low	TNormal	wmean(4.0,EnCon,5.0,EnvInsl)	0.001	Literature (Sadineni et al., 2011); (Macdonald, 2002) + Experts

The possibility of controlling each IEQ factor is extremely valuable for the occupants' comfort. Kim et al. (2017) conducted an extensive literature review and classified occupant personal controls into thermostat control, shade control, ventilation control (fan control and window opening), and light control. Each control is included in the BN as a Boolean node as shown in Table 33.

Table 33. CPTs for control possibility

Node name	ID	Type of node	States	CPT	Source
Ventilation control	VentControl	Boolean	Yes No	0.5 0.5	Literature (Kim et al., 2017); (Frontczak et al., 2012) + Experts
Temperature control	TempCont	Boolean	Yes No	0.5 0.5	
Shade control	ShadCont	Boolean	Yes No	0.5 0.5	
Light control	LigCont	Boolean	Yes No	0.5 0.5	
Acoustic attenuator	AcousAtte	Boolean	Yes No	0.5 0.5	Experts
Ventilation filter	VentFilter	Boolean	Yes No	0.5 0.5	

For the nodes related to acoustic quality, interior and exterior acoustic were defined as ranked nodes and no information was found about the most used in non-residential buildings (Table 34).

Table 34. CPTs for acoustic quality nodes

Node name	ID	Type of node	States	CPT			Source
				Expression	Mean (μ)	Variance (σ^2)	
Interior acoustic insulation	InAcIns	Ranked	High Medium Low	TNormal	0.5	0.5	Experts

Envelope acoustic insulation	EnAcIns	Ranked	High Medium Low	TNormal	0.5	0.5	

Regarding the space adequacy, the most influential factors (cleanliness, ergonomics, accessibility and flexibility) (Frontczak et al., 2012) were defined as ranked type. The CPTs for these nodes have a high variance, since their values depends on the occupant perception (Table 35).

Table 35. CPTs for space adequacy nodes

Node name	ID	Type of node	States	CPT			Source
				Expression	Mean (μ)	Variance (σ^2)	
Cleanliness	Clean	Ranked	High Medium Low	TNormal	0.5	0.5	Literature (Frontczak et al., 2012) + Survey
Ergonomics of furnishing	ErgFur	Ranked	High Medium Low	TNormal	0.5	0.5	
Accessibility	Acce	Ranked	High Medium Low	TNormal	0.5	0.5	
Space flexibility	SpaceFlex	Ranked	High Medium Low	TNormal	0.5	0.5	

For exterior conditions in winter and summer, the nodes were defined as ranked type as illustrated in Table 36. Uncertainty in the exterior condition has been handled by a normal distribution to quantify uncertainty in both ambient temperature and relative humidity (Huang, Huang, & Wang, 2015).

Table 36. CPTs for exterior condition nodes

Node name	ID	Type of node	States	CPT			Source
				Expression	Mean (μ)	Variance (σ^2)	
Exterior condition winter	ExtConWint	Ranked	Mild Cold Extreme cold	TNormal	0.5	0.5	Literature (Huang, Huang, &

Exterior condition summer	ExConSumm	Ranked	Mild Hot Extreme hot	TNormal	0.5	0.5	Wang, 2015)

The *Heating type* and *Cooling type* were defined as labelled nodes with the following states: radiant, all-air, others, and not applicable. For *Ventilation type*, three states were defined: natural, forced, and mixed.

Regarding the importance of the parent nodes for each IEQ factor and space adequacy, several studies were consulted in the existing literature (Dogrusoy & Tureyen, 2007; Kim & de Dear, 2012; Frontczak et al., 2012; Karmann et al., 2017). Domain experts were also asked to refine the importance of the variables. In general, thermal comfort is considered the most important parameter influencing overall satisfaction (Frontczak & Wargocki, 2011; Kim & de Dear, 2012). Furthermore, occupants with ample adaptive opportunities also express high levels of satisfaction with IEQ (Kim & de Dear, 2012). Table 37 illustrates the CPTs for IEQ, space adequacy and building comfort nodes.

Table 37. CPTs for IEQ, space adequacy and building comfort nodes

Node name	ID	Type of node	States	CPT			Source
				Expression	Mean (μ)	Variance (σ²)	
Acoustic quality	AcQ	Ranked	Very High High Medium Low Very Low	TNormal - Partitioned expression - Ventilation type	wmean(3.0,IntIns, 3.0,EnAcoust,3.0, AcousAtte)	0.001	Literature (Karmann et al., 2017); (Frontczak et al., 2012); (Dogrusoy et al., 2007); (Kim & de Dear 2012) + Survey + Experts
Air quality winter	AiQW	Ranked	Very High High Medium Low Very Low	TNormal Partitioned expression – Ventilation type and exterior condition winter	wmean(5.0,HVCo ,5.0,DesConEr4,3.0,VentControl,1.0 ,VentFilter)	0.001	
Air quality summer	AiQS	Ranked	Very High High Medium Low Very Low	TNormal Partitioned expression – Ventilation type and exterior condition winter	wmean(5.0,HVCo ,5.0,DesConEr4,3.0,VentControl,1.0 ,VentFilter)	0.001	
Air quality	AiQ	Ranked	Very High High	TNormal	wmean(1.0,AiQW ,1.0,AiQS)	0.001	

			Medium Low Very Low				
Thermal quality winter	ThQW	Ranked	Very High High Medium Low Very Low	TNormal - Partitioned expression – Heating type	wmean(2.0,HVCo,5.0,DesConEr4,2.0,Envelope_performance,3.0,TempControlW,4.0,ExtConWint)	0.001	
Thermal quality summer	ThQS	Ranked	Very High High Medium Low Very Low	TNormal - Partitioned expression – Cooling type	wmean(2.0,HVCo,5.0,DesConEr4,2.0,Envelope_performance,3.0,TempControlW,4.0,ExtConWint)	0.001	
Thermal quality	ThQ	Ranked	Very High High Medium Low Very Low	TNormal - Partitioned expression - Heating and Cooling type	wmean(1.0,ThQW,1.0,ThQS)	0.001	
Light quality	LiQ	Ranked	Very High High Medium Low Very Low	TNormal - Partitioned expression - WWR	wmean(3.0,Light_control,5.0,DesConErT_2,3.0,Shade_control)	0.001	
Space adequacy	SpQua	Ranked	Very High High Medium Low Very Low	TNormal	wmean(5.0,Clean,5.0,Accessibility,3.0,SpaceFlex,5.0,ErgFur)	0.001	
Building Comfort Performance	BuildCon	Ranked	Very High High Medium Low Very Low	TNormal	wmean(4.0,LiQ,4.0,AcQ,3.0,SpQua,5.0,ThQ,4.0,AiQ)	0.01	

7.6 Data validation

The proposed BN model was validated with two academic buildings on the Campus Nord of the UPC. Table 38 shows their main characteristics. The main use of building CN-A4 is for lectures, while building CN-B2 mainly contains offices. The characteristics of these buildings were obtained from the technical inspection using the proposed BIS, and the text-mining approach to analyze the maintenance requests. Aggregated data (regular and sporadic users) were presented for the satisfaction survey results. However, differences were found for different users.

Table 38. Buildings CN-A4 and CN-B2 characteristics

Characteristics	**Building CN-A4**	**Building CN-B2**
Area (m²)	2,674	1,124
Year of construction	1991	1990
Façade area (m²)	1,786	962
Openings area (m²)	408	132
Roof area (m²)	697	398
Building geometry	F > R	F > R
Window glazing W/(m²K)	5.8 (Low)	5.8 (Low)
Façade insulation W/(m²K)	0.53 (Medium)	0.53 (Medium)
Roof insulation W/(m²K)	0.45 (Medium)	Skylights (Low)
Shade factor	0% (Low)	0% (Low)
Window wall ratio	23 (Medium)	14 (Low)
Occupancy density (m^2/person)	1.74 (High)	5.38 (Low)
Heating type	Radiant	Radiant
Cooling type	N/A	Air-water
Ventilation system	Natural	Mixed
Envelope condition		
Façade detachment	Low	Medium
Façade cracking	Low	Low
Façade water problems	Low	Medium
Roof biological action	Low	Low
Roof water problems	Low	Low
Roof cracking	Low	Low
Doors/Windows operational problems	Low	Low
Doors/windows water problems	Low	High
HVAC system condition		
HVAC operational supply problems	Low	Medium
HVAC operational fixtures problems	Low	High
Satisfaction survey results		
Thermal quality winter	3.58 (satisfied)	2.57 (neutral)
Air quality winter	3.56 (satisfied)	2.57 (neutral)
Thermal quality summer	2.33 (neutral)	2.14 (neutral)
Air quality summer	2.81 (neutral)	2.71 (neutral)
Light quality	3.64 (satisfied)	3.71 (satisfied)

Cleanliness	3.33 (satisfied)	3.57 (satisfied)
Space adequacy	3.42 (satisfied)	3.43 (satisfied)
Acoustic quality	2.86 (neutral)	3.29 (satisfied)
Accessibility	3.58 (satisfied)	3.29 (satisfied)
Overall comfort	3.47 (satisfied)	3.29 (satisfied)

First, a forward propagation analysis was conducted to obtain the probabilities of each comfort factor when the evidence was established for their parent nodes. The results of the forward propagation were then validated with the results of the satisfaction survey of the selected buildings.

When the acoustic quality was analyzed, evidence on the characteristics of buildings CN-A4 and CN-B2 was entered in the parent nodes (Figure 33). The probability of having a high level of acoustic quality was higher in building CN-B2, which is in accordance with the satisfaction survey results. The most probable cause is the type of ventilation system. Building CN-B2 has mixed ventilation, while Building CN-A4 only has natural ventilation. Therefore, in CN-B2, windows can be closed to prevent excessive traffic noise from outside, if necessary. Another cause could be the high occupancy density of building A4 (1.74 m^2/person), which is mainly devoted to classes. In contrast, the spaces in building CN-B2 are designated as office buildings, with a low occupancy density (5.38 m^2/person).

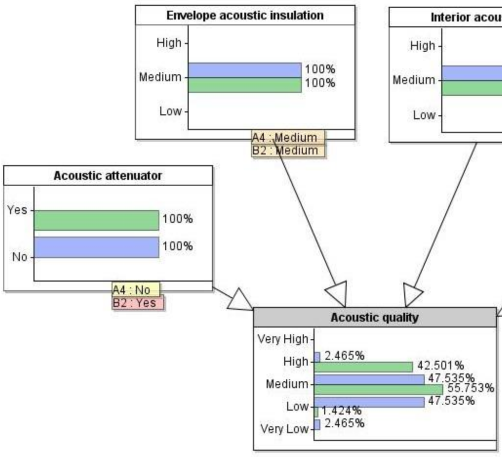


Figure 33. Acoustic quality for building CN-A4 (blue) and CN-B2 (green)

The light quality for the buildings is illustrated in Figure 34. In both buildings, the end user can control the artificial light, but occupants can only control the sun glare through shades in the building CN-A4 (Figure 35). Building CN-A4 has a higher probability of obtaining good light quality than building CN-B2. In the survey results, respondents complained about the low daylight and high artificial light levels in building CN-B2. The low WWR is the most probable cause of the dissatisfaction of users of building CN-B2. The satisfaction survey results indicated the same average level for light quality in both buildings.

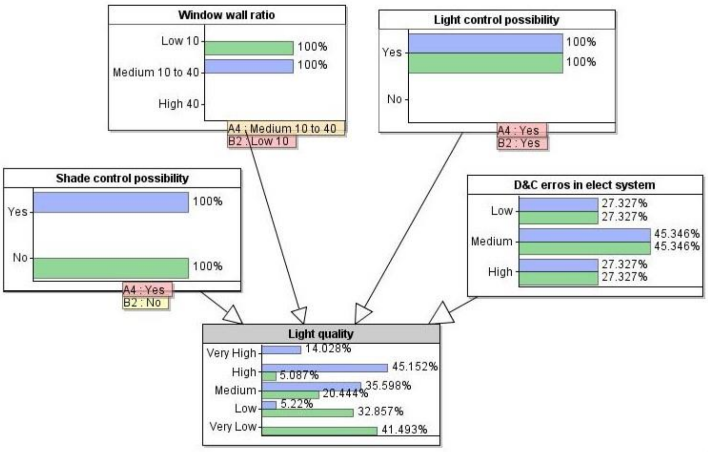


Figure 34. Light quality for building CN-A4 and CN-B2

(a) (b)

Figure 35. Shade control: (a) building CN-A4 and (b) building CN-B2

Buildings CN-A4 and CN-B2 have different thermal quality characteristics. Building CN-A4 only has a heating system and building CN-B2 has a heating and cooling system. Even with a cooling system, building CN-B2 has a probability of 66.7% of medium thermal quality. This is because the condition of the HVAC system has a probability of 43.3% of being low, and the envelope condition a probability of 24.3%. The results of the BN model were compared with the survey results, which showed that end users are not satisfied with the thermal quality in the summer in building CN-B2. The results suggested that it is not enough to have a cooling system in a building to produce high thermal comfort; the maintenance and smooth running of this equipment also influences end users' perceptions of thermal quality. The forgiveness factor could also influence the satisfaction of end users. End users of building CN-B2 would expect higher thermal quality, since there is a cooling system to acclimatize the building in summer. In contrast, end users of building CN-A4 would not expect higher thermal quality in summer, since the building does not have a cooling system. Some studies support this evidence that forgiveness is greater when the most desirable features are present in a building (Hellwig, 2015). People working in air-conditioned spaces are isolated from the outdoor environment, therefore they expect their buildings to provide consistent thermal environmental conditions regardless of outdoor weather conditions (Jungsoo Kim & De Dear, 2012).

Considering air quality, the satisfaction survey results revealed that the air quality in summer was similar in both buildings. However, building CN-A4 had a higher probability of having comfortable air quality than building CN-B2. Forgiveness is greater for buildings with natural ventilation. End users may be more likely to tolerate otherwise excessively uncomfortable conditions in buildings with natural ventilation (Leaman & Bordass, 2007). In passively ventilated buildings, more adaptive mechanisms (e.g., operable windows) are typically available to the occupant for comfort and consequently support greater individual awareness of the available adaptive opportunities.

7.7 Model verification

7.7.1 Sensitivity analysis

A sensitivity analysis was carried out to verify the BN model. It is possible to see diagrammatically which nodes have the greatest impact on any selected target node, and in which states, as illustrated in Figure 36. From a purely visual perspective, the length of the bars can be thought of as the measure of the impact of that node on building comfort performance (target node). The formal interpretation is that the probability of Building comfort performance being Very High given the results of the parent nodes rises from 0.1% (when thermal quality is Very Low) to 9.5% (when thermal quality is Very High). It can be concluded that the probability of a building having very high comfort levels is more sensitive to changes in the states of thermal quality, acoustic quality, and air quality, and least sensitive to changes in space quality and light quality. The results are in agreement with previous studies that claim that building users consider thermal comfort to be the most important parameter influencing overall satisfaction, followed by acoustic comfort and satisfaction with air quality that were considered of similar importance, and visual comfort as the least important factor (Frontczak & Wargocki, 2011).

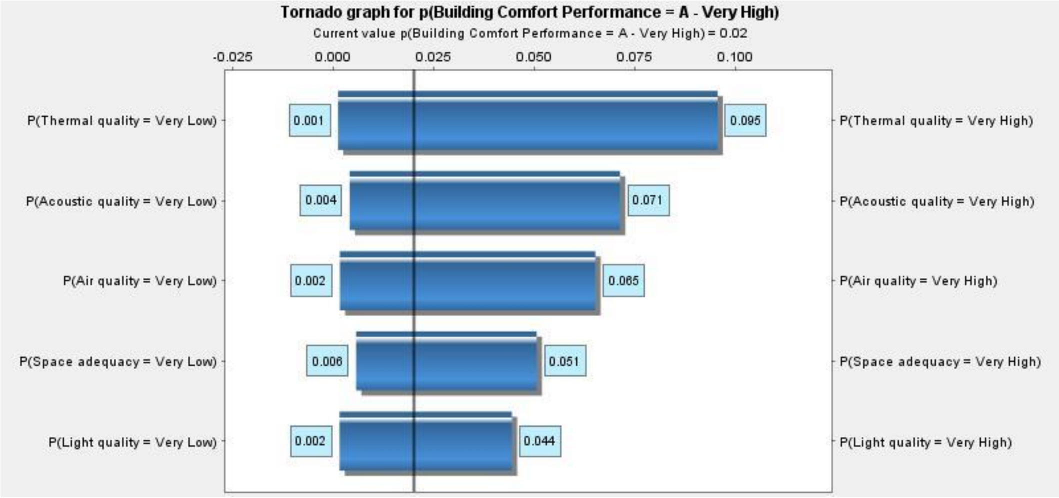


Figure 36. Tornado graph to analyze the sensitivity of Building Comfort Performance (Very High = 2.0%)

A sensitivity analysis was also conducted for thermal quality, air quality, and light quality. Similar thermal quality results were obtained for winter and summer. Figure 37 illustrates the impact of six variables when the thermal quality in summer is Very High (4.7%). Clearly, cooling type, design errors and exterior condition in summer have the greatest impact. Design errors could be related to selection of the wrong type of equipment, or incorrect design of system capacity.

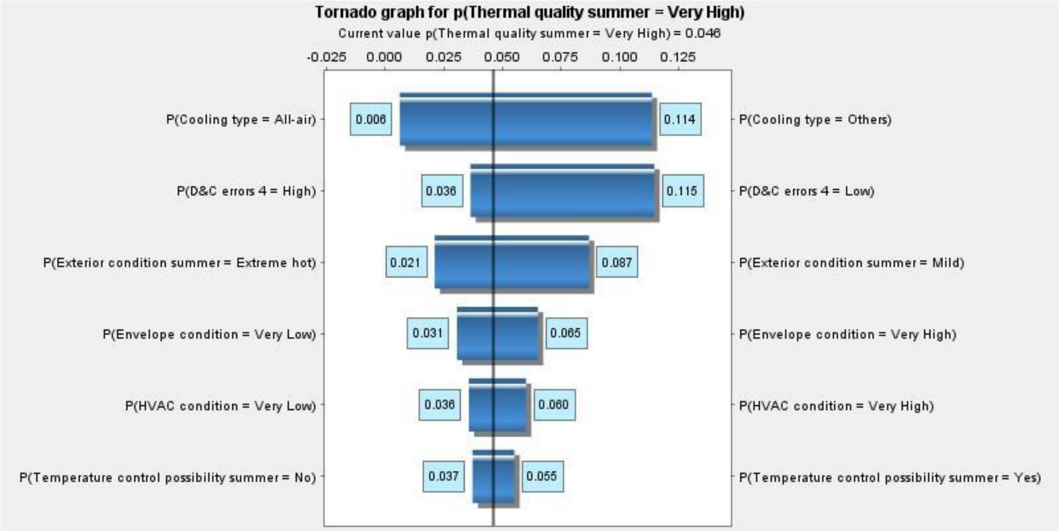


Figure 37. Tornado graph to analyze the sensitivity of Thermal quality in summer (Very High = 4.7%)

A sensitivity analysis was also conducted for the air quality and similar results were obtained for winter and summer. Figure 38 illustrates the impact of seven variables when the air quality in winter is Very High (7.7%). The ventilation type and exterior condition in winter have the greatest impact. Design errors and occupancy density also have a considerable impact. The denser the occupancy of a space, the stuffier the air could be if the ventilation system is not designed correctly.

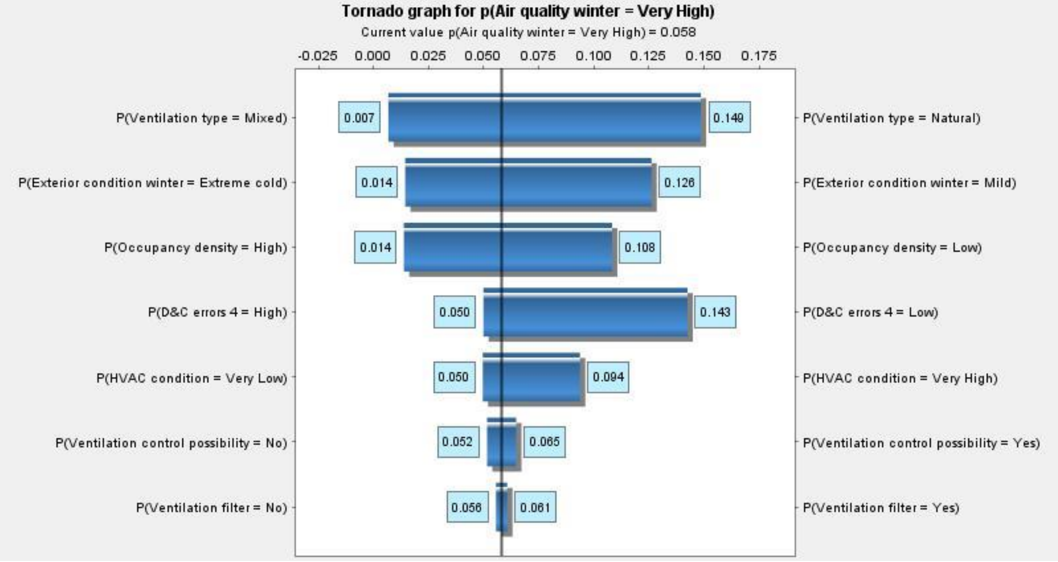


Figure 38. Tornado graph to analyze the sensitivity of Air quality in winter (Very High = 7.7%)

The sensitivity analysis for light quality is shown in Figure 39. The formal interpretation is that the probability of light quality being Very High given the results of the parent nodes rises from 1.6% (when design errors are High) to 36.9% (when design errors are Low). The window-wall-ratio has the greatest impact on light quality, indicating that a medium ratio (between 10 to 40%) is the most comfortable solution. The light control possibility and the shade control possibility have similar impacts on light quality.

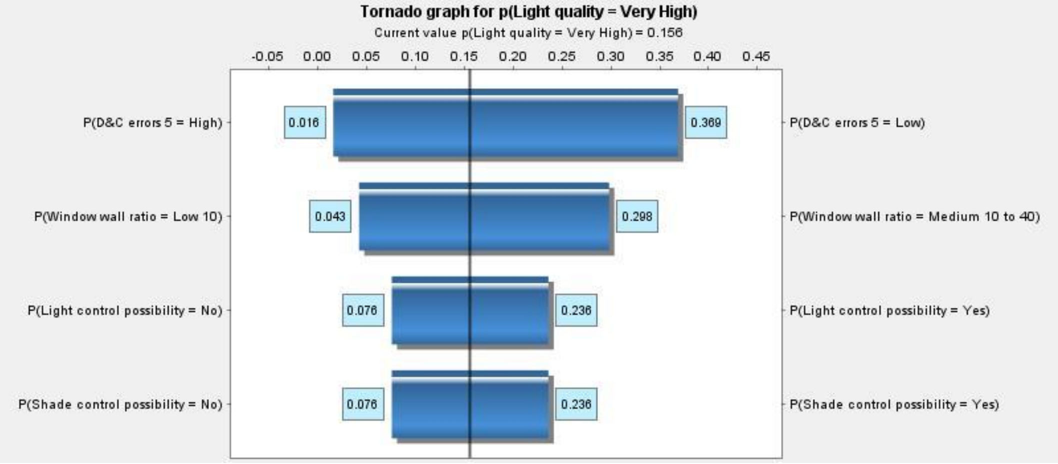


Figure 39. Tornado graph to analyze the sensitivity of Light quality (Very High = 15.6%)

7.7.2 Case study - building comfort scenarios

To evaluate the applicability of the proposed model, CN-C2 building from Campus Nord was used as a case study. The selected building was constructed in 1989 and has 2,124 square meters. The main characteristics of this building are shown in Table 39. Table 39 also includes the results of the technical inspection conducted on the building envelope and the problems with the HVAC system.

Table 39. Characteristics of CN-C2 building

Characteristics	
Façade area (m²)	1,791
Openings area (m²)	272
Roof area (m²)	442
Building geometry	F >> R
Window glazing W/(m²K)	5.7 (Low)
Façade insulation W/(m²K)	0.42 (Medium)
Roof insulation W/(m²K)	0.45 (Medium)
Shade factor (%)	65 (Medium)
Window wall ratio	15 (Low)
Occupancy density (m^2/person)	5.85 (Low)
Heating type	Radiant
Cooling type	Direct-expansion
Ventilation system	Natural
Envelope condition	
Façade detachment	Low
Façade cracking	Low
Façade water problems	Low
Roof biological action	Low
Roof water problems	High
Roof cracking	Low
Doors/Windows operational problems	Low
Doors/windows water problems	Low
HVAC system condition	
HVAC operational supply problems	Low
HVAC operational fixtures problems	High

The characteristics of the building were entered in the model as evidence to assess its comfort performance. The results are shown in Table 40. CN-C2 building has a probability of 2.87% of being very high and 35.56% of being high comfort performance.

Table 40. Comfort performance results for the case study

Indicator	Performance Level				
	Very Low	Low	Medium	High	Very High
Building comfort performance	**0.15**	**8.47**	**51.95**	**36.56**	**2.87**
Thermal quality	0.95	2.95	62.32	33.78	0.00
Thermal quality in winter	0.00	0.79	55.66	43.55	0.00
Thermal quality in summer	0.00	3.49	72.63	23.69	0.19
Air quality	0.00	0.04	5.85	58.44	35.67
Air quality in winter	0.00	0.08	7.50	54.56	37.86
Air quality in summer	0.00	0.08	7.50	54.56	37.86
Light quality	12.82	27.92	32.95	20.83	5.48
Acoustic quality	2.47	47.53	47.53	2.47	0.00
Space adequacy	0.00	0.00	19.76	67.89	12.35

The results demonstrated that the most probable level of acoustic quality in the CN-C2 building is low/medium (47.53%). CN-C2 had a high probability of space adequacy being high (67.89%). The air quality had a probability of 58.44% of being high, while the thermal quality presented a probability of 62.32% of being medium. Regarding the thermal quality in summer, the results revealed a probability of 72.63% of being medium. This result could be attributed to the low condition of the HVAC system.

The light quality is the IEQ factor with the most probable result of being low. The most probable reason for this result is the low WWR, which limits the daylight (Figure 40). However, preferred illuminance levels in offices with daylight vary widely from one person to another, as reported by (Galasiu & Veitch, 2006). In addition, desired quantities of additional electric light vary with the type of task and the distance from the window (Galasiu & Veitch, 2006). To increase the light quality of this building, further investigation is necessary to ensure that the level of artificial light is adequate for all the workspaces and/or to provide additional control options to occupants such as the possibility of choosing the electric lighting level. Control systems are more acceptable to both occupants and facility managers when they are simple and easy to use (Galasiu & Veitch, 2006). Installing individual lights for work stations and improving the daylight by locating the work stations close to windows (in depth rooms) might have a great impact on the comfort perceptions of regular users that spend most of the time on the building.


Figure 40. Building CN-C2

The low condition of the HVAC system might be the cause of low levels of thermal quality and thus comfort performance. Therefore, a what-if scenario to improve the thermal quality was defined to conduct a backward propagation analysis. An observation was made setting the HVAC condition as very high and changing the preventive maintenance of the HVAC system to Yes. This scenario led to a reduction in the probability of defects in the HVAC system, and consequently, improved thermal quality. Before the renovation, the thermal quality was most likely to be medium (62.32%). The result of the proposed scenario predicted that the thermal quality would be improved, with 55.01% probability of being high (Table 41). These results corroborate that poor maintenance and problems in the HVAC systems can cause discomfort to users.

Table 41. Thermal quality prediction after renovation

Indicator	Performance Level				
	Very Low	Low	Medium	High	Very High
Thermal quality	0.00	0.78	40.94	55.01	3.27

Scenarios to evaluate the comfort of different groups of users (regular and sporadic) could also be performed. For instance, differences were obtained when specific common spaces of the buildings were evaluated in the satisfaction survey conducted on the university campuses. Sporadic users (i.e., students) were more dissatisfied with the thermal and air quality than the regular users (i.e., professors and administrative staff). Therefore, the proposed model may help analyze and compare the level of satisfaction of different groups of occupants in relation to retrofits and/or maintenance actions.

7.8 Conclusions

The assessment of building comfort performance involves the analysis of multiple variables under uncertainty. It is difficult to use traditional methods to quantify and assess building comfort from such uncertain variables. Therefore, this chapter presented the development of a novel BN model to evaluate the comfort performance of existing buildings. Unlike deterministic models, the proposed BN can model building comfort as a probabilistic process, providing levels of comfort performance using probability distributions.

This model includes a comprehensive, structured, robust model for causal factors that affect building comfort. The capability of the proposed model is demonstrated by applying it to real buildings. The IEQ factor and space adequacy are key issues for the health and comfort of occupants in non-residential buildings. The results showed that the BN model can estimate the building comfort level when the characteristics of the building and the environmental conditions are known. However, when evidence about the IEQ and space (gathered through the questionnaire survey) are included, the model also provides the most probable causes for dissatisfaction. Therefore, the proposed model helps facility managers to make informed decisions to enhance the comfort of buildings, and consequently occupant satisfaction.

Knowledge about people’s comfort priorities may be used as guidelines in the construction and renovation of buildings so that building occupants’ satisfaction can be maximized. The high impact factors in the BN model were illustrated using a sensitivity analysis. Moreover, scenario analyses provided the capacity for deeper understanding of potential responses of the model, helping facility managers to optimize building operation strategies to increase building comfort performance. Besides using the model as a performance management tool, facility managers can create hypothetical scenarios and simulate outcomes before finalizing a renovation or retrofitting plan. This will provide the manager with quantitative and visual comparisons between decision options.

Chapter 8

Bayesian network model for assessing a building’s energy performance

8.1 Introduction

This chapter describes the development of the subnet related to the building’s energy performance, which is one of the categories defined in Chapter 4. The BN model provides an effective way to assess the energy performance of existing buildings. The model also presents an understanding of the causality chain between multiple factors that affect energy performance and helps to identify energy efficiency opportunities in the O&M phase.

8.2 Building energy assessment methods

Buildings account for 40% of the total energy use and 36% of the total CO_2 emission in Europe (European Commission 2018). Commercial, office and university buildings are classified amongst the buildings with the highest energy consumption (Chung & Rhee, 2014). For this reason, a variety of initiatives for energy consumption reduction were promoted, such as the Energy Performance Building Directive (EPBD) 2002/91/EC, its recast 36/EC/2010, and the amending 2018/844/EU. Particularly, such policy aims the monitoring and diagnostics of the energy performance of the buildings in the O&M stage (Hong et al., 2015). EPBD defines energy performance as “the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes, *inter alia*, energy used for heating, cooling, ventilation, hot water and lighting”.

Existing methods to evaluate a building’s energy performance can be classified into energy audit methods, statistical methods, and hybrid methods (Hong et al., 2015). In an energy audit method, also known as engineering method, physical principles are used to predict the energy performance of the building (Bordbari et al., 2018). This prediction can be done by calculating the theoretical energy performance of the building using equations or simulation tools such as EnergyPlus, DesignBuilder, among others (Hong et al., 2015). In the statistical method, historical data is used to develop experimental models for energy consumption analysis (Safa, Safa, Allen, Shahi, & Haas, 2017). These models can be developed in numerous ways, but regression analysis, neural networks, and support vectors machines are the most common approaches (Hong et al., 2015). For the hybrid method, both physical principles and historical energy use data are considered to predict a building's dynamic energy performance (Hong et al., 2015).

Despite the contributions of previous methods, they have many limitations, such as the lack of validation data, the small amount of input variables, the complexity for using them, and the focus on construction elements and environmental factors only (e.g., climate) (Zhao & Magoulès, 2012; Safa et al., 2017). Also, there is a lack of research quantifying the relationships between variables related to the building operation and energy performance. Studies have extensively evaluated the sensitivity of models to the buildings' technical design parameters. However, the variables related to operation energy management have rarely been evaluated, and they are very important elements that impact building energy consumption (Azar & Menassa, 2012; Gul & Patidar, 2015). Most studies do not take into account the operational condition of the HVAC systems, neither how the buildings systems are routinely managed and operated (Gul & Patidar, 2015; Tian et al., 2018).

It is also important to notice that most of the reported work available in the technical literature does not deal with an important aspect of energy performance prediction: the uncertainty (Hopfe, Augenbroe, & Hensen, 2013; Bordbari et al., 2018). Numerous parameters that impact building energy performance are inherently uncertain, such as climate, occupant behavior, and indoor environmental conditions (Tian et al., 2018). As these input parameters are not accurately known, it is imprudent to assume deterministic values for them (Hopfe et al., 2013). A more realistic approach is to introduce ranges of uncertainty in the parameters themselves from underlying approximations (Hopfe et al., 2013). This can be done with a Bayesian approach, in which unknown parameters can be assigned with prior distributions that quantify prior beliefs based on expert knowledge (Tian et al., 2018). Expert knowledge are derived from a pool of sources (e.g., experiments, surveys, expert knowledge, industry standards) (Heo et al., 2012). Prior distributions are then updated through a Bayes' theorem, in which prior knowledge is combined with new observed information in order to improve distributions of unknown parameters (Tian et al., 2018).

To bridge this gap, the model presented in this thesis define the causal factors on energy performance at the O&M stage without the need for an intensive process, such as the exhaustive collection of data that is typically required by simulation and credit based tools. The goal is to develop a simple model, which make it feasible the collection of the data required and the assessment of the building energy performance in real use.

8.3 Methodology

The main steps to construct a BN model were described in Chapter 3. Figure 41 illustrates the steps for building a BN model to assess a building's energy performance, and a detailed description about these steps is provided in the following subsections. For brevity, similar steps described in Section 6.3 are not repeated here.

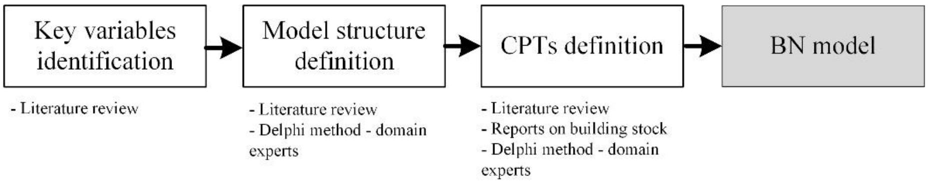


Figure 41. Main steps to build the BN model for building energy performance

8.3.1 Key variables identification

The key variables affecting building energy performance were identified by a literature review. This included the definition of the factors and indicators affecting building energy performance.

8.3.2 Model structure definition

The definition of the BN model structure was divided into two main steps:

i. First, a literature review was conducted to analyze the relationships (cause-effect) of key variables influencing building energy performance;
ii. Second, domain experts were consulted using an adaptation of the Delphi method (Wright & Rowe, 1999). Experts in the field of building performance were consulted to improve the model structure, which implicate on adding intermediate nodes or establishing missing relationships.

8.3.3 Conditional probability tables definition

The CPTs of each node of the model were defined by two main steps:

i. First, literature review and reports on the European building stock (e.g., BPIE, 2011; EU Building Stock Observatory, 2018) were consulted to define the pattern (i.e., probability distribution) of some nodes;
ii. Second, for the nodes in which no data was available, information was elicited from experts. The importance of some variables was elicited from domain experts, obtaining a prior distribution that quantify prior beliefs about the parameters.

8.3.4 Model evaluation

The model evaluation consisted of two steps:

i. Computerized model verification: a sensitivity analysis was performed to obtain an understanding of the most significant factors of the model and to verify whether the model response conforms to expectations.
ii. Operational verification: two case studies were selected to assess the behavior of parts of the model for different scenarios.

8.4 BN model structure

Alongside the key factors identified in Section 2.2.5, an additional literature review was conducted to identify the most relevant variables regarding building energy performance. The analysis starts from the conjecture that energy performance is influenced by the performance of each building system (Borgstein et al., 2016): heating, cooling, ventilation, hot water, and lighting systems (Figure 42).

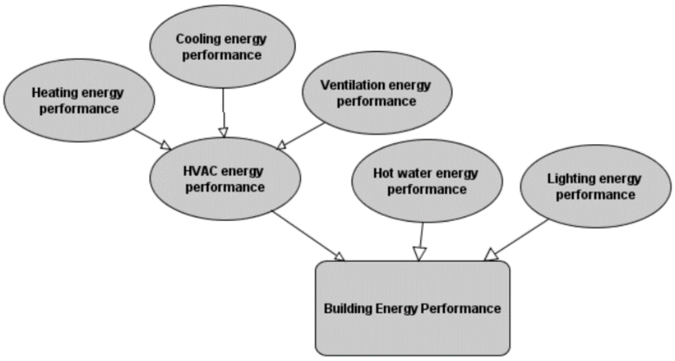


Figure 42. Building systems influencing building energy performance

There is a wide variety of HVAC systems, in terms of size, features, and the amount of energy consumed. Factors that influence HVAC energy performance include (Hellwig, 2015; Safa et al., 2017; Tian et al., 2018):

- The energy demand, including heating and cooling demand, and ventilation rate
- The design and efficiency of the HVAC system
- The condition of the HVAC system including how, when and for how long the HVAC system is operated every day
- The level of monitoring and maintenance of the HVAC system.

Figure 43 illustrates the main variables influencing heating, cooling and ventilation energy performance.

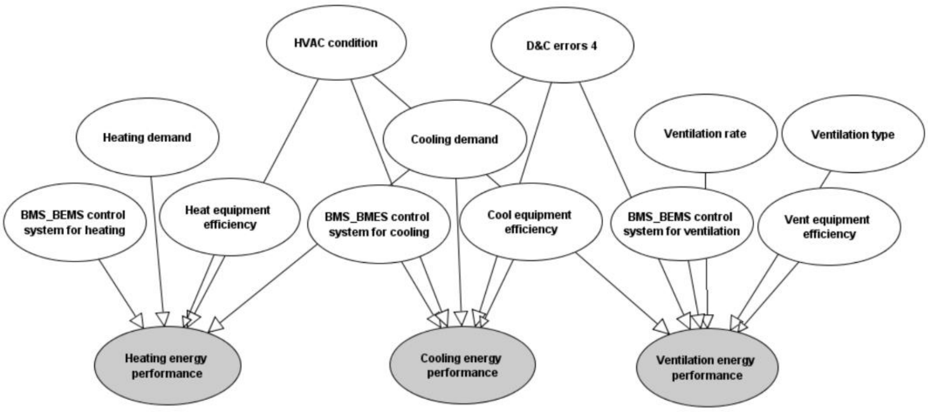


Figure 43. Variables influencing heating, cooling and ventilation energy performance

Design errors within the HVAC system refer to the wrong design of the system. A good HVAC system design depends on the architecture of the building. If there are single thermal zones, then centralized systems are the best option. However, for buildings with different thermal zones, decentralized systems are a better option. Office and academic buildings have rooms with different time and temperature requirements (i.e., different room dimensions, internal gains, and uses). Hence, a good design would include zoning and different equipment (e.g., fan coils) to control temperature and effectively power off in unused or unoccupied zones.

Making the most of natural ventilation is a simple and cost effective way to achieve substantial energy savings. A good design of natural ventilation relies on air flow through openings into a room or building, preferably from opposite sides. HVAC systems incorporating free cooling or heat recovery systems should also be taken into consideration. Identifying where excess heat (e.g., sunlight, office equipment, and lighting) is coming from and designing specific systems for these cases is also really important. For instance, data servers produce a large amount of heat, therefore, specific cooling systems must be used for the spaces where they are located.

Old buildings might not have included cooling when they were designed, and refurbishments and cooling systems may have been incorporated later. Space limitations and installation costs are some possible reasons for selecting the wrong cooling systems, or at least not the best system for the specific building. This is the case of incorporating air conditioners in some offices where only radiators for heating where installed originally. These systems consume a lot of electricity and may not be suitable for high zone buildings with different requirements. Therefore, the selection of the HVAC system is crucial for its energy performance.

The operation and maintenance are other critical aspects when evaluating the HVAC energy performance (Gul & Patidar, 2015). The condition of HVAC systems has a significant influence on the energy use (Safa et al., 2017). Building energy analysis usually assumes that HVAC systems operate in ideal conditions, but the performance of HVAC systems is affected by a number of factors, such as oversizing, aging, maintenance, ant the usual wear and tear (Tian et al., 2018). Moreover, the management of HVAC systems is another contributor factor. The adoption of BMS and BEMS provide potential to optimize the energy consumption of buildings as well as to detect failures in their service systems (Hellwig, 2015).

The ventilation energy performance is conditioned by the ventilation rate. The Spanish regulation Royal Decree 1027/2007 (RITE, 2007) defines the minimum fresh (outdoor) air rates based on occupancy and type of use.

The HVAC energy performance also depends on the heating and cooling demand. Energy demand consists of the required net energy, which is based on the weather conditions, indoor temperature and air quality requirements, while considering the contributions from internal gains, solar gains and losses due to building properties, i.e., heat transmission and airflows (EN ISO 13790:2008).

The heating and cooling demand can be calculated by the many simulation tools available that heavily rely on large databases, such as EnergyPlus, DesingBuilder, TRNSYS, eQUEST, and ESP-r (Hong et al., 2015). These simulation tools calculates the theoretical energy performance of the building.

The energy demand can also be obtained from the “Simplified hourly method” (detailed in ISO 13790:2008) which calculates the heating and cooling loads required per hour, with positive values for heating and negative values for cooling. The method considers the heat transfer by ventilation and infiltration, and heat and solar gains through opaque envelope and windows (Lizana, Serrano-jimenez, Ortiz, Becerra, & Chacartegui, 2018). Heat gains include the internal gains, i.e., the thermal energy from people, lighting and appliances that heat the indoor environment (ASHRAE, 2009). Heat from occupants depends on the metabolic activity, age and occupancy density (m^2/person) of the conditioned area (EN ISO 13790:2008). The solar gains are related to the thermal properties (e.g., insulation) of the building envelope. The measure of heat loss through a material is referred to as the U-value (Papadopoulos, 2005). Windows, doors, walls and roofs may gain or lose heat, therefore increasing the energy demand for cooling or heating (Al-Homoud, 2005).

The geometry of the building is another important variable on the heating and cooling demand. The shape factor is defined as ratio between the heated volume of the building and the sum of all heat loss surfaces that are in contact with the exterior (EN 15217:2007). There are more heat losses for a greater heat loss surface area, so a small shape factor implies a low energy demand (Parasonis et al., 2012). The WWR described in the previous chapter is also considered one of the most influential parameters on energy demand (Pino et al., 2012).

Environmental condition (e.g., weather), building envelope condition, and use intensity (e.g., occupant behavior) are other contributor factors for the heating and cooling energy demand (Hopfe et al., 2013; Tian et al., 2018).

Figure 44 illustrates the variables influencing heating and cooling demand.

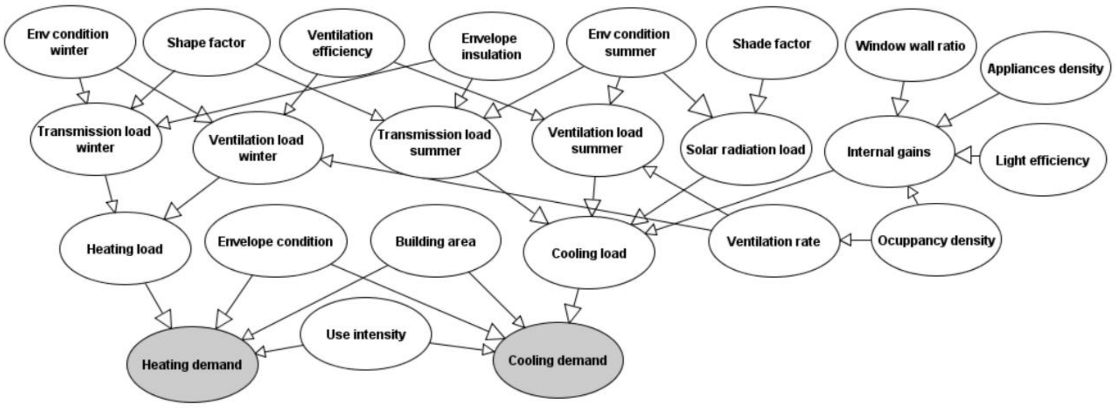


Figure 44. Variables influencing heating and cooling demand

The Lighting energy performance is mainly affected by the lighting demand (Ryckaert, Lootens, Geldof, & Hanselaer, 2010; Aghemo, Blaso, & Pellegrino, 2014), and is also strongly dependent on lighting controls (EN 15193:2007). BMS can be used to integrate daylight, artificial lighting and strategies based on the occupancy of spaces to optimize light energy use (Aghemo et al., 2014). The lighting demand depends on the illuminance required, occupancy schedule and the percentage of daylight, which varies in function of the WWR and the building geometry (EN 15193:2007). Figure 45 illustrates the variables influencing lighting energy performance.

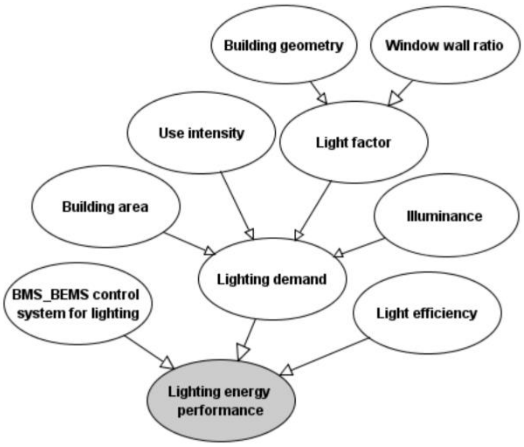


Figure 45. Variables influencing lighting energy performance

The Hot water energy performance is influenced by the hot water demand which is dependent on the type of activity carried out in the building. Moreover, the BMS control system for hot water, and the condition of the plumbing system are other contributing factors for the energy performance of the hot water system. The good operating conditions of the plumbing system (e.g., well insulated pipes) results on low energy loss in the distribution system (Balaras & Argiriou, 2002). On site renewable heat generation (e.g., biomass boilers, solar thermal installation) can be used to cover a substantial fraction of the energy needed to heat water. Figure 46 illustrates the variables influencing hot water energy performance.

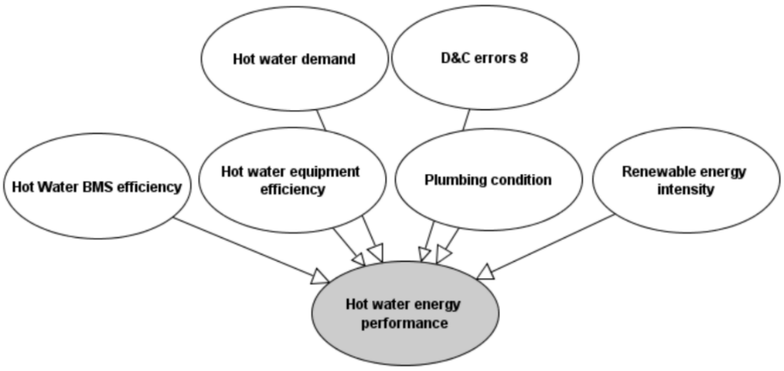


Figure 46. Variables influencing hot water energy performance

8.4.1 Delphi method results

To check and refine the relationships among the building's energy performance variables, interviews were undertaken with domain experts using an adaptation of the Delphi method. Five experts were interviewed during September and October of 2018. Experts were asked to analyze the model and validate, add, change, or erase the existing causal factors and relationships, if necessary. Experts stressed the importance of the correct design of the HVAC system and the its condition when assessing the energy performance of buildings in use. A poor maintained equipment may result in higher energy use, making preventive maintenance a key process for the efficient operation of the building systems. In addition, they stressed the importance of the envelope insulation to determine the energy demand of buildings. Poor thermal insulation is the main cause of a high energy demand.

8.4.2 Directed acyclic graph for building energy performance

The relationships identified in the literature and by the experts were used to define the model structure. The DAG for building energy performance is depicted in Figure 47.

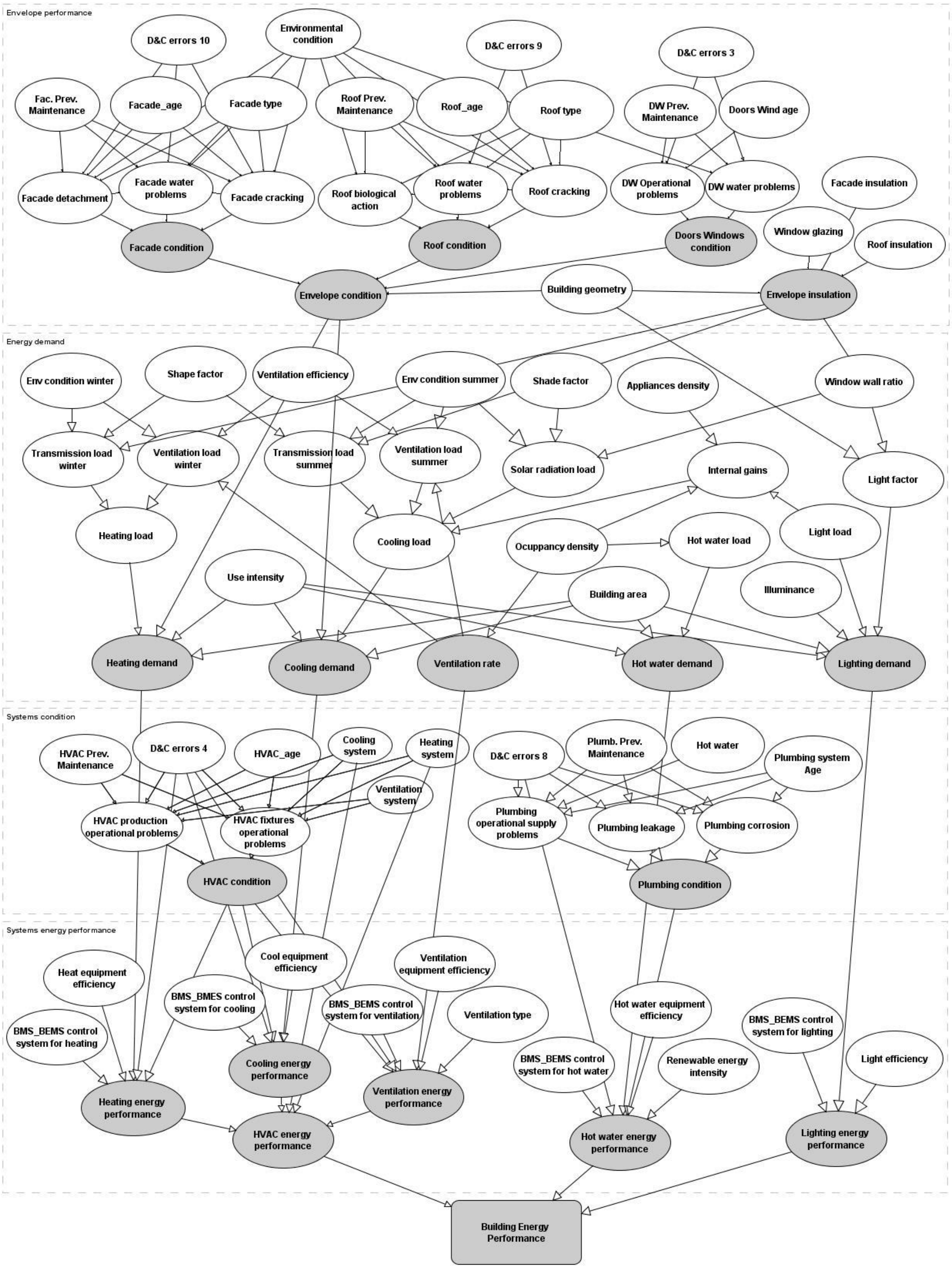


Figure 47. BN model for building energy performance

8.5 CPTs definition

Detailed knowledge of energy performance of the non-residential building stock is still limited (BPIE, 2014). Energy use in non-residential buildings is a complex organizational issue due to the heterogeneity of activities (e.g., lecture, halls, laboratories, offices) and energy services (e.g., HVAC, hot water and lighting) that take place in these buildings (Chung & Rhee, 2014).

Literature review and experts' knowledge were used to define the CPTs of each node of the BN model. As explained in the Chapter 6, the CPTs were defined as generic as possible, enabling the model to be applied in the European context. However, probability distributions for some variables can be adapted to a specific context (region/country).

The CPTs for the *Envelope performance, HVAC condition* and *Plumbing condition* were presented in the Chapters 6 and 7.

The CPTs for *heating demand*, *cooling demand*, *ventilation rate*, *hot water demand*, and *lighting demand* were initially planned to be calculated with the learning from data functionality of AgenaRisk tool, using the EM algorithm. However, a large database with buildings with different locations and characteristics is required to get more accurate results. Therefore, based on existing methods and standards, such as EN ISO 13790:2008 and ISO 52016-1:2017, the DAG for the energy demand was developed. Future steps will include obtaining the CPTs for all the nodes related to the energy demand. For the purpose of this thesis, and to validate and use the model, the energy demand are obtained from simulation tools (e.g., EnergyPlus, DisgnBuilder) or energy performance certificates.

The European building stock observatory (BPIE, 2014) provides data about the European building stock, including technical building systems that are used to define the nodes and define levels to benchmark. Building energy benchmarks are representative values for common building types which can be used to compare with an actual building. Reference values enable the comparison between the energy performance of a given building and the energy performance of similar buildings at the national or regional level (EN15217:2007).

The CPTs for the nodes related to the BMS and BEMS control systems were defined as labelled types, considering the rates established by the classification system in EN 15232:2016. This standard specifies levels to assess the impact of building automation and control systems on the energy performance of buildings, as these systems increase operational and energy efficiencies. Class A energy efficiency controls are fully programmable and able to perform a wide range of control strategies. Class D are considered non-efficient energy controls or any control available.

The CPTs for the nodes related to the HVAC system, hot water and lighting energy performance were defined in Table 42. The distribution functions were defined based on the information reported in the literature (BPIE, 2014; Heo, Augenbroe, Graziano, Muehleisen, & Guzowski, 2015; Bordbari et al., 2018; Tian et al., 2018) and domain experts' opinion.

Table 42. CPTs for systems energy performance

Node name	ID	Type of node	States	CPT			Source
				Expression	Mean (μ)	Variance (σ^2)	
Heating energy performance	HeatEnPerf	Ranked	Very High High Medium Low Very Low	TNormal – Partitioned expression – BMS/BEMS	wmean(5.0,HeatingDemand,1.0,HVCo,2.0,DesConEr4,3.0,HeatEquipEfficiency)	0.01	Literature (BPIE, 2014; Heo et al., 2015; Bordbari et al., 2018; Tian et al., 2018) + Experts
Cooling energy performance	CoolEnPerf	Ranked	Very High High Medium Low Very Low	TNormal – Partitioned expression – BMS/BEMS	wmean(5.0,CoolingDemand,1.0,HVCo,2.0,DesConEr4,3.0,CoolEquipEfficiency)	0.01	
Ventilation energy performance	VentEnPerf	Ranked	Very High High Medium Low Very Low	TNormal – Partitioned expression – Vent system + BMS/BEMS	wmean (3.0,HVCo,5.0,DesConEr4,1.0,Vrate,4.0,VentEquipEfficiency)	0.01	
Hot water energy performance	HotWatEnPerf	Ranked	Very High High Medium Low Very Low	TNormal – Partitioned expression – BMS/BEMS + D&C8	wmean(5.0,HotWatdemand,1.0,HotWatRenewable,1.0,PlumbCon,2.0,DesConEr8,3.0,HotWatEquipEfficiency)	0.01	
Lighting energy performance	LightEnPerf	Ranked	Very High High Medium Low Very Low	TNormal – Partitioned expression – BMS/BEMS	wmean(3.0,LigDemand,1.0,LightEquiEfficiency)	0.01	

For the *Building energy performance* node, the CPTs were defined as a probability distribution function considering the impact of the systems on the whole building performance. Taking into account the building systems, the HVAC is the one with the highest energy consumption (Bakar et al., 2015). HVAC systems account for 40-60% of the total energy consumption of buildings, and lighting accounts for 5–15% (Ryckaert et al., 2010; Harish & Kumar, 2016).

Table 43. CPTs for building energy performance

Node name	ID	Type of node	States	CPT			Source
				Expression	Mean (μ)	Variance (σ²)	
Building Energy Performance	BuildEnPerf	Ranked	Very High High Medium Low Very Low	TNormal	wmean(1.0, HotWatEnPerf,3.0,LightEnPerf,5.0, HVACEnPerf)	0.01	Literature (Ryckaert et al., 2010; Bakar et al., 2015; Harish & Kumar, 2016) + Experts

8.6 Model verification

8.6.1 Sensitivity analysis

A sensitivity analysis was carried out to verify the BN model. The analysis takes into account buildings located in climates that require heating and cooling. In Figure 48, the length of the bars can be considered as the measure of the impact of that node on the Building energy performance. It can be concluded that the probability of Building energy performance being very high is more sensitive to heating and cooling energy performance. Ventilation was not found to be relevant because the BN model was developed using the existing building stock. Typically, mechanical ventilation is not incorporated in old existing buildings. For instance, forced ventilation were only installed in buildings around 2000, after regulations establishing mechanical ventilation requirements for non-residential buildings took effect. The regulation forces to incorporate air renovation in all occupied areas of buildings. In the future, the relevance of ventilation in energy performance will need to be revised based on the future stock of buildings. Hot water energy performance has the lowest influence in the energy performance due to the low consumption on academic and office buildings. If other types of buildings (e.g., gyms) were considered, then the importance of the hot water on the energy performance would be higher.

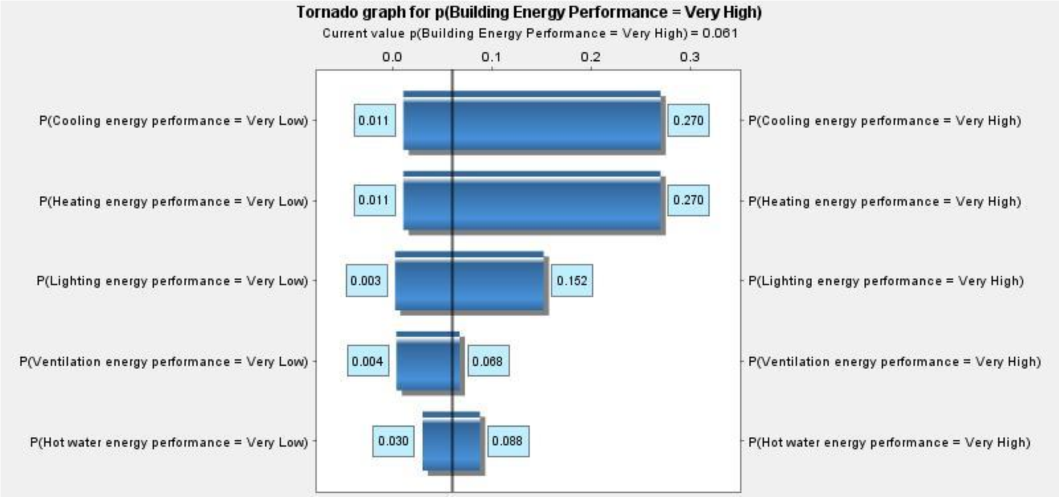


Figure 48. Tornado graph to analyze the sensitivity of building energy performance (Very High = 6.1%)

A sensitivity analysis was also conducted for heating energy performance, as illustrated in Figure 49. The formal interpretation is that the probability of heating energy performance being Very High, given the results of the parent nodes, ranges from 0.2% (when Heating demand is High) to 16.4% (when heating demand is Low). It can be concluded that heating demand and heat equipment efficiency are the variables with the largest impact.

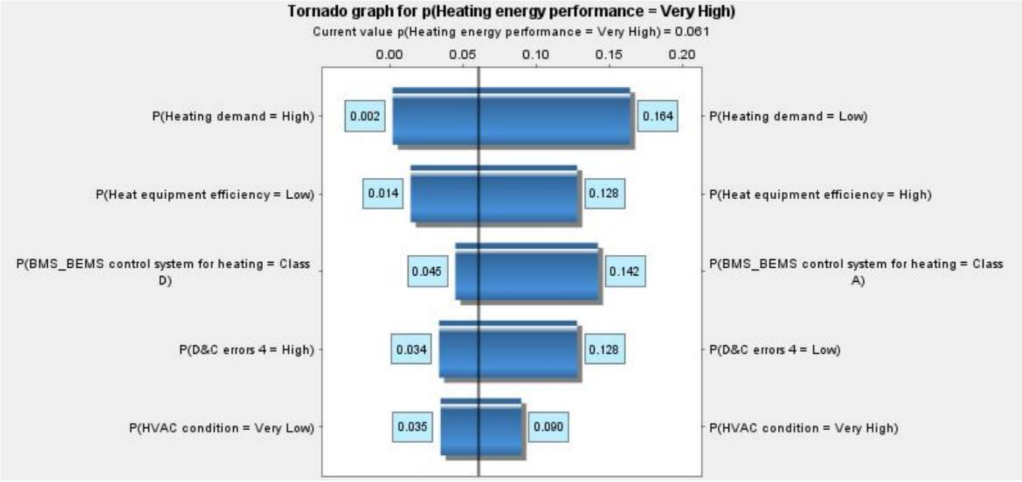


Figure 49. Tornado graph to analyze the sensitivity of heating energy performance (Very High = 6.1%)

8.6.2 Case study - building energy scenarios

To test the model and evaluate its accuracy under real operating conditions, a case study was selected. The building selected was CN-C2, also presented in Chapters 6 and 7. Additional information about the building systems is shown in Table 44. The energy demand for heating and cooling, as well as the ventilation rate and lighting demand, were calculated using the standard EN ISO 13790:2008 and obtained from the existing energetic certificate facilitated by the facility manager of the Campus department.

CN-C2 building was constructed before the introduction of energy legislation that specifies a minimum U-value for building envelope. Therefore, it presents a high heating energy demand. The low cooling demand is attributed to the short period of summer with activities at the building, which are concentrated for the most part during the winter period.

Table 44. Characteristics of CN-C2 building

Characteristics	
Heating system	Radiant - Condensing boiler
Heat equipment efficiency	Low
BMS/BEMS control for heating	Class C
Heating demand (kWh/m^2.year)	44.5
Cooling system	Direct-expansion - Splits
Cool equipment efficiency	Medium
BMS/BEMS control for cooling	Class C
Cooling demand (kWh/m2.year)	18.00
Ventilation system	Natural
Ventilation rate	Low
Ventilation BMS efficiency	-
Hot water demand (liters/day.person)	2
BMS/BEMS control for Hot Water	-
Hot water equipment efficiency	-
Renewable energy intensity	-
Light efficiency	Low
BMS/BEMS control for Lighting	Class D

Evidence was set in the model using CN-C2 building characteristics and the results revealed that the building energy performance is most likely to be low (42.67%) (Table 45). The heating energy performance has the most probable level of being low (59.57%), while the cooling energy performance is most likely to be high (51.70%). The ventilation system is natural, which is a passive design feature used to ventilate buildings with no energy consumption. The hot water energy performance has a probability of 52.34% of being high. The worst system performance of the building is the lighting, with a probability of 57.54% for being very low.

Table 45. Energy performance results for the case study

Indicator	Performance Level				
	Very Low	Low	Medium	High	Very High
Building energy performance	**8.43**	**42.67**	**41.00**	**7.61**	**0.29**
HVAC energy performance	2.31	28.46	52.37	16.06	0.80
Heating energy performance	26.96	59.57	13.24	0.23	0.00
Cooling energy performance	0.04	2.67	38.93	51.7	6.66
Ventilation energy performance	0.00	0.00	0.00	0.00	100
Hot water energy performance	0.03	2.84	34.19	52.34	10.60
Lighting energy performance	57.54	38.11	4.30	0.05	0.00

Based on the results presented in Evidence was set in the model using CN-C2 building characteristics and the results revealed that the building energy performance is most likely to be low (42.67%) (Table 45). The heating energy performance has the most probable level of being low (59.57%), while the cooling energy performance is most likely to be high (51.70%). The ventilation system is natural, which is a passive design feature used to ventilate buildings with no energy consumption. The hot water energy performance has a probability of 52.34% of being high. The worst system performance of the building is the lighting, with a probability of 57.54% for being very low.

Table 45, some scenarios were performed with the goal of improving the energy performance of the building. First, the HVAC energy performance could be improved by retrofitting the envelope insulation. This action would reduce the heating and cooling demand. Previous studies revealed that improved insulation reduces the heat loss or gain from the building (Yun, Jeong, Han, & Youm, 2013). A strong correlation between the annual cooling energy demand and envelope thermal transfer value was identified by (Hung & Kang, 2014).

The low performance of the heating system could be attributed not only to the low envelope insulation but also to the inefficient heat equipment, which consists of an old condensing boiler, with more than 30 years of use. Therefore, a retrocommissioning could be undertaken, which consists of a process to improve the efficiency of an existing building's equipment and systems (Dall'O, Speccher, & Bruni, 2012). Upgrading the existing heating system to an energy efficient equipment would improve the energy performance of the building, as observed by (Ruparathna, Hewage, & Sadiq, 2016). Using effective monitoring systems to control the heating system is another proposed measure. The main controls used in the heating system of building CN-C2 are time, temperature and boiler controls. A what-if scenario was performed, considering the upgrade of the BEMS to a Class B, and the substitution of the inefficient heat equipment for one with high efficiency. The results predicted that the heating energy performance would improve after this action, as shown in Table 46.

Table 46. Energy performance indicators prediction after renovation

Indicator	Performance Level				
	Very Low	Low	Medium	High	Very High
Heating energy performance	0.00	19.31	62.01	17.88	0.80
HVAC energy performance	0.14	5.99	40.56	45.05	8.26
Lighting energy performance	1.51	28.51	55.42	14.24	0.32

Regarding the lighting system, the low WWR is one of the contributing factors for the high use of artificial light in the building. Moreover, a large number of old T8 lamps are currently used in the building. The replacement of lights by energy saving lamps would reduce lighting loads, improving the lighting energy performance. A lighting control system, such as daylight sensors, is another important aspect that would improve lighting energy performance. A what-if scenario was also performed for this case, considering the upgrade of the BEMS for lighting system control to a Class B, and replacing the lamps for efficient ones. The results predicted that the lighting energy performance would improve as shown in Table 46.

8.7 Conclusions

The importance of improving the energy efficiency in existing buildings has been emphasized by several European policies. Building energy performance is influenced by a multitude of uncertain parameters, such as environmental conditions, envelope performance, and building systems performance. The management of buildings in operation may also significantly affect energy performance. Consequently, the analysis of a building’s energy performance requires an understanding of the relationships between these variables under uncertainty.

This chapter presented a BN model to assess energy performance of existing buildings. The results showed that the developed model is capable of estimating the building energy performance when characteristics of the building and its operation are known. Facility managers and owners can use the BN model to guide their decisions when managing building energy performance. Similarly, policy makers can apply the BN model to evaluate the performance of a larger building stock, understand the interactions between causal factors, and devise strategies that optimize the overall performance of the building stock.

The proposed BN model differs from prediction models that heavily rely on large databases for simulation models, as the simplicity of the proposed BN model makes it feasible to the collection of the required data and the assessment of the building energy performance without intensive processes. Analysis using simple indicators, linking energy demand data with building operation and management, can point to interesting insights and informed decisions about building performance. The purpose of this BN model is not to substitute or improve existing simulation models but rather evaluate the whole energy performance of a building taking into account the operation and maintenance of the building and its systems.

The effectiveness of the proposed BN model was evaluated through sensitivity analyses and scenarios were made using an academic building. The energy performance of the case study was predicted using what-if scenarios. Strategies to improve energy performance were also discussed, including retrocommissioning.

Chapter 9

Integrated Bayesian network model for building performance management

9.1 Introduction

In Chapters 6, 7 and 8, the development of the three parts of the BN model (subnets) was presented, representing each of the building performance categories defined. This chapter explains the validation of the three integrated subnets. A holistic analysis of building performance is presented and a case study is selected to demonstrate the interactions and study them in a more realistic and comprehensive manner.

Moreover, this chapter explores an approach to integrate the data related to the variables of the BN model. Based on the methods and models for data integration proposed by many researchers, and also described in Chapter 2, this chapter explores the location and link sources of the data in BIM models.

9.2 An integrated model for building performance management

In Chapters 1 and 2, a critical review was performed on the need for a holistic approach for the management of building performance. Typically, different tools are used to assess a building’s performance in different aspects. This includes POE to assess occupants’ satisfaction and well-being (Preiser & Vischer, 2005; Li et al., 2018), indexes to assess the condition of building elements (Silva et al., 2016), and building rating systems (e.g., BREEAM, LEED) to assess performance regarding energy use and environmental impacts (Haapio & Viitaniemi, 2008; Wang et al., 2012).

Most of the mentioned tools do not facilitate continuous building performance assessment and are not flexible for practical implementation (Grussing & Liu, 2014; Ruparathna et al., 2017). The assessment of performance is not integrated, resulting in a long process divided into several isolated steps. Moreover, previous studies tend to be highly specific and often present linear models on indicators related to a specific performance aspect, overlooking potential trade-offs that may occur between them (Grussing & Liu, 2014; Holopainen et al., 2014; Azar et al., 2016).

There is a complex relationship of causality between the three performance categories defined in this thesis. The variables (factors and indicators) from one of the performance categories may affect other variables presented in the other categories. For instance, for a given building envelope condition, higher thermal loads would be obtained to reach interior comfort temperature, which would also result in higher energy consumption, and consequently reduce the energy performance of the building. The effects of deterioration on building systems also affect users' comfort (Grussing & Liu, 2014). Poorly maintained indoor environments have been linked to discomfort and health problems (Abisuga et al., 2016). An energy-efficient building might not provide a comfortable and high-quality working condition for the occupants. Conversely, a high energy use for heating and cooling of buildings does not necessarily correlate with a high satisfaction of the occupants (Kalz & Pfafferott, 2014).

In order to address this gap, this thesis devised a model for the operational performance management of buildings using a BN approach. To analyze the relationships and assess a building's performance holistically, the subnets are joined in an object-oriented BN (OOBN) (Fenton & Neil, 2012). OOBNs are suitable to conceptualize complex systems in terms of smaller, interlinked components, and this aspect is predominantly relevant to multidisciplinary problems (Chen & Pollino, 2012).

The variables involved in the three subnets of the model are highlighted in Figure 50.

Occupancy density is a variable that may affect some building defects, such as interior partitions or flooring surface defects (condition subnet), air quality (comfort subnet), hot water load and internal gains (energy subnet). In this case, occupancy density is an inherent characteristic of the building. Other variables that may vary during the use and maintenance of the building may also affect different domains. This is the case of the ventilation type. Old buildings may not have forced ventilation, which lessens air quality but also reduces energy consumption and potential defects in HVAC system. On the other hand, if forced ventilation is incorporated in these buildings, the air quality may improve but the energy consumption may increase.

Preventive maintenance can be used to reduce the probability of having defects, impacting the condition of building elements and systems (condition subnet). Particularly, the envelope condition is a variable that influences the thermal quality (comfort subnet) and the heating and cooling demand (energy subnet). The HVAC condition (condition subnet) may also affect the air and thermal quality (comfort performance subnet) and the HVAC energy performance (energy subnet). Indeed, envelope condition and HVAC system condition are two essential variables for the integrated assessment of building performance.

Environmental agents regard another variable that may provoke several defects (e.g., water problems in roof, façade and doors/windows) (condition subnet), affect the occupant's perception on thermal quality (comfort subnet), and affect the heating and cooling energy demand (energy subnet).

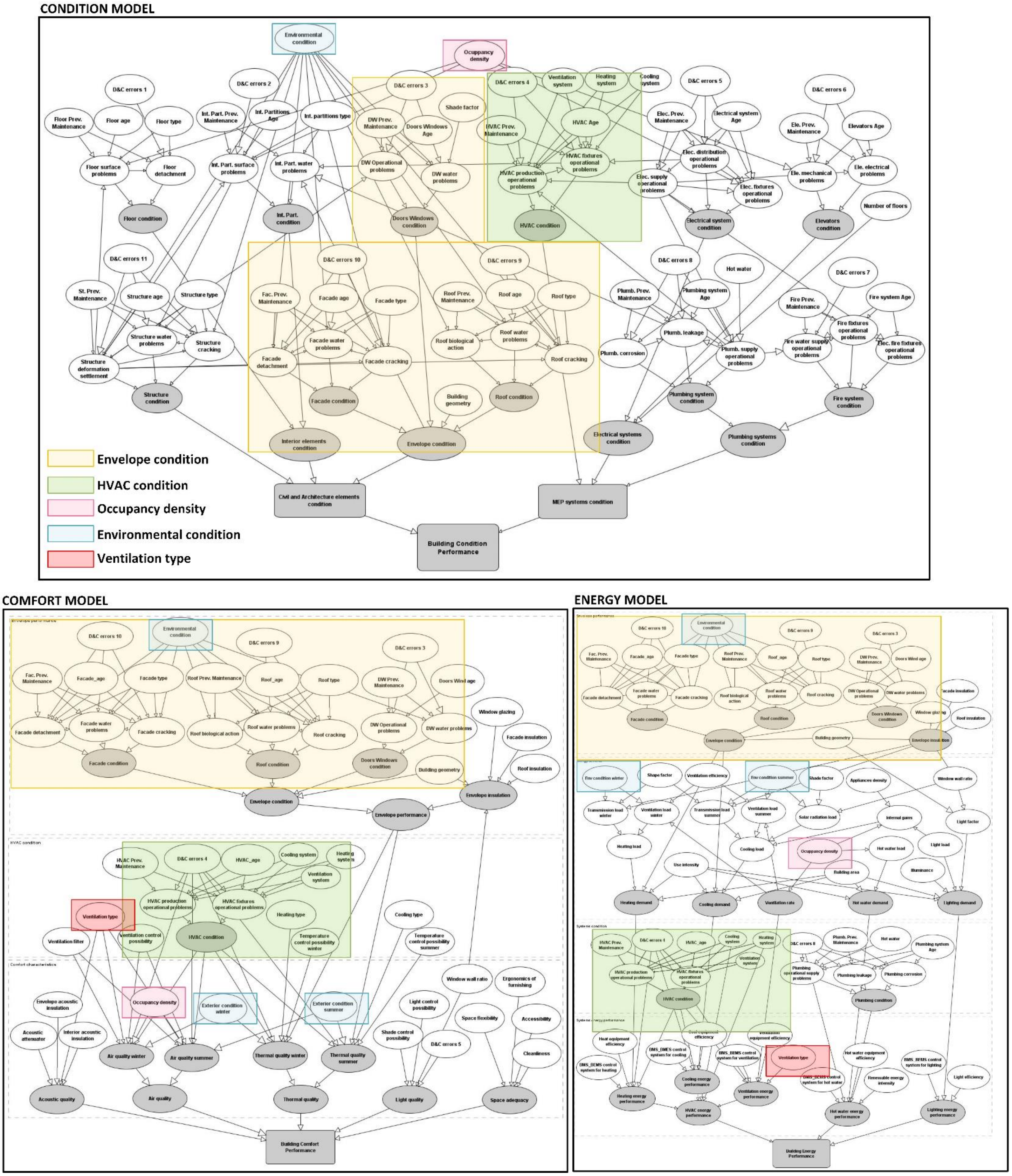


Figure 50. OOBN: common variables between the subnets

9.3 Practical applications of the model

The applicability of the proposed model can be summarized in the following items:

(i) Assessment of a building’s performance: the model can be used to holistically assess the performance of an existing building, i.e., considering condition, comfort and energy performance. Moreover, the model can be used to identify the relationships between these categories and understand the underlying interdependencies regarding building performance. The causal-effect between indicators and factors can be easily identified in the BN model.

(ii) Identification of causal factors: the model can be used to find out causes of problems, identify potential deficiencies and results of low performance. This characteristic allows the definition of a causal explanation for a given result, in order to reach a better understanding of the performance assessment results, and consequently support decisions to improve building performance.

(iii) Prediction of performance through renovation and retrofit scenarios: the model can be used to predict the performance of buildings by proposing renovation and retrofit scenarios, or changes in the operation and management of the building. The causal relationships of the many variables and their probabilistic dependencies can be used as a decision support system for facility managers at the O&M phase, balancing benefits among the three performance categories. Corrective maintenance actions can be planned, such as repairing, retrofitting, or replacement of elements and systems.

(iv) Prioritization of maintenance actions: the model can be used to prioritize maintenance actions at building level and building portfolio level (group of buildings). The application at building level is designed to support decisions about renovation of a building. Indicators with high impact on building performance can be identified by forecasting the results when these indicators are changed or improved. For instance, if a repair is conducted in a certain building element, the indicators can determine the impact of this action on the performance of an entire building, by changing variable states and observing the automatically updated decision outcomes. The outcome of the causal model will help building owners and facility managers to have a sense of where attention should be focused and where the budget should be allocated to improve the performance of buildings. Application at building portfolio level can be used to compare buildings, identifying the buildings with worst performance and that require major changes. This is especially valuable for institutions with a tight budget for managing many buildings, such as university campuses and public administrations. Institutional stakeholders should be interested in obtaining a greater longevity for buildings and systems, minimizing the need for changes, refurbishment or demolition and reconstruction. Moreover, this characteristic can be used to optimize government incentives for high quality buildings. Performance levels could be used by the administrations to propose mandatory performance evaluations of existing buildings and create incentives for high-performance buildings. Many governments around the world have specific goals for energy reduction and high-quality buildings in terms of structural safety and health. Thus, government institutions can promote incentives in order to support renovation/retrofit actions to achieve these goals.

9.4 Case study

The academic building CN-C2, already presented in previous chapters, was selected as a case study to demonstrate the applications of the integrated BN model.

9.4.1 Assessment of a building's performance and identification of causal factors

The characteristics of the CN-C2 building were set in the model as evidence to assess its performance holistically. The results of the performance indicators are shown in Table 47.

Table 47. Indicator results for the case study

Indicator	Performance Level				
	Very Low	Low	Medium	High	Very High
Building condition performance	**6.39**	**14.89**	**24.77**	**29.30**	**24.65**
Civil and Architecture elements condition	**0.00**	**1.00**	**15.12**	**50.10**	**33.78**
Structure condition	0.54	5.43	24.14	45.36	24.53
Envelope condition	0.00	0.08	5.08	43.52	51.32
Façade condition	0.00	0.00	0.00	33.32	66.68
Roof condition	0.00	4.87	75.23	19.90	0.00
Doors/windows condition	0.00	0.00	0.08	35.91	64.01
Interior partitions condition	0.00	0.00	0.08	36.84	63.08
Floor condition	0.00	0.00	0.08	36.84	63.08
MEP systems condition	**0.04**	**2.38**	**29.79**	**53.67**	**14.12**
HVAC condition	0.00	0.55	34.34	57.07	8.04
Plumbing condition	0.00	10.26	79.49	10.25	0.00
Elevator condition	0.00	0.00	2.80	47.19	50.01

Electrical system condition	0.00	0.00	12.32	75.36	12.32
Fire system condition	0.00	0.00	0.03	33.42	66.55
Building comfort performance	**0.15**	**8.68**	**52.28**	**36.11**	**2.78**
Envelope performance	0.45	3.56	59.50	36.49	0.00
Thermal quality	0.00	3.34	63.92	31.9	0.84
Thermal quality in winter	0.00	0.00	57.99	41.26	0.75
Thermal quality in summer	0.00	4.08	73.72	21.99	0.21
Air quality	0.00	0.04	5.85	58.44	35.67
Air quality in winter	0.00	0.08	7.50	54.56	37.86
Air quality in summer	0.00	0.08	7.50	54.56	37.86
Light quality	12.82	27.92	32.95	20.83	5.48
Acoustic quality	2.47	47.53	47.53	2.47	0.00
Space adequacy	0.00	0.00	19.76	67.89	12.35
Building energy performance	**8.43**	**42.67**	**41.00**	**7.61**	**0.29**
HVAC energy performance	2.31	28.46	52.37	16.06	0.80
Heating energy performance	26.96	59.57	13.24	0.23	0.00
Cooling energy performance	0.04	2.67	38.93	51.7	6.66
Ventilation energy performance	0.00	0.00	0.00	0.00	100
Hot water energy performance	0.03	2.84	34.19	52.34	10.60
Lighting energy performance	57.54	38.11	4.30	0.05	0.00

In general, the category that presents the worst results regards energy performance, with a probability of 42.67% of having a medium performance. The comfort presents a probability of 51.95% of having a medium performance, followed by the building condition with a 29.30% chance of having a high performance.

Based on the results presented in Table 47, the following aspects are of interest for discussion:

- Relationships between heating energy performance, thermal quality, and envelope performance: the envelope performance results for building CN-C2 presented a medium performance level due to the low condition of the roof and the low thermal insulation of the envelope. As a result, the building presents a high heating demand. The heating demand is also associated with the use intensity of the building, which concentrates the use period during winter season. The thermal quality results in winter also revealed a medium performance level. Air leaks through cracks or holes in walls, ceilings, doors and windows reduce envelope condition, and thus increase heating demand which reduces energy performance.

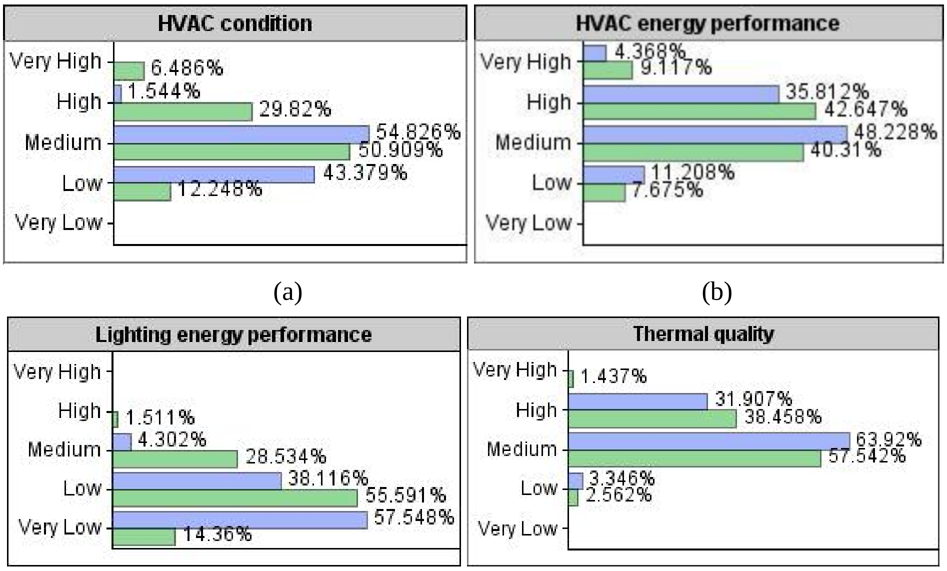
- Relationship between ventilation energy performance and air quality: although natural ventilation is considered an energy efficient alternative to reduce energy use, the results revealed a low level of comfort regarding the indoor air quality. The natural ventilation adopted by CN-C2 may not be enough to freshen the air of rooms with a high occupation. Moreover, the use of natural ventilation is compromised during winter due to weather conditions, i.e., low probability of opening windows in cold days. Complaints regarding the quality of the air were obtained from the satisfaction survey conducted in the building.
- Relationship between light quality and lighting energy performance: the results revealed a probability of having a medium level for light quality, which is attributed to low WWR that restrains the use of daylight. In agreement, the lighting energy performance results revealed a very low performance level. This result could also be assigned to the low WWR, and the use of inefficient light sources. The majority of the lamps used in the building are old and inefficient.

9.4.2 Prediction of performance through renovation and retrofit scenarios

Based on the performance results, interventions (i.e., scenarios) to improve the performance of the building were analyzed considering the implications between the different performance categories.

Operation management improvement:

The first scenario regards a change in the operation management of the building, which could help facility mangers visualize the implications when managing building performance. This includes adopting a preventive maintenance for the building element and systems and a more efficient energy management of the systems. For example, areas of the building where daylight controls could be used might be identified. Daylight controls are photoelectric devices that turn off or dim the lights in response to the natural lighting, and consequently save energy. The management of the HVAC system could also be improved, including control of the external environmental conditions, and the specific operating requirements of the zones of the building. In this sense, a what-if scenario was defined to predict the results when preventive maintenance for HVAC system is ‘Yes’, and the BMS/BEMS control system for HVAC and lighting systems is Class B. The prediction results revealed that the HVAC condition would improve (Figure 51(a)), due to the reduction of probability of having problems in the system. Likewise, the HVAC energy performance (Figure 51(b)), the light energy performance (Figure 51(c)), and the thermal quality (Figure 51(d)) would also improve.



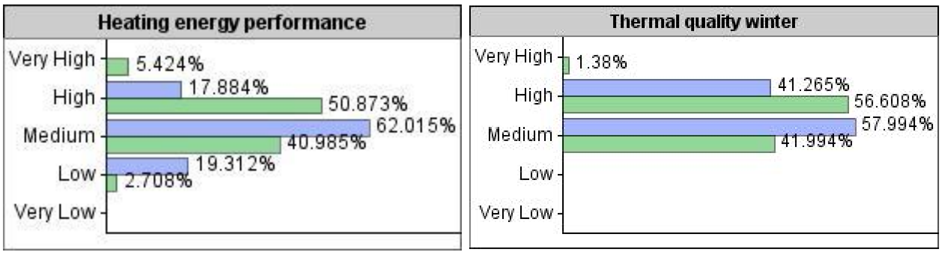
(a) (b)

(c) (d)

Figure 51. Comparison between the original results (blue) and the results predicted with the proposed changes (green) for the: (a) HVAC condition, (b) HVAC energy performance, (c) Lighting energy performance, and (d) Thermal quality

Rehabilitation of the building envelope:

Another scenario is the rehabilitation of the building envelope. Improving the envelope condition by reducing ventilation losses and introducing high levels of insulation could reduce the heating demand, improve the heating energy performance, and improve the thermal quality during winter as well. In this sense, a what-if scenario was defined to predict the results of heating energy performance and thermal quality during winter when the envelope performance is very high. The results revealed that heating energy performance would be improved (Figure 52(a)) and thermal quality during winter would increase (Figure 52(b)).

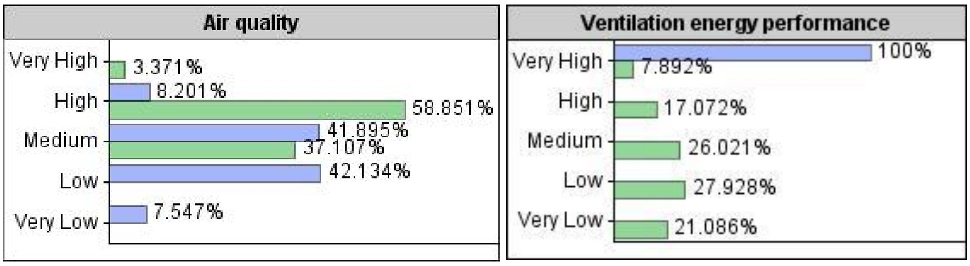


(a) (b)

Figure 52. Comparison between the original results (blue) and the results predicted with the proposed changes (green) for the: (a) Heating energy performance and (b) Thermal quality during winter

Retrofitting of the ventilation system:

The third scenario regards the implications of a retrofitting of the ventilation system. A mixed mode ventilation strategy could be adopted to improve the air quality of the building, which allows natural ventilation to be used for most of the year and mechanical ventilation to serve only when and where it is necessary. Considering this aspect, a scenario was made to include a mixed mode ventilation and air filters on the CN-C2 building. The prediction results revealed that the air quality would be improved (Figure 53(a)). On the contrary, the ventilation energy performance would be reduced (Figure 53(b)). However, there is high uncertainty on the results of ventilation energy performance, due to the low predictability on the use of mechanical or natural ventilation.

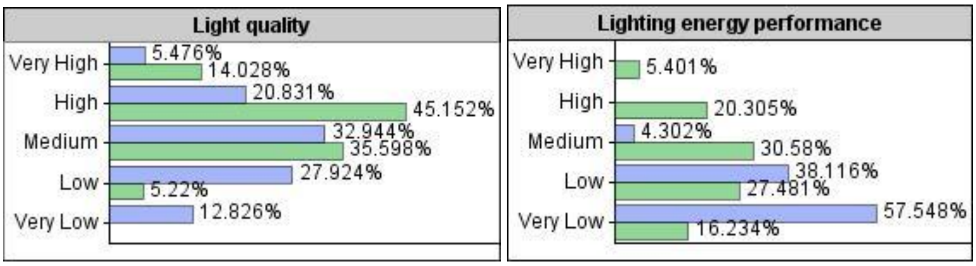


(a) (b)

Figure 53. Comparison between the original results (blue) and the results predicted with the proposed changes (green) for the: (a) Air quality and (b) Ventilation energy performance

Openings enlargement:

Currently, the CN-C2 building presents a low WWR, which results in a high light demand of artificial light, and also discomfort to users regarding light quality. This is particularly related to the design of the building. Typically, in the design phase, all the aspects of comfort are rarely taken into account. The majority of the design problems related to architecture are not possible to be improved. However, some might be feasible. In this case, enlarging the opening and using windows with low thermal transmittance might be a good option to improve the whole performance of the building. Therefore, a what-if scenario was defined to check the implications of increasing the WWR (between 10 to 40%) of the building. The prediction results revealed that the light quality would be improved, as illustrated in Figure 54(a). Likewise, the lighting energy performance would be improved (Figure 54(b)).



(a) (b)

Figure 54. Comparison between the original results (blue) and the results predicted with the proposed changes (green) for the: (a) Light quality and (b) Lighting energy performance

9.4.3 Prioritisation of maintenance actions

The proposed model provides an objective method to quantify performance, defining performance levels for buildings. Therefore, all the buildings from the university campus could be evaluated in order to prioritize maintenance actions. This evaluation can help identifying buildings with low performance levels and the ones that require major changes. This applicability of the BN model can be used to support the Facility Campus department to make decisions to improve the building stock and support a better management of their resources.

9.5 Data integration with Building Information Modeling

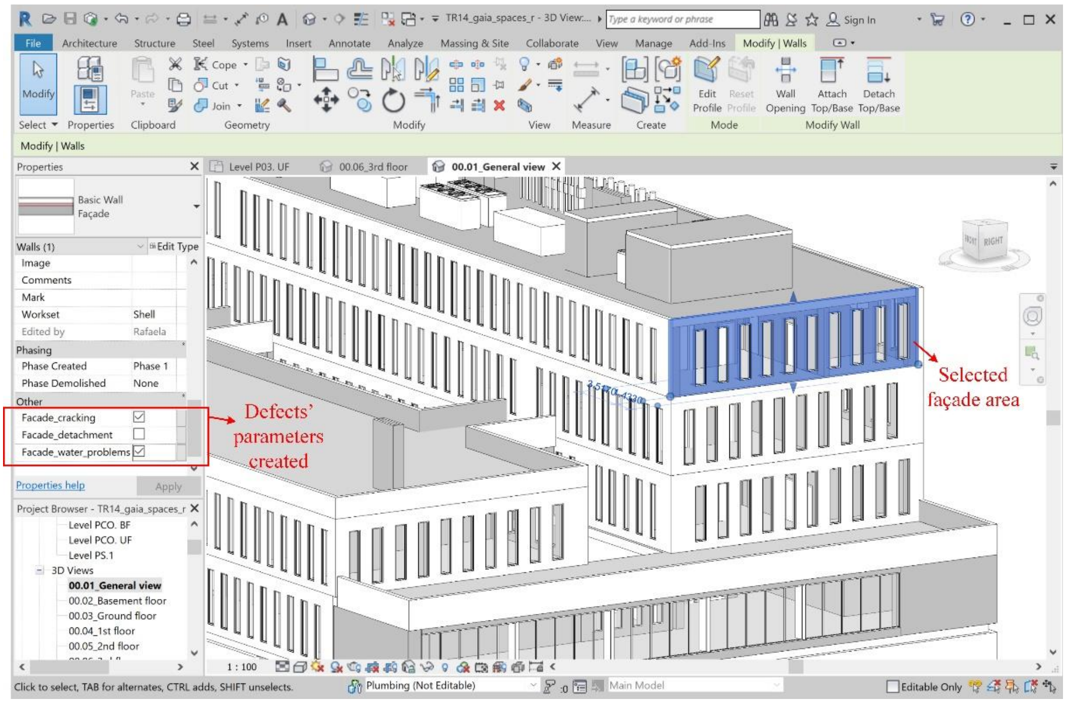
Although software systems have been introduced to support FM processes, facilities data and information is fragmented (Becerik-gerber et al., 2012). Bortolini, Forcada, and Macarulla (2016) described that buildings may have many sophisticated sensors and computerized systems capable of delivering data about the status and performance of its elements and systems. However, there is little to no practical use regarding most of these data. The management systems in many facilities are separated and independent from one another, which means that FM heavily relies on numerous different and incompatible systems in order to manage buildings (Wong, Ge, & He, 2018). The lack of integrated data makes it extremely hard for facility managers to make optimum maintenance decisions, making the process of gathering information time consuming and less intuitive (Chen et al., 2013; Motamedi et al., 2014).

Chapter 5 explained different data collection methods, existing tools and systems to collect information of existing buildings. Building information comes from different sources, such as paper-based and in digital format. In order to manage a building holistically, it is important to use knowledge from across these sources (Curry et al., 2013). BIM is the appropriate technology for data integration, as it provides a platform to perform the seamless exchange of information throughout the lifecycle of buildings, with the integration of different technologies (Akcamete et al., 2011; Motawa & Almarshad, 2013; Cavka et al., 2017; Habibi, 2017; Pishdad-Bozorgi et al., 2018; Chen et al., 2018). The previous work on the potential benefits of data integration using BIM in the O&M phase was presented in Chapter 2.

Therefore, this section explores where to store the data collected from the different sources into BIM models. These data provide the inputs to the developed BN model.

The agreement and commitment to use the same terms in the same way for an interest domain is one of the first steps for data integration. For the categorical organization of data, OmniClass classification system may be used. OmniClass has become the object-oriented standard for BIM data, especially in terms of data-exchange methods such as the COBie (Mayo & Issa, 2016). The general building characteristics (e.g., building geometry, spaces, material properties, equipment) can be modeled and represented in BIM using the standardized codes provided in Table 21 of OmniClass^{TM} 2006.

The defects detected in the BIS (described in Section 5.3.1) can be linked with BIM elements/objects, as described by (Lee, Chi, Wang, Wang, & Park, 2016). The main defects that affect a building resulted in a defect taxonomy. Taxonomy consists of a classification system for improved information management (EN 15221-4:2011). Using the defect taxonomy, shared parameters can be created for each building element and system. A template incorporating three parameters was created for the three main defects in façades to illustrate this process. Figure 55 shows the example using TR-14 building modeled in *Revit Autodesk* software. The facility manager can then check ('Yes'/'No') for the existence of cracking, detachment and water problems in the selected façade. This parameter could also represent the impact of the defect (e.g., low, medium, high), as proposed in Section 5.3.1.3. The parameters can be created for all elements and systems. If required, large building elements (e.g., façades) may be modelled as the aggregate of smaller parts, enabling the identification of defects in specific parts. The information about defects should be updated once a corrective action is conducted to repair such defect. This approach may help facility managers to control the condition of the building.



Properties

Basic Wall
Façade

Walls (1)

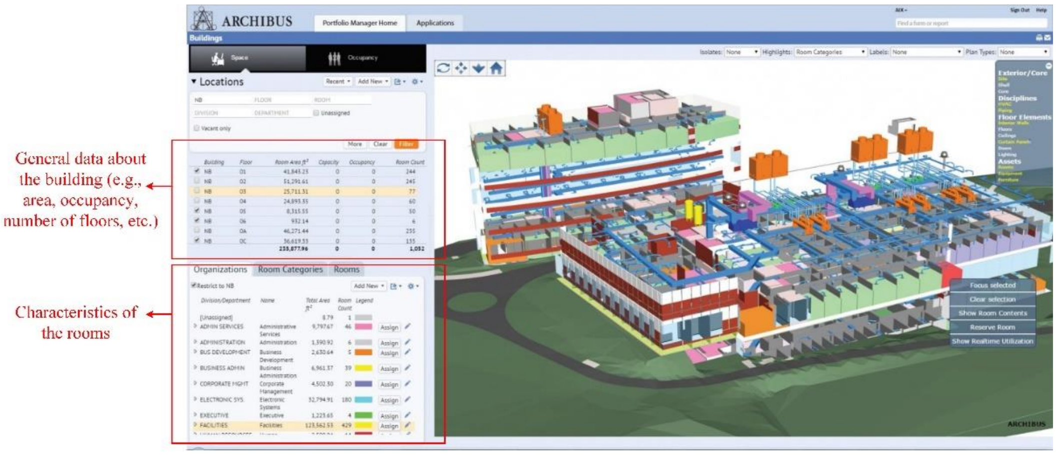
Image	
Comments	
Mark	
Workset	Shell
Edited by	Rafaela
Phasing	
Phase Created	Phase 1
Phase Demolished	None
Other	
Facade_cracking	☑
Facade_detachment	☐
Facade_water_problems	☑

Defects' parameters created

Selected façade area

Figure 55. Parameters created to illustrate defects in the façade

Maintenance requests collected from CMMS and their analysis (described in Section 5.3.2) can be linked with BIM models, to visualize clusters, spatially and temporally. Clusters are groups of maintenance requests that can be analyzed by month/year and visualized in zones in BIM models. This can help finding the zones of the building that have more problems. This process may enable the identification of common problem areas and seasonal trends, generating the root cause analysis of maintenance issues, as proposed by (Akcamete et al., 2011). Currently, commercial maintenance management systems are capable of integrating maintenance requests with BIM models. However, some data must be adapted to be used in the BN. Additionally, there are limitations regarding data capture, and analysis of data including causes of failures in many of the FM systems currently available on the market, such as ARCHIBUS, EcoDomus, Onuma and Maximo (Chen et al., 2018; Wong et al., 2018). Figure 56 shows an example of an FM system connected with a BIM model. General characteristics of the building can be assigned and information about the installed systems and corresponding documents can be attached (e.g., installation manual, warranty information).



NB | FLOOR | ROOM
DIVISION | DEPARTMENT | ☐ Unassigned
☐ Vacant only

More | Clear | Filter

	Building	Floor	Room Area ft²	Capacity	Occupancy	Room Count
☑	NB	01	41,843.23	0	0	244
☐	NB	02	51,291.61	0	0	245
☐	NB	03	25,711.31	0	0	77
☐	NB	04	24,893.35	0	0	60
☑	NB	05	8,315.55	0	0	50
☑	NB	06	932.14	0	0	6
☐	NB	0A	46,271.44	0	0	235
☑	NB	0C	36,619.33	0	0	135
			235,877.96	**0**	**0**	**1,052**

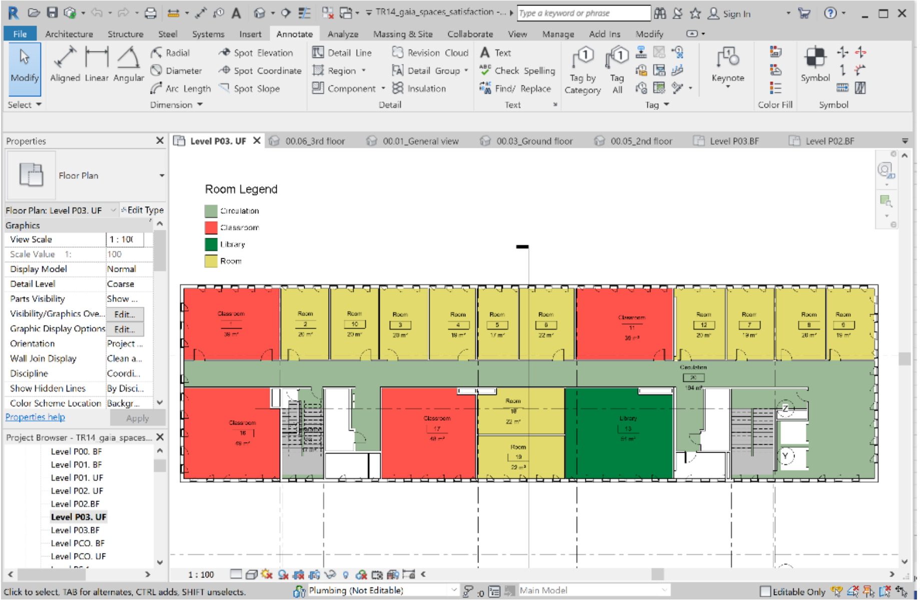
Organizations | Room Categories | Rooms

☑ Restrict to NB

Division/Department	Name	Total Area ft²	Room Count	Legend		
[Unassigned]		8.79	1	⬜		
ADMIN SERVICES	Administrative Services	9,797.67	46	🟥	Assign	✎
ADMINISTRATION	Administration	1,390.92	6	⬜	Assign	✎
BUS DEVELOPMENT	Business Development	2,630.64	5	🟧	Assign	✎
BUSINESS ADMIN	Business Administration	6,961.37	39	🟨	Assign	✎
CORPORATE MGMT	Corporate Management	4,502.30	20	🟪	Assign	✎
ELECTRONIC SYS	Electronic Systems	32,794.91	180	🟦	Assign	✎
EXECUTIVE	Executive	1,223.65	4	🟩	Assign	✎
FACILITIES	Facilities	123,562.53	429	🟨	Assign	✎

Figure 56. Example of an existing FM system linked with a BIM model (Source: ARCHIBUS 2016)

BIM can also be used to visualize the data aggregated from satisfaction surveys. The questionnaire (described in Section 5.4.1) included questions about the occupant satisfaction about different spaces of a building (e.g., offices, classes and common areas). The results about the satisfaction of these different spaces could be linked with the corresponded spaces in the BIM model. This could be done by writing a code using the application programming interface (API) for Autodesk Revit, for example. API allows external application developers to integrate their applications with Autodesk Revit. This process makes it easier to identify patterns of spatial distribution of performance problems (Hua et al., 2014). In addition, if the satisfaction survey includes questions about a specific room, a fine-grain analysis could be performed, and therefore more precise. Figure 57 illustrates an example of a color scheme to visualize the thermal quality satisfaction about different spaces in building TR-14. This visualization process enables the identification of spatial areas with higher discomfort (e.g., rooms in red color).



Properties

Floor Plan

Floor Plan: Level P03. UF

Graphics

View Scale	1 : 100
Scale Value 1:	100
Display Model	Normal
Detail Level	Coarse
Parts Visibility	Show ...
Visibility/Graphics Ove...	Edit...
Graphic Display Options	Edit...
Orientation	Project ...
Wall Join Display	Clean a...
Discipline	Coordi...
Show Hidden Lines	By Disci...
Color Scheme Location	Backgr...

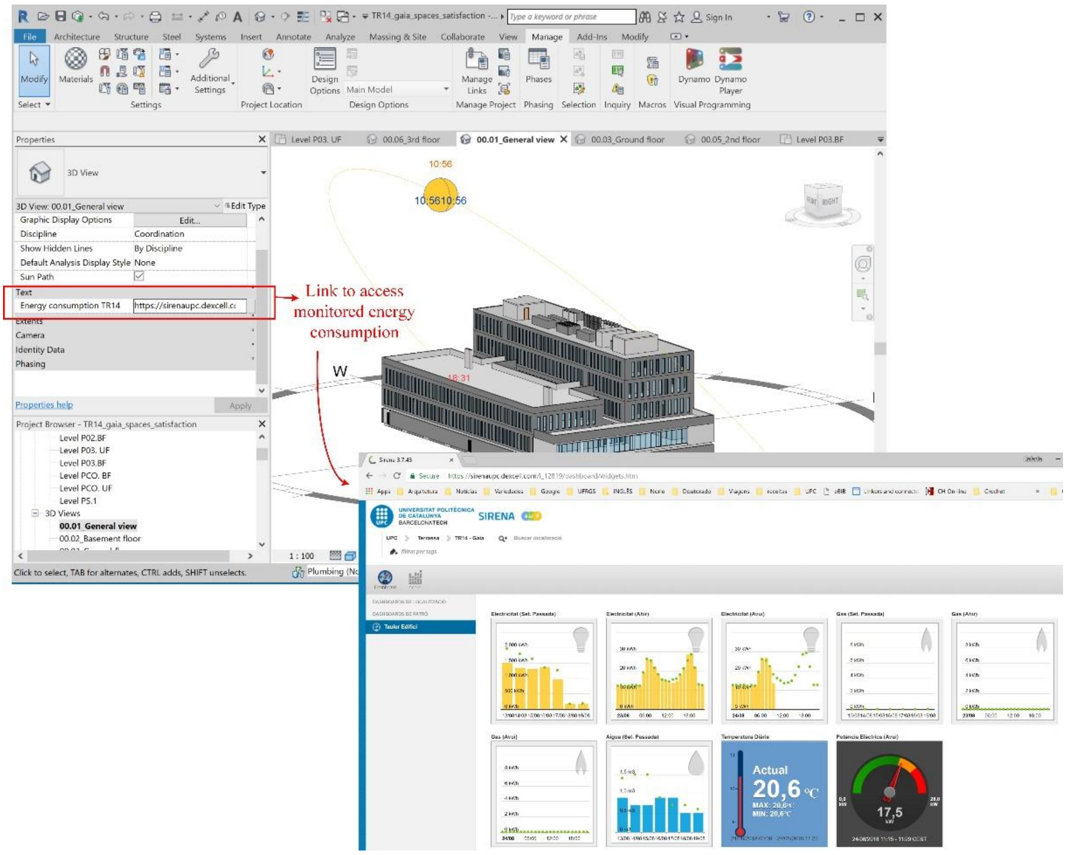
Project Browser - TR14_gaia_spaces...

Level P00. BF
Level P01. BF
Level P01. UF
Level P02. UF
Level P02.BF
Level P03. UF
Level P03.BF
Level PCO. BF
Level PCO. UF

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Figure 57. Spatial mapping of satisfaction survey in a color scheme

Energy data from BMS can also be integrated into a BIM model, as conducted in (Oti, Kurul, Cheung, & Tah, 2016). As illustrated in Figure 58, a parameter was created in *Revit* to access monitored energy consumption of TR-14 building. The UPC project *Sistema de Información del consumo de Recursos Energéticos y de Agua* (SIRENA) is an online tool to integrate the information about: gas, electricity and water consumption measurements `(https://sirenaupc.dexcell.com)`. Different consumption indexes (i.e., kWh/ m2, kWh/person, kWh/ECTS, kWh/h of use) can be generated and plotted out for each building of UPC, allowing an easy and permanent assessment.



3D View: 00.01_General view

Graphic Display Options: Edit...

Discipline: Coordination

Show Hidden Lines: By Discipline

Default Analysis Display Style: None

Sun Path: ☑

Text

Energy consumption TR14: https://sirenaupc.dexcell.c

Project Browser - TR14_gaia_spaces_satisfaction

Figure 58. Example of a parameter created to access monitored energy consumption

The proposed integrations are simple and may be the first step in integrating the different sources of building performance data. Figure 59 illustrates a schematic representation of the sources to be integrated in BIM, which has the potential to incorporate other factors such as the exterior conditions (weather), occupancy, among others. BIM models will serve as a domain database in the management of diverse building data. Such integration may facilitate FM processes, and consequently optimize the analysis of building performance. With the access to these data via an integrated repository, it would be possible to extract and insert such data in performance assessment models. For instance, the possibility of connecting a BIM model with the proposed BN model might be explored. This approach will simplify the data sharing and support the decision-making regarding the improvement of building performance.

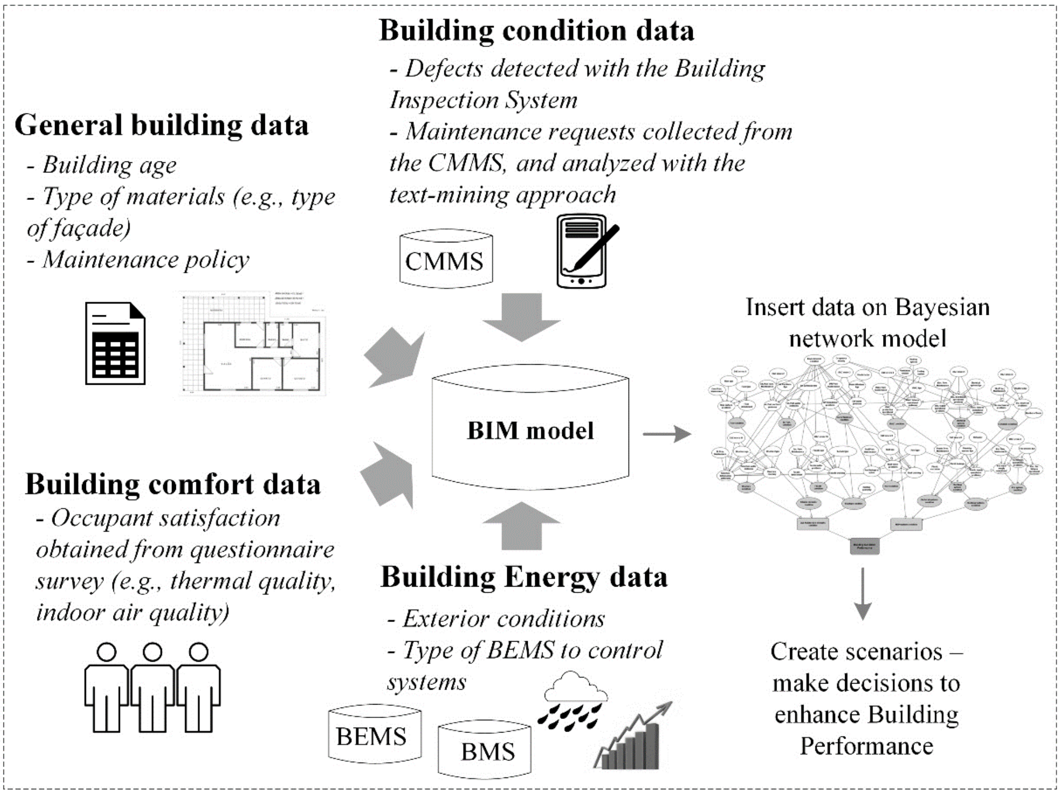


Figure 59. Schematic representation of data integration in BIM for building performance assessment

9.6 Conclusions

The management of building performance at the O&M phase involve different, and often conflicting, set of requirements. This chapter presented the relationships between condition, comfort and energy building performance categories. The common variables between the three parts (subnets) of the BN model were highlighted. The applications of the proposed model were discussed, which included: the assessment of a building's performance holistically, the identification of causal factors, the prediction of building performance through renovation and retrofit scenarios, and the prioritization of maintenance actions.

A case study demonstrated the applicability of the proposed model, including the implications of improving the condition and energy performance of buildings, while achieving a comfortable and healthy indoor environment. The proposed model proved to be an effective quantitative approach for reasoning with uncertainty. Building performance can be evaluated using indicators obtained from technical inspections, annual user satisfaction surveys, and the expert judgment of the facility managers. Decisions about either the renovation or the operation of buildings may have profound impacts on obtaining buildings that present not only a good state of conservation, but that are also comfortable and energy-efficient.

Different data sources are required to obtain information regarding the many variables that compose the proposed BN model. Gathering such data in existing buildings is a typically arduous task due to lack of data standardization. Therefore, a data integration using BIM models was introduced. Simultaneously, the ways that such integration may improve building performance management were discussed.

Chapter 10

Conclusions

This chapter concludes the thesis with a summary of the main contributions. The research objectives are reviewed to examine whether they have been achieved. Additionally, some future research directions are suggested, based on the delimitations in this work.

10.1Main contributions

This thesis made original contributions to the management of a building's performance, from both theoretical and practical perspectives.

The scientific contribution of this work consists of adopting an integrated and holistic approach for the management of building performance, considering condition, comfort, and energy performance. This work proposed a novel method to improve the understanding of relationships between indicators and factors related to performance by using a BN approach. Thus, the main theoretical contribution entails the development of a robust and efficient BN model to assess a building's performance in a causal analysis reasoning process. The main advantage of BN is that it can deal with uncertainty and attain better levels of performance and accuracy than those obtained with classical linear models.

From the practical perspective, this thesis developed a model to support FM on decision-making about building performance, which includes analysis of renovation and retrofitting actions. The proposed model can be used to facilitate information sharing, simplify the process of decision-making and improve the collaboration among stakeholders (e.g., facility managers, occupants, owners). In contrast to classical statistics, BNs can be used to model causal factors, making them an ideal tool for predictions and diagnostics. The graphical nature of the proposed BN model makes it a powerful communication tool, showing the causal relationships between the variables. The cause-effect relationships can be seen easily, which helps facility managers at the O&M phase regarding building performance, finding out a causal explanation for a given performance result.

The proposed model provides flexibility, as it is possible to combine subjective (e.g., expert knowledge) and objective data (e.g., data collected from inspections). This characteristic is a great advantage, especially when objective data is scarce, or when expert opinion may be required in the model. BNs can be used to make predictions with incomplete data. If no observation is entered, then the model assumes prior distributions. The model can be easily updated, or previous beliefs may be modified in light of new evidence. The adaptability of BNs also gives them a longer life span than most other models.

The evaluation of building performance with the proposed BN model combines the perspective of different stakeholders, namely: facility managers, occupants, and owners. The first perspective relates to the technical view of professionals that manage buildings, in order to guarantee the well-functioning of the built environment. This point of view also relates to the technical inspections to evaluate the state of conservation of buildings and how buildings are operated and managed regarding energy efficiency. The second perspective regards the occupants' perception on the buildings in use, based on their experience and interactions with these buildings. Lastly, the owner's view regards an interest on previous perspectives, particularly on the increase of their assets' value. It also includes the owner's concern on providing a safe and comfortable building for its occupants, as well as achieving an energy efficient building due to environmental and financial aspects.

The applications of the model provide benefits for the different stakeholders. Facility managers can use the model to find out causal factors, analyze renovation and retrofitting scenarios, prioritize maintenance actions, and make informed decisions to enhance the performance of the building. Owners can evaluate the performance of their buildings and find out how their investments on preventive maintenance may impact the comfort of the occupants or the energy efficiency. Public administrations can benefit of this tool to mandate the analysis of building performance from building owners, obtaining the performance of the non-residential building stock. They can then use this information to define and allocate financial resources to improve the average performance of the building stock. Researchers can also take advantage of the proposed model by using it for different research objectives. For example, they can analyze the results and perform a trade-off between the three performance categories proposed. Moreover, they can benefit from the several tools proposed in this thesis, such as the analysis of the proposed building inspection system, the method to evaluate the condition of systems, and the structure of the questionnaire regarding occupant's comfort.

Furthermore, the contributions of this thesis were compared with the objectives initially stated.

The first objective was to identify and analyze shortcomings in the current approaches addressing building performance assessment. In this sense, Chapter 2 imparted the findings of a literature review carried out regarding existing methods to evaluate building performance, including risk assessment. After identifying different stakeholders' requirements and defining the main factors affecting building performance, uncertainties involved in building performance assessment were explored. Based on a critical review of the related literature, Chapter 2 also presented the identification of the challenges and obstacles faced by facility managers during the management of buildings at the O&M phase. A literature review regarding the use of BIM at the O&M phase is also provided.

The second objective was to define the most relevant performance categories, indicators and factors to assess a building's performance at the O&M phase. In this sense, Chapter 4 identified the three main performance categories based on literature review, a focus group and surveys with experts on the subject. The defined categories are: safety and assets working properly, health and comfort, and energy efficiency. Also, the main factors and indicators to assess the performance of a building regarding these categories were identified.

The third objective of this thesis was to define the different sources of data for building performance assessment and where to locate such data in BIM models. In this sense, Chapter 5 presented existing tools and the development of methods to facilitate data gathering related to the three performance categories defined. A detailed building inspection system was developed, with the establishment of the most relevant defects and problems in buildings. The most common defects in building elements and most common problems in systems were defined with literature review and surveys. A method to define the impact of defects and problems was also proposed. As there is no standard method to define the condition of building systems in the literature, a text-mining approach to analyze the maintenance requests from end users was developed. Moreover, a survey to obtain end user satisfaction regarding building comfort was proposed. Chapter 5 also discussed about how BIM models can facilitate the identification of data. In this sense, suggestions regarding where to store the data in BIM were proposed in Chapter 9.

The fourth objective was to devise a BN model, including the causal relationships between the identified factors and indicators, to assess the performance of an existing building in different aspects. In this sense, the development of the model was divided into the three performance categories previously defined, and then presented in separated chapters. Chapter 6 presented the BN model related to the assessment of building condition. The proposed model provided a better understanding of the various elements and systems within buildings and the interactions between them. Moreover, the model may be an important tool to assist in the elaboration of building maintenance plans. The acknowledgement of the building condition degree on risk analysis can be used to define the priority order of the interventions to be carried out, ranging from low (optimal condition) to high (danger to the building). Chapter 7 presented the BN model related to the assessment of building comfort. Analysis of the main causes of discomfort, related to the IEQ and space adequacy, were identified with literature review and survey. The results of the proposed model allow facility managers to make informed decisions to enhance the comfort of occupants, and consequently occupant satisfaction. Chapter 8 presented the BN model related to the assessment of building energy performance. It provided an analysis of the main variables impacting energy efficiency and how the operation and management of the building influences the energy performance. Chapter 9 integrates the three models, providing a probabilistic risk analysis to assess building performance holistically. The analysis support decision-making on the necessary actions, regarding the priority order of service execution, to be defined by the facility manager in order to enhance building performance.

The fifth objective was to verify and validate the developed BN model. In this sense, an individual evaluation was provided in Chapters 6, 7 and 8, for each subnet of the model. Sensitivity analysis and what-if scenarios analyses were undertaken to examine the sensitivity of predictions, or conclusions against initial assumptions. Several case studies were also used to validate the proposed model. Chapter 9 concluded the verification of the three models integrated, and a case study demonstrated the different applications of the proposed model.

10.2Future research

This research raised some topics that could be addressed in future works:

- Create a database to calibrate and refine the CPTs of the model under different climate, building typologies, and new or existing buildings.
- Obtain the CPTs to get the energy demand within the Building Energy Performance subnet. These CPTs could not be obtained from experts, so then a huge database is

required to learn the CPTs from data. Future steps will focus on obtaining this database and create the CPTs for this part of the subnet.

- Integrate the different sources of data in BIM and develop a plugin to automatically link these data with the proposed BN model. This integration would maximize the practicality of the BN model as a decision making tool.
- Collect physical measurements about the IEQ factors. Then, the analysis between subjective responses of end users and the objective measures of IEQ parameters could be compared, and also incorporated as evidence in the BN model.
- Create a user friendly application to define some node patterns based on the building location or country (e.g., types of façade) and to visualize results.
- Validate the BN model in other buildings from different countries and different uses. The application of the proposed model can be explored defining other scenarios.
- Analyze the economic impact of the proposed scenarios to support the decision making about renovation and retrofit actions.
- Adapt the model to specific country or region and use the proposed BN model to assess if buildings fulfill with predefined regulations. Then, the model can be used as an assessment tool by public administrations.

Publications

Journal papers:

Bortolini, R. & Forcada, N. (2018). Building Inspection System for evaluating the Technical Performance of existing buildings. *Journal of Performance of Constructed Facilities* 32(5):04018073. doi: 10.1061/(ASCE)CF.1943-5509.0001220.

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Bortolini, R. & Forcada, N. Bayesian network model for assessing a building's condition performance. *Construction and Building Materials.* (submitted).

Bortolini, R. & Forcada, N. A probabilistic-based approach to support the performance assessment of existing buildings. *Journal of Cleaner Production.* (under review).

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Appendix

A. Questionnaire for Building Performance assessment

Section 1: Interviewee's details

1. Please specify the subject of your degree
☐ Technical degree subjects (Architect/Engineer)
☐ Administrative degree subjects (Business and Finance)
☐ Technician
☐ Other:

2. Please specify your work experience type
☐ Owner side
☐ Facility service side
☐ Professor/Researcher
☐ Other:

3. Please specify your work experience activity
☐ Designer
☐ Construction manager
☐ Maintenance
☐ Facility manager
☐ Energy manager
☐ Asset manager
☐ Consultant
☐ Other:

4. Please specify the years of your working experience
☐ Less than 10 years
☐ Between 11 and 19 years
☐ More than 20 years

Section 2. Building performance categories

Performance can be described as behavior in service of a facility for a specified use. The table below shows the main important areas to consider when assessing the performance of a building based on a literature review and experts opinion.

Areas	Description
Safety and Assets working properly	It is related to structural and physical condition of the building and the correct functioning of its elements
Health and Comfort	It is related to the air quality, thermal comfort, light and acoustic quality in building spaces
Suitability of space	It is related to the availability of space to perform activities, including its accessibility and ergonomic aspects
Cleanness of spaces	It is related to the cleaning of spaces
Energy efficiency	It is related to the control of the growth in energy consumption

5. Are all the terms understandable?

☐ 1 (Not understandable)
☐ 2

☐ 3
☐ 4
☐ 5 (Very understandable)

6. Do you think these areas represent the most significant aspects for assessing the performance of a building?

☐ Yes
☐ No

7. If not, please justify:

Section 3: Definition of factors

Environmental agents

Environmental agents might affect the performance of a building. This is related to different factors related to the building location and type of exterior condition, as show in the table below.

Environmental agents	Description
Weather condition	Solar radiation, wind, temperature, humidity, snow and rain water loads
Surrounding environment	Type of environment such as industrial, seaside, and if there is vegetation, pollutants, chemicals
Natural disasters	Storms, fire, landslide, earthquakes
Geological conditions	Type of soil such as clay, sand, loam

8. Are all the terms understandable?

☐ 1 (Not understandable)
☐ 2
☐ 3
☐ 4
☐ 5 (Very understandable)

9. Do you think these terms cover the most relevant environmental agents that might affect the performance of a building in general?

☐ Yes
☐ No

10. If not, please justify:

Building properties

The performance of a building can also be affected depending on the characteristics of the building. The table below shows the properties that might influence the performance of a building in general.

Building properties	Description

Type of structure/façade/roof	Type of material and its properties (i.e., porosity, acoustical absorption, resistance, thermal conductivity, etc)
Age	The period of time the building was built until the present
Type of heating/cooling system	The type of system/equipment to heat and cool the building (i.e., gas-fired heaters, electric heaters, central heat, split unit, etc)
Geometry	The shape of the building including height
Orientation	Solar orientation of façades
Type of use	The building typology (i.e., schools, shopping centers, offices, government buildings, etc)

11. Are all the terms understandable?

☐ 1 (Not understandable)
☐
☐
☐
☐ 5 (Very understandable)

12. Do you think these terms cover the main building properties that might affect the performance of a building in general??
☐ Yes
☐ No

13. If not, please justify:

Section 4: Defects on construction elements and systems.

The detection of building defects is an important task to assess the performance of a building. The aim of this section is to determine the most influential defects on the performance of a building. This classification aims to be generic to be applied to any type of construction solution.
Think back over all the years of your experience and choose a building that you worked with.

14. Select the building typology you are thinking (not residential)
☐ Academic building
☐ Office building
☐ Government building
☐ Commercial building
☐ Other:

Structure:
15. In the structure, which defects influence majoritarily the performance of a building?
☐ Biological action and change (e.g., mold, microbiological and plants growth)
☐ Chemical action and change (e.g., corrosion in metalic structure, bars with corrosion)
☐ Cracking (e.g., cracks in pillars)
☐ Deformation/Settlement (e.g., deflection in a beam, pillar deformed, fatigue, landslip)
☐ Structural vibration
☐ Surface problems (e.g., honeycombs in concrete, efflorescence, delamination, discoloration of concrete)

☐ Water problems (e.g., excess moisture in slabs)
☐ Detachment/Broken (e.g., part of the concrete broken)
☐ Other:

Façade:

16. In the façade, which defects influence majoritarily the performance of a building?
☐ Biological action and change (e.g., plants, algae growth)
☐ Chemical action and change (e.g., oxidation of metalic components)
☐ Cracking (e.g., fissure in panels of the covering)
☐ Surface problems (e.g., efflorescence, bumps, dips, graffiti, discoloration of the painting,
☐ deposit of dirt, uneven covering)
☐ Water problems (e.g., condensation, rising damp from floor, penetration damp)
☐ Detachment/Broken (e.g., tile broken, detachment of façade covering)
☐ Other:

Roofing:

17. In the roofing, which defects influence majoritarily the performance of a building?
☐ Biological action and change (e.g., birds action, gutters clogged with leaves)
☐ Chemical action and change (e.g., oxidation of metal components)
☐ Cracking (e.g., cracks in roof covering)
☐ Deflection (e.g., deflection of roof structure)
☐ Surface problems (e.g., efflorescence, bumps, dips, uneven covering, discoloration, deposit of dirt)
☐ Water problems (e.g., leaks, entrapped water, accumulation of moisture)
☐ Detachment/Broken (e.g., waterproofing detached)
☐ Other:

Flooring:

18. In the flooring, which defects influence majoritarily the performance of a building?
☐ Chemical action and change (e.g., change of color due to cleaning with chemical product)
☐ Cracking (e.g., cracks floor covering)
☐ Surface problems (e.g., efflorescence, soiled, hitch/scratch, discoloration, uneven surface of covering)
☐ Water problems (e.g., entrapped water, accumulation of moisture)
☐ Detachment/Broken (e.g., floor covering broken)
☐ Other:

Interior partitions:

19. In the interior partitions, which defects influence majoritarily the performance of a building?
☐ Cracking (e.g., fissures in plaster boards)
☐ Surface problems (e.g., dips, discoloration, paint peeling, blister)
☐ Water problems (e.g., moisture due to a broken pipe, condensation due to not insulated window)
☐ Detachment/Broken (e.g., detachment of a plaster wall)
☐ Other:

Doors/windows:

20. In the doors/windows, which defects influence majoritarily the performance of a building?
☐ Biological action and change (e.g., lichens in windows)
☐ Chemical action and change (e.g., corrosion of the window frame and ironmongery)
☐ Surface problems (e.g., uneven door, paint peeling)
☐ Water problems (e.g., moisture concentration in wood window frame)
☐ Detachment/Broken (e.g., window glass broken)

☐ Operational faulty functioning (e.g., door do not close, broken rolling window shutter)
☐ Other:

Electrical system:

21. In the electrical system, which defects influence majoritarily the performance of a building?

☐ Operational fault functioning of electrical supply elements (e.g., transformer problems, voltage, frequency, stoppage of electricity supply)
☐ Accumulation of dirt in electrical distribution elements
☐ Insulation problems in electrical distribution elements (e.g., cables insulation damaged)
☐ Operational faulty functioning of electrical distribution elements (e.g., electric sparks, short circuit)
☐ Operational faulty functioning of electrical fixtures (e.g., faulty functioning of equipment, light burnt)
☐ Other:

Plumbing system:

22. In the plumbing system, which defects influence majoritarily the performance of a building?

☐ Algae in water supply tanks
☐ Corrosion in water supply elements (e.g., corrosion of solar panel)
☐ Leakage in water supply elements (e.g., leakage in water tanks)
☐ Operational faulty functioning of water supply elements (e.g., equipment malfunction, problems with temperature, pressure, water level, vibration)
☐ Microorganisms in water distribution elements (e.g., microorganisms in pipes)
☐ Corrosion in water distribution elements (e.g., corrosion of pipes and valves)
☐ Accumulation of dirt in water distribution elements (e.g., pipes clogged)
☐ Insulation problems in water distribution elements (e.g., pipes insulation damaged)
☐ Leakage in water distribution elements (e.g., pipes leakage)
☐ Plumbing fixtures broken (e.g., sanitary equipment broken)
☐ Leakage in plumbing fixtures (e.g., leakage in water tap)
☐ Operational faulty functioning of plumbing fixtures (e.g., water tap not working)
☐ Other:

HVAC system:

23. In the HVAC system, which defects influence majoritarily the performance of a building?
    ☐ Algae in water tanks
    ☐ Corrosion in HVAC production elements
    ☐ Leakage in HVAC production elements
    ☐ Operational faulty functioning of HVAC production elements (e.g., chiller malfunction, noisy boiler, mechanical problems, fan motor failure)
    ☐ Microorganisms in HVAC distribution elements (e.g., microorganisms in pipes)
    ☐ Corrosion in HVAC distribution elements (e.g., corrosion of ducts and pipelines)
    ☐ Accumulation of dirt in HVAC distribution elements (e.g., dirt in filters and ducts)
    ☐ Insulation problems in HVAC distribution elements (e.g., pipes insulation damaged)
    ☐ Leakage in HVAC distribution elements (e.g., pipes leakage)
    ☐ Leakage in HVAC fixtures elements (e.g., leakage in air unit, condensation dripping from diffuser)
    ☐ HVAC fixtures broken (e.g., grills broken)
    ☐ Operational faulty functioning in HVAC fixtures elements (e.g., excessive noise and vibration of air unit, thermostat malfunction)
    ☐ Other:

Fire system:

24. In the fire system, which defects influence majoritarily the performance of a building?

- ☐ Algae in water supply tanks
- ☐ Corrosion in water supply elements
- ☐ Operational faulty functioning of water supply elements (e.g., equipment malfunction, pressure problems)
- ☐ Microorganisms in water distribution elements (e.g., microorganisms in pipes)
- ☐ Corrosion in water distribution elements (e.g., corrosion of valves)
- ☐ Leakage in water distribution elements (e.g., pipes leakage)
- ☐ Accumulation of dirt in water distribution elements (e.g., pipes clogged)
- ☐ Leakage in fire fixtures (e.g., water leakage in sprinkler)
- ☐ Fire fixtures broken (e.g., sprinkler broken)
- ☐ Operational faulty functioning of fire fixtures (e.g., smoke detector not working, fire alarm malfunction, fire hose not working, fire extinguisher not working)
- ☐ Other:

Elevator:

25. In the elevator, which defects influence majoritarily the performance of a building?
    - ☐ Corrosion in the distribution elements (e.g., cables with corrosion)
    - ☐ Operational faulty functioning of distribution elements (e.g., mechanical problems, electric motor with excessive noise, abrupt landing, overheating of control system)
    - ☐ Accumulation of dirt in elevator cabin
    - ☐ Elevator cabin parts broken (e.g., buttons broken)
    - ☐ Operational faulty functioning of elevator cabin elements (e.g., doors not closing properly)
    - ☐ Other:

26. Do you agree that these terms cover all potential defects that might appear in a building?
    - ☐ Yes
    - ☐ No

27. If not, please justify:

28. Additional comments:

B. Satisfaction survey

Section 1: Interviewee’s details

29. Gender:
- ☐ Male
- ☐ Female
- ☐ Other:

30. Age:

Section 2. Workplace details.

- ☐ Please select the campus you have been working:
- ☐ Campus Terrassa
- ☐ Campus Nord

31. Please select the name of the building you have been working.

32. On which floor of the building is your workspace located?
- ☐ 1st floor
- ☐ 2nd floor
- ☐ 3rd floor
- ☐ 4th floor
- ☐ 5th floor
- ☐ Other:

33. Please write the name of the room you have been working:

34. How long have you worked in this building?
- ☐ Less than 1 year
- ☐ Between 1 and 5 years
- ☐ More than 5 years

35. Which of the following do you personally adjust or control in your workspace (Check all that apply)
- ☐ Window blinds or shades
- ☐ Room air-conditioning unit
- ☐ Portable heater
- ☐ Permanent heater
- ☐ Adjustable air vent in wall or ceiling
- ☐ Ceiling fan
- ☐ Portable fan
- ☐ Thermostat
- ☐ Operable window
- ☐ None of these
- ☐ Other:

Section 3. Satisfaction with the workplace.

36. Indicate the degree of your satisfaction in relation to the different aspects of your **workplace**:

	Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied
Thermal sensation in summer	☐	☐	☐	☐	☐
Thermal sensation in winter	☐	☐	☐	☐	☐

Air quality in summer	☐	☐	☐	☐	☐
Air quality in winter	☐	☐	☐	☐	☐
Light quality	☐	☐	☐	☐	☐
Cleanliness	☐	☐	☐	☐	☐
Space adequacy	☐	☐	☐	☐	☐
Acoustic quality	☐	☐	☐	☐	☐

If you are dissatisfied, which of the following contribute to your dissatisfaction

37. Thermal quality:
☐ Always too hot
☐ Often too hot
☐ Occasionally too hot
☐ Occasionally too cold
☐ Often too cold
☐ Always too cold

38. Air quality:
☐ The air is stuffy
☐ The air is dry
☐ The air is humid
☐ There are disturbing odors
☐ Other:

39. Light quality:
☐ Glare of sunlight
☐ Lack of daylight
☐ Dark
☐ Impossibility to control light
☐ Low level of artificial light
☐ High level of artificial light
☐ Other:

40. Space adequacy:
☐ Quantity of space (m2)
☐ Circulation space
☐ Privacy
☐ Ergonomic of chair and table
☐ Availability of equipment (furniture, printer, etc)
☐ Lack of flexibility
☐ Other:

41. Acoustic quality
☐ Noise from air conditioner unit
☐ Noise from lights
☐ Noise from exterior machines
☐ People talking loud in the corridor
☐ Noise from elevator
☐ No insulation between rooms
☐ Other:

Section 4. Satisfaction with the common spaces.
For the following questions, in case you do not use some common area, please select as not applicable.

42. Indicate the degree of your satisfaction in relation to the different aspects of the **classrooms**:

	Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied	Not applicable
Thermal sensation in summer	☐	☐	☐	☐	☐	☐
Thermal sensation in winter	☐	☐	☐	☐	☐	☐
Air quality in summer	☐	☐	☐	☐	☐	☐
Air quality in winter	☐	☐	☐	☐	☐	☐
Light quality	☐	☐	☐	☐	☐	☐
Cleanliness	☐	☐	☐	☐	☐	☐
Space adequacy	☐	☐	☐	☐	☐	☐
Acoustic quality	☐	☐	☐	☐	☐	☐

If you are dissatisfied, which of the following contribute to your dissatisfaction
(Repeat questions 9 to 13)

43. Indicate the degree of your satisfaction in relation to the different aspects of the **lobby, corridors, stairways**:

	Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied	Not applicable
Thermal sensation in summer	☐	☐	☐	☐	☐	☐
Thermal sensation in winter	☐	☐	☐	☐	☐	☐
Air quality in summer	☐	☐	☐	☐	☐	☐
Air quality in winter	☐	☐	☐	☐	☐	☐
Light quality	☐	☐	☐	☐	☐	☐
Cleanliness	☐	☐	☐	☐	☐	☐
Space adequacy	☐	☐	☐	☐	☐	☐
Acoustic quality	☐	☐	☐	☐	☐	☐

44. Indicate the degree of your satisfaction in relation to the different aspects of the **laboratories**:

	Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied	Not applicable
Thermal sensation in summer	☐	☐	☐	☐	☐	☐
Thermal sensation in winter	☐	☐	☐	☐	☐	☐
Air quality in summer	☐	☐	☐	☐	☐	☐
Air quality in winter	☐	☐	☐	☐	☐	☐
Light quality	☐	☐	☐	☐	☐	☐
Cleanliness	☐	☐	☐	☐	☐	☐
Space adequacy	☐	☐	☐	☐	☐	☐

Acoustic quality	☐	☐	☐	☐	☐	☐

45. Indicate the degree of your satisfaction in relation to the different aspects of the **conference rooms**:

	Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied	Not applicable
Thermal sensation in summer	☐	☐	☐	☐	☐	☐
Thermal sensation in winter	☐	☐	☐	☐	☐	☐
Air quality in summer	☐	☐	☐	☐	☐	☐
Air quality in winter	☐	☐	☐	☐	☐	☐
Light quality	☐	☐	☐	☐	☐	☐
Cleanliness	☐	☐	☐	☐	☐	☐
Space adequacy	☐	☐	☐	☐	☐	☐
Acoustic quality	☐	☐	☐	☐	☐	☐

46. Indicate the degree of your satisfaction in relation to the different aspects of the **restrooms**:

	Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied	Not applicable
Thermal sensation in summer	☐	☐	☐	☐	☐	☐
Thermal sensation in winter	☐	☐	☐	☐	☐	☐
Air quality in summer	☐	☐	☐	☐	☐	☐
Air quality in winter	☐	☐	☐	☐	☐	☐
Light quality	☐	☐	☐	☐	☐	☐
Cleanliness	☐	☐	☐	☐	☐	☐
Space adequacy	☐	☐	☐	☐	☐	☐
Acoustic quality	☐	☐	☐	☐	☐	☐

47. Indicate the degree of your satisfaction in relation to the different aspects of the **lunchrooms**:

	Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied	Not applicable
Thermal sensation in summer	☐	☐	☐	☐	☐	☐
Thermal sensation in winter	☐	☐	☐	☐	☐	☐
Air quality in summer	☐	☐	☐	☐	☐	☐
Air quality in winter	☐	☐	☐	☐	☐	☐
Light quality	☐	☐	☐	☐	☐	☐
Cleanliness	☐	☐	☐	☐	☐	☐
Space adequacy	☐	☐	☐	☐	☐	☐
Acoustic quality	☐	☐	☐	☐	☐	☐

Section 5. Satisfaction with other aspects of the building.

48. How satisfied are you with the accessibility of the building?
☐ Very dissatisfied
☐ Dissatisfied
☐ Neutral
☐ Satisfied
☐ Very satisfied

49. How satisfied are you with the state of preservation of the building and its service systems?
☐ Very dissatisfied
☐ Dissatisfied
☐ Neutral
☐ Satisfied
☐ Very satisfied

50. If you are dissatisfied with state of preservation of the building, which of the following contribute to your dissatisfaction:
☐ Structure vibrating
☐ Façade covering may fall down
☐ Aesthetic problems (wall needed to be painted)
☐ Doors/windows do not work properly
☐ Lights burnt
☐ Elevator not working
☐ Equipment not working (air-conditioner, projectors, computers, etc.)
☐ Other:

51. Indicate your overall satisfaction with the building that you work:
☐ Very dissatisfied
☐ Dissatisfied
☐ Neutral
☐ Satisfied
☐ Very satisfied

52. Additional comments:

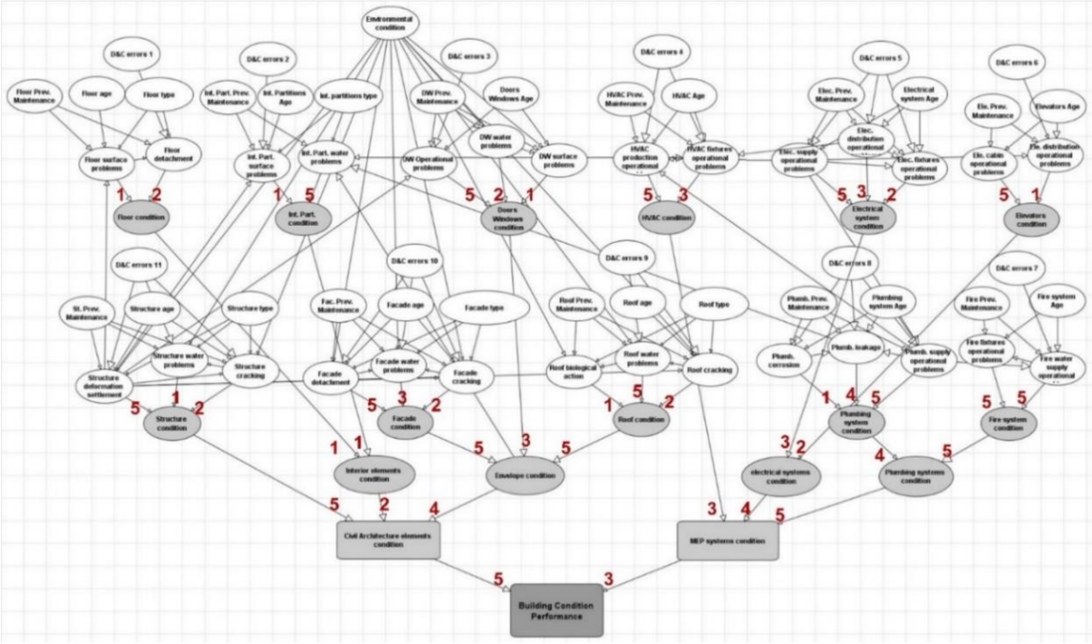
C. Questionnaire to elicit expert domain opinion

Expert’s experience (role and years): ____

The questions are referred to the existing non-residential building stock (academic, offices and commercial buildings). The term “existing buildings” is used to simplify it.

BUILDING CONDITION PERFORMANCE MODEL

1. Check the importance of the variables (weights 1 to 5) regarding each individual construction element/system and building condition.



2. In general, think about FM practices in existing buildings, in which percentage Preventive Maintenance is conducted in each construction element/system? And how often is renovation conducted in each element/system?

Construction elements/systems	Preventive Maintenance	Renovation	How certain you are? (1 – not certain, 2 – certain, 3 – very certain)
Structure			
Façade			
Roof			
Doors / Windows			
Interior partitions			
Floor			
HVAC			
Plumbing			
Fire system			
Electrical system			
Elevator			

3. In which percentage preventive maintenance can reduce the probability of occurrence of defects in:
- Construction elements: ( ) less than 30% ( ) 50% ( ) more than 70%
- Systems: ( ) less than 30% ( ) 50% ( ) more than 70%

4. How Design & Construction errors and the age in these construction element/systems affects its performance? (1 to 5)

Construction elements/systems	Design & Construction errors	Age	How certain you are? (1 – not certain, 2 – certain, 3 – very certain)
Structure			
Façade			
Roof			
Doors Windows			
Interior partitions			
Floor			
HVAC			
Plumbing			
Fire system			
Electrical system			
Elevator			

5. Think about the existing building stock, and provide the % of the most common types of materials (constructive solution):

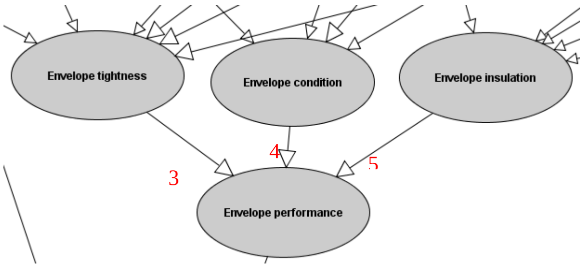
Structure type	%	How certain you are? (1 – not certain, 2 – certain, 3 – very certain)
Concrete		
Masonry		
Steel		
Others		
Façade type		
Conc. panels / Masonry		
Metal panels		
Glazed		
Others		
Roof type		
Flat concrete		
Flat metal panels		
Slopped		
Others		
Floor type		
Continuous		
Discontinuous		
Others		
Interior partitions		
Masonry walls		

Light partition walls

Others

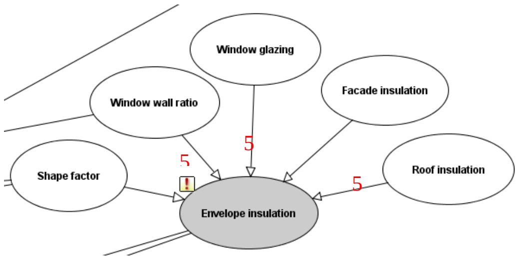
BUILDING COMFORT PERFORMANCE MODEL

6. When analyzing the envelope performance, check the importance of the variables (tightness, condition, insulation).



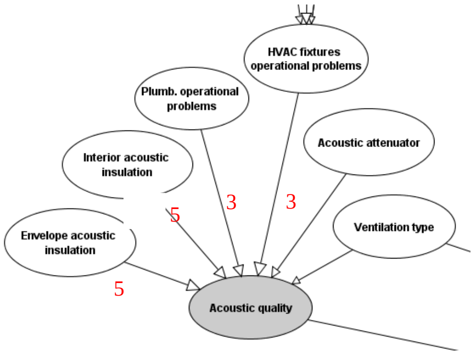
How certain you are? ( )1 ( )2 ( )3

6.1. **Envelope Insulation:**



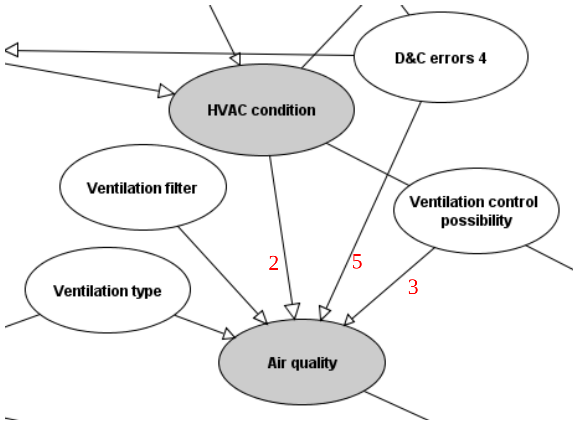
How certain you are? ( )1 ( )2 ( )3

7. **Acoustic quality**: Check the importance of the variables regarding acoustic quality.



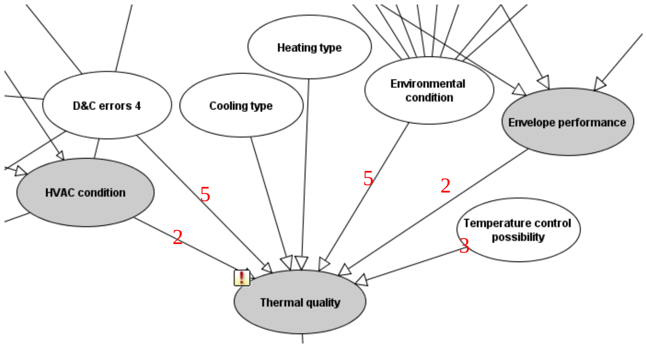
How certain you are? ( )1 ( )2 ( )3

8. **Air quality**: Check the importance of the variables regarding air quality.



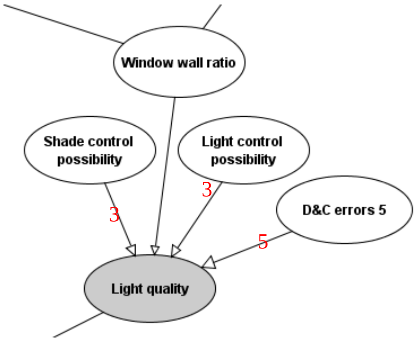
How certain you are? ( )1 ( )2 ( )3

9. **Thermal quality**: Check the importance of the variables regarding thermal quality



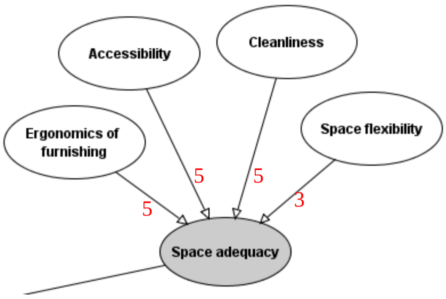
How certain you are? ( )1 ( )2 ( )3

10. **Light quality**: Check the importance of the variables regarding light quality.



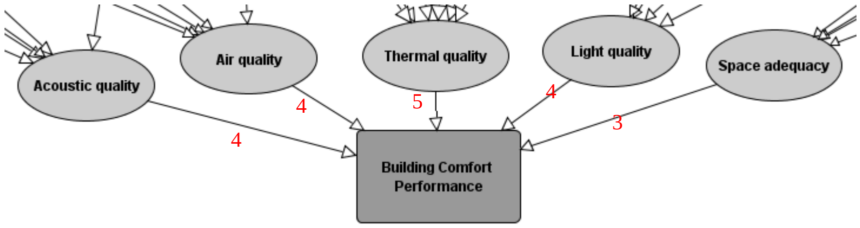
How certain you are? ( )1 ( )2 ( )3

11. **Space adequacy**: Check the importance of the variables regarding space adequacy.



How certain you are? ( )1 ( )2 ( )3

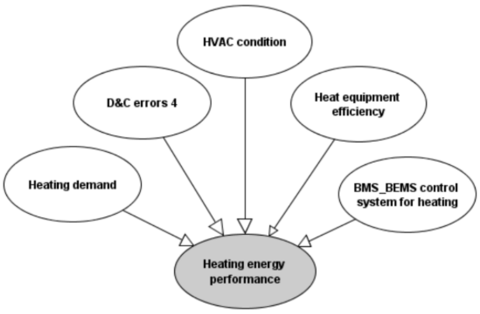
12. Check the importance of the variables regarding building comfort.

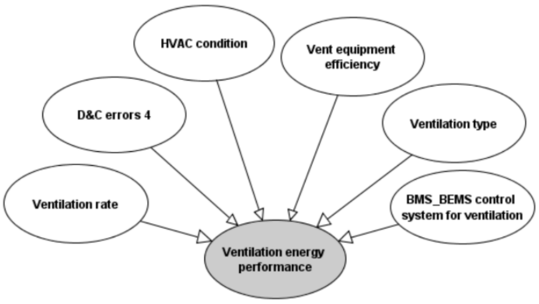


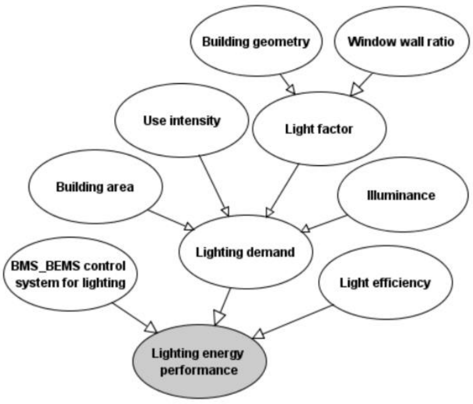
How certain you are? ( )1 ( )2 ( )3

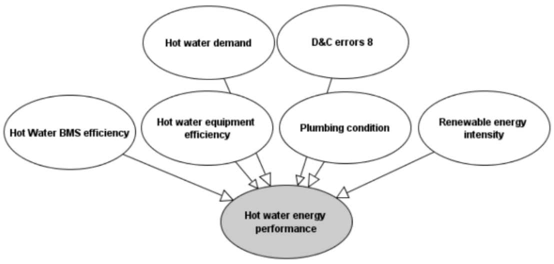
BUILDING ENERGY PERFORMANCE MODEL

13. Rate the importance of the variables (weights 1 to 5) regarding building energy performance.









How certain you are? ( )1 ( )2 ( )3

D. Magnitude of each defect type – inspection database

Building	Facade Water problems		Facade Cracking		Facade Detachment		Roof Water		Roof Cracking		Roof Biological	
	N of defects /m2 façade	Magnitude	N of defects /m2 façade	Magnitude	N of defects /m2 façade	Magnitude	N of defects/m2 roof	Magnitude	N of defects/m2 roof	Magnitude	N of defects/m2 roof	Magnitude
CN-A1-A2	0.094	Low	0.000	Low	0.031	Low	0.000	Low	0.000	Low	0.000	Low
CN-A3	0.392	Medium	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low
CN-A4	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low
CN-A5	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low
CN-A6	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low
CN-B1	0.537	High	0.067	Low	0.067	Low	0.000	Low	0.000	Low	0.000	Low
CN-B2	0.312	Medium	0.000	Low	0.312	Medium	0.000	Low	0.000	Low	0.000	Low
CN-B3	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low
CN-B4-B5	0.000	Low	0.049	Low	0.049	Low	0.000	Low	0.000	Low	0.000	Low
CN-B6	0.259	Medium	0.000	Low	0.000	Low	0.000	Low	0.575	High	0.000	Low
CN-C1	0.106	Low	0.000	Low	0.035	Low	0.000	Low	0.000	Low	0.000	Low
CN-C2	0.000	Low	0.000	Low	0.000	Low	0.679	High	0.000	Low	0.226	Low
CN-C3	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low
CN-C4	0.189	Low	0.000	Low	0.000	Low	0.187	Low	0.000	Low	0.187	Low
CN-C5	0.000	Low	0.000	Low	0.226	Low	0.000	Low	0.000	Low	0.000	Low
CN-C6	0.001	Low	0.000	Low	0.067	Low	0.000	Low	0.000	Low	0.000	Low
CN-D1	0.000	Low	0.000	Low	0.000	Low	0.259	Low	0.000	Low	0.000	Low
CN-D2	0.000	Low	0.000	Low	0.000	Low	0.685	High	0.000	Low	0.000	Low
CN-D3	0.000	Low	0.197	Low	0.000	Low	0.000	Low	0.561	High	0.000	Low
CN-D4	0.000	Low	0.000	Low	0.000	Low	0.162	Low	0.323	Medium	0.000	Low
CN-D5	0.328	Medium	0.000	Low	0.066	Low	0.000	Low	0.156	Low	0.156	Low
CN-D6	0.000	Low	0.189	Low	0.377	Medium	0.000	Low	0.000	Low	0.161	Low

Building	Doors/Windows Functional		Doors/Windows Water		Plumbing Corrosion		Floor Detach		Floor Cracking		Floor Surface	
	N of defects/m2 openings	Magnitude	N of defects/m2 openings	Magnitude	N of defects/m2	Magnitude	N of defects /m2 floor	Magnitude	N of defects/m2 floor	Magnitude	N of defects /m2 floor	Magnitude
CN-A1-A2	0.000	Low	0.000	Low	0.280	Medium	0.051	Low	0.013	Low	0.038	Low
CN-A3	0.007	Low	0.000	Low	0.053	Low	0.026	Low	0.000	Low	0.000	Low
CN-A4	0.002	Low	0.000	Low	0.598	High	0.000	Low	0.000	Low	0.000	Low
CN-A5	0.000	Low	0.000	Low	0.093	Low	0.000	Low	0.000	Low	0.000	Low
CN-A6	0.000	Low	0.017	Medium	0.185	Low	0.000	Low	0.024	Low	0.071	Low
CN-B1	0.000	Low	0.025	Medium	0.807	High	0.035	Low	0.000	Low	0.211	Low
CN-B2	0.000	Low	0.182	High	0.979	High	0.076	Low	0.000	Low	0.379	Medium
CN-B3	0.000	Low	0.002	Low	0.221	Low	0.000	Low	0.044	Low	0.000	Low

CN-B4-B5	0.000	Low	0.000	Low	0.184	Low	0.000	Low	0.000	Low	0.101	Low
CN-B6	0.000	Low	0.060	Medium	0.637	High	0.000	Low	0.000	Low	0.043	Low
CN-C1	0.000	Low	0.000	Low	0.554	High	0.000	Low	0.000	Low	0.225	Low
CN-C2	0.004	Low	0.004	Low	0.518	High	0.000	Low	0.000	Low	0.040	Low
CN-C3	0.004	Low	0.000	Low	0.565	High	0.000	Low	0.000	Low	0.021	Low
CN-C4	0.000	Low	0.015	Medium	0.161	Low	0.000	Low	0.021	Low	0.084	Low
CN-C5	0.005	Low	0.015	Medium	0.434	Medium	0.000	Low	0.000	Low	0.057	Low
CN-C6	0.000	Low	0.022	Medium	0.147	Low	0.000	Low	0.000	Low	0.063	Low
CN-D1	0.000	Low	0.000	Low	0.138	Low	0.019	Low	0.000	Low	0.077	Low
CN-D2	0.000	Low	0.000	Low	0.402	Medium	0.034	Low	0.034	Low	0.034	Low
CN-D3	0.000	Low	0.000	Low	0.711	High	0.000	Low	0.034	Low	0.236	Low
CN-D4	0.000	Low	0.013	Medium	0.516	High	0.328	Medium	0.000	Low	0.131	Low
CN-D5	0.000	Low	0.007	Low	1.085	High	0.465	Medium	0.033	Low	0.232	Low
CN-D6	0.000	Low	0.010	Medium	0.037	Low	0.000	Low	0.000	Low	0.459	Medium

Building	Interior Water		Interior Cracking		Interior Surface		Structure Cracking		Structure Water		Structure Deform	
	N of defects/m2	Magnitude	N of defects/m2	Magnitude	N of defects/m2	Magnitude	N of defects/m3	Magnitude	N of defects/m3	Magnitude	N of defects/m3	Magnitude
CN-A1-A2	0.180	Low	0.085	Low	0.069	Low	0.080	Low	0.016	Low	0.000	Low
CN-A3	0.077	Low	0.011	Low	0.011	Low	0.077	Low	0.099	Low	0.000	Low
CN-A4	0.154	Low	0.066	Low	0.000	Low	0.143	Low	0.220	Low	0.000	Low
CN-A5	0.086	Low	0.032	Low	0.021	Low	0.011	Low	0.139	Low	0.000	Low
CN-A6	0.020	Low	0.030	Low	0.030	Low	0.119	Low	0.079	Low	0.000	Low
CN-B1	0.213	Low	0.489	Medium	0.138	Low	0.223	Low	0.053	Low	0.000	Low
CN-B2	0.310	Medium	0.828	High	0.345	Medium	0.759	High	0.517	High	0.000	Low
CN-B3	0.100	Low	0.251	Medium	0.017	Low	0.234	Low	0.602	High	0.000	Low
CN-B4-B5	0.047	Low	0.042	Low	0.014	Low	0.103	Low	0.070	Low	0.000	Low
CN-B6	0.133	Low	0.100	Low	0.000	Low	0.250	Low	0.100	Low	0.000	Low
CN-C1	0.108	Low	0.123	Low	0.137	Low	0.058	Low	0.151	Low	0.000	Low
CN-C2	0.045	Low	0.011	Low	0.011	Low	0.090	Low	0.067	Low	0.000	Low
CN-C3	0.008	Low	0.095	Low	0.000	Low	0.103	Low	0.055	Low	0.000	Low
CN-C4	0.171	Low	1.203	High	0.334	Medium	0.334	Medium	0.067	Low	0.000	Low
CN-C5	0.115	Low	0.168	Low	0.088	Low	0.468	Medium	0.106	Low	0.000	Low
CN-C6	0.249	Low	0.091	Low	0.159	Low	0.102	Low	0.181	Low	0.000	Low
CN-D1	0.105	Low	0.000	Low	0.035	Low	0.014	Low	0.063	Low	0.000	Low

CN-D2	0.142	Low	0.142	k	0.026	Low	0.155	Low	0.000	Low	0.000	Low
CN-D3	0.098	Low	0.800	High	0.168	Low	0.463	Medium	0.014	Low	0.000	Low
CN-D4	0.098	Low	1.104	High	0.131	Low	0.251	Medium	0.011	Low	0.000	Low
CN-D5	0.125	Low	3.224	High	0.401	Medium	0.360	Medium	0.318	Medium	0.000	Low
CN-D6	0.178	Low	2.761	High	1.353	High	0.478	Medium	0.014	Low	0.000	Low

E. Magnitude of each problem type – maintenance requests database

Building	Area (m2)	Electrical operational fixtures problems		Electrical operational distribution problems		Electrical operational supply problems		Plumbing leakage		Plumbing operational supply problems	
		N of maintenance requests/ m2.year	Magnitude	N of maintenance requests/ m2.year	Magnitude	N of maintenance requests/ m2.year	Magnitude	N of maintenance requests/ m2.year	Magnitude	N of maintenance requests/ m2.year	Magnitude
CN-A1	3967.00	1.109	Medium	0.040	Low	0.000	Low	0.353	Low	0.101	Low
CN-A2	3886.00	3.098	High	0.165	Low	0.051	Low	0.484	Medium	0.165	Low
CN-A3	3783.00	1.523	Medium	0.211	Low	0.021	Low	0.190	Low	0.201	Low
CN-A4	2674.00	3.052	High	0.284	Low	0.015	Low	0.524	High	0.150	Low
CN-A5	3216.12	1.455	Medium	0.050	Low	0.012	Low	0.211	Low	0.112	Low
CN-A6	3243.79	2.121	High	0.271	Low	0.173	Low	0.407	Medium	0.691	High
CN-B1	2478.75	1.226	Medium	0.129	Low	0.048	Low	0.678	High	0.662	High
CN-B2	1124.00	2.527	High	0.712	High	0.178	Low	1.601	High	0.605	High
CN-B3	2262.95	1.591	Medium	0.106	Low	0.071	Low	0.583	High	0.177	Low
CN-B4-B5	5981.31	0.655	Low	0.080	Low	0.000	Low	0.201	Low	0.140	Low
CN-B6	2196.77	2.258	Medium	0.000	Low	0.018	Low	0.528	High	0.164	Low
CN-C1	4334.29	0.987	Low	0.157	Low	0.046	Low	0.452	Medium	0.129	Low
CN-C2	2124.49	1.563	Medium	0.226	Low	0.056	Low	0.395	Low	0.358	Medium
CN-C3	4597.84	3.045	High	0.226	Low	0.087	Low	0.426	Medium	0.078	Low
CN-C4	4337.89	2.029	Medium	0.083	Low	0.000	Low	0.599	High	0.240	Low
CN-C5	4833.21	2.127	Medium	0.240	Low	0.025	Low	0.588	High	0.066	Low
CN-C6	4072.38	1.228	Medium	0.069	Low	0.069	Low	0.354	Low	0.147	Low
CN-D1	4353.44	1.130	Medium	0.101	Low	0.110	Low	0.276	Low	0.055	Low
CN-D2	1989.21	1.609	Medium	0.181	Low	0.000	Low	0.865	High	0.060	Low
CN-D3	2529.93	1.012	Low	0.158	Low	0.063	Low	0.791	High	0.427	Medium
CN-D4	2518.69	1.906	Medium	0.143	Low	0.064	Low	0.397	Low	0.365	Medium
CN-D5	2581.55	0.790	Low	0.015	Low	0.015	Low	0.434	Medium	0.124	Low
CN-D6	2678.42	0.567	Low	0.105	Low	0.030	Low	0.179	Low	0.299	Medium
TR-12	3198.24	0.863	Low	0.013	Low	0.050	Low	0.288	Low	0.113	Low
TR-14	7377.84	0.070	Low	0.049	Low	0.011	Low	0.119	Low	0.005	Low
TR-30	1349.85	0.919	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low
TR-31	4698.00	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.000	Low
TR-32	4535.16	0.000	Low	0.000	Low	0.000	Low	0.000	Low	0.101	Low
TR-45	3142.78	0.305	Low	0.038	Low	0.000	Low	0.509	Medium	0.165	Low
TR-1	9429.20	0.925	Low	0.021	Low	0.042	Low	0.420	Medium	0.081	Low

TR-2	2939.67	0.653	Low	0.054	Low	0.054	Low	0.286	Low	0.163	Low
TR-3	2576.96	0.140	Low	0.047	Low	0.047	Low	0.000	Low	0.000	Low
TR-4	7625.86	0.404	Low	0.031	Low	0.021	Low	0.157	Low	0.005	Low
TR-5	11491.63	1.243	Medium	0.024	Low	0.014	Low	0.219	Low	0.028	Low
TR-6	2344.00	0.580	Low	0.000	Low	0.051	Low	0.017	Low	0.051	Low
TR-7	2623.83	0.579	Low	0.046	Low	0.000	Low	0.335	Medium	0.046	Low
TR-8	6445.86	0.453	Low	0.006	Low	0.031	Low	0.211	Low	0.025	Low
TR-9	2392.69	3.093	High	0.067	Low	0.100	Low	0.869	High	0.150	Low
TR10	2217.98	2.002	Medium	0.325	Medium	0.054	Low	0.667	High	0.054	Low
TR11	2778.97	0.533	Low	0.058	Low	0.000	Low	0.259	Low	0.072	Low

Building	Number of lifts	HVAC operational production problems		HVAC operational fixtures problems		Electrical Fire operational fixtures problems		Elevator operational mechanical problems		Elevator operational electrical problems	
		N of maintenance requests/ m2.year	Magnitude	N of maintenance requests/m2 .year	Magnitude	N of maintenance requests/ m2.year	Magnitude	N of maintenance requests/ m2.year	Magnitude	N of maintenance requests/m2.year	Magnitude
CN-A1	1.00	0.040	Low	0.151	Low	0.000	Low	7.600	Medium	0.000	Low
CN-A2	1.00	0.113	Low	0.885	Low	0.000	Low	10.800	Medium	0.000	Low
CN-A3	1.00	0.116	Low	0.782	Low	0.000	Low	43.600	High	8.800	Medium
CN-A4	1.00	0.120	Low	0.778	Low	0.000	Low	24.800	High	1.200	Low
CN-A5	1.00	0.112	Low	0.336	Low	0.000	Low	1.600	Low	1.200	Low
CN-A6	1.00	2.824	High	1.011	Medium	0.000	Low	18.800	High	1.200	Low
CN-B1	1.00	0.145	Low	1.630	Medium	0.097	Low	25.200	High	0.000	Low
CN-B2	1.00	0.498	Medium	3.772	High	0.214	High	19.200	High	0.000	Low
CN-B3	1.00	0.212	Low	1.962	Medium	0.053	Low	32.400	High	6.000	Medium
CN-B4-B5	1.00	0.027	Low	0.602	Low	0.000	Low	10.800	Medium	1.600	Low
CN-B6	1.00	0.073	Low	1.038	Low	0.073	Low	2.000	Low	1.200	Low
CN-C1	2.00	0.037	Low	3.230	High	0.055	Low	3.200	Low	1.800	Low
CN-C2	1.00	0.075	Low	2.636	High	0.000	Low	1.200	Low	1.200	Low
CN-C3	1.00	0.035	Low	2.071	High	0.000	Low	62.800	High	5.600	Medium
CN-C4	1.00	0.037	Low	1.402	Medium	0.000	Low	6.000	Medium	0.400	Low
CN-C5	1.00	0.033	Low	1.183	Medium	0.025	Low	6.400	Medium	0.000	Low
CN-C6	2.00	0.039	Low	2.583	High	0.000	Low	7.400	Medium	0.000	Low
CN-D1	1.00	0.037	Low	0.413	Low	0.055	Low	8.400	Medium	0.400	Low
CN-D2	1.00	0.080	Low	2.192	High	0.000	Low	2.000	Low	2.400	Low
CN-D3	1.00	0.063	Low	2.356	High	0.158	Medium	24.000	High	12.000	High
CN-D4	1.00	0.064	Low	1.668	Medium	0.000	Low	28.800	High	2.800	Low

CN-D5	1.00	0.062	Low	1.364	Medium	0.000	Low	16.000	High	2.400	Low
CN-D6	1.00	0.060	Low	1.598	Medium	0.000	Low	6.000	Medium	2.400	Low
TR-12	1.00	0.050	Low	0.663	Low	0.013	Low	1.600	Low	2.000	Low
TR-14	2.00	0.022	Low	0.710	Low	0.016	Low	0.000	Low	0.000	Low
TR-30	0.00	0.119	Low	0.415	Low	0.089	Low	-	N/A	-	N/A
TR-31	0.00	0.034	Low	0.000	Low	0.000	Low	-	N/A	-	N/A
TR-32	0.00	0.035	Low	0.026	Low	0.000	Low	-	N/A	-	N/A
TR-45	0.00	0.051	Low	0.356	Low	0.051	Low	-	N/A	-	N/A
TR-1	2.00	0.017	Low	0.751	Low	0.187	Medium	10.800	Medium	0.600	Low
TR-2	1.00	0.054	Low	0.640	Low	0.041	Low	2.400	Low	0.000	Low
TR-3	0.00	0.062	Low	0.062	Low	0.000	Low	-	N/A	-	N/A
TR-4	1.00	0.021	Low	0.378	Low	0.063	Low	7.200	Medium	1.200	Low
TR-5	2.00	0.014	Low	0.484	Low	0.077	Low	9.200	Me	2.400	Low
TR-6	0.00	0.068	Low	0.205	Low	0.000	Low	-	N/A	-	N/A
TR-7	1.00	0.061	Low	0.747	Low	0.152	Medium	7.600	Medium	0.000	Low
TR-8	1.00	0.025	Low	0.366	Low	0.019	Low	0.000	Low	0.400	Low
TR-9	1.00	0.067	Low	0.552	Low	0.000	Low	0.400	Low	0.000	Low
TR10	1.00	0.072	Low	1.154	Medium	0.162	Medium	3.600	Low	0.000	Low
TR11	1.00	0.058	Low	0.360	Low	0.000	Low	3.200	Low	0.800	Low