DISSERTATION

MULTI-CRITERIA DECISION-MAKING APPROACH FOR BUILDING MAINTENANCE IN FACILITY MANAGEMENT

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ABSTRACT

MULTI-CRITERIA DECISION-MAKING APPROACH FOR BUILDING MAINTENANCE IN FACILITY MANAGEMENT

Facility Management (FM) encompasses multi-disciplinary processes to ensure the built environment functions properly for its intended use and service. Maintenance practices are critical to sustaining the longevity of the built environment. As buildings continue to age, there is an increasing need for effective maintenance practices and strategies. In addition, cost and financial constraints require enhanced processes in building maintenance decision-making to assure the resources are allocated efficiently to get the best possible outcome.

Building maintenance decisions present challenges to FM professionals. These challenges arise from the complexity of building systems as well as the participation of multiple stakeholders in the process, such as the property owner, facility manager, engineer, project supervisors, technicians, and occupants. The overarching goal of this dissertation is to develop a systematic and structured multi-criteria decision-making (MCDM) approach for building maintenance practices in a resource-constrained environment. To do so, this dissertation includes three separate but related studies; each focusing on the essential pieces of the MCDM approach.

The first study identified the set of fundamental criteria needed for constructing an MCDM model for FM decision-making utilizing the results of a nationwide survey conducted with the members of the International Facility Management Association (IFMA) and the Leadership in Educational Facilities (APPA) in the United States, two globally recognized FM

organizations. The first study also has an exploratory aspect and tries to establish the decision-making and condition assessment practices currently used in FM practices.

The second study focused on developing a resource-efficient and quantitative condition assessment (CA) framework to establish a condition rating value. Condition information is essential in the decision-making process of building maintenance; however, financial challenges limit the practice of CA, which currently is mostly based on visual inspections and likely to generate a subjective outcome. Fuzzy sets theory is utilized to obtain a quantitative condition rating value that would be less subjective than that obtained through visual inspections, as fuzzy sets theory deals with imprecise, uncertain, and ambiguous judgments with the membership relations.

In the third study, an MCDM method, Choosing by Advantages (CBA), is used to develop a structured and systematic decision-making approach in building maintenance and FM. CBA allows the identification of the most-value generating alternative in the absence of cost and financial constraints, which helps to eliminate the dominancy of financial considerations in the decision-making process. In addition, CBA provides a practical framework to decision-makers in FM with various backgrounds, allowing the participation of multiple stakeholders in the process.

This study contributes to the body of knowledge in the FM domain by identifying criteria in the building-maintenance decision-making process, developing a less subjective and quantitative CA framework, and demonstrating an MCDM method for a systematic approach in building-maintenance decision-making. Additionally, this study will benefit FM professionals and decision-makers at all levels by helping to prioritize maintenance activities, justify maintenance budget requests, and support strategic planning.

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DEDICATION

To the memory of my father…

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CHAPTER 1: Introduction

Facility management (FM) has an interdisciplinary structure that integrates architecture, engineering, construction, and real estate with the human dimensions of the built environment. Beyond being a supportive service, FM applies operations and management principles to enhance the long-term goals of organizations. In addition, the performance of the built environment has an undeniable impact on the success of core-business (Atkin & Brooks, 2015). The application of FM principles varies widely based on the organizational needs and strategic planning. This requires effective decision-making under uncertainty and competitive circumstances (Nutt, 2000).

Resource constraints, the growing number of aging buildings, and a lack of proper maintenance strategies are the main reasons for lower building performance (Eweda et al., 2013), which also have negative impacts on occupant comfort and productivity. As these challenges increase, effective management strategies in building maintenance and FM become critical in the pursuit of sustaining the longevity of buildings, along with ensuring proper function of their intended design and construction purposes.

The first chapter of this dissertation presents the purpose, research questions and outline include three separate but related studies; each focusing on essential pieces of the dissertation.

1.1. Purpose and Research Question

The primary purpose of this research is to support building maintenance decisions in FM by developing a systematic and structured decision-making framework in a resource-constrained environment. Moreover, the research has been motivated by the following challenges revealed in the current decision-making process: the absence of the consideration of multiple criteria in building maintenance decision-making, dependence of the process on past experience, and expert opinion, and the need for enhanced processes for building maintenance practices. The focus of the research is on building maintenance needs that require repair and replace decisions mainly for heating, ventilation, and air conditioning (HVAC) equipment in buildings such as air handling units (AHU), chillers, and rooftop Units (RTU).

In light of these challenges, this study aims to answer the following overarching research question: *What is a systematic and structured way of building maintenance decision making for repair and replace decisions in a resource-constrained environment?*

Addressing the research question focuses on developing a multi-criteria decision-making (MCDM) approach by conducting the following three separate but related studies:

The first study focuses on developing and ranking a set of fundamental and general criteria needed for constructing a MCDM model for use in building maintenance processes across a variety of facility types. In addition, the first study has an exploratory aspect to establish the decision-making and condition assessment practices currently used in FM.

The second study develops a resource efficient quantitative condition assessment framework that can be less subjective and serves as an alternative to visual inspections in establishing a condition rating. An implementation example of the developed framework for heating, ventilating, and air conditioning equipment is provided in the second study.

Third study focuses on demonstrating a structured and systematic decision-making approach in building maintenance and FM by utilizing a MCDM method. The Choosing by Advantages (CBA) method was utilized to provide a practical framework for FM decision-makers with various backgrounds. CBA also helps to identify the most-value generating decision alternative by taking the cost into account as a parameter separate than the established criteria.

1.2. Research Outline

This study investigated developing a MCDM framework for a more systematic and structured way to make FM decisions comprising: (i) the identification of significant criteria for building maintenance decisions, (ii) the development of a condition assessment framework utilizing FM data and fuzzy sets theory, and (iii) the implementation of an MCDM model in repair and replace decisions of building equipment utilizing CBA method.

The decision-making approach developed in this study assists the building equipment level and is not limited to a specific facility type. Even though the developed framework is applicable for a set of equipment, the decision-making process for the network level, such as a set of buildings, is not in the interest of this study. The decision alternatives in the study are repair, replace, and do nothing with the decision-making problem of *"Which building maintenance decision alternative: repair, replace, or do nothing, is more effective in a resource-constrained environment of FM considered for individual building equipment?"*

A brief summary for each study focusing on the essential pieces of the MCDM approach, are presented as follows:

Chapter 2: Identification of the Criteria for Building Maintenance Decisions in Facility Management: First Step to Developing A Multi-Criteria Decision-Making Approach.

The objectives of the first study are: (i) investigate the common issues of FM, such as budget cuts and resource constraints, that lead to the lack of essential practices in FM such as condition assessment; (ii) identify significant criteria for building maintenance decision-making; (iii) better understand the decision-making and condition assessment practices in FM; and (iv) identify any possible relations in FM practices with the characteristics of organizations. Moreover, the first study presents the results of a nationwide survey conducted with members of the International

Facility Management Association (IFMA) and the Leadership in Educational Facilities (APPA) in the United States. The findings provided a total of 11 criteria to use in building maintenance decision-making: code compliance, condition, cost, duration, funding availability, health and safety, occupancy, impact of failure, scheduling, strategic business planning, and sustainability. In addition to the criteria developed, this study revealed statistically significant differences in the mean rankings of some of these criteria between public and private organization participant groups. These differences support the need for the development of an MCDM framework that can be customizable by each organization.

Chapter 3: Condition Assessment Framework for Facility Management Based on Fuzzy Sets Theory

The focus of the second study was to develop a condition assessment (CA) framework as part of any effective FM strategy. This effort developed a practical CA framework utilizing FM data in the absence of visual inspection and walk-through surveys. The developed framework uses mean time between failures (MTBF), age-based obsolescence, facility condition index (FCI), occupant feedback, and preventive maintenance cycle variables with the fuzzy sets theory for obtaining a less subjective and more quantitative condition rating. Condition is often determined with linguistic terms: bad, poor, average, good, and excellent. The fuzzy sets theory aids in minimizing the subjectivity of these linguistic terms that by using variables and membership functions. In identifying the membership functions of each variable, several individual techniques were utilized such as using computerized maintenance management system (CMMS) data, expert opinion, occupant feedback, and industry standards. The effective use of CMMS and FM data is promising in developing resource-efficient building maintenance and FM strategies. The obtained condition rating provides a quantitative condition value for the MCDM approach of this dissertation as well as a baseline for strategic planning in FM departments.

Chapter 4: A Multi-Criteria Decision-Making Approach for Building Maintenance Strategy Selection using Choosing by Advantages

A new generation MCDM method Choosing by Advantages (CBA) is utilized in the third study. The main advantage of CBA is to identify the most-value generating alternative in the absence of cost consideration. In other words, in the CBA method, the cost is defined as a constraint, not a value; thus, it is considered as a separate factor which included in the process after the determination of other values. Other advantages of CBA are enabling group-decision making and the ease of its structure for decision-makers. As a promising effort in utilizing CBA in FM, third study may lead to several future studies such as comparing the results of CBA and traditional decision-making approaches or other decision-making methods utilized in FM.

The following chapters of this dissertation comprise three studies with their introduction, background, methodology, results, example implementations, discussions, and conclusions with future research recommendations. The final chapter summarizes and highlights the significant findings of the three studies with research contributions and recommendations for future research.

1.3. References

Atkin, B., & Brooks, A. (2015). *Total Facility Management*. John Wiley & Sons.

Eweda, A., Zayed, T., & Alkass, S. (2013). Space-based condition assessment model for buildings: Case study of educational buildings. *Journal of Performance of Constructed Facilities*, *29(1)*, 1-12.

Nutt, P. C. (2000). Decision-making success in public, private and third sector organizations: finding sector dependent best practice. *Journal of Management Studies*, *37(1)*, 77-108.

CHAPTER 2: Identification of the Criteria for Building Maintenance Decisions in Facility Management: First Step to Developing a Multi-Criteria Decision-Making Approach [1]

2.1. Introduction and Purpose

Effective facility management (FM) strategies are essential to an organization's ability to achieve its business objectives. FM is a multi-disciplinary process that provides the necessary services for the built environment to support an organization's missions and improve occupant comfort. Organizational needs vary in the pursuit of long-term goals; therefore, the key to an effective FM strategy is to understand and address these needs along with an organization's culture and values (Roper & Payant, 2014).

Building maintenance constitutes essential practices to sustain the performance of buildings within required standards as well as decrease the impact of equipment and system failures (Au-Yong et al., 2014). Therefore, building maintenance practices have a remarkable effect on the longevity of a building. An online survey conducted in 2012 revealed that maintenance and repair activities comprise 79% of total FM activities in the functional responsibilities of FM organizations (Becerik-Gerber et al., 2012). Costs to repair and maintain buildings also continue to rise; the International Facility Management Association's (IFMA) Operations and Maintenance Benchmarks report noted that average maintenance costs increased by 72% between 2007 and 2017 (IFMA, 2017).

Building maintenance decisions ensure that building systems, components, and equipment work effectively together. Cavalcante, Alencar, and Lopes (2017) stated that building

[1] Besiktepe, D., Ozbek, M. E., & Atadero, R. A. (2020). Buildings MDPI, 10(9), 166.

maintenance decisions are a challenge for most facility management professionals. Since maintenance processes involve a great variety of factors, which complicates making decisions in such environments, the need for a mechanism capable of assisting the characterization of complex scenarios arises. Multi-criteria decision-making (MCDM) emerged as a branch of operations research designed to facilitate the resolution of complex issues with conflicting criteria. A variety of MCDM methods have been developed to solve various problems under different circumstances and fields of application (Jato-Espino et al., 2014).

Given the importance of building maintenance and related decisions, the overarching goal of this study is to develop and rank a set of fundamental and general criteria needed for constructing an MCDM model for use in building maintenance processes across a variety of facility types. Building maintenance decisions in this study refer to repair, replace, defer, or 'do nothing' alternatives for a building system, component, or equipment, which focuses on each maintenance activity as a discrete decision. Given that, the decision-making of the selection of building system, component, or equipment subject to maintenance activity is not in the scope. This study also has an exploratory aspect and tries to establish the decision-making and condition assessment practices currently used. To do so, the study utilizes the results of a nationwide survey conducted with the members of the International Facility Management Association (IFMA) and the Leadership in Educational Facilities (APPA) in the United States, two globally recognized FM organizations. IFMA is the largest FM organization in the world, including more than 23,000 members in over 100 countries and APPA represents more than 18,000 educational facilities professionals from 1300 learning institutions worldwide. The results of this study can help establish the current status of FM and can be used for the development of an MCDM model with a condition assessment framework for use in building maintenance processes.

2.2. Background

The information provided in the background section of this paper comprises current challenges, the need for MCDM in the context of building maintenance and FM, and applications of MCDM in the built environment. In addition to the current literature presented in the background section, specific studies utilized in revealing various criteria for building maintenance decision-making are presented in the methodology section.

2.2.1. Current Challenges in Building Maintenance and FM

Building maintenance and FM practices constitute a significant portion of buildings' life cycle (Lewis et al., 2014). Building systems are complicated, and FM and maintenance practices aim to ensure the longevity of these systems as well as the built environment. The challenges that limit the development of effective management strategies in FM were highlighted in several studies. These challenges can be summarized as follows: (i) controlling multiple maintenance projects, (ii) integration of energy and workplace management, (iii) performance-based contracts, (iv) utilizing technological advances, (v) the lack of commissioning and hand over models, and (vi) outsourcing and service delivery (Atkin & Brooks, 2015; East & Liu, 2006; East et al., 2013; Rondeau et al., 2012).

Resource constraints and aging building stock were discussed in the context of FM and building maintenance as two main challenges that affect the performance and life cycle of the built environment (Kim & Ebdon, 2020; Kohler & Yang, 2007). The impact of aging buildings and the need for effective management strategies to increase the longevity of aged buildings were reported in several public records of the US Government Accountability Office, the General Services Administration, and the National Research Council (GAO, 2018; NRC, 2008; NCR, 2012; Robinson & Foell, 2003). Moreover, the United States Energy Information Administration

(EIA) 2012 commercial buildings energy consumption survey (CBECS) states that more than half of the commercial buildings in the United States were constructed before 1980, and the median age of buildings was reported as 32 years in 2012 (EIA, 2012).

The following studies by respected FM organizations also highlight the aging building stock in the United States and Canadian provinces. The IFMA (2017) published a report in 2017 that represents the results of a survey conducted with 2193 FM professionals in 33 broad industry categories with more than 98,000 buildings across 50 states in the United States and eight Canadian provinces and territories. The increasing number of aging buildings in 29 facility categories such as office, industrial, assembly, retail, education, hospital, and residential is highlighted in the report. In addition, 26% of the buildings in the dataset are 31–50 years, and another 27% were 51–100 years, as of 2017 (IFMA, 2017). A Sightlines (2018) report that explored more than 52,000 buildings on 360 higher education campuses in the United States stated that almost 52% of these buildings are over 25 years old. Despite the construction of new buildings in the last decade, the total percentage of buildings over 50 years old increased by 4% (Sightlines, 2018).

Along with aging buildings has come an increase in the investment of new building construction, but this has resulted in a lack of interest in existing buildings and their maintenance needs (Kaiser, 2016). Furthermore, maintenance and operation costs contain a significant amount of the total life-cycle cost after the completion of construction. Hence, the efforts in developing cost-effective strategies have increased recently and will continue to be important (Che-Ghani et al., 2016).

Cost constraints, lack of funding, budget cuts, and the lack of proper maintenance management are the main reasons for lower performance of facilities (Eweda et al., 2015).

According to Zavadskas and Vilutiene (2006), the efficiency of maintenance depends on planning, design, and commissioning processes that require qualified and experienced personnel, proper equipment, and expertise. Additionally, the maintenance process needs a multi-disciplinary approach, including engineering, commercial, cultural, economic, environmental, and social aspects (Olanrewaju & Abdul-Aziz, 2015) Given these factors, aging buildings and limited resources are important challenges in developing effective building maintenance and facility management strategies. Moreover, the needs of maintenance processes and buildings depend on many factors, which are usually project-specific, making the decision-making process complex in building maintenance and FM.

The challenges in building maintenance and FM led many researchers to focus their efforts on developing effective management strategies. Technological developments, such as building information modeling (BIM) (Pishdad-Bozorgi et al., 2018; Wang & Piao, 2019) data exchange and computerized maintenance management systems (CMMS), generic asset management frameworks, preventive maintenance strategies, and other advances in building maintenance and FM (Cigolini et al., 2008) are discussed in current studies. However, these studies appear to be few or partial in the existing literature (Hassanain et al., 2003). In addition, a comprehensive literature review conducted in maintenance performance measurement (Simões et al., 2011) identified that the building maintenance and FM areas are in need of more research efforts to address increasing challenges.

2.2.2. The Need for MCDM in Building Maintenance

One of the ways to address the challenges in building maintenance and FM is to improve the outcome of decision-making process with a structured and a systematic approach. Since building maintenance decisions are complex in nature with conflicting criteria, an MCDM approach may be an effective method to address the challenges.

The application of MCDM enables decision-makers to create their own set of essential criteria for the maintenance strategy selection process according to needed characteristics (Lin et al., 2014). Moreover, Yin et al. (2011) determined the importance of different stakeholders' participation in the decision-making process of building maintenance. FM executives, project managers, supervisors, occupants, and property owners are the primary stakeholders in building maintenance decision-making. A decision-making approach enabling group decision-making is essential for effective building maintenance decisions.

Yau (2012) stated that it is clear a decision-maker should consider multiple issues when considering the building maintenance process. These issues can cover both physical and social factors, and instead of a single-criterion consideration, a multi-criteria approach has to be used in the process. In addition, reducing maintenance costs and time is also a key maintenance management demand (2012). Wu et al. (2016) emphasized that most of the early decision-making models depended on the single type of event and criteria. Because of the complexity of the process, different requirements of different maintenance needs and possible correlations between different events caused the need for multi-criteria decision-making models for building maintenance.

2.2.3. Applications of MCDM in the Built Environment

Several studies have investigated the application of decision-making models for complex engineering and management problems, including multiple variables with conflicting goals, uncertainty, and risks. A comprehensive review of the application of 22 MCDMs in 11 categories of the construction industry showed that the Analytic Hierarchy Process (AHP) was implemented more than other methods, whether on its own or in combination with other applicable methods (Jato-Espino et al., 2014). AHP comprises pairwise comparisons of criteria and sub-criteria within a hierarchical model of a decision-making problem. The main criteria are judged in pairs for their relative importance in a comparison matrix (Saaty, 1987). After AHP, the most common methods were the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Elimination and Choice Expressing Reality (ELECTRE) in the applications of MCDMs (Jato-Espino et al., 2014). TOPSIS was developed by Yoon and Hwang (1995), and it considers the decision-making problem as a geometric system in which the alternatives were specified with their positive and negative distances to the benefit and cost criteria (Yoon & Hwang, 1995). ELECTRE is an outranking method with the comparison of concordance and discordance relationship of criteria within specified limits (Roy, 1991).

Another study (Bakht & El-Diraby, 2015) explored the existing research on architecture, engineering, and construction (AEC) and decision-making to review decision-making trends over the last five decades. The publications in the American Society of Civil Engineers (ASCE)'s Journal of the Construction Division and the Journal of Construction Engineering and Management were analyzed around the subject areas of project management, construction management, bidding and tendering, and performance and productivity. Their results showed that the decision-maker profile has changed over time from an individual to a group in the AEC industry. The increasing trend of including end-users of the built environment in AEC decision-making processes was highlighted in the study's findings as well. Moreover, the change in decision-making tools from a deterministic to probabilistic nature is one possible explanation for the increasing complexity in the decision objectives of AEC (Bakht & El-Diraby, 2015).

MCDM models have been implemented for building maintenance problems in the literature, though, the context of these problems was limited. Cavalcante et al., (2017) focused on the maintenance inspection scheduling problem in residential complexes during the builder's warranty period. The preference ranking organization method for enrichment evaluation (PROMETHEE) was utilized based on a delay-time concept in their study (Cavalcante et al., 2017). PROMETHEE is an ordering method in decision-making with weighted criteria and a preference function (Brans & Vincke, 1985).

AHP was implemented for lighting maintenance decision-making, including re-lamping cost evaluation, carbon dioxide emission evaluations, and comprehensive evaluation for decision-making on lighting maintenance alternatives. Carbon dioxide emissions from the crew and travel time for re-lamping were considered in the context of environmental conservation as well. AHP combined cost and environmental criteria for the optimal maintenance alternative selection (Chen et al., 2018)

Maintenance strategies incorporate several aspects comprising economic, environmental, technical, and social that need to tie into sustainable practices. Ighravwe and Oke (2019) implemented MCDM models with sustainability criteria for selecting the best maintenance strategy: predictive, preventive, corrective, and condition-based for public buildings. The lack of a systematic maintenance strategy selection and the prevalence of uncertainty in maintenance decisions were emphasized in their study (Ighravwe & Oke, 2019).

Despite the fact that decision-making is pivotal in building maintenance and FM, a limited number of studies have focused on this problem in the current literature. In addition, very few studies have looked at how MCDM approaches have been integrated into decision-making processes in FM. In light of these gaps in the literature, and as a first step of constructing an

MCDM model, this study develops a set of criteria for use in building maintenance processes in FM based on a literature review and an online survey.

2.3. Research Methodology

A literature review was conducted to reveal the significant criteria for building maintenance decision-making processes. Additionally, a nationwide online survey was conducted with the members of IFMA and APPA to verify the criteria identified through the literature, rank their importance, and identify any additional criteria for the model.

2.3.1. Step 1 – Criteria Identification through Literature Review

Identifying relevant selection criteria comprises an essential part of any decision-making process. Building maintenance decision-making often must consider complex, conflicting, and competing criteria, as well as to identify the relative importance of the criteria. In this study, current efforts were investigated for a better understanding of the types of decision-making problems and their corresponding criteria in the subject matter. The target of the literature review was studies performed in the last two decades, focusing on the most recent efforts.

The literature search was conducted in a wide range of areas, including maintenance management in manufacturing and industrial production, together with building maintenance. The search strategy comprised the following keywords: “maintenance management”, “facility management”, “building maintenance”, and “decision-making”, in several combinations with “criteria”, “factor”, “strategy”, “policy”, and “prioritization”. Studies reporting criteria or factors that influence building maintenance processes and decision-making practices were included in the literature review for criteria identification. Examples of the criteria and corresponding studies in the literature are listed in Table 1 in chronological order.

Table 1

Examples of the criteria in the literature

Reference	Study Area	Identified Criteria
Johnson and Wyatt, 1999	Prioritizing major items of maintenance and maintenance programs	- Legal, safety, cost, condition, and operational considerations - Building status - Physical condition - Importance of building occupation, the effect on occupants - Cost implications - Effects on service provision
Bevilacqua and Braglia, 2000	The factors for the selection of the maintenance type of an oil refinery	- Investment cost - Safety and environmental problems - Failure costs - Reliability - Mean time between failures - Mean time to repair - The criticality of the machine maintenance: safety, machine importance for the process, maintenance cost, failure frequency, downtime length, machine type, and production loss cost - Maintenance direct costs - Production costs
Parida and Chattopadhyay, 2007	The performance measurement criteria for the building maintenance activities	- Mean time between failure - Downtime - Maintenance cost - Type of maintenance task (planned vs. unplanned) - Health and safety - Security and environment - Employee satisfaction
Chang and Pan, 2007	Airport facilities maintenance policy selection	Breakdown consequences - Safety - Operation - Secondary damage Cost - Loss of production - Repair cost in man-hours - Repair cost of material Importance - Ease of failure detection - Bottleneck - Complexity of the system - Redundancy

Reichelt et al., 2008	Maintenance strategy selection for municipal buildings	- The costs of maintenance - Fulfillment of building user needs and expectations - The quality of maintenance of building structures and equipment - The efficiency of the maintenance process
Ali et al., 2010	Factors affecting housing maintenance costs in Malaysia	- Building materials - Building services - Building age and condition - Type of structure - Use of property - Failure to execute maintenance at the right time - New health and safety regulations - Budget constraints
Flores-Colen et al., 2010	Criteria for prioritization of predictive maintenance of building façade	Physical performance - Type of the maintenance solution - Sustainability impacts - Preventive maintenance - Building's age - Remaining service life - Date of the last intervention Risk - The effects of the maintenance activity on the building and façade - Occupants' criticality of the areas affected Cost - Cost of the maintenance activity - The loss of use - The recurrent issues
Yau, 2012	Multi-Criteria Decision-Making (MCDM) for homeowner's participation in building maintenance	- Cost affordability - Building condition
Lin et al., 2015	Analytical Hierarchy Process (AHP) for procurement strategy selection in building maintenance	- Client's requirements - Project characteristics - External environmental factors
Kim et al., 2019	Facility Management (FM) decision-making for energy efficiency efforts in building maintenance	- Economic feasibility - Environmental impact - Institutional characteristics - Occupant impact - Technical practicality

Decision-making problems in these studies can be grouped into two main categories: (i) the selection of maintenance strategy or policy and (ii) prioritizing maintenance activities. Not all of these problems were addressed with the MCDM approach; however, the factors or criteria discussed in the selected literature provided the foundation to revealing the criteria utilized in this study. Consequently, criteria were identified from the literature based on the frequency of their occurrence. The most frequent criteria in the studies reviewed were, respectively: (1) cost, (2) occupancy, (3) health and safety, (4) condition, and (5) sustainability.

The example studies present various facility types with a higher frequency of identified criteria in different contexts. It is important to note that the identified criteria are applicable to any facility types as they represent fundamental criteria for decision-makers in building maintenance. In addition, specific criteria depending on facility type, such as "functional spaces", which refers to clinical, nursing, and support areas in healthcare facilities were not included in the criteria list of this study (Ali & Hegazy, 2014).

In addition to these five criteria frequently mentioned in the literature, four more criteria were also discussed in the literature and considered relevant, therefore they are also included in this study: (6) funding availability, (7) code compliance, (8) duration, and (9) scheduling. In light of the selected literature, it is apparent that maintenance cost is critically important in building maintenance decision-making. Thus, if the available funds are not adequate, building maintenance practices will be ineffective or insufficient (Riley & Cotgrave, 2005). Building codes address the structural system, electrical and mechanical systems, fire safety, accessibility, security, building envelope, energy consumption, and materials. These codes are fundamental parts of the regulation of building construction in the United States. Code compliance is mandatory for new construction as well as any repair or replace activity in existing buildings to protect public health and safety (Martin, 2005). The complexity of maintenance activities with conflicting tasks requires effective planning and scheduling of these activities. Hence, maintenance scheduling, which is the timing of any maintenance activity in the calendar year, should be considered along with business objectives. In addition, the duration of the maintenance activity is an integral part of maintenance scheduling (Hopland & Kvamsdal, 2016). Subsequently, the identified criteria and their definition in this study are presented in Table 2 in alphabetical order. The authors acknowledge that the identified criteria may be interpreted differently based on the maintenance activity or the context of the decision-making problem (e.g., code compliance requirements differ for roofing and heating, ventilation, and air conditioning (HVAC) maintenance needs), the identified list provides fundamental and general criteria for decision-makers in building maintenance activities. Having said this, it is important to note that based on the needs of individual problems, decision-makers may add specific criteria to this fundamental list.

Table 2

Identified criteria for building maintenance decision-making through literature review

Criterion	Definition
Code Compliance	Compliance of the equipment with the most current building codes
Condition	Existing condition of the equipment at the time of maintenance activity decision
Cost	Total estimated cost of the maintenance activity
Duration	Total time span of the maintenance activity, such as 2 months, 1 year, etc.
Funding Availability	Available funds of the maintenance budget related to the maintenance activity
Health and Safety	Health and safety threats caused by the failure of the equipment
Occupancy	Purpose of the occupancy of the building where the equipment exists, such as classroom, research lab, office, meeting room, etc.
Scheduling	The time of the maintenance activity in the calendar year, such as from January to March, in July, etc.
Sustainability	Impact of the maintenance activity on the sustainability of the equipment

2.3.2. Step 2 – Survey Development and Data Collection

Prior to developing the survey, researchers had several discussions with local FM professionals in the state of Colorado to determine if the criteria identified through literature review were applicable in the decision-making process from their perspectives. The common feedback gathered from these discussions was that cost and funding availability were dominant criteria in the building maintenance decisions. However, several instances, such as any maintenance need becoming a threat to the health and safety of occupants, require individual consideration with higher priority regardless of cost and funding availability. In addition, current condition, regulatory requirements and code compliance, and sustainability were highlighted in terms of predominating cost and funding availability in certain circumstances.

With these in mind, an online survey was developed with the purpose of verifying the criteria identified through the literature, ranking their importance, and identifying any additional criteria for building maintenance decision-making. Moreover, to support the exploratory nature of this study and to help establish the current status of FM, the survey included questions related to the current decision-making practices of building maintenance and current condition assessment.

The online survey targeted members of IFMA and APPA. These associations are well known for having a vast majority of professionals involved in corporate and higher education FM practices in the United States as well as at the global level. The roles of survey participants ranged from directors of facilities, assistant directors of facilities, and facility managers. The target population of the survey comprised the decision-makers in FM and building maintenance.

Twenty-one questions comprising ranking, multiple-choice, and open-ended questions were developed in the survey, with the approximate time of 10–15 min to complete. Qualtrics XM web-based account provided by Colorado State University was utilized for conducting the survey and data storage. A pilot survey was conducted prior to the distribution of the online survey; participation included 23 academic and professional members of FM. The pilot survey participants were selected from the population of FM professionals in the state of Colorado and academics in the researchers' institution. Based on feedback from the pilot survey, minor revisions were made to the multiple-choice questions, such as the ability to select more than one answer as an option.

The online survey instrument was approved by the Colorado State University Institutional Review Board in the exempt category and distributed by personalized e-mails, e-mail listings of IFMA and APPA, online forum groups, and social media networks of FM professionals in LinkedIn. Given that the survey was promoted in LinkedIn groups composed of professionals working in the FM domain who can be non-members of IFMA and APPA, the authors used the demographic questions to confirm that the participants had relevant experience in the FM domain, as presented in Figure 1 and Figure 2.

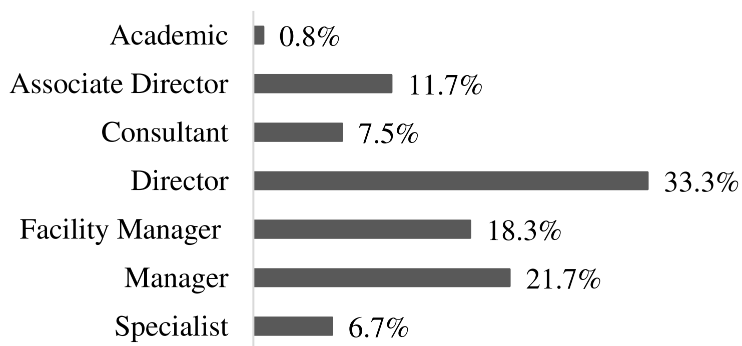

Figure 1

Job titles of survey participants

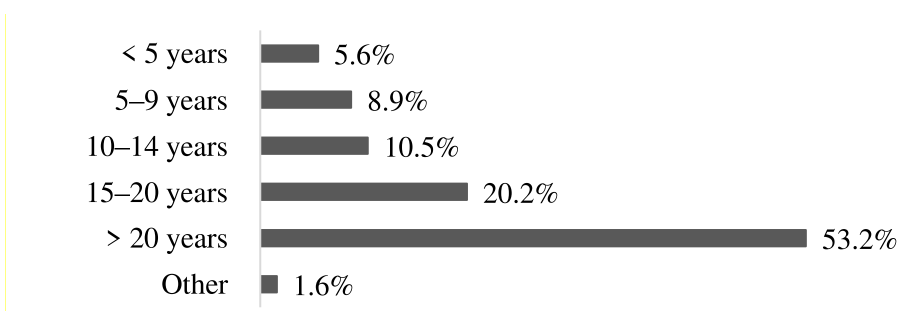

Figure 2

Participants' work experience in FM

The online survey was open for ten weeks, and two reminders were sent to the target groups. A total of 219 responses were recorded in the web-based account, and 127 responses were included for full analysis as the remainder of responses were incomplete. Even though the response rate was impossible to calculate due to promotion of the survey in social media of FM professionals with membership numbers not known, the authors would like to acknowledge that they value the responses that were provided by qualified and experienced FM professionals in this survey. It is important to note that this study does not make any inference about the entire FM population based on our sample size.

2.4. Data Analysis and Results

Data were exported to Microsoft Excel, and analysis was performed in IBM Statistical Package for the Social Sciences (SPSS) Statistics 26 and NVivo qualitative data analysis software. Quantitative data from the online survey were analyzed using descriptive and inferential statistical analysis methods. The descriptive analysis comprises percentages and mean ranking determination, while the inferential analysis includes a two-sample t-test. Content analysis was performed for qualitative data from open-ended questions with conceptual analysis.

2.4.1. Characteristics of Online Participants and Their Organizations

Almost 80% of the collected responses were from the United States, provided by 97 survey participants. Ten percent of the responses were from Canada, and the remaining responses were from Australia, China, India, Malaysia, Qatar, Trinidad and Tobago, United Arab Emirates, and the United Kingdom. Forty-four percent of the participants were employed in educational institutions; the remaining 56% were in non-educational sectors. In addition, 46.8% of the participants work in the public sector and 53.2% work in the private sector.

Directors, associate directors, facility managers, and other managerial positions in FM comprise 85% of the survey participants, as the targeted population of the online survey was decision-makers in FM and building maintenance. The distribution of the survey participants' positions is presented in Figure 1. Almost 75% of the survey participants had more than 15 years of FM experience, as presented in Figure 2. Considering these, it can be concluded that the majority of responses were collected from experienced FM executives who have a significant role in the decision-making process of building maintenance.

These demographics showing that the respondents are composed of professionals with relevant positions and experiences support the reliability of the results. The main purpose of the study is to develop a set of criteria in building maintenance decision-making and having the vast majority of the survey participants (85%) as decision-makers is a significant indicator of the reliability of their responses. In addition, it is important to note that the years of experience provided by survey responders are specific to their experience in FM, which also supports the reliability with almost 75% of respondents reporting more than 15 years of experience.

Participants were asked to provide information on the size of their department and the scale of the facilities or institutions served by their department. Of the participants' departments, 58.1% include less than 100 employees. Figure 3 shows the distribution of the department size of the participant's FM departments.

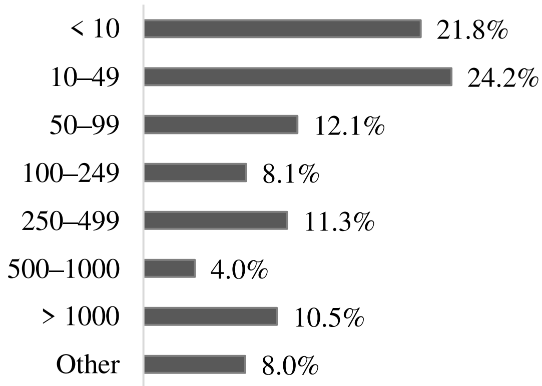

Figure 3

The total number of employees in the participant's FM department

The total gross square meter (m^2) of the facilities or institutions served by the participants' departments varies significantly and is presented in Figure 4.

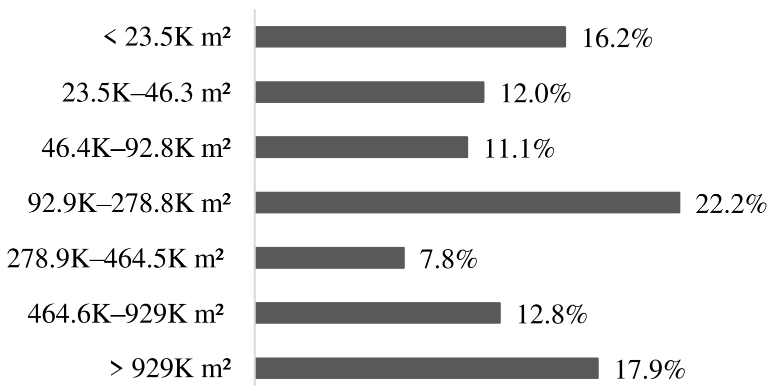

Figure 4

Total gross square meter (m^2) served by the participants' FM department

Participants also provided information on the maintenance budget managed by their FM department. The definition of maintenance budget in this study comprises the budget of corrective and preventive maintenance activities and excludes capital and operations budgets in FM. More than 60% of the participants manage less than US $5 M of the maintenance budget, and the distribution of the maintenance budgets of the participants' FM departments is presented in Figure 5.

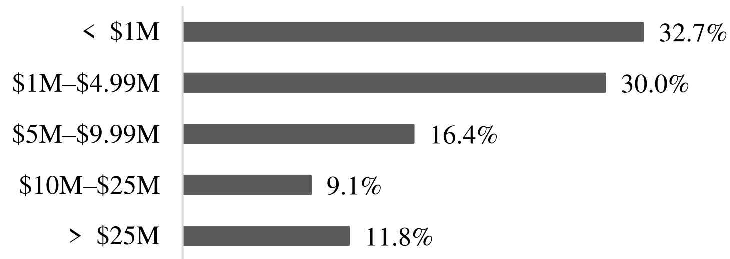

Figure 5

Maintenance budget of participants' FM departments in US dollars

2.4.2. Ranking of Criteria Identified through the Literature Review

Participants were asked to rank the nine criteria identified through the literature review based on the order of importance for maintenance alternatives: code compliance, condition, cost, duration, funding availability, health and safety, occupancy, scheduling, and sustainability. The ranking scale was from 1 to 9, representing: "1" is the most important, and "9" is the least important. The mean ranking values of each criterion showed that "Health and Safety" ranked as the most important criteria with the mean ranking value of 1.90. "Code Compliance (2.93)" and "Condition (3.28)" criteria were ranked as the second and third most important criterion, respectively. The mean importance of rankings of the identified criteria is presented in Table 3.

Table 3

The mean importance ranking of building maintenance decision-making criteria

Criteria	Mean Ranking
Health and Safety	1.90
Code Compliance	2.93
Condition	3.28
Cost	4.44
Funding Availability	4.94
Occupancy	6.02
Sustainability	6.98
Duration	6.98
Scheduling	7.52

The mean importance of rankings for the identified criteria provided an overall understanding of their significance within the entire sample population. The feedback from the local FM professionals in public organizations prior to the survey development highlighted that cost and funding availability are the most important in building maintenance decision-making. However, the ranking values established that “Health and Safety”, “Code Compliance”, and “Condition” are predominant compared to “Cost” and “Funding Availability”. Considering these, the researchers aimed to reveal any statistically significant differences within criteria ranking among the sample population between public and private organizations. Consequently, the mean importance of criteria rankings and their statistically significant differences (if any) were investigated between public and private organizations.

A statistically significant difference was identified ($p < .05$) in public vs. private organization participants for the ranking of the “Condition” criterion. The public organization participants ranked “Condition” higher than private organization participants. Moreover, the “Sustainability” ranking was significantly statistically different ($p < .05$) between public vs. private organization participants. Private organization participants ranked “Sustainability” higher than public organization participants. The p-values of two-sample t-tests are presented in Table 4 within related sample groups.

Table 4

Mean importance ranking and two-sample t-test p-values for private and public organization participants

	Public	Private	
	Mean	**Mean**	***p*-Value**
Health and Safety	1.9123	1.7879	0.6080
Condition	**2.8421**	**3.6212**	**0.0030 ***
Code Compliance	3.0702	2.8788	0.6240
Cost	4.4912	4.4545	0.8810
Funding Availability	4.7895	5.0455	0.4800
Occupancy	5.9649	6.0758	0.7700
Duration	7.1053	6.9545	0.5620
Sustainability	**7.3860**	**6.6212**	**0.0450 ***
Scheduling	7.4386	7.5606	0.6460

* $p < .05$

The mean ranking importance of criteria has the potential to identify possible differences in FM and building maintenance practices among participant groups. Given that, statistically significant differences for individual criterion can be considered as an indicator to determine the FM organizations' efforts based on their existing challenges. Particularly in the "sustainability" criterion case, the reason behind the higher ranking of this criterion in private organizations compared to public ones might be due to the additional costs of sustainable practices. Although it is not possible to determine the causes of the statistically significant differences in the mean rankings as part of this study, these results are interesting in terms of supporting the need for further research.

2.4.3. Additional Criteria through the Survey Results

Participants were also asked to provide additional decision-making criteria that were not suggested in the ranking question of the survey. Eighty-one survey participants provided 198 additional criteria or factors for building maintenance decisions. However, 51 out of 198 were similar to the identified nine criteria of the study, such as “regulatory issues”, “financial considerations”, “occupant satisfaction”, etc., and they were excluded from further analysis. The remaining 147 criteria or factors were analyzed in NVivo qualitative data analysis software. The purpose of the content analysis performed in NVivo software is to identify the frequency of the additional criteria suggested by the respondents in the survey. NVivo grouped linguistically similar words in single word categories with their frequencies from the list of 147 criteria. The participants also had the opportunity to provide the importance of their suggested criteria as “major” or “minor”. The provided importance for the suggested criteria was “major” for 124 criteria out of 147.

The results of the NVivo analysis provided a preliminary understanding of concepts related to additional criteria provided by the survey respondents. Word categories and their frequencies of the additional criteria (including synonyms or closely related words) are presented in Table 5. The presented results are provided by NVivo as they were exported, and there is no additional clustering performed prior to the data upload into the software.

Table 5

The results of content analysis in NVivo software

Word	Count	Weighted Percentage (%)	Similar Words
plan	13	3.77	plan, planned, planning, plans, program, project, projects
business	9	2.83	business
impact	9	2.67	affected, impact
operations	9	2.15	control, function, operational, operations, performance, run, work
critical	8	2.52	critical, criticality
failure	7	2.20	failure

risk	7	2.20	risk
requirements	6	1.89	demands, expectancy, need, needed, requirements
consequence	6	1.42	consequence, effect, effective, event, issues, results
future	5	1.57	future
replacement	5	1.57	renewal, replacement
support	5	1.57	funding, support
initiatives	5	1.10	initiatives, innovative, institution, institutional, knowledge
asset	4	1.26	asset, assets
customer	4	1.26	customer
expenditure	4	1.26	expenditure, expenditures, spending
management	4	1.26	deal, management
space	4	1.26	space
staff	4	1.26	staff
technology	4	1.26	technological, technologies, technology

The researchers observed two main concepts from the word category and frequency results of the NVivo analysis: “Strategic Business Planning” and “Impact of Failure”. The word frequencies of “plan,” “business,” “operations,” “critical,” “future,” and “requirement” were associated with the concept of “Strategic Business Planning”. The two key fundamentals of strategic business planning are effectively setting the direction of the organization and implementing operational processes to achieve business objectives within that direction (Reading, 2002). In the concept of FM and building maintenance, strategic business planning can be defined as aligning FM functions with the organization’s business continuity with a clear understanding of the organization’s goals and objectives in the short-term and long-term (Atkin & Brooks, 2015; Chotipanich, 2004). For instance, in the case of relocation planning of the organization, maintenance activities need to be rescheduled or sustained.

In addition, “impact,” “failure,” “consequence,” “risk,” and “replacement” were connected with “Impact of Failure”. The failure of any system, equipment, or component has several consequences, such as threats to health and safety, environment, occupant comfort, and loss of energy and operational efficiency (Wu et al., 2010) For example, the failure of HVAC equipment or systems may affect the entire building, since these systems are complex and centralized (Au-Yong et al., 2014).

As a result of the content analysis, researchers incorporated “Strategic Business Planning” and “Impact of Failure” into the list of identified criteria in this study. The two additional criteria were synthesized based on the researchers’ observations of the similarities and frequencies of the linguistic meanings of keywords, as described above. Table 6 represents the criteria for building maintenance decision-making identified in this study.

Table 6

The final list of building maintenance decision-making criteria in this study

Criteria
Code Compliance
Condition
Cost
Duration
Funding Availability
Health and Safety
Impact of Failure
Occupancy
Scheduling
Sustainability
Strategic Business Planning

2.4.4. Decision-Making Practices in Building Maintenance

Around 45% of the participants provided that "Past Experience and Expert Opinion" were their current primary decision-making practices in building maintenance. Past experience and expert opinion refer to obtaining the input of project managers and supervisors related to maintenance needs and decision-making. The two other practices provided in the survey were "Run-to-Failure" and "MCDM models". Run-to-failure is considered making maintenance decisions when the system or component or equipment breaks down, and MCDM models are identified as mathematical models that help decision-makers based on a set of criteria. MCDM models and run-to-failure practices constitute around 20% of the responses individually, and 15% of the participants provided different practices for their building maintenance decision-making under the "Other" category. Each of the answers provided under the "Other" category reflected the individual practices of the participants, and they could not be grouped under similar categories. However, common themes in the mentioned practices are identified as follows: life cycle assessment, life cycle cost analysis, deferred maintenance, and maintenance history. The distribution of the building maintenance decision-making practices of survey participants is provided in Figure 6.

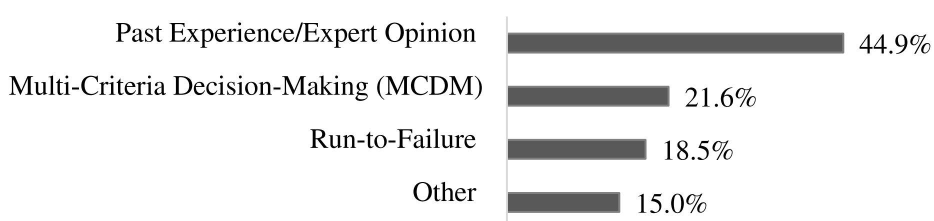

Figure 6

Distribution of decision-making practices in building maintenance

An open-ended question followed the multiple-choice question to gather the participants' recommendations on the best practice of building maintenance decision-making. Based on the qualitative analysis conducted in NVivo software, the common themes in the best practice of decision-making recommendations can be summarized as follows: (i) energy consumption and performance analysis, (ii) return of investment (ROI), (iii) cost–benefit analysis, (iv) life cycle cost analysis, (v) financial policy of the institution, and (vi) facility condition index (FCI). These recommendations can be considered as part of effective FM practices, which then lead to better decisions. However, none of them can be referred to as a decision-making practice, let alone a best practice.

2.4.5. Condition Assessment Practices in Building Maintenance

Local FM professionals involved in the discussions prior to the survey development indicated that due to the lack of resources, condition assessment had not been practiced sufficiently in their institutions for more than a decade. Following this feedback, the researchers collected information about existing condition assessment practices of survey participants. Two specific questions were asked to participants: (i) who conducts condition assessments and (ii) how condition assessments are performed in their institutions. The first question indicates the individuals and/or parties involved in the condition assessment practices such as consultant, contractor, and in-house staff. The way condition assessments are performed was the second question, including remote sensors, non-destructive testing, and visual inspection. These questions were designed as multiple-response, and the participants had the opportunity to select more than one practice in each question.

The results show that 126 participants provided 247 answers for the individuals and/or parties involved in their condition assessment practices. Consultant and in-house staff comprised the majority of the answers. In addition, visual inspection was mentioned as the most common way of condition assessments were practiced, with almost 50% of the answers. The distribution of condition assessment practices is shown in Figure 7 and Figure 8. Additionally, other methods utilized in condition assessment included analysis of historical maintenance records, review of the energy use and repair costs, and occupant observations and comments.

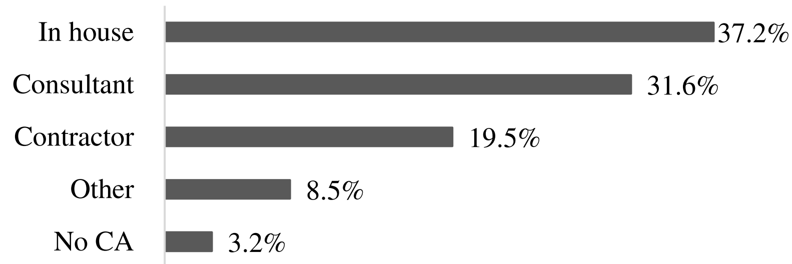

Figure 7

Distribution of the individuals conducting condition assessment

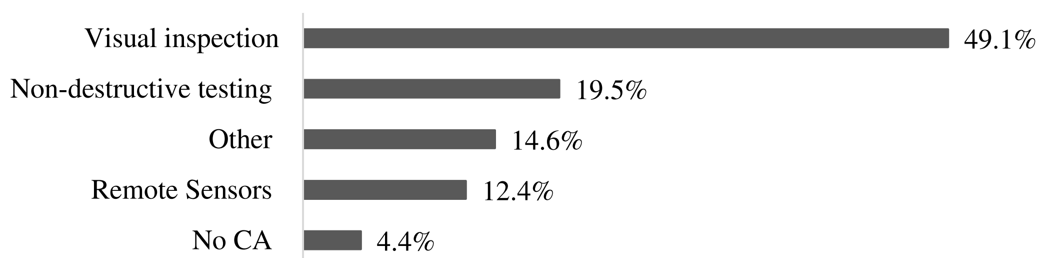

Figure 8

Distribution of the methods utilized in condition assessment

2.5. Discussion and Conclusions

The primary purpose of this study was to develop and rank a set of criteria needed for constructing an MCDM model for use in building maintenance processes in FM. To do so, the study incorporated a literature review and an online survey with FM professionals, including ranking, multiple-choice, and open-ended questions. The findings provided as a total of 11 criteria to use in building maintenance decision-making: code compliance, condition, cost, duration, funding availability, health and safety, occupancy, impact of failure, scheduling, strategic business planning, and sustainability. It is important to note that these criteria comprise a fundamental and general list for building maintenance decision-making problems, and individual systems and facility types might require the consideration of additional criteria.

The survey results assisted in revealing the importance of nine of these criteria identified through the literature review, respectively: (1) health and safety, (2) code compliance, (3) condition, (4) cost, (5) funding availability, (6) occupancy, (7) sustainability, (8) duration, and (9) scheduling. Interestingly, the mean importance rankings highlighted the importance of "Health and Safety", "Code Compliance", and "Condition" above "Cost" and "Funding Availability," which were anticipated to be dominant criteria. In addition, the researchers determined two more criteria from the feedback of survey participants regarding additional criteria to be considered in the process: "Impact of Failure" and "Strategic Business Planning". All of these criteria will be utilized in the researchers' future implementation of MCDM within a case study.

The findings suggest that "Condition" was identified as one of the top criteria in building maintenance decision-making, highlighting the need for effective condition assessment practices. Further research is required to better reveal the time interval, capacity, and process of condition assessment practices. In addition, documentation and reporting of condition assessment practices are important to get the maximum benefit from condition assessment outputs.

“Sustainability” criterion was ranked with lower importance compared to other criteria in the survey. Possible reasons behind this might be the misconception of sustainability, the multifaceted nature of sustainability as a concept in terms of social, economic, and environmental considerations, and the additional upfront costs of sustainable practices. In some cases, repairing equipment might be considered as more sustainable compared to replacement, and overall building maintenance practices assist sustainability concepts in the long-term. However, it is not possible to determine the main reason for the lower importance of the sustainability criterion within this study, and further research on sustainability practices in FM is necessary.

To support the exploratory nature of this study, current building maintenance decision-making and condition assessment practices were revealed in the survey results. Almost half of the participants provided that “Past Experience and Expert Opinion” is their current primary decision-making practice in building maintenance. Furthermore, the survey results showed that around 75% of the participants had more than 15 years of FM experience, and more than 70% of these participants were serving in director, facility manager, or other manager positions in the FM industry. While this shows a large amount of experience, it also reveals that the workforce is aging in the administrative and executive levels of the FM industry. As a consequence, this aging workforce of executives in FM will be transitioning to retirement in the near future, and the need for a systematic and structured way for building maintenance decision-making is important. Additionally, training, scholarship, and education programs, as well as effective pipeline strategies, have the potential to address the aging workforce of FM professionals in the administrative and executive levels.

Visual inspection was identified to be the most common method utilized in condition-assessment, and only 4.4% of the participants reported the lack of condition assessment method in their FM practices. On the other hand, the discussions with local FM professionals prior to the survey development highlighted the lack of condition assessment practices. In addition, condition assessments conducted by in-house teams, consultants, or contractors, who comprise the majority of entities in the survey results, increase the need of additional funding. Given that, resource effective condition assessment practices are essential in building maintenance and FM.

Resource allocation with the focus of maximizing the outcome has a significant effect on the performance of the built environment. It is evident that the resource constrained environment of FM affects the quality of maintenance services, which then affects occupant satisfaction, the performance of the built environment, and the mission of organizations. The criteria identified in the context of this study fills a gap in the lack of comprehensive criteria in building maintenance decision-making. Additionally, the findings of the study revealed that criteria such as “Health and Safety”, “Code Compliance”, and “Condition” have higher importance compared to “Cost” and “Funding Availability”. Even though financial constraints influence FM practices to a large extent, the nature and complexity of building maintenance requires comprehensive criteria, as evidenced by the summarized findings.

In addition to the criteria developed, this study revealed statistically significant differences in the mean rankings of some of these criteria between public and private organization participant groups. These differences support the need for the development of an MCDM framework that could be customizable by each organization. As a first step in developing an MCDM approach, the scope of this study is limited to identifying and ranking a set of criteria that can be used for building maintenance decisions. Future studies can utilize the identified criteria in the development of a full scale MCDM model. Moreover, the applicability and significance of identified criteria in different FM contexts such as healthcare, industrial, educational, and office can be investigated. In addition, the future studies can reveal the differences in building maintenance and decision-making practices in public and private institutions.

The findings further revealed that the current decision-making practices depend mostly on expert opinion; however, the decision-makers in the FM industry are aging. Systematic and structured decision-making practices in building maintenance will have a significant contribution to address this challenge as well as establishing effective FM strategies.

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CHAPTER 3: Condition Assessment Framework for Facility Management Based on Fuzzy Sets Theory

3.1. Introduction and Purpose

Condition assessment (CA) is a fundamental practice of facility management (FM) that provides information regarding the current condition of the built environment to plan appropriate actions for preventing future deficiencies. ASTM International (formerly known as American Society for Testing and Materials), defines CA as a walk-through survey of the built environment with the goal of identifying physical deficiencies, defects, and maintenance needs of building systems, components, or equipment. The "condition" in ASTM's definition refers to determining the physical state of building systems, components, or equipment utilizing the descriptions of excellent, good, fair, poor, satisfactory, unsatisfactory, etc. (ASTM, 2015). In this study, ASTM's definition of "condition" is used as an accepted definition for the physical state of a building system, component, or equipment.

Budgetary issues and resource constraints are major obstacles to implementing essential FM practices, such as CA. As part of traditional CA practices, visual inspections and walk-through surveys require additional resources, and the need for resource-efficient processes in condition assessment is apparent. In addition, the subjective results of visual inspection decrease the effective use of condition assessment for strategic planning and decision-making in FM (Straub, 2003). To better utilize the outcome of condition assessment in building maintenance and FM, less-subjective, data-driven, and quantitative processes are necessary.

In light of the need for an enhanced approach to CA, this study aims to develop a quantitative CA framework that can be less subjective and an alternative to visual inspections, to establish a condition rating value for building maintenance in FM. Furthermore, this study provides an implementation example of the developed framework for heating, ventilating, and air conditioning (HVAC) equipment using a brief case study. HVAC equipment is targeted in the case study because they are high-value assets of buildings with a high impact on building performance and energy efficiency in cases of any defects (Au-Yong et al., 2014). The proposed condition rating value is derived using mean time between failures (MTBF), age-based obsolescence, facility condition index (FCI), occupant feedback, and preventive maintenance cycle variables. Fuzzy sets theory is utilized to obtain a quantitative condition rating value that would be less subjective than that obtained through visual inspections, as fuzzy sets theory deals with imprecise, uncertain, and ambiguous judgments with the membership relations.

The proposed framework benefits FM departments in the absence of, or as an alternative to, visual inspection and walk-through surveys. The proposed framework allows for a holistic assessment and a comprehensive understanding of the condition by considering multiple variables from different resources, such as a computerized maintenance management system (CMMS), expert opinions, occupants, and industry standards. As such, the condition rating obtained through this framework supports decision-making for building maintenance management as well as strategic planning.

The CA framework proposed in this study is illustrated through a brief case study using the framework to determine the condition of chiller equipment in a higher education institution in the state of Colorado. This case study demonstrates how fuzzy sets theory can be applied with identified condition variables focused on the HVAC system. It is important to note that different building equipment or systems may require the consideration of additional variables. Furthermore, not all of the identified variables in the framework may be applicable to other types of building equipment. Acknowledging this fact, additional condition variables based on the equipment type might improve the accuracy of the condition rating value obtained through developed CA framework. Also, developed framework can be used in the absence of or to support the visual inspections or walk-through surveys and additional assessment might be required for identifying the absolute condition.

3.2. Background

The background section of this study comprises the importance of condition information, current CA studies in FM, and fuzzy sets theory with its applications in CA practices. Through the literature review, it was identified that the application of fuzzy concepts in the context of CA in building maintenance and FM is limited. Therefore, studies in civil and structural engineering CA are also presented in the background section to reveal the benefits of fuzzy concepts in CA processes.

3.2.1. The Importance of Condition Information

The National Center for Education Statistics (NCES) highlights the significance of facilities' condition information as a primary source for effective maintenance management and maintenance decision-making. Additionally, NCES indicates the need for having accurate and timely condition information as an increasing demand in the resource-constrained environment of FM (NCES, 2018). Condition information can be utilized as a benchmark for preventive maintenance, maintenance prioritization, and performance measurement (Lavy, 2008).

Instead of determining the condition at a particular moment in time, an over-time condition analysis provides trends of deterioration and the information that helps to improve building maintenance practices (Kaleba, 2013). Moreover, over-time condition information has the potential to assist budget projections as well as resource allocation. The National Research Council's Stewardship of Federal Facilities study (NRC,1998) identified the lack of quantitative information to justify maintenance budgets, which is essential for presenting maintenance funding requests. FM professionals must be able to effectively communicate and establish maintenance needs with the executive level while determining the risks of possible failures. Considering these demands, condition data and information is essential for developing effective building maintenance and FM practices.

One of the most common practices of CA in FM is using the Facility Condition Index (FCI) as an indicator of condition. The FCI considers solely the financial aspect of condition based on the formula that divides the value of deferred maintenance cost by the value of total replacement cost on a scale between 0 and 100, where 0 is the best condition (Cecconi et al., 2019). Even though FCI is applicable, starting from the equipment level to the overall building level, Dejaco, Cecconi, and Maltese (2017) identified the index as an "imperfect" measure of the condition. The critical issue for the use of FCI is the need for a standardized calculation for the deferred maintenance or maintenance needs of a system, component, or equipment (GAO,1998).

A comprehensive study (Cecconi et al. 2019) investigated various approaches in calculating FCI and deferred maintenance, starting from its first version represented by Rush (1991). Despite FCI's wide acceptance in the current FM practice, different approaches in the calculations make its use inconsistent. The extended versions of FCI, such as the ones including major rehabilitation and replacement costs and costs of future maintenance recommendations, also decrease the efficiency of FCI as an indicator of the condition. Subsequently, the importance of condition data and information remain obvious in FM, as well as the need for a holistic approach in CA practices that considers multiple indicators of the existing condition of buildings, systems, and equipment in addition to the deferred maintenance cost or other financial indicators.

3.2.2. Current CA studies in FM

Teicholz and Edgar (2001) referred to CA as a static tool that focuses on building deficiencies rather than its capability to support strategic FM planning. Their study identified the limitations in CA practices as follows: (i) absence of life cycle information, (ii) inconsistency in data collection and reporting, (iii) lack of integration with other FM data such as maintenance history, and (iv) subjectivity of the assessments (Teicholz & Edgar, 2001). After almost two decades, similar issues continue to be reported in CA practices emphasizing the need for a structured and less subjective method with quantitative results (Mayo & Karanja, 2018).

Recent studies in CA and FM have mostly utilized visual inspection and walk-through surveys as part of their processes, which may or may not be feasible due to resource issues, but even if feasible could lead to subjectivity in the process. In addition, these studies used various condition rating scales with linguistic definitions. The relevant studies and their focus are presented in chronological order in Table 7.

Table 7

Recent Studies in CA applied to the FM area

Studies	Focus
Brandt & Rasmussen (2002)	Condition checklist for identifying the needs for retrofitting and functional obsolescence
Uzarski et al., (2002)	The U.S. Army Engineering and Research Development Center, Construction Engineering Research Laboratory (ERDC-CERL) condition assessment system BUILDER that uses condition indexes within the range of failed to excellent (seven-point scale)
Grussing et al., (2006)	Condition prediction model using the Weibull probability distribution function and visual inspection data

Abbott et al., (2007)	A five-point color-coded condition rating system for identifying the required maintenance needs with budget allocation
Singh Ahluwalia (2008)	Visual guidance for condition assessment with location-based inspection practice (four-point scale)
Salim & Zahari (2011)	Development of a building condition rating on a scale from 1 (highest) to 5 (lowest) that considers building type, building age, visual inspection, and the cost of repair
Eweda et al., (2015)	Space-based condition assessment model using the analytical network process (ANP), the analytical hierarchy process (AHP) techniques, and multi-attribute utility theory (MAUT) (six-point scale)

Common characteristics of these studies include: (i) use of subjective and linguistic condition rating and index values, (ii) lack of considering multiple variables for CA, (iii) limited use of existing FM data such as maintenance history, CMMS, or occupant feedback in the CA process, (iv) dependence of CA on expert judgment and visual inspection, and (v) lack of standardized and resource-efficient processes. In addition, limited efforts have been made to integrate structured multi-criteria techniques, such as AHP, revealing the research gap of a standardized and quantitative process in CA and FM. Also, these studies rely on visual inspection or walk-through surveys, which is the primary source of subjectivity in existing CA practices. Moreover, both in-house operations and out-sourcing in CA require additional resource allocation mainly for visual inspection or walk-through surveys, which increases the need for resource-efficient practices. Consequently, the limitations identified by Teicholz and Edgar (2001) in CA practices still remain and a holistic and comprehensive approach is needed to address these existing issues.

3.2.3. Fuzzy Sets Theory and its Applications in CA

Zadeh first introduced the fuzzy sets theory, which is the fundamental concept of fuzzy logic, fuzzy control, fuzzy decision-making, fuzzy neural network, and other fuzzy techniques, in

1965 (Zadeh, 1965). Since then, there have been extensive applications of fuzzy sets theory in several concepts and areas. Fuzzy sets theory seeks to resolve the ambiguity in subjective judgments measured in linguistic terms. For vague or approximate judgments such as “big,” “very high,” “average,” “too fast,” and “poor,” the nature of human language is fuzzy, and the definition of these linguistic judgments varies in different contexts (Chan et al., 2009). Fuzzy sets theory aids in translating uncertain linguistic variables into numerical and quantitative representations characterized by membership functions. The elements in a fuzzy set may have partial membership in the set ranging between 0 and 1, where the representation of 0 is no membership, and 1 is full membership.

Fuzzy techniques have been increasingly applied in construction management research areas since the beginning of the 1990s. Chan et al. (2009) conducted a comprehensive literature review of 52 journal articles to overview the applications of fuzzy techniques in construction management research. Their study revealed that the fuzzy research efforts in construction management could be classified into three fields: (i) fuzzy sets theory, (ii) fuzzy logic, and (iii) hybrid fuzzy applications. Furthermore, fuzzy research in construction management focuses on decision-making, performance, evaluation/assessment, and modeling applications (Chan et al., 2009).

A recent study investigating fuzzy techniques in construction engineering and management supported the increasing trend of fuzzy applications in the field (Fayek, 2020). Fuzzy hybrid techniques with MCDM, optimization, machine learning, risk analysis, and contingency determination were highlighted in the same study. Moreover, the application of fuzzy techniques was determined “essential” in the problems involving expert judgment and subjective uncertainty (Fayek, 2020).

The application of fuzzy sets theory and fuzzy concepts in the CA literature for building or infrastructure elements has been mostly performed in civil and structural engineering. Mitra et al. (2010) utilized fuzzy sets theory to transfer the visual inspection data of corrosion-distressed reinforced concrete building elements into a quantitative condition index. Their study highlighted that the obtained condition index can support the decision-making process about repair needs of the assessed concrete elements (Mitra et al., 2010). Additional studies utilizing fuzzy concepts in CA were focused on the evaluation of pipe condition including structural damage and environmental risks (Yan & Vairavamoorthy, 2004), airport pavement condition and maintenance-needs assessment (Fwa et al., 2004), and condition assessment of reinforced concrete bridges (Sasmal et al., 2006). These studies indicate that the use of fuzzy concepts benefits CA processes by dealing with subjectivity and decreasing time, costs, and efforts in the process. Additionally, fuzzy concepts were used for the performance evaluation and the remaining life assessment of reinforced concrete bridge girders (Anoop et al., 2007) and for modeling the service-life prediction of exterior natural stone claddings (Silva et al., 2016) that supports developing effective maintenance strategies.

However, the use of fuzzy concepts in building maintenance and FM has not received enough attention in the existing literature. Hadipriono (1988) proposed using fuzzy sets theory for performance evaluation of facilities during and after the construction period. Another study proposed a fuzzy sets-based framework for facility life-cycle cost analysis for handling the subjective uncertainty of expert opinion in the process (Sobanjo, 1999). Fuzzy concepts were used in the selection of a performance-based procurement system for maintenance and FM services such as roofing contractors and janitorial services with the backward chaining method

(Kashiwagi, 1994). Though, none of these studies focused on utilizing fuzzy concepts in the CA process of a building system or equipment.

Applications in civil and structural engineering areas show the promise of fuzzy sets to aid in addressing the subjectivity in the CA process as well as to develop resource-effective CA practices. In addition, very few studies utilized fuzzy concepts in the context of building maintenance and FM, revealing the gap of fuzzy applications in the FM area.

3.2.4. Motivation of the Study

Condition has several impacts on the performance and function of a building. Also, condition information has the potential to assist in failure detection, prevention, and maintenance planning, which then supports effective resource allocation and occupant comfort (Uzarski et al., 2002). Without proper knowledge of the condition, it is impractical to sustain effective building maintenance strategies.

Prior to this study, the researchers held several discussions with FM professionals in the state of Colorado regarding common issues in the FM industry. These discussions supported that due to the lack of sufficient resources, visual inspections and walk-through surveys were not performed regularly in their organizations, neither were any other systematic ways to assess the condition of their buildings, systems, and equipment used. These FM professionals and their organizations were reliant mostly on expert judgment. Another issue mentioned in these discussions was the subjectivity of CA processes and the need for a less subjective and more quantitative condition rating value. Although FCI is a common practice in FM, the FM professionals confirmed that FCI only provides condition information from the financial perspective.

FM data, including maintenance history and maintenance backlog in CMMS, building automation, energy management, building performance, recommissioning data, and occupant feedback, are often underutilized in developing effective FM strategies (Korka et al., 1997; Suprabhas & Dib, 2017). Subsequently, CMMS data comprising the corrective and preventive maintenance activities in building maintenance have the potential to support the development of less subjective, quantitative, and data-driven CA practices (Bartels, 2014).

The challenges due to subjectivity and the lack of standardized CA practices in building maintenance and FM need to be addressed with a systematic and resource-efficient approach. Although condition assessment is critical in successfully implementing effective building maintenance and FM strategies, in practice, there are many challenges. Mostly, these come from dependence on visual inspections and walk-through surveys, which may or may not be feasible due to resource issues. Additionally, even if they are feasible, they lead to subjectivity in the process. Even with accurate expert opinions, existing CA practices often involve subjectivity resulting in a qualitative outcome such as “bad,” “poor,” “good,” etc.

Applying fuzzy sets theory in civil and structural engineering CA are promising to overcome these challenges. In addition, the limited number of studies in the applications of fuzzy concepts in CA and FM reveals the gap in consideration of fuzzy sets theory and fuzzy concepts in CA practices. In light of these, the motivation of the proposed CA framework is to utilize FM data such as equipment failures in CMMS and occupant feedback, as well as expert opinion and industry standards, which are mostly underutilized, in the absence of, or alternative to, visual inspections or walk-through surveys. Moreover, this study aims to decrease the subjectivity in the interpretation of condition obtained with the FM data utilizing fuzzy sets theory.

3.3. Methodology

The CA framework proposed in this study was developed through the integration of the following steps based on the application of the fuzzy sets theory: (1) identification of the variables which may represent the condition of building equipment through a literature review; (2) development of condition scales for each variable integrating expert opinion, literature review, and industry standards; (3) determination of the membership functions for condition variables based on condition scales and fuzzification; (4) defuzzification and obtaining condition rating. The methodology of the condition assessment framework is presented in Figure 9. The following subsections provide details of the proposed CA framework.

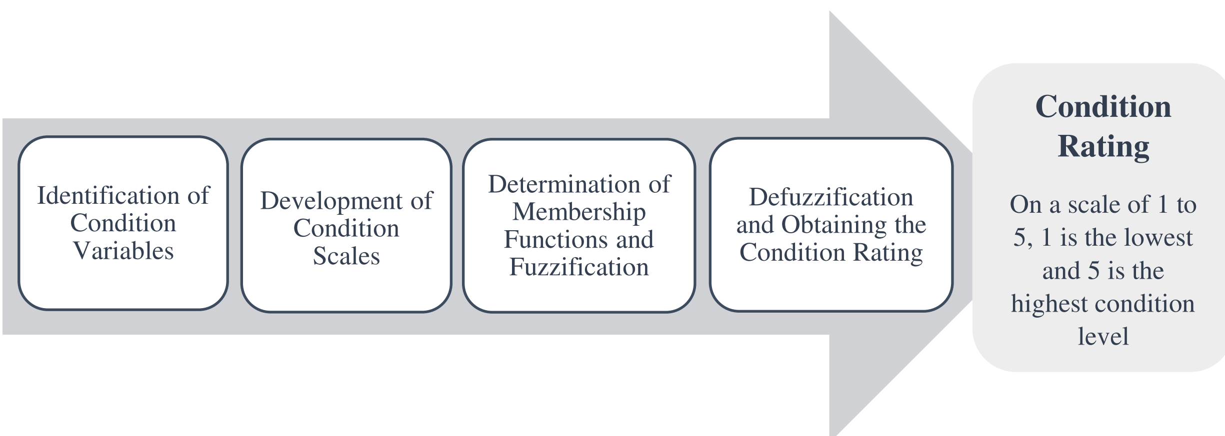

Figure 9

Methodology of the proposed CA framework based on fuzzy sets theory

3.3.1. Identification of Condition Variables

The condition of buildings and their equipment depends on several factors such as age, climate, occupancy, material type, equipment type, and maintenance performance (Ahzahar et al., 2011). In addition, several studies revealed the factors that contribute to building equipment deterioration, degradation, or failures, including service life, failure trends, and maintenance strategy (Balaras et al., 2005). It is apparent that CA in building maintenance and FM must consider multiple factors.

The condition variables identified in this study focused on HVAC equipment as a representative example of the proposed framework. HVAC equipment is mostly considered a high-value asset, and they have a significant i on building performance (Zhang & Hong, 2017). Any issue or failure in HVAC equipment may have severe impacts on the building and its occupants (Goyal et al., 2015). In addition, a recent study in building maintenance revealed that HVAC equipment receives a higher number of work orders in CMMS data (Besiktepe et al., 2019).

The condition variables in this study identified for high-value HVAC equipment such as chillers, air handling units (AHU), and rooftop units (RTU) are: (i) Mean Time Between Failures (MTBF), (ii) Age-based Obsolescence, (iii) Facility Condition Index (FCI), (iv) Occupant Feedback, and (v) Preventive Maintenance Cycle. These variables are proxy measures for determining the condition of the equipment. The following subsections discuss the identified condition variables, with detailed explanations as well as their computations and measures.

3.3.1.1. Mean Time Between Failures (MTBF)

Building systems are complex and failures may occur at the equipment and component level due to deterioration, lack of preventive maintenance, and improper operation and maintenance practices. Although effective FM strategies aim to enhance the efficiency of these systems, breakdowns are inevitable through the lifecycle of building systems. In addition to several other definitions, Torell and Avelar (2004) discussed the definition of “failure” within equipment and component levels. Equipment level failure was identified as the breakdown of essential parts that sustain the equipment's required functions. Additionally, component-level failure comprises the breakdown of components, which decreases the required performance of equipment without the termination of its required function (Torell & Avelar, 2004). Based on these definitions, the focus of this study is on equipment level failures, management of which is critical to reduce the downtime and functional loss of equipment that affect the building performance and occupant comfort.

Equipment failures may result from several reasons, such as systematic, operational, and random issues. These failures lead to other problems, affecting operations, building performance, and occupant comfort. Tracking equipment failures and identifying any trends in these failures are critical in maintenance management (Murthy et al., 2002). Preventive and corrective maintenance data support the reliability, availability, and maintainability of the building equipment and assists identification of failure trends (Schuman & Brent, 2005). Integrating failure trend information in maintenance planning and prioritization is important in the success of maintenance practices and performance (Tsang et al., 1999).

Mean time between failures (MTBF), is the average period between breakdowns, and an essential indicator for the reliability and availability of equipment, leading to determining its performance and condition. MTBF has broad applications in manufacturing, industrial and electronic equipment. In addition, the use of MTBF is important in information technology (IT) and mission-critical businesses building equipment such as chillers, AHU, and RTU. The reliability and availability information are essential in mission-critical businesses building equipment to ensure the continuity of the business.

Computerized maintenance management systems (CMMS) in building maintenance comprise a large amount of data regarding building equipment performance and failure (Labib, 2004). CMMS is a tool that supports maintenance functions of any organization based on information technology, including asset management, maintenance planning and monitoring, work order and day-to-day activity tracking features (Lopes et al., 2016). Manufacturing, production, and utility management areas have integrated CMMS and its data in developing effective maintenance management strategies (O'Donoghue & Prendergast, 2004). The use of CMMS in building maintenance and FM has been limited and the capabilities of CMMS underutilized, especially in strategic planning and decision-making (Arno et al., 2016; Hale et al., 2005; Tanaka & Gotoh 1998; Thompson et al., 2018). However, a recent study revealed that CMMS data in FM, despite its wide use in tracking day-to-day activities, has potential to identify failure trends that will assist developing effective maintenance and FM strategies (Besiktepe et al., 2020).

Moreover, Hale et al. (2005) presented operations and maintenance data collection efforts on 240 power generation, power distribution, and HVAC items in various facilities. Their study was intended to prioritize maintenance procedures with calculated availability values such as MTBF (Hale et al., 2005). Another study focused on HVAC systems failure mode and effects analysis and proposed the use of MTBF as a "powerful metric" in their model (Yang et al., 2018). Although the CMMS software is capable of data storage regarding the average time between breakdowns, the use of MTBF is not a common practice in building maintenance.

Considering these facts, this study focused on utilizing CMMS data in identifying failure trends of building equipment, specifically investigating the mean time between failures (MTBF) concept. The study proposes the use of MTBF as one of the variables representing the condition of the equipment in the developed CA framework. Specifically, MTBF is calculated as the ratio of the equipment's annual working hours to the number of failures obtained from CMMS data presented in equation (1).

$$MTBF = \frac{Annual\ Hours\ of\ Operation}{Annual\ \#\ of\ Failures\ in\ CMMS} \quad (1)$$

The annual hours of operation in equation (1) differ according to the location, climatic conditions, occupancy, facility type, and organization's operational policy. For instance, while a chiller works 24/7 in a manufacturing facility, a chiller in an office building might work 17 hours (5:00 am-10:00 pm) a day. The annual number of failures in the same equation refers to the number of failures gathered from the work orders in the organization's CMMS. However, not all work orders indicate failures that correspond to equipment conditions. Work orders generated because of water flow issues, operator errors, or building automation system (BAS) errors are external and indirect issues and they are not related to the equipment condition. Therefore, they are not considered as part of MTBF in the proposed CA framework. It is essential to identify the failure source of work orders to utilize them in the proposed condition assessment framework. In other words, while a work order related to operator error would not be included in the "Annual # of Failures (CMMS)" in equation (1), a work order related to "pressure issues" or "loud noise" would be considered. Because pressure issues or loud noise most likely arise from any issues related to the equipment parts, such as the motor and related to the equipment condition. The "annual hours of operation" and the "annual number of work orders (CMMS)" utilized in equation (1) would be determined for related equipment individually in each case.

3.3.1.2. Age-Based Obsolescence

Any part of the built environment is subject to deterioration, a natural part of its lifecycle and the aging process. Even though deterioration is unavoidable, effective operation and maintenance practices help minimize impacts that lead to decreased service life of the built environment (Richardson, 2002). The effective age of equipment, which considers the impact of the operation and maintenance practices on the deterioration and aging of the equipment, can be established based on the operation and maintenance practices of any organization.

The total time between when building equipment is put into service until it deteriorates to the minimum acceptable level of performance is determined as its "service life" (Balaras et al., 2005). Several research efforts focused on the service life and life cycle assessment of buildings and building systems, equipment, and components (Cabeza et al., 2014; Grant & Ries, 2013; Rauf & Crawford, 2015). Multiple factors affect the service life of building equipment, such as design and material selection, temperature changes, corrosion, moisture and water, chemical leakage, and change in the occupancy of the building (Richardson, 2002). The consideration of service life in the condition assessment process of building systems, equipment, and components were highlighted in recent research studies where age and the impact of deterioration and degradation were the main indicators (Uzarski et al., 2002; Cecconi et al., 2014). Predictions for the expected service life of any building equipment or component are challenging (Grussing et al., 2006) and most building equipment can continue to perform the necessary functions even after they complete their expected service life with higher risks of failure, higher maintenance costs, and lower performance (Grussing, 2015). Therefore, the condition information needs to consider the period where equipment serves beyond its expected service life.

Age is an important indicator in condition assessment; however, depending on the operational conditions, maintenance actions, and environmental factors, the condition may differ for the same type of equipment at the same age. In addition, the impact of age on the deterioration cannot be considered to be linear in time. Therefore, there is no single curve that can be adopted to identify the change in condition of an equipment solely based on its (Grussing, 2014). Considering these facts, the proposed condition assessment framework in this study considers the impact of time on the condition of the equipment with "age-based obsolescence" identified in Grussing's study (2014) and the calculation is presented in equation (2).

$$Age - Based\ Obsolescence = \frac{Age}{Expected\ Service\ Life} \qquad (2)$$

Grussing's study used the obsolescence index as a proxy indicator, solely based on age without any adjustment, such as inspection observations [60]. The obsolescence index based on a Weibull probability model used to project condition degradation over time, is used in their study to consider functional loss deriving from age-based obsolescence. In addition, expected service life in equation (2) derived from Grussing's study and it indicates the period between the equipment's install year and end of use. The age-based obsolescence variable contributes to identifying the condition of equipment as a function of time. This is different from how the previously discussed variable MTBF contributes to identifying the condition of equipment, as a function of failures.

The Preventive Maintenance Guidebook of Building Owners and Managers Association (BOMA) International, which is produced by a globally recognized organization with more than 16,500 members maintaining 9 billion square feet of commercial properties, has determined the estimated service life (average useful life) of building systems (BOMA, 2010). The estimated service life of ten HVAC system categories, based on "3500 operating hours, 1800 equivalent full load hours use/year and a normal amount of on-off cycles, with regular preventive maintenance properly performed at prescribed frequencies," were identified in the guidebook (BOMA, 2010, p.76). The identified service lives for HVAC equipment in the guidebook are accepted as baseline for age-based obsolescence calculation in this study. Individual components and parts of HVAC equipment might have different service lives, and climatic and environmental conditions might have an increased or decreased impact on the estimated service life of these components. A focus on the condition at the component level is not in the scope of this study, therefore the guidebook of BOMA provides a representative value for service life in the illustrative case study. Utilized values need to be considered individually for various cases concerning operating conditions and maintenance levels.

Although it is widely accepted that the older the equipment is, the worse its condition, the service life and condition of building equipment does not depend on age alone. Notwithstanding this, the "age-based obsolescence" variable utilized in this study uses the ratio of age and expected service life which considers the equipment's functionality beyond its expected service life. As mentioned earlier, operation and maintenance practices are important and might impact the age-based obsolescence as well. The effects of operation and maintenance practices on condition are considered separately as individual condition variables in the proposed CA framework, as will be described in the subsequent sections.

3.3.1.3. Facility Condition Index (FCI)

Financial challenges in FM lead to a common practice in building maintenance, which is postponing the repair needs of building equipment, systems, or components to align with available funds (Kaiser, 2016). This concept is called deferring the maintenance, or deferred maintenance. Hamid et al. (2007) investigated the cause and effects of deferred maintenance on higher education buildings. In addition to financial constraints, poor FM strategies that result in allocating current resources to emergencies was revealed as another cause of deferred maintenance in their study (Hamid et al., 2007).

As mentioned previously, the FM industry commonly uses FCI as a single variable to identify the condition of buildings and their systems, but this value reflects the condition only from a financial perspective and it is not feasible to use it as a single variable to identify the condition. Additionally, various calculations of the FCI reveal a lack of consistency in its value, as well as ineffective use in practice (Mayo & Karanja, 2018). However, FCI is a valuable piece of information in the condition assessment process as a proxy reflecting the existing maintenance log. In addition, a well-defined approach in the calculation of FCI would benefit the condition assessment by including deferred maintenance information in the process.

This study uses the FCI as one of the condition variables in the proposed CA framework. The equation for FCI calculation in this study is presented in equation (3).

$$FCI = \frac{Deferred\ Corrective\ Maintenance\ Cost}{Total\ Replacement\ Value} \tag{3}$$

FCI in this study uses the corrective maintenance backlog in the deferred maintenance cost estimation. In other words, the deferred maintenance cost definition in this study includes only the deferred costs of corrective maintenance activities that are often related to the repair and replace decisions in building maintenance activities. Moreover, corrective maintenance activities reflect the current condition of building equipment, including unplanned and day-to-day activities are considered in the deferred maintenance definition of this study. Hence, the deferred maintenance costs of preventive maintenance or any other maintenance activities such as remodeling, renovation, and capital renewal are not included in the accepted deferred maintenance definition. Because the remodeling, renovation, and capital renewal costs are not directly related to the current condition of the building or component, and the focus of each variable in the study is mainly to identify the current condition of building equipment based on different perspectives.

The total replacement value of the equipment subject to condition assessment is utilized as the benchmark in computing the FCI. The total replacement value is identified as the cost of replacing the equipment without considering any wear and tear due to its age or operational requirements. Since the wear and tear due to the equipment age is considered in the “age-based obsolescence” condition variable of this study, it’s not considered in the total replacement value to avoid double counting the effect of the same variable in the framework. If the deferred maintenance cost of the equipment is closer to the total replacement value, the condition rating of this equipment based on the deferred maintenance cost will be worse. Depending on the type of equipment, total replacement value might include the required construction and demolition costs to replace that equipment.

3.3.1.4. Occupant Feedback

Significant research has focused on identifying building performance by occupant surveys through conducting post-occupancy evaluation (POE). Utilizing occupant feedback, POE compares the building's actual performance to the intended criteria and measures over the life cycle of the building (Ozturk et al., 2012). The occupant feedback in this study refers to feedback on maintenance issues and performance, which is different from POE.

Artan et al. (2018) integrated occupant feedback to use BIM in FM effectively. Their study showed that occupant feedback includes the location of the maintenance problem, source of the problem, and the time when the problem occurred. This information has the potential to assist in condition assessment practices. Another study by Zagreus et al. (2004) identifies building occupants as "a rich source of information" in indoor environmental quality, which is also supported by effective operation and maintenance strategies. Goins and Moezzi (2012) revealed the importance of utilizing occupant feedback in determining building performance. Their study analyzed occupant complaints related to thermal comfort, air quality, lighting, acoustics, and cleanliness. It specifically mentioned that occupant feedback gathered in their case studies were useful for operators in revealing maintenance problems and necessary actions to address these problems (Goins & Moezzi, 2012).

Therefore, this study proposes the use of occupant feedback as one of the variables representing the condition of equipment in the developed CA framework. At the beginning of this study, the researchers conducted a pilot survey with occupants of a mixed-use building (office and student center) in a higher education institution in the state of Colorado. The purpose of the survey was to collect occupants' annual maintenance feedback based on common maintenance complaints such as too hot, too cold, light bulb change, electrical outlet failure, electricity cut off, equipment noise, and ceiling leak. Moreover, the occupants' feedback regarding these issues was collected based on location or space in the building and time of year measured on a monthly basis. Based on the frequency of the complaints and location, it was possible to identify equipment issues serving that area. For instance, higher frequency of "too hot" issues in May, June, July, August most likely refers to HVAC equipment issues. The occupants took the survey once to provide their feedback for one year with monthly breakdown.

However, the results showed that the occupants only provided general feedback based on their complaints or maintenance issues for the year they have asked. They could not provide the timing of the maintenance issues with monthly breakdown.

In light of these facts, occupant feedback in this study is aimed to be collected by a short survey focusing on occupants' comfort level with the building performance experience. Since the focus of the case study is on HVAC equipment, the multiple-choice thermal comfort question was developed as follows:

Q1. Please indicate your annual thermal comfort level considering space (room/office area/lab etc.) where you spent most of your time in the building, on a scale of 1 to 5. (1 represents bad, 5 represents excellent)

1- Bad	*2- Poor*	*3- Average*	*4- Good*	*5- Excellent*

Following this, the second question is open-ended and requests the occupants' response for any feedback regarding maintenance performance or ongoing issues.

Q2. Please provide your feedback regarding your answer in question 1 with specific information that you would like to provide for any thermal comfort-related maintenance issues.

The results of the first question are planned to be analyzed by quantifying the mean of answers. Since the second question comprises qualitative responses, any possible trend of similar feedback, such as cold issues during the winter season, frequent ceiling leak or equipment noise, are aimed to be identified by content analysis and the frequency of the feedback based on equipment type.

Conducting a survey for a single piece of equipment or a single maintenance issue would not be feasible, with the opportunity to collect very limited information. Any effort gathering occupant feedback would need to be more comprehensive, as utilized in previous research efforts, including all types of maintenance issues (Goins & Moezzi, 2012). While this is acknowledged, it is worth mentioning that the main point of utilizing the “occupant feedback” variable in this study is to emphasize its importance and value in the CA process. In addition, the developed short survey in the illustration is a preliminary effort for collecting occupant feedback and the development of an occupant survey for gathering maintenance feedback could be an additional future research study with a comprehensive approach on the data analysis such as analyzing and integrating qualitative and quantitative results.

3.3.1.5. Preventive Maintenance Cycle

Preventive maintenance is regularly performed maintenance to improve equipment performance and prolong service life. For instance, a filter in an AHU is replaced every 3 or 6 months and replacement is considered part of preventive maintenance practices (Wang & Hong, 2013). Several studies in the literature focus on the benefits of preventive maintenance on the performance of equipment, effective scheduling of preventive maintenance, and fault detection aspects of preventive maintenance (Kwak et al., 2004; Wiggins & Brodrick, 2012). Au-Yong et al. (2014) studied the impact of HVAC performance on occupant satisfaction. Their study revealed that appropriate preventive maintenance strategies have a positive impact on occupant comfort and satisfaction. It’s beyond dispute that preventive maintenance is an essential piece of effective maintenance practices. A robust preventive maintenance program will increase the longevity of equipment as well as buildings and their systems.

Given these, “preventive maintenance cycle” is considered one of the variables representing the condition of the equipment in the developed CA framework. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 180-2018: “Standard practice for inspection and maintenance of commercial building HVAC systems” is utilized as a base standard for the preventive maintenance practices in this study.

ASHRAE is a global organization focusing on building systems, energy efficiency, indoor air quality, and sustainability with the mission of continuous education, research, and industry standards development (ASHRAE, 2020). ASHRAE 180-2018 comprises the standard practice for inspection and maintenance of HVAC equipment in buildings to provide consistency in maintenance practices and improve thermal comfort, energy efficiency, and indoor air quality in buildings.

The total number of maintenance activities annually in the standard is accepted as the benchmark value. The annual number of preventive maintenance work orders compiled from the CMMS database was compared to the benchmark value. In other words, the ratio of the equipment's annual preventive maintenance work orders to the total number of preventive maintenance activities recommended in ASHRAE Standard 180-2018 were found and utilized as the “Preventive Maintenance Cycle” condition variable in the proposed CA framework. The computation of the preventive maintenance cycle variable is presented in equation (4).

$$Preventive\ Maintenance\ Cycle\ = \frac{Annual\ \#\ of\ PM\ work\ orders}{Annual\ \#\ of\ PM\ activities\ in\ ASHRAE\ 180-2018} \quad (4)$$

Time is an important component in the maintenance process, and the effect of deferring any maintenance activity may have an additional impact on the condition of equipment. Deferring preventive maintenance activities may progressively accelerate the deterioration process. However, this study does not consider the progressive impact of missing preventive maintenance activities on the condition of equipment due to its limited scope.

To summarize the preceding discussion, the variables that are included in the proposed CA framework, their computations, and the origin of data with reference standards are presented in Table 8.

Table 8

Variables Considered in the Developed CA Framework

Condition Variables	Computation	Data Origin and Reference Standards
1- Mean Time Between Failures (MTBF)	$\frac{Annual\ Hours\ of\ Operation^{1a}}{Annual\ \#\ of\ Failures_{1b}}$	*1a*- FM data (based on building and equipment type, unit loading, geographic location) *1b*- CMMS data (annual # of work orders per equipment)
2- Age-Based Obsolescence	$\frac{Age^{2a}}{Expected\ Service\ Life_{2b}}$	*2a*- The age of the equipment at the time of CA *2b*- BOMA (suggested expected service life for HVAC equipment)
3- Facility Condition Index (FCI)	$\frac{Deferred\ Corrective\ Maintenance\ Cost^{3a}}{Total\ Replacement\ Value_{3b}}$	*3a*- FM data (corrective maintenance backlog) *3b*- FM data (the cost of replacing the equipment without considering any wear and tear)
4- Occupant Feedback	*The analysis of occupant satisfaction survey data regarding building maintenance* ^{4a}	*4a*- Occupant satisfaction survey focusing on the building maintenance performance
5 - Preventive Maintenance (PM) Cycle	$\frac{Annual\#\ of\ PM\ \ work\ orders^{5a}}{Annual\ \#\ of\ PM\ activities\ in\ ASHRAE\ 180-2018_{5b}}$	*5a*- CMMS data (annual # of PM per equipment) *5b*- ASHRAE 180-2018 (suggested annual # of PM in the standard)

3.3.2. Development of Condition Scales

The five-point condition rating scale: bad, poor, average, good, and excellent is used to identify equipment conditions in this study. The condition scale was then utilized in the application of fuzzy sets theory to obtain corresponding values of equipment condition in a numerical representation. The condition scale utilized in this study is presented in Figure 10.

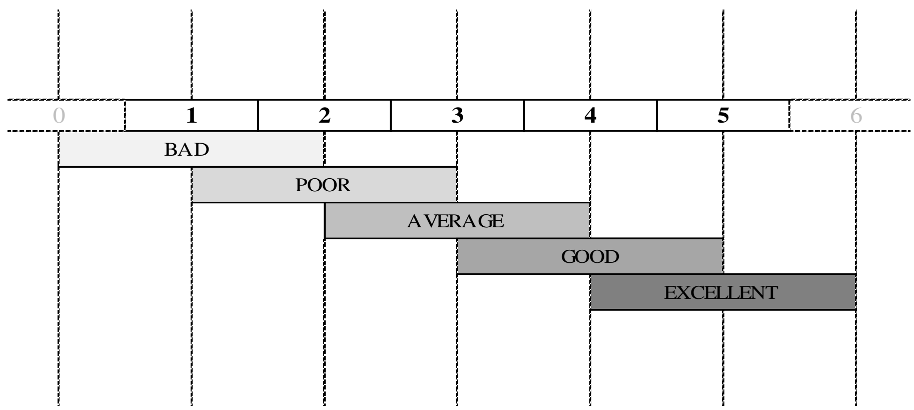

Figure 10

Condition rating scale used in this study

Even though the utilized scale is referred to as a five-point scale, the corresponding values of each condition refer to a set of numbers represented in Figure 10. For example, the "average" condition numerically comprises the set of numbers between 2 and 4, where the "good" condition comprises the set of numbers between 3 and 5. The set of numbers can be mathematically represented as follows for "average" and "good" condition examples:

$f(x) = 2 < x < 4$, where x represents "average" condition,

$f(x) = 3 < x < 5$, where x represents "good" condition.

Based on these, any number between 3 and 4 would refer to both "average" and "good" conditions, in other words, they overlap. Linguistically, any condition between average and good can be expressed as “above average” or “pretty good”. However, the definition of these expressions may change from person to person, including subjective judgment with inconsistency. Subsequently, fuzzy sets theory aids in translating linguistic definitions into numerical representations with their degree of memberships. As such, the numerical representation of any condition has varying degrees of memberships in the fuzzy sets. Based on the identified range of fuzzy sets for each condition, crisp values such as 1,2,3,4, and 5 best correspond to the related condition. For instance, 3 best corresponds to “average” condition, where 4 best corresponds “good” condition. Any value between 3 and 4 is identified with the degree of its membership (using a range of 0 to 1), such as 0.25 membership of average condition and 0.75 membership of good condition. Details of the membership concept of fuzzy sets theory are provided in section 3.3.3.

The values of condition variables best correspond to condition definitions are identified based on different data sources, as presented in Table 8. The condition variables identified in this study include equipment specific and general variables. MTBF and preventive maintenance cycle variables can be treated as equipment specific, where aged-based obsolescence, FCI, and occupant feedback are general variables, which is important in the development of condition scales for individual variables. As mentioned earlier, based on equipment and building type, condition variables might vary as well as their best corresponding values to condition definitions. This study focuses on using multiple variables for the condition assessment considering failure trends, cost, deterioration, human perspective, and maintenance practices, which can be represented with other variables for different building equipment. While acknowledging that the best corresponding values of condition variables to bad, poor, average, good, and excellent condition are determined with different methods in this study.

Expert opinion is utilized in determining the relation of MTBF values with the condition definitions. In other words, expert opinion is needed to determine the actual MTBF hours for each condition definition as best corresponding values such as: 1241 hours best correspond to average condition. The identified values of MTBF for the condition definitions are equipment specific in the case study example and based on equipment type, working hours and operating conditions MTBF might vary.

For the age-based obsolescence condition variable, the condition scale is adapted from a comprehensive study by Grussing (2014), performed for the life cycle asset management methodologies for buildings. The condition index and age/expected service life curve in their study is presented in Figure 11. The curve fits the concept of considering functional loss based on age and expected service life in the proposed CA framework. Their study developed the curve based on the Weibull probability distribution model for condition degradation of building systems over time identified in Grussing et al.'s study (2006).

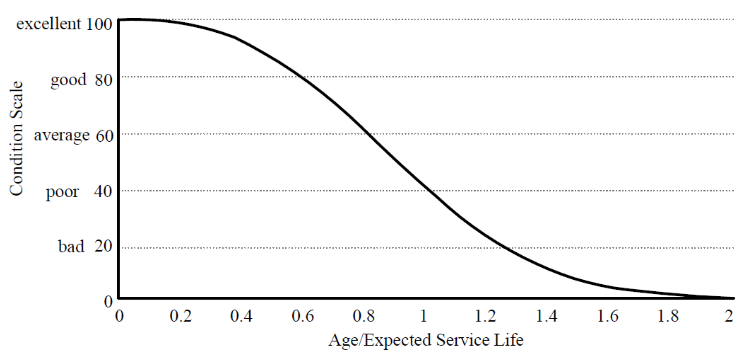

Figure 11

Condition index and age-based obsolescence curve adapted from Grussing (2014, with the permission of American Society of Civil Engineers (ASCE)[2])

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[2] The original material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers. The original material may be found at https://doi.org/10.1061/(ASCE)IS.1943-555X.0000157

In the computation of the curve, age and the expected service life of the building components are considered as main indicators with respect to the condition index of 0 to 100. Where 100 refers to no obsolescence and 0 refers to total deterioration, (Grussing, 2014). While adapting the curve, the condition index in the y axis is normalized to the five-point condition scale utilized in this study. The 0-100 scale is normalized to a bad, poor, average, good, and excellent condition scale, with 20 referring to "bad" condition and 100 referring to "excellent" condition. Since this study's condition scale is referred to a five-point scale, the normalized values of Grussing's condition index utilized in this study follow the same five-point interval. Therefore, value 20 in the Grussing's condition index refers to bad condition (numerical value 1) in the utilized condition scale of this study.

Although, the FCI concept has inconsistencies within various computations of deferred maintenance, this study considers deferred corrective maintenance activities in FCI computation. The FCI concept is first introduced by Rush in 1991 and within three decades since its first introduction, scales ranging from three levels to five levels have been used. This study utilized the five-level condition scale of FCI, which is consistent with the logic and structure of the proposed CA framework. The ratio of the deferred maintenance cost to total replacement value ranges from zero to 100 percent, the five-level condition scale of FCI adapted in this study is: good (0-5%), fair (6-10%), poor (11-30%), critical (31-50%), and divest (51-100%) based on the original formula and scale concept developed by Rush in 1991. The lower the value of FCI reflects the better condition within different intervals in the scale considering the exponential impact of deferred maintenance.

The best corresponding values of occupant feedback variable to condition definitions are determined based on the same five-point scale used in the survey questionnaire. As mentioned previously, the presented survey questionnaire for gathering occupant feedback in this study is a preliminary effort emphasizing the importance of utilizing occupant feedback in the CA processes. Lastly, for the best corresponding values of preventive maintenance cycle variable, ASHRAE standard 180-2018 is utilized as a benchmark for the excellent condition. The total annual number of preventive maintenance activities for the water-cooled chiller is obtained from the standard and that number is assigned as the best corresponding value for excellent condition. Since preventive maintenance practices are critical for the longevity of the equipment and the full application of suggested preventive maintenance activities in ASHRAE 180-2018 is determined as the establishing value for excellent condition. The following values of preventive maintenance cycle that best correspond to the good, average, poor, and bad conditions are determined by the researcher with equal intervals. Table 9 represents the values best corresponding to condition definitions for each variable in the proposed CA framework.

Table 9

The values best corresponding to condition definitions for each variable

Condition Definition	MTBF (hours)	Age-Based Obsolescence (Grussing, 2014)	FCI	Occupant Feedback (mean of the occupant answers)	Preventive maintenance cycle (based on ASHRAE 180-2018)
Bad	620.5	1.25	51-100 %	1	6
Poor	886.4	1.00	31-50%	2	11
Average	1241	0.80	11-30%	3	17
Good	2068.3	0.60	6-10%	4	22
Excellent	6205	0.10	0-5%	5	28

3.3.3. Determination of Membership Functions and Fuzzification

Membership function, which is a fundamental concept of fuzzy sets theory, is the numerical description of the relation of variables with the condition scale (Ross, 2010). Membership functions provide the numerical representation of a relationship such as "0.8 grade or degree of membership" instead of "very good" or "very poor" that identifies the value of belonging for that variable in the condition scale. The shape of the membership function varies based on the interval and the upper and lower bound values for each variable. Even though there are no certain rules or guidelines nor a consensus for generating the appropriate membership function, it is recommended that the generation of the membership functions should be flexible (Medasani et al., 1998). Ross (2010) suggested six methods to assign membership values or functions: (i) intuition, (ii) inference, (iii) rank ordering, (iv) neural networks, (v) genetic algorithms, and (vi) inductive reasoning. In addition, there are two main approaches for developing the membership function in the literature: expert-driven and data-driven (Fwa et al., 2004; Fayek, 2020; Mitra et al., 2010; Ross, 2010; Sasmal et al., 2012;).

Triangular and trapezoidal-shaped membership functions are the most commonly used, based on their simplicity and flexibility in several kinds of problems (Fayek, 2020). In addition, Barua et al., (2013) mentioned the use of trapezoidal and triangular membership functions were "practical" compared to other different shapes. According to Norwich and Turksen (1984), the membership values should be defined on intervals. In their study, a method called "direct rating procedure" was identified, where the subject is presented with a series of values and then the membership degree to rate each value is determined (Norwich & Turksen, 1984).

In this study, single values that best correspond to the condition definitions (bad, poor, average, good, and excellent) are determined in Table 3, and these values have the full membership for the corresponding conditions. As such, for example, in the "occupant feedback" condition variable, mean value 3 best corresponds to the "average condition" of the equipment with full membership, and mean value 4 best corresponds to the "good condition" with full membership. Occupant feedback values between 3 and 4 are associated with the "degree of membership" or "the grade of membership" with corresponding numbers from 0 to 1, based on the membership function.

As a graphical representation of the membership function concept, Figure 12 shows a triangular membership function for the occupant feedback variable with corresponding intervals of condition scale: bad, poor, average, good, and excellent. In the figure, the y axis represents the membership values where the x axis represents the corresponding values of the variable. Based on the membership function in Figure 12, a mean value of 3.7 occupant feedback has 0.7 degree of membership to good condition and 0.3 degree of membership to average condition, which can be linguistically expressed as "slightly below good condition" or "considerably above average condition".

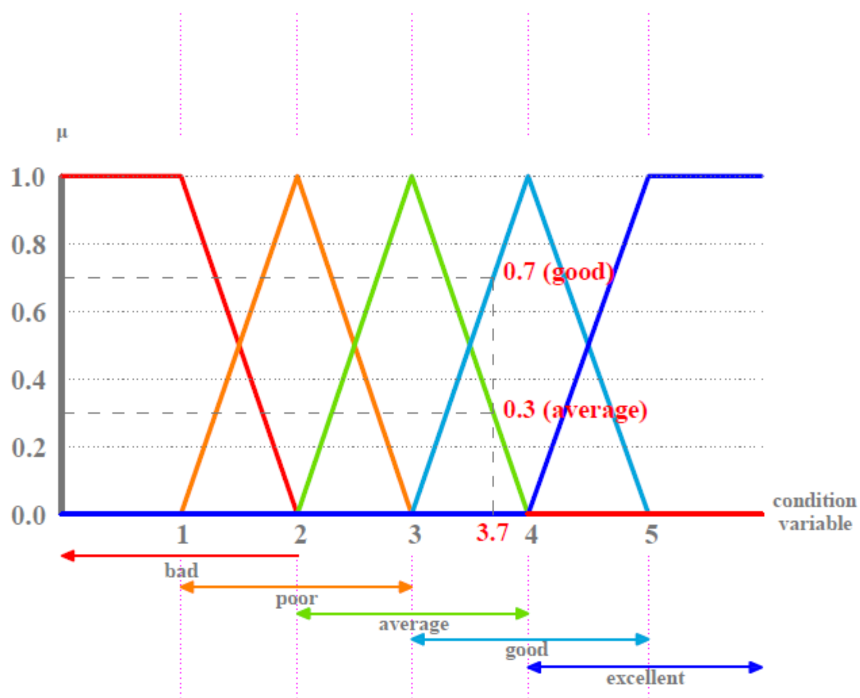

Figure 12

Example of a triangular membership function with the corresponding condition scale

As these different linguistic phrases indicate, it is not possible to describe the relation of the value 3.7 to the condition scale with a single linguistic expression, this is where fuzzy sets theory is useful to express this relation mathematically. Moreover, since there is no membership for the other conditions: bad, poor, excellent; the degree of membership of value 3.7 to these conditions will be zero. In light of these, the mathematical representation of the membership function as a discrete fuzzy set for the value of 3.7 is as follows:

$$f\ (3.7)\ =\ \{\ \frac{0.00}{1}\ +\frac{0.00}{2}\ +\ \frac{0.30}{3}\ +\ \frac{0.70}{4}\ +\ \frac{0.00}{5}\ \}$$

The numbers in the numerator represent the degree of membership and the denominators represent the best corresponding value of the occupant feedback for each condition, respectively. The division and addition notation in the membership function are only used for illustration of the discrete fuzzy set, and they do not represent the binary operations of addition and division. The calculation of the function, which is the defuzzification step in fuzzy sets theory, is explained in section 3.3.4

Even though the best corresponding values regarding the condition definitions are determined for membership functions in Table 3, the relation of the condition definitions with respect to crisp numbers are still not deterministic and have uncertainty. In addition, regarding Figure 4, each condition is identified by a set of triangular or trapezoidal areas, as a result of the subjectivity in the linguistic expressions. For instance, the mean value of occupant feedback 3 is determined as the best corresponding value for “average condition”; however, any mean value of occupant feedback within 2 and 4, under the triangular area of the function are still considered in “average condition” with partial belonging. Given that, the process of expressing a single value with corresponding scale in the form of discrete fuzzy sets is identified as fuzzification in fuzzy sets theory. However, while fuzzification is referred to as converting crisp values into fuzzy values (Ross, 2010), it is clear that the relation of the crisp values to the condition are not deterministic and in the condition scale crisp values have uncertainty arising from the linguistic and subjective definitions of each identified condition.

The membership function used for the variables of this study is represented in equation 5, and the triangular and trapezoidal shapes of the membership function are illustrated in Figure 13 and Figure 14, respectively. The values a, b, and c in the equation represent the boundaries of membership functions in fuzzy sets theory. The triangular and trapezoidal membership functions are selected in the fuzzy sets theory application of this study, which is explained in detail in section 3.3.4.

$$f\ (x|a,b,c) = \begin{cases} 0 & for\ b < x < a, \\ \dfrac{2(x-a)}{(b-a)\ (c-a)} & for\ \ a \leq\ x\ \leq c, \\ \dfrac{2(b-x)}{(b-a)(b-c)} & for\ c < x \leq b. \end{cases} \qquad (5)$$

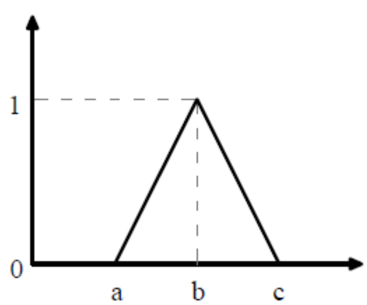

Figure 13

Triangular membership function

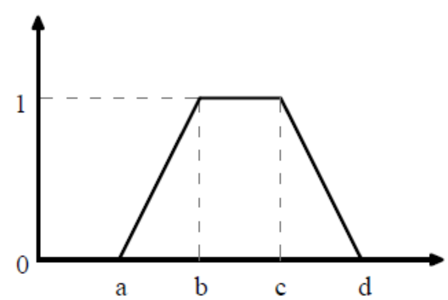

Figure 14

Trapezoidal membership function

3.3.4. Defuzzification and Obtaining the Condition Rating

Defuzzification, which is the last step of implementing the fuzzy sets theory, produces a quantifiable value by converting membership values into a single scalar quantity (Ross, 2010).

Several methods are described in the literature for defuzzifying fuzzy output. Ross (2010) and Hellendoorn and Thomas (1993) focused on four methods: (1) max membership principle, (2) centroid method, (3) weighted average method, and (4) mean max membership. While there is not a clear guideline in the literature for the selection of a defuzzification method, Hellendoorn and Thomas (1993) identified some criteria for defuzzification methods, including: continuity, disambiguity, plausibility, computational complexity, and weight counting. These criteria consider the impact of the method on the final output. For instance, continuity, is described as "a small change in the input of the fuzzy controller should not result in a large change in output" and computational complexity emphasizes the importance of the practical applications of methods (Hellendorn & Thomas, 1993, p. 115).

The weighted average method is the most frequently used defuzzification method because of its computational efficiency and simplicity (Ross, 2010). Based on these, the weighted average method is the preferred defuzzification method in this study. The weighted average method uses the mean, or the centroids, of the respective membership functions in its computation. Including multiple variables with the goal of obtaining one single condition variable, defuzzification is an important step of the fuzzy sets theory application in the proposed CA framework that allows combining several fuzzy variables into one single rating. For example, for obtaining one single number with the following two fuzzy discrete sets, the application of defuzzification with the weighted average method is presented below.

$$f\,(3.7) = \left\{ \frac{0.00}{1} + \frac{0.00}{2} + \frac{0.30}{3} + \frac{0.70}{4} + \frac{0.00}{5} \right\}$$

$$f\,(24) = \{ \frac{0.00}{1} + \frac{0.00}{2} + \frac{0.00}{3} + \frac{0.67}{4} + \frac{0.33}{5} \}$$

$$Z^* = \frac{[(3\,x(0.30)) + (4\,x(0.70)] + [(4\,x(0.67)) + (5\,x(0.33)]}{(0.30 + 0.70 + 0.67 + 0.33)} = 4.015$$

**defuzzified value*

3.4. Implementation of the Proposed CA Framework

The CMMS and FM data of the chiller equipment utilized in the case study were collected from a higher education institution in the state of Colorado. The characteristics of the building and the chiller are given in Table 10.

Table 10

Characteristics of the case study building and the chiller

Building		**Chiller**	
Building Type	Office and Classroom	**Chiller Type**	Water-cooled condenser (Vapor compression – Screw)
Building Age	38 years	**Chiller Age**	8 years
Building Area	156.261 gross square feet	**Chiller Capacity**	200 tons

The CMMS data comprises the corrective and preventive work orders of the chiller. Corrective maintenance work orders related to the chiller's condition, such as pressure issues or loud noises, are included in the MTBF calculation of the case study. In addition, preventive maintenance work orders were utilized in the computation of the “preventive maintenance cycle” variable. Deferred maintenance cost, the total replacement value of the chiller, and the chiller's present age were obtained from the higher education institution's FM department. As mentioned earlier, occupant feedback was intended to be collected with a survey instrument; however, during this study's data collection process, most of the buildings in the state of Colorado, much like elsewhere across the globe, were not occupied due to the COVID-19 pandemic precautions and safety protocols. Therefore, an assumed value was utilized for the occupant feedback variable in this case study just to be able to show how the developed framework can be implemented.

The following subsections explain the development of the membership functions, fuzzification in discrete fuzzy sets, and defuzzification with the collected data in a brief case study. Development of the membership functions with the data is explained for each condition variable individually. The final step, defuzzification, illustrates how to obtain the condition rating as an output of the proposed CA framework.

3.4.1. Development of Membership Functions

3.4.1.1. Membership Function for the Mean Time Between Failures (MTBF) Variable

The membership function of the MTBF is developed based on expert opinion. The number of failures corresponding to each condition level was determined by the higher education institution's facility manager. The researcher acknowledges that the feedback of multiple experts would increase the accuracy of the corresponding membership functions; however, in this case study, the feedback of one expert was utilized for illustration purposes.

The chiller's working hours for the calendar year are reported as 17 hours per day (5:00 am - 10:00 pm) from the FM department; and consequently, the chiller's annual working hours are 6205 hours (17 hours x 365 days = 6205 hours annually). As given in equation (1), the annual working hours as a ratio to the annual number of failures is the MTBF condition variable in this study. Even though the expert opinion provides the best corresponding annual number of failures per each condition, the boundaries in the linguistic definitions are uncertain due to these definitions' subjectivity. The identified annual number of failures for each condition are utilized in the MTBF calculation in equation (1) for obtaining best corresponding values of MTBF for each condition definition. The membership functions regarding bad, poor, average, good, and excellent conditions of MTBF are presented in Figure 15. Since the best corresponding values of the MTBF in condition descriptions are identified with a single value in Table 9, the shape of the membership function is triangular, as that single value refers to the peak value in the function with full membership. Even though each function's shape is triangular, each triangle's interval is not the same or equally divided.

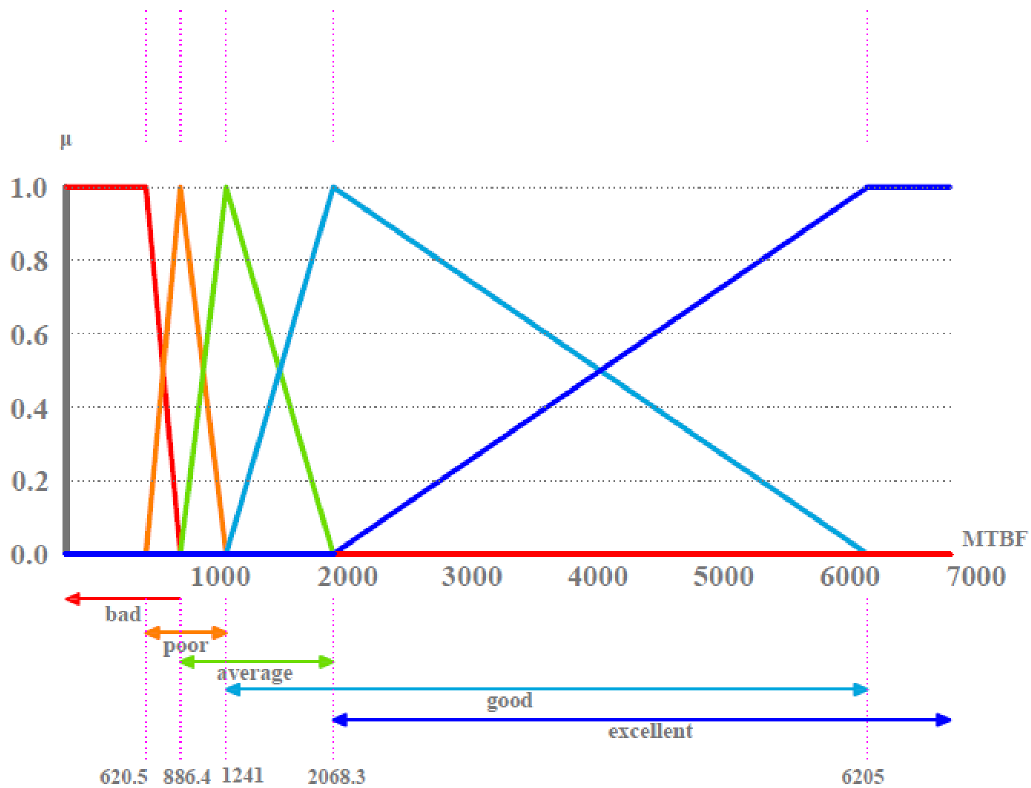

Figure 15

Membership functions of the condition scale for MTBF

3.4.1.2. Membership Function for the Age-Based Obsolescence Variable

Grussing (2014) emphasized consideration of the service life in the life cycle asset management for buildings. Because of the complexity of building systems and equipment, a building has increased maintenance needs as its age increases. In addition, several factors such as climatic conditions, operation and maintenance practices, and occupancy can contribute to the uncertainty in these needs, which substantially impacts the lifecycle of buildings, systems, and equipment (Grussing, 2014).

The estimated service life for the water-cooled chiller is determined as 20 years in the BOMA (2010) reference. When the chiller's remaining service life is 20 years, the present age is 0, and the corresponding condition is “excellent”. Based on the adapted curve when the equipment reaches to the estimated service life of 20 years its condition is considered as poor. As mentioned earlier, most equipment might serve more than its estimated life depending on the operations and maintenance practices. In light of these, the membership function of the age-based obsolescence variable is presented in Figure 16. Similar to the MTBF membership functions, the values of the age-based obsolescence variable best corresponding to the condition descriptions are identified with a single value in Table 9. The shape of the membership function is triangular, each triangle's interval is not the same or equally divided.

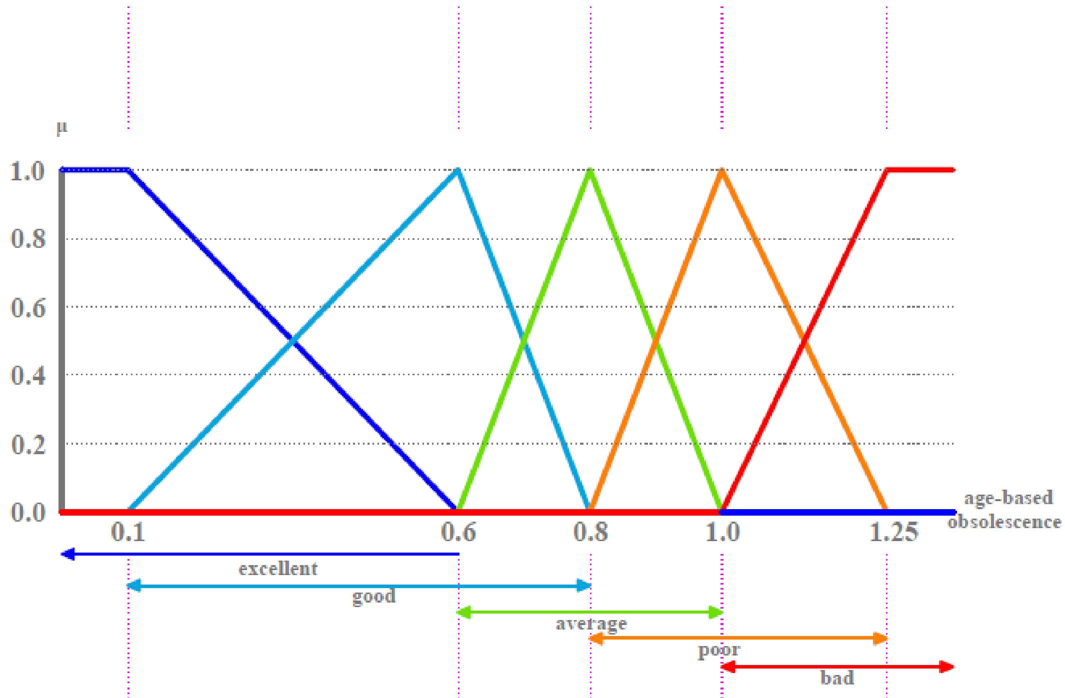

Figure 16

Membership functions of the condition scale for Age-based Obsolescence

3.4.1.3. Membership Function for the Facility Condition Index (FCI) Variable

The definition of the deferred maintenance cost in this study considers the costs of deferred corrective maintenance activities regarding equipment condition. The FM department where the data were collected reported that the estimated total replacement value for the water-cooled chiller is $ 285,000. When the chiller's deferred maintenance cost is $ 285,000, which is the total replacement value, the corresponding condition is “bad”. Conversely, if the deferred maintenance cost is $ 0 the corresponding condition is “excellent”. The higher the deferred maintenance cost, the poorer the condition in the scale. In addition, Facilities Maintenance & Repair Costs with RS*Means* Data (2020) can be used to identify the total replacement value of the equipment subject to CA.

The membership function of the FCI condition variable is presented in Figure 17. It is important to note that the corresponding percentages of the ratio of deferred maintenance cost to total replacement value in condition definitions refer to an interval or a set of values; therefore, the shape of the membership function is trapezoidal. In other words, the peak values in the membership function with the full membership fall into the interval of percentages such as 0-5% or 6-10%.

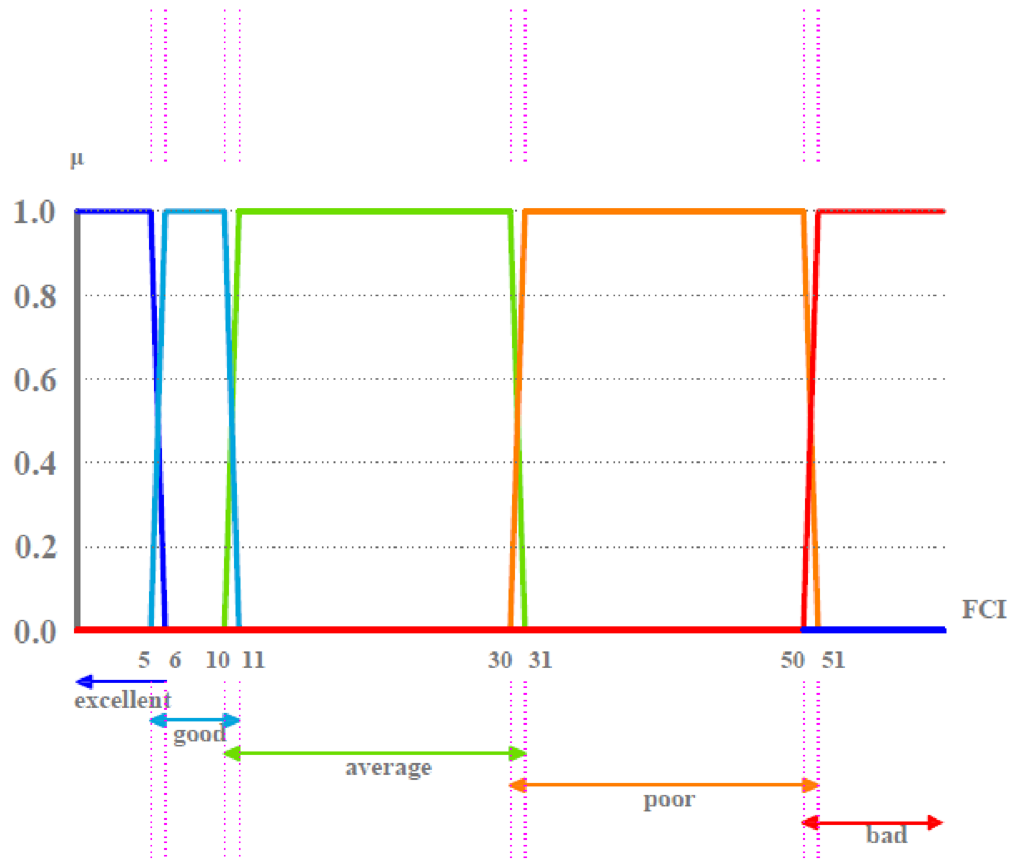

Figure 17

Membership functions of the condition scale for Facility Condition Index (FCI)

3.4.1.4. Membership Function for the Occupant Feedback Variable

As discussed earlier, the occupant feedback condition variable is intended to be identified through a short occupant survey. Even though the survey could not be performed in the context of this study, the five-point Likert scale used in the survey is directly corresponds to values of condition scale for "occupant feedback". For simplicity and consistency purposes, the membership functions for the "occupant feedback" condition variable are developed as triangular functions, presented in Figure 18.

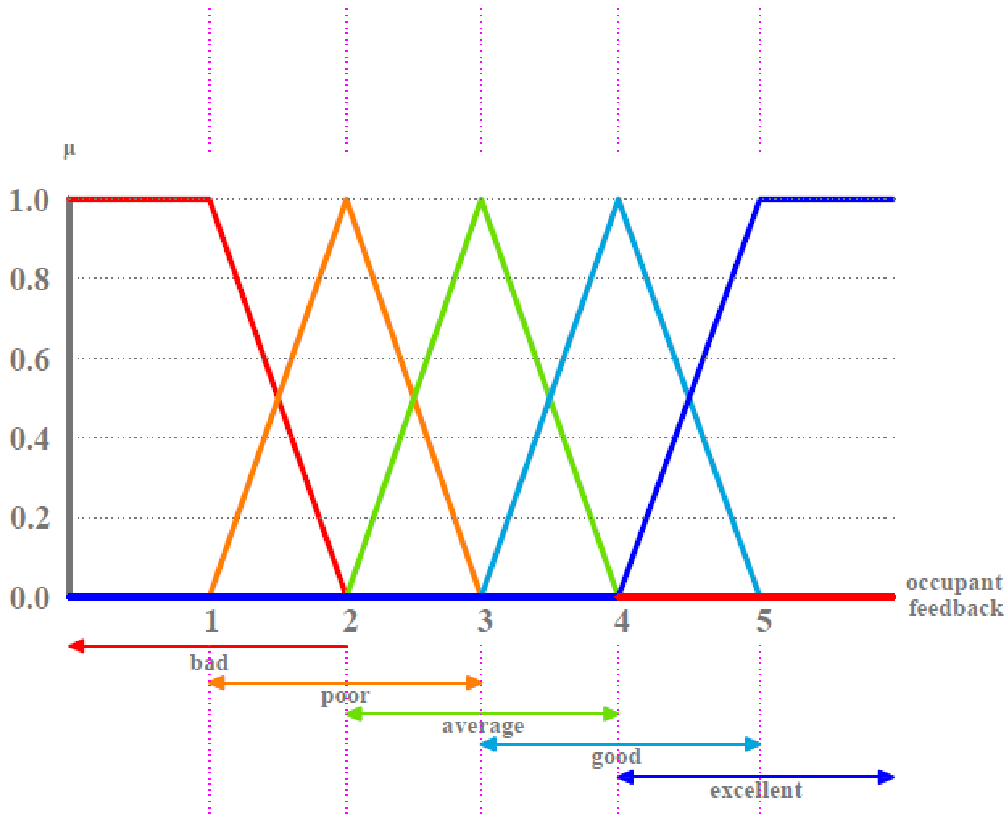

Figure 18

Membership functions of the condition scale for Occupant Feedback

3.4.1.5. Membership Function for the Preventive Maintenance Cycle Variable

Membership functions for the preventive maintenance variable are developed based on the maintenance cycles identified in the ASHRAE standard 180-2018. When the number of preventive maintenance activities performed for the chiller is 28 annually, which is the total value obtained from the standard, the corresponding condition is “excellent”. For simplicity and practicality, the corresponding condition values are assumed within equal intervals, as presented in Figure 19. It is important to acknowledge that the input of expert opinions for the preventive maintenance cycle is important. and the preventive maintenance numbers obtained from the standard might be discussed with the maintenance supervisor or FM of the organization.

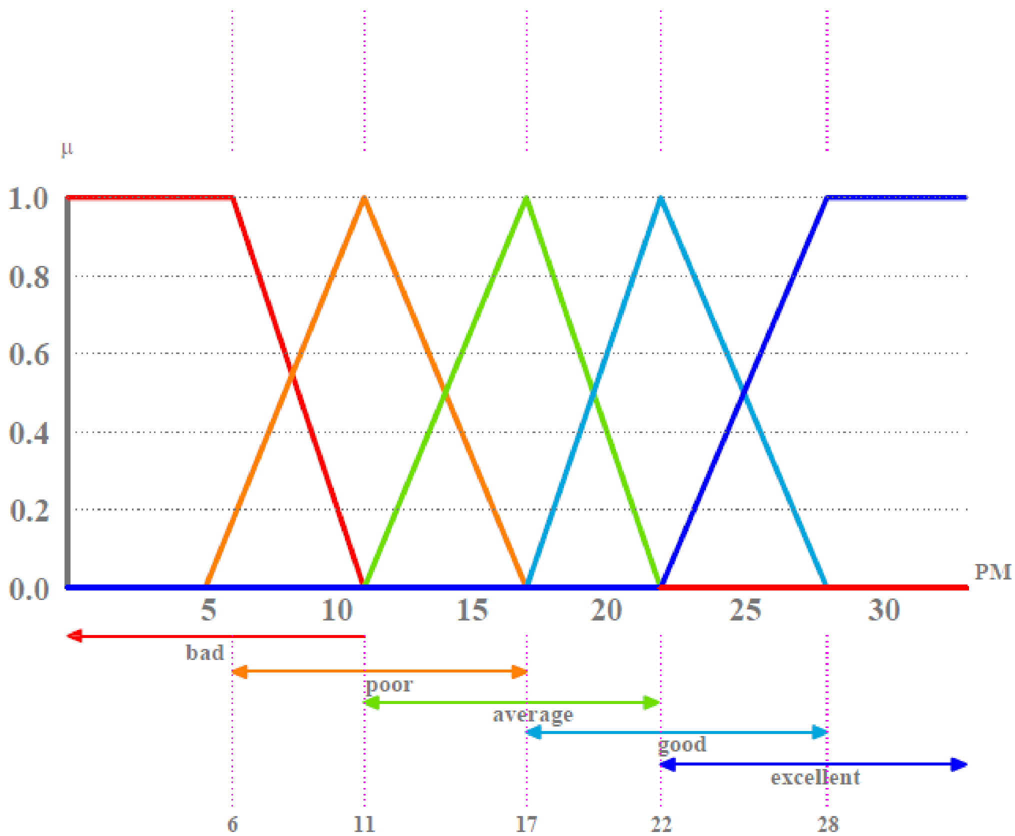

Figure 19

Membership functions of the condition scale for Preventive Maintenance Cycle variable

3.4.2. Fuzzification in Discrete Fuzzy Sets

The identified condition variables of the proposed framework were computed based on the collected data and computations detailed in the methodology section.

a. Mean Time Between Failure (MTBF)

Annual working hours = 17 hours/day x 365 days = 6205 hours

The annual number of failures in CMMS data = 4

MTBF = 6205 / 4 = **1551 hours (linguistic condition "above average")**

b. Age-based obsolescence

Estimated Service life = 20 years

Present Age = 8 years

Age-based obsolescence = 8 / 20 = **0.4 (linguistic condition "very good")**

c. Facility Condition Index (FCI)

Deferred Maintenance Cost = $4,500

Total Replacement Value = $285,000

FCI = (4,500 / 285,000) x 100 = **1.6 % (linguistic condition "excellent")**

d. Occupant Feedback

The assumed mean of the occupant feedback is **4.2** on the Likert scale. **(linguistic condition "above good")**

e. Preventive Maintenance Cycle

The annual number of preventive maintenance activities conducted = 24

ASHRAE 180-2018 annual number of preventive maintenance activities recommended = 28

Preventive Maintenance Cycle = 24 (linguistic condition "very good")

The chiller's measured condition for each variable and the discrete fuzzy sets representation based on the membership functions of each condition variable are presented in Table 11.

Table 11

Chiller condition data and fuzzy discrete sets

Condition Variables	**Condition Data**	**Fuzzy Discrete Sets**
MTBF	1551 hours	$f\ (1551)\ =\ \{\ \frac{0.00}{1}\ + \frac{0.00}{2}\ +\ \frac{0.60}{3}\ +\ \frac{0.40}{4}\ +\ \frac{0.00}{5}\ \}$
Age-based obsolescence	0.4	$f\ (0.4)\ =\ \{\ \frac{0.00}{1}\ + \frac{0.00}{2}\ +\ \frac{0.00}{3}\ +\ \frac{0.60}{4}\ +\ \frac{0.40}{5}\ \}$
FCI	1.6%	$f\ (1.6)\ =\ \frac{0.00}{1}\ + \frac{0.00}{2}\ +\ \frac{0.00}{3}\ +\ \frac{0.00}{4}\ +\ \frac{1.00}{5}$
Occupant Feedback	4.2	$f\ (4.2)\ =\ \{\ \frac{0.00}{1}\ + \frac{0.00}{2}\ +\ \frac{0.00}{3}\ +\ \frac{0.80}{4}\ +\ \frac{0.20}{5}\ \}$
Preventive Maintenance Cycle	24	$f\ (24)\ =\ \{\ \frac{0.00}{1}\ + \frac{0.00}{2}\ +\ \frac{0.00}{3}\ +\ \frac{0.67}{4}\ +\ \frac{0.33}{5}\ \}$

3.4.3. Defuzzification and Obtaining the Condition Rating

Based on the membership functions, fuzzy discrete set representations of the five variables, and the weighted average defuzzification method, the chiller's obtained condition rating value is 4.27 on the 1 to 5 scale, with 1 representing bad and 5 representing excellent. The weighted average method uses the degree of membership values as the weight of each condition variable.

$$CR = \frac{[3x(0.6)+4x(0.4)]+[4x(0.6)+5x(0.4)]+[+5x(1.0)]+[4x(0.8)+5x(0.2)]+[(4x(0.67)+5x(0.33)]}{0.6+0.4+0.4+0.6+0.3+0.7+0.8+0.2+0.67+0.33} = 4.27$$

Considering the data for the brief case study, corresponding linguistic condition for the condition variables are presented in Table 12.

Table 12

Linguistic condition for condition variables

Condition Variables	**Linguistic condition**
Mean time between failures (MTBF)	Above average
Age-based obsolescence	Very good
Facility Condition Index (FCI)	Excellent
Occupant Feedback	Above good
Preventive Maintenance Cycle	Very good

It is clear that without the mathematical representation of fuzzy sets theory, it is not possible to obtain one single definition expressing the overall condition of the chiller. Utilizing fuzzy sets theory, the obtained condition value 4.27 can be expressed as "slightly above good" if there is a need to use any linguistic definitions.

3.5. Discussion, Conclusions, and Future Research

The effectiveness of decisions for building maintenance activities often relies on condition information, which involves subjectivity and uncertainty as part of the visual inspection or walk-through survey processes. Common linguistic definitions of CA; namely bad, poor, average, good, and excellent are subject to human judgment, and the association of these definitions to the condition may vary from one expert to another (Lee & Aktan 1997; Uzarski et al., 2002). In addition, the use of these definitions in CA may lead to misinterpretation.

This study developed a less subjective and more quantitative CA framework, as an alternative to visual inspections, to obtain a condition rating value for building maintenance in FM. Furthermore, this study illustrated an example implementation of the framework to heating, ventilating, and air conditioning (HVAC) equipment using a brief case study. Mean time between failures (MTBF), age-based obsolescence, facility condition index (FCI), occupant feedback, and preventive maintenance cycles were identified as variables that can be used to obtain the proposed condition rating value. Along with these variables, fuzzy sets theory, which deals with imprecise, uncertain, and ambiguous judgments with the membership relations, was utilized to obtain a less subjective and quantitative condition rating value.

The values utilized in the brief case study are representative measures for implementing fuzzy sets theory. In identifying the membership functions, several individual techniques were utilized such as using CMMS data, expert opinion, occupant feedback, and industry standards. The effective use of CMMS and FM data is promising in developing resource-efficient building maintenance and FM strategies. This study is an important step in utilizing CMMS data for CA practices. It also reveals the possibility of using CMMS data in FM, in addition to tracking daily activities or work orders.

This study contributes to the body of knowledge in the FM domain by introducing a framework that uses multiple variables in the CA process (as opposed to a single source of information such as visual inspections) and utilizes fuzzy sets theory in the context of building maintenance and FM. It is worth mentioning that every variable identified in this study might be the topic of an individual future research study to further refine the variables use. For instance, the development of the occupant feedback survey for maintenance issues might be a more comprehensive effort focusing on several building systems. Moreover, other variables such as MTBF and preventive maintenance cycle might be studied in the context of different building equipment and building types. For example, the condition variables or condition rating scale for building equipment in a healthcare facility might be different from similar equipment in an office building.

The proposed CA framework does not require additional resources or funding, which is a significant constraint in existing FM practices; the framework merely requires applying the principles of fuzzy sets theory to readily available data to obtain a condition rating. The obtained condition rating may potentially benefit FM departments by helping to prioritize maintenance activities, justify maintenance budget requests, and support decision-making processes. The issue of subjectivity in visual inspection and walk-through surveys is addressed by using multiple variables and by applying fuzzy sets theory. Moreover, the integration of CMMS data, expert opinion, occupant feedback, and industry standards provides a systematic approach in the CA process, which also increases the efficiency and reliability of the process outcome.

Further studies can be extended to include other building equipment in the CA process. It is worth mentioning that different building equipment or systems may require considering additional factors, as the identified factors for HVAC equipment might not be applicable for other equipment or systems. For example, while the mean time between failures (MTBF) is a variable that is relevant to the condition assessment of HVAC equipment, assessing a building façade may need a different variable that considers the climate or environmental factors. Moreover, future research efforts can focus on identifying additional condition variables for other building equipment or systems. The reliability of the obtained condition rating value in the proposed CA framework can be further investigated by comparing it to the outcome of traditional CA methods such as visual inspection or expert opinion. Future studies can also investigate if and how the condition rating obtained through the proposed framework can be used in conjunction with, and thus supplement, condition ratings obtained through visual inspections and walk-through surveys.

In addition, future studies can focus on the development of the membership functions for the proposed CA framework including several experts. The outcome of the different defuzzification methods can be investigated in applications of fuzzy sets theory. This study is a promising effort for future applications of fuzzy concepts in the CA, building maintenance and FM areas, providing a systematic and mathematical approach to linguistically ambiguous results.

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CHAPTER 4: A Multi-Criteria Decision-Making Approach for Building Maintenance Strategy Selection using Choosing by Advantages

4.1. Introduction and Purpose

The decision-making process in building maintenance is based on human judgment, with the influence of multiple individual variables affecting the final decision. Multi-criteria decision-making (MCDM) is a branch of operations research and management science that has numerous applications with different models in various areas (Munier et al., 2019). MCDM helps decision-makers rank and/or select alternatives with conflicting criteria within a systematic and structured process (Abdel-malak, et al., 2017).

Building maintenance decision-making in facility management (FM) is a complex process and requires the participation of several stakeholders such as the owner, facility managers, engineers, project supervisors, technicians, and occupants that makes the process even more complex (Arroyo et al., 2016). Moreover, the integration of various sources of information as well as considering multiple criteria is critical in building maintenance decision-making (Motawa & Almarshad, 2013) to increase the efficiency of decisions. Based on a comprehensive literature review, it is clear that current FM and building maintenance decisions are mostly made without a systematic process. In addition, experience-based and subjective decision-making, mostly with a large focus on funding availability, decreases the efficiency of final decisions in FM planning (Wang & Piao, 2019).

Maintenance activities are essential to promote longevity of the built environment as well as to support business continuity (Ko, 2009). Effective maintenance strategies sustain better condition levels that extend the service life of the built environment (Grussing & Marrano, 2007). The cost of maintenance activities is increasing which comprise the highest costs in FM activities (Lavy & Jawadekar, 2014). Additionally, the lack of systematic decision-making approaches in building maintenance and FM still exists, which are essential for developing resource effective maintenance strategies (Chen et al., 2018; Wetzel & Thabet, 2015).

Considering these facts, the main purpose of this study is to demonstrate a structured and systematic decision-making approach in building maintenance and FM by utilizing a MCDM method. The utilized decision-making method, CBA, provides a practical framework to decision-makers in FM with various backgrounds. The main advantage of CBA is that it allows for the identification of the most-value generating alternative in the absence of cost. In other words, the cost is defined as a constraint, not a value; thus, cost is a factor included in the decision-making process separately after the determination of other values. Other advantages of CBA are facilitating group decision-making and the ease of its structure for decision-makers.

This study benefits FM professionals by proposing a step-by-step decision-making approach that considers multiple criteria and their advantages. Moreover, by promoting the use of a structured and systematic decision-making method, this study supports the development of effective FM strategies that improve the outcome of maintenance decisions. For illustration purposes, the proposed MCDM method is implemented in a hypothetical decision-making problem for heating, ventilation and air conditioning (HVAC) equipment with the participation of the researcher and an FM executive.

4.2. Background

Building maintenance in FM has several constraints that affect the decision-making process, such as limited resources, cost and financial limitations, aging buildings, deferred maintenance backlog, and the complexity of making decisions in a resource-constrained environment (East & Liu, 2006; Kim & Ebdon, 2020; Kohler & Yang, 2007). Several previous research efforts have been undertaken with various MCDM methods to address these challenges. The background section reviews recent studies in building maintenance and MCDM, as well as applications of CBA. The background section also includes the motivation of this research.

4.2.1. Current Studies in Building Maintenance Strategy Selection And MCDM

In a recent study, Wang and Piao (2019) developed a maintenance policy selection framework with the integration of building information modeling (BIM), Analytical Hierarchy Process (AHP), and fuzzy MCDM that enables effective resource allocation. In addition, the MCDM approach was applied to maintenance strategy selection problem in different contexts such as oil refineries, municipal buildings, construction, manufacturing, and transportation (Bevilacqua & Braglia, 2000; Reichelt et al., 2008; Shafiee, 2015). These research efforts reveal the benefits of using MCDM in complex maintenance strategy selection problems such as providing a systematic approach, decreasing subjectivity, integrating qualitative and quantitative information, evaluation of social, technical, and economic factors, and enabling group decision-making.

In addition to the maintenance strategy selection, current study areas of MCDM in the context of building maintenance and FM are summarized in Table 13 chronologically.

Table 13

Recent studies in MCDM applied to the FM area

References	Focus of the study	MCDM method
Gilleard & Yat-lung (2004)	Benchmarking in FM	Analytical Hierarchy Process (AHP)
Zavadskas & Viluente (2012)	Decision support for the FM of a residential district	AHP and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

Jin Lin et al. (2015)	Procurement Strategy Selection in Building Maintenance Work	AHP
Cavalcante et al. (2017)	MCDM Model to Support Maintenance Planning in Residential Complexes	Preference ranking organization method for enrichment evaluation II (PROMETHEE II)
Carnero & Gómez (2017)	Preventive Maintenance Planning for Electric Power Facility	Multi-attribute Utility Theory (MAUT) and PROMETHEE
Chen et al. (2018)	Lighting Maintenance Decision-Making	AHP

A recent meta-review of 88 scientific publications presenting 25 methods showed the most common MCDM methods used in the construction management field are AHP and TOPSIS (Jato-Espino et al., 2014). Operations and manufacturing research areas have several applications of MCDM for facility layout design and facility location selection problems that are not in the context of this study (Ertuğrul & Karakaşoğlu, 2008; Chen et al., 2014; Chou et al., 2008; Farahani et al., 2010; Kahraman et al., 2003; Melo et al., 2007; Snyder, 2006).

As mentioned earlier, the recent research efforts have determined that MCDM provides a systematic and less subjective way of including several sources of information in the decision-making process. As such, the use of MCDM methods is promising in decision-making problems of FM. However, none of the recent efforts focused on the selection of repair or replace alternatives with respect to maintenance needs in the context of building maintenance and FM.

4.2.2. Choosing by Advantages (CBA) and its Applications

CBA is a new generation MCDM method developed by Jim Suhr in 1999 (Suhr, 1999). Instead of focusing on pairwise comparisons or weighing the criteria, CBA considers the importance of advantages of decision alternatives (Arroyo et al., 2015). The advantages of decision alternatives are "favorable dissimilarities in quality or difference in quantity between the characteristics of decision alternatives" (Suhr, 1999, pg.27) CBA is identified as a superior value-based, sound, and transparent decision-making method compared to other MCDM methods (Abraham et al., 2013). Cost is kept as a separate factor in CBA that is included in the process after the identification of the importance of advantages for each decision alternative. Prior application areas of CBA are limited to lean construction, structural and architectural design strategy selection, sustainable material and systems selection, tendering and bidding procedure, and subcontractor selection (Abraham et al.,2013; Arroyo, 2014; Arroyo et al., 2016; Demirkesen & Bayhan, 2019; Lee et al., 2010).

It is important to note that the terminology of CBA has differences compared to other MCDM methods, which are presented in the methodology section of this study. For example, "criterion" in other methods is identified as "factor" in the CBA method. For consistency in the rest of the study, "factor" is used to refer to an element or component of any decision that influences the final decision. In addition, the relative weights of the factors, which are included in most other MCDM methods, are not considered in CBA. In other words, the CBA method does not include assigning an individual number to represent the importance of each individual factor (Suhr, 1999).

Martinez et al. (2016) utilized CBA for the formwork system selection of an affordable housing project. Their findings revealed that CBA benefits the group decision-making approach, which is also important in the context of building maintenance and FM. Another recent study developed a decision-making framework with CBA to select safety technologies for highway construction (Nnaji et al., 2018). Their study emphasized the value-generating approach of CBA by eliminating the dominant effect of cost in the decision-making process. The ease and user-friendly structure of CBA was one of the highlights of their application as well.

Providing a practical framework, CBA has received increasing attention in architecture, engineering, and construction (AEC) areas. In addition, studies comparing the output of CBA and other MCDM methods reported that CBA is superior to other methods such as AHP, weighting, rating, and calculating (WRC), and best value selection (BVS) in terms of supporting collaboration among stakeholders, transparency, consistency, and decreasing subjectivity (Arroyo et al. 2015; Arroyo et al., 2016; Schöttle & Arroyo, 2017; Torres-Machi et al., 2019). The summarized findings are promising for utilizing CBA in maintenance decision-making problems in FM.

4.2.3. Research Motivation

The complexity of decision-making problems in building maintenance arises from the complexity of building systems as well as the need for considering multiple and conflicting factors in the process. Moreover, the decision-making process becomes more challenging when including several stakeholders evaluating the conflicting factors and decision alternatives jointly to obtain the best possible outcome. The motivation of this study is based on the need for a systematic and structured way of decision-making in building maintenance and FM. Adding onto an earlier study already identifying the factors to be utilized in the proposed MCDM approach (Besiktepe et al., 2020), this study presents the application of a MCDM method using those utilizing the identified factors.

After considering different MCDM methods applied in similar contexts, CBA was selected for the MCDM method used in this study. The practical structure and ease of use identified in recent studies are two of the many reasons for applying CBA as a decision-making method. Considering other MCDM methods, especially the ones with complex mathematical structures in operations research, CBA fits the various backgrounds of stakeholders in FM.

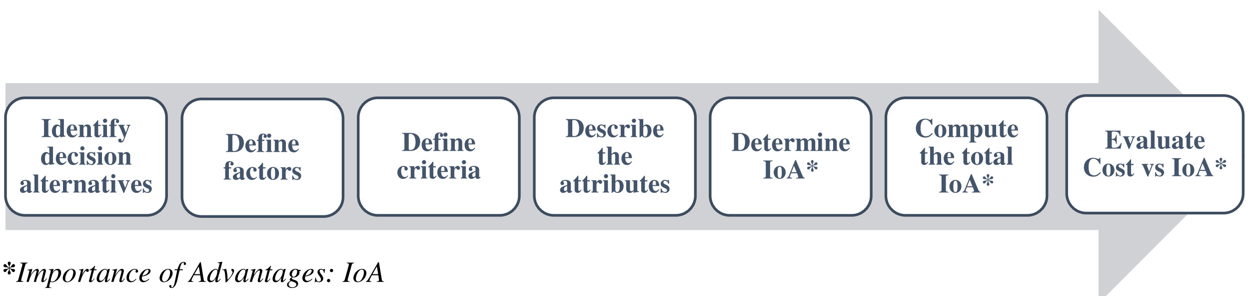
Within two decades after its first presentation, CBA has been applied in many different contexts in the AEC area. However, an extensive review of the literature showed no application or investigation of CBA in the building maintenance and FM context. Given this, another important reason for using CBA in this study is to introduce this method into the building maintenance and FM domain.

Furthermore, the most important reason for using CBA in this study is the value-based approach of the method that keeps the cost as a separate factor. With this fact, CBA fits the decision-making problem of *"Which building maintenance decision alternative: repair, replace, or do nothing, is more effective in a resource-constrained environment of FM considered for individual building equipment?"* in this study. The results of the study by Besiktepe et al. (2020) provided that factors such as health and safety, code compliance, and condition have higher importance in the ranking of the decision criteria compared to cost and funding availability. However, many FM practitioners still might consider the cost and funding availability as dominant factors in maintenance decision making. Subsequently, CBA benefits the process by considering the cost as a constraint and includes cost at the last step of the process after evaluating other factors.

Finally, subjectivity is part of any decision-making approach, and it is not possible to totally eliminate the impact of subjectivity in the process (Suhr, 1999, p.23). Acknowledging this fact, CBA considers the advantages of the decision alternatives rather than assigning weights or pair-wise comparisons, which aids in decreasing subjectivity in the process by evaluating each decision alternative with respect to each of the factors. Therefore, this study provides a systematic decision-making approach considering the dynamics of FM as well as the nature of the decision-making problem. In addition, the study promotes the use of a practical MCDM method in the context of building maintenance and FM.

4.3. Methodology

The methodology of the demonstrated decision-making framework follows the seven steps of the CBA method (Arroyo et al., 2018; Martinez et al., 2016: Suhr, 1999). The schematic representation of the methodology is shown in Figure 20. As mentioned earlier the CBA method has its own terminology, an understanding of which is critical for the CBA methods consistent use. Before explaining the steps, the terminology of CBA is presented in section 4.3.1.



******Importance of Advantages: IoA*

Figure 20

Steps in the CBA Method

4.3.1. CBA Terminology

CBA terminology has significant importance in applying its method (Suhr, 1999) and six leading terms in the context of CBA are presented as follows:

- **Factor:** An element or component of a decision (refers to the criterion in other MCDM methods).
- **Criterion:** Decision rule, which can be a *"want"* or *"must"* criterion.
- **Attribute:** A characteristic or consequence of a decision alternative.

- **Advantage:** A benefit or gain between decision alternatives based on criteria and attribute.
- **Importance of Advantage (IoA):** The numerical representation of the advantage of factors compared to the least preferred in 0 to 100 scale.
- **Paramount advantage:** The highest numerical advantage, often assigned as 100 (Suhr, 1999).

4.3.2. Steps of CBA

The seven steps of CBA (Suhr, 1999) are discussed in more detail using an example for flooring material selection. The example was selected for its simplicity to demonstrate the steps and the meaning of the terms used in CBA.

<u>Step 1: Identify Decision Alternatives</u>: Decision alternatives are the options for the final selection in the decision-making process. For instance, alternatives in the material selection problem of flooring might be hardwood, carpet, ceramic tile, vinyl or linoleum.

<u>Step 2: Define factors</u>: Factors are the elements or components that influence the final decision. Factors the flooring material selection example may include, color, style or look, cost, ease of installation, flooring grades or performance requirements for the project.

<u>Step 3: Define criteria</u>: Rules regarding the judgment of factors in the process are identified as criteria in CBA. Criteria help to make decisions, in the flooring material selection example for the factor of color "lighter colors are better" might be a criterion. Considering *"want"* or *"must"* criteria in CBA, "lighter colors are better" is a want criterion and "the color must be compatible with the colors identified in the applicable material specifications" would be a must criterion.

Step 4: Describe the attributes: Attributes are characteristics or consequences of each individual alternative considering the factors. For instance, the attribute of the decision alternative “carpet” for the factor “color” could be grey or light, while the attribute of the decision alternative “hardwood” could be brown or dark for the same factor.

Step 5: Determine the importance of advantage (IoA): Determining the advantages includes evaluating the advantages of each decision alternative on a scale of 0 to 100, where 100 represents the paramount advantage. The advantages of alternatives must be considered for each factor individually. For the above example of decision alternatives “carpet” and “hardwood”, the carpet might have 100 IoA because the identified criterion is “lighter colors are better” where hardwood, due to its dark color, might have lower IoA compared to the carpet. The assigned values of IoA are based on decision-makers' consensus and judgment. As an example, a study Torres-Machi et al. (2019) utilizing a CBA method used quartiles (25, 50, 75,100) for IoAs in their application.

Step 6: Compute the total IoA for each alternative: Before including the cost of the alternatives in the decision-making process, the total of advantages for each alternative is obtained as the sum of IoAs. The highest total numerical value of IoA represents the most preferred alternative in terms of advantages before considering the cost of alternatives in the process.

Step 7: Evaluate cost and IoA: Assessment of the costs of decision alternatives versus the total IoAs is the final step of CBA. Arroyo et al., (2018) developed a graphical representation including IoA on the Y-axis and cost on the X-axis; however, a comparison table for evaluating cost and total IoA is mostly utilized for this step in the literature.

4.3.3. Decision Alternatives

Even though the primary objective of systematic decision-making methods is to determine the best possible alternative, identifying available decision alternatives is extremely important to achieve the desired outcome of the process (Arbel & Tong, 1982). Yearly maintenance decisions often comprise repair, replace, and do-nothing alternatives depending on the context of the maintenance needs (Tambe et al., 2013). In addition, deferring maintenance activities, which is postponing the necessary maintenance activities of any equipment or system due to several constraints, is a widely accepted practice in FM. Given that, "defer" can be a decision alternative in the building maintenance decision-making based on the organization's maintenance management and FM strategies. At the time of decision-making, "defer" and "do nothing" result in taking no action; however, defer might be considered as including a commitment to consider the required maintenance action in the following year's budget or even in the current year's activities if more funding becomes available later. It is important to note that including different decision alternatives in the process is mostly based on the decision-makers' preferences as well as the organizations' strategies. For example, based on the "defer" decision alternative, "defer repair" or "defer replace" can be additional decision alternatives, including more certainty, priority, and obligation.

Considering these details, this study utilized three decision alternatives: repair, replace, and do nothing with the consensus of the researcher and the FM executive who participated in the implementation of the CBA method. The context and scale of the repair and replace activities vary based on the equipment and building type and can also be classified on component and equipment levels. Even though there are only three decision alternatives considered in the implementation of the CBA method in this study, decision alternatives depend on the maintenance needs of the equipment, decision-maker's preferences, and strategic plans of the organization. For example, do-nothing might not be a decision alternative in a case where the risk of equipment failure is not tolerable, such as mechanical equipment serving an operating room in a healthcare facility.

4.4. Example Implementation of CBA in Building Maintenance Strategy Selection

The CBA method is implemented in a hypothetical decision-making problem for a piece of HVAC equipment with medium level maintenance issues in an office building. In this scenario, it is assumed that the organization plans to relocate to a new building in its long-term planning. The researcher and an FM executive, who has more than 25 years of FM experience participated as the stakeholders in the implementation of CBA. Prior to the implementation, the researcher provided the details of the CBA method and its terminology with an example case to the FM executive, with the purpose of confirming the method's ease of use and practicality. The FM executive described the CBA method as "medium user friendly" and expressed their willingness to use the method in their organization to support the decision-making processes. The systematic approach in CBA and the step-by-step process were highlighted as positive feedback from the FM executive. The determination of IoAs for each alternative and factor was mentioned as a challenge in their feedback. However, they agreed that the consensus of decision-makers in the overall process aids to overcome this challenge, considering the multiple stakeholders in FM decision-making.

The seven steps of CBA including the details of the hypothetical problem are explained as follows:

1) *Identify Decision Alternatives:* The decision alternatives based on the decision-making problem are:

- Repair
- Replace
- Do nothing.

2) *Define factors:* The factors regarding the decision-making problem were previously identified within a comprehensive effort (Besiktepe et al., 2020). The nine factors utilized in the example implementation of CBA in this study are provided with their definitions as follows:
    - Code Compliance: Compliance of the equipment with the most current building codes.
    - Condition: Existing condition of the equipment at the time of maintenance activity decision.
    - Duration: Total time span of the maintenance activity, such as 2 months, 1 year, etc.
    - Health and Safety: Health and safety threats caused by the failure of the equipment.
    - Impact of Failure: The impact of the failure of equipment such as threats to environment, occupant comfort, and loss of energy and operational efficiency.
    - Occupancy: Purpose of the occupancy of the building where the equipment exists, such as classroom, research lab, office, meeting room, etc.
    - Scheduling: The time of the maintenance activity in the calendar year, such as from January to March, in July, etc.
    - Sustainability: Impact of the maintenance activity on the sustainability of the equipment.

- Strategic Business Planning: Aligning FM functions with the organization's business continuity with a clear understanding of the organization's goals and objectives in the short-term and long-term.

As mentioned earlier, cost is treated as a constraint in CBA, allowing the financial constraints to be considered after evaluating other factors. In addition to the nine factors listed above, cost and funding availability were identified as individual factors in the Besiktepe et al. study (2020), and these two are considered constraints rather than factors. In case the available funds are not adequate to perform a selected alternative due to its cost, the decision-maker will consider other alternatives based on the funding availability. Therefore, funding availability was also considered as a constraint in this study and was treated separately after evaluating other factors. In summary, from the list provided above, the cost and funding availability are kept separate from other factors in the CBA implementation and included in the process at the very last step.

3) *Define criteria*: Based on the definitions of factors, the criteria needed to judge the alternatives are presented in Table 14.

Table 14

Factors and Criteria of CBA application

Factor	Criteria for CAB	Rationale
Code Compliance	Higher code compliance is better.	Keeps the buildings and equipment up to date on most recent codes and regulations.
Condition	Higher condition rating is better.	Provides the required performance of the building and equipment.
Duration	Shorter duration is better.	Gives less disturbance to occupants and building function.
Health and Safety	Fewer threats caused by the failure of equipment is better.	Reduces the risk of accidents and injuries.
Impact of Failure	Less impact is better.	Supports the building's functional continuity and performance.

Occupancy	Allowing for more important type of occupancy is better.	Supports the productivity and organization’s functionality.
Scheduling	Compatible with the business scheduling is better. ex: summer is better	Supports business continuity.
Strategic Business Planning	Higher alignment with planning is better.	Aids in achieving the organization’s business objectives.
Sustainability	Higher is better.	Leads to a better future for the next generations.

Criteria might comprise *“want”* or *“must”* criterion, where must criterion refer to a specified value based on a standard, specification, etc. In the implementation example of CBA, all criteria are treated as *“want”* criteria. Depending on the situation, code compliance, health and safety, duration, scheduling, and sustainability might all be considered as *“must”* criteria based on current codes, industry standards, or the organization’s policy. This study focuses on a generic implementation of CBA method, and different case studies might determine *“must”* criteria for the utilized factors in this study.

4) *Describe the attributes:* Attributes are the characteristics or consequences of each alternative based on factors. For example, for the condition factor (represented with a 1-5 scale, 1 representing bad and 5 representing excellent) the attribute of the replace alternative is 5, because the replace alternative will increase the condition level of the equipment to excellent. When the existing condition rating of the equipment is assumed as 2.5, the attribute of the repair alternative is identified as 3.5, based on the content of the repair activity. The attributes of each alternative in the implementation example for factors and decision alternatives are presented in Table 15. Within the decision alternatives, the least preferred attribute for each factor is underlined in this step and then assigned with zero IoA in the next step.

5) *Determine the IoA:* The IoA is a number between 0-100 representing the preference of the decision maker(s) that is assigned to each alternative. A three-point scale with the values 35, 70, 100 representing low, medium, and high value of the identified attributes was utilized in the CBA implementation, determined by the consensus of the researcher and the FM executive. The most preferred alternative based on a factor and its criterion is assigned a 100 IoA as a paramount advantage.

6) *Compute the total IoA for each alternative:* The total IoA for each decision alternative is quantified by the sum of IoAs that are identified considering each factor. The total IoA represents the total importance of each decision alternative: repair, replace, and do-nothing based on factors and criteria. The total IoAs of the implementation example are presented in Table 15.

7) *Evaluate cost vs. IoA:* In the final step, the total IoA of each alternative based on the criteria is compared that includes the cost of alternatives and available funding. Decision-makers can choose the best available alternative with given cost and financial constraints, which is the key principle of CBA. The total IoAs with cost and funding availability information are presented in Table 16. For this example, funding is assumed available for both Repair and Replace alternatives, since if there is not available funding for the Replace alternative, only the Repair alternative could be considered, regardless of IoAs.

Table 15

Representation of CBA application with three-point IoA scale (35, 70, 100)

Factors and Criteria	Alternatives								
	Repair			Replace			Do Nothing		
	Attribute	Advantage	IoA	Attribute	Advantage	IoA	Attribute	Advantage	IoA
Factor 1: Code Compliance Criterion: Higher code compliance is better. Keeps the buildings and equipment up to date on most recent codes and regulations.	Medium	Medium compliance	70	High	Higher compliance	100	**< Low**	Low compliance	0
Factor 2: Condition (1-5) Criterion: Higher condition rating is better. Provides the required performance of the building and equipment.	3.5	1 level increase from the current condition	70	5	2.5 level increase from the current condition	100	**2.5**	Do not have any impact on the condition	0
Factor 3: Duration (weeks) Criterion: Shorter duration is better. Gives less disturbance to occupants and building function.	2	2 weeks more	100	**12**	12 weeks more	0	0	No time required	100
Factor 4: Health & Safety Criterion: Fewer threats caused by the failure of equipment is better. Reduces the risk of accidents and injuries.	Medium	Average threats	70	< Low	No threats	100	**High**	High threats	0
Factor 5: Impact of Failure Criterion: Less impact is better. Supports the buildings functional continuity and performance.	Low	Low impact	70	< Low	No impact	100	**High**	High impact	0
Factor 6: Occupancy Criterion: Allowing for more important type of occupancy is better. Supports the productivity and organization's functionality.	Medium	Medium benefit	70	High	High benefit	100	**< Low**	No benefit	0
Factor 7: Scheduling Criterion: Compatible with the business scheduling is better. ex: summer is better Supports the business continuity.	Medium	Along with the scheduling at the medium level	70	**< Low**	Does not along with scheduling	0	High	Along with the scheduling at the high level	100
Factor 8: Strategic Business planning Criterion: Higher alignment with planning is better. Aids in achieving the organization's business objectives.	Low	Along with the business objectives at the low level	35	**< Low**	Does not along with the business objectives	0	High	Along with the business objectives at the high level	100
Factor 9: Sustainability Criterion: Higher is better. Leads to a better future for the next generations.	Medium	Medium sustainability	70	High	Higher sustainability	100	**< Low**	Very Low sustainability	0
Total IoA			**625**			**600**			**300**

Table 16

Decision alternatives with the total IoAs, cost and funding availability with 3-point IoA scale

Alternatives	∑ IoA (3 point)	Cost	Funding Availability
Repair	625	$ 15,000	Yes
Replace	600	$ 85,000	Yes
Do nothing	300	$ 0	N/A

Based on the judgement of the researcher and the FM executive in this hypothetical scenario of an HVAC equipment with medium maintenance issues in an office building; the repair decision alternative has a total of 625 IoA, whereas replace alternative has a total of 600 IoA and do nothing has a total of 300 IoA, as presented in Table 16. The repair alternative is the best considering the total IoAs, in the absence of cost and funding availability. In other words, the repair alternative is the most value-generating alternative without the cost and funding availability constraints. However, since the total IoAs are very close in the repair and replace alternatives, the replace alternative might still be selected as the best in the absence of cost and funding availability.

Including cost and funding availability, it is evident that the do nothing alternative is the most affordable option with no cost; however, the total IoA is the lowest for do nothing compared to other alternatives, which shows that the option is not feasible. The repair alternative has the highest total IoA with a lower cost, and the replace alternative has 25 IoA less compared to the repair alternative with an additional cost of $70,000. Considering IoAs, cost, and funding availability together in the process provides a comprehensive understanding and ability to make the final judgement with a clear understanding of advantages of each alternative based on factors and their criteria with the financial availability. Because the case study in the implementation example is hypothetical, presenting the final alternative selection considered not necessary by the researcher and the FM executive.

4.4.1. Sensitivity Analysis

Since the literature does not provide a structured guideline in the determination of IoAs other than the decision-makers consensus, this study explored the impact of IoAs in the CBA method with a sensitivity analysis. Torres-Machi et al. (2019) used a quartile scale (25, 50, 75, 100) for IoAs in their application, as one of the very few examples of using a specified IoA scale in the recent literature. Their quartile scale is utilized in the sensitivity analysis of IoAs in the CBA method and compared to the results of using the three-point scale previously shown in the implementation example.

The same scenario with its decision alternatives, factors, attributes, and criteria is implemented with a quartile IoA scale (25, 50, 75, 100) is presented in Table 17. The main benefit of the quartile scale was that it provided a better opportunity to further distinguish medium level attributes with two values 50 and 75 whereas the three-point scale only provided one value 70. As a result, the total IoAs for the repair alternative resulted in a lower total with the quartile IoA scale. Although the attributes of factors for the repair alternative identified as medium in both implementations, in the quartile IoA scale some attributes were considered to have a 75 IoA where some were considered with 50 IoA based on the criteria, attributes, and decision-makers' judgment. Different scales or intervals can be used in the determination of IoAs in the CBA method while considering the fact that decision-makers' consensus is critical for assigning IoA values.

Table 17

Representation of CBA application with quartile IoA scale (25, 50, 75, 100)

Factors and Criteria	Alternatives								
	Repair			Replace			Do Nothing		
	Attribute	Advantage	IoA	Attribute	Advantage	IoA	Attribute	Advantage	IoA
Factor 1: Code Compliance Criterion: Higher code compliance is better. Keeps the buildings and equipment up to date on most recent codes and regulations.	Medium	Medium compliance	75	High	Higher compliance	100	**< Low**	Low compliance	0
Factor 2: Condition (1-5) Criterion: Higher condition rating is better. Provides the required performance of the building and equipment.	3.5	1 level increase from the current condition	75	5	2.5 level increase from the current condition	100	**2.5**	Do not have any impact on the condition	0
Factor 3: Duration (weeks) Criterion: Shorter duration is better. Gives less disturbance to occupants and building function.	2	2 weeks more	100	**12**	12 weeks more	0	0	No time required	100
Factor 4: Health & Safety Criterion: Fewer threats caused by the failure of equipment is better. Reduces the risk of accidents and injuries.	Medium	Average threats	50	< Low	No threats	100	**High**	High threats	0
Factor 5: Impact of Failure Criterion: Less impact is better. Supports the buildings functional continuity and performance.	Low	Low impact	75	< Low	No impact	100	**High**	High impact	0
Factor 6: Occupancy Criterion: Allowing for more important type of occupancy is better. Supports the productivity and organization's functionality.	Medium	Medium benefit	50	High	High benefit	100	**< Low**	No benefit	0
Factor 7: Scheduling Criterion: Compatible with the business scheduling is better. ex: summer is better Supports the business continuity.	Medium	Along with the scheduling at the medium level	50	**< Low**	Does not along with scheduling	0	High	Along with the scheduling at the high level	100
Factor 8: Strategic Business planning Criterion: Higher alignment with planning is better. Aids in achieving the organization's business objectives.	Low	Along with the business objectives at the low level	25	**< Low**	Does not along with the business objectives	0	High	Along with the business objectives at the high level	100
Factor 9: Sustainability Criterion: Higher is better. Leads to a better future for the next generations.	Medium	Medium sustainability	50	High	Higher sustainability	100	**< Low**	Very Low sustainability	0
Total IoA			**550**			**600**			**300**

The total IoAs obtained with the quartile scale (25, 50, 75, 100) and cost and funding availability information are presented in Table 18 for each decision alternative.

Table 18

Decision alternatives with the total IoAs, cost and funding availability with quartile IoA scale

Alternatives	∑ IoA (quartile)	Cost	Funding Availability
Repair	550	$ 15,000	Yes
Replace	600	$ 85,000	Yes
Do nothing	300	$ 0	-

Before financial constraints are included in the CBA process, the quartile scale provided that the replace alternative was the best option with the highest total IoA. Considering the cost and funding availability, an additional $ 70,000 cost in the replace alternative provides 50 IoAs more than repair. In other words, spending an additional $ 70,000 by selecting the replace alternative provides less than 10% advantage in this case. With obtaining different results in three-point and quartile scale, it is evident that the CBA method is sensitive to IoA values and scales. This has an important impact on the results of the method as well as the process.

Finally, it is the decision makers' judgement that determines the worth of the total advantage vs. additional cost among alternatives. It is important to mention that no decision-making method provides the one best solution to any problem, since human perception and judgement are undeniable pieces of the process.

4.4.2. Multiple Equipment Maintenance Strategy Selection

The CBA method might also potentially benefit the maintenance decision-making problem of multiple pieces of equipment in the same building or across multiple buildings. Although the implementation example presented here focused on a single piece of equipment to present the CBA method; in practice possible scenarios most likely would include multiple pieces of equipment. The importance of funding availability is likely to be more critical in maintenance decision-making processes that consider multiple pieces of equipment. Replacing one piece of equipment may necessitate only repairing another piece of equipment based on funding, even though the CBA may indicate replacing both is the preferred option.

To investigate the potential benefit of CBA in the maintenance decision-making of multiple pieces of equipment, a brief example is presented in Table 19. In this example, the total IoAs and cost information for repair and replace decision alternatives are provided for three pieces of equipment. The total available funding for the equipment is $50,000. For equipment #1, the repair alternative has an additional 67% advantage over the replace alternative with $15,000 less cost. The repair alternative has 14% advantage over the replace alternative for equipment #2 with $10,000 less cost. The replace alternative has 150% advantage over the repair alternative for equipment #3 with $15,000 additional cost. Repair for all three equipment is affordable within the available $50,000 but replacing all three is not possible.

Considering the $50,000 of total available funding, decision makers can determine the most value-generating combination of spending the total funding for repair vs replace alternatives with the worth of total advantage vs cost. With this brief example, CBA might be promising for the resource allocation of maintenance needs for multiple equipment either in the same building or in a building portfolio.

Table 19

Example of multiple equipment's total IoAs vs Cost

	∑ IoA		**Cost**	
	Repair	**Replace**	**Repair**	**Replace**
Equipment #1	500	300	$10,000	$25,000
Equipment #2	400	350	$5,000	$15,000
Equipment #3	200	500	$15,000	$30,000

4.5. Discussion, Conclusions, and Future Research

In addition to several challenges in building maintenance and FM, the complexity of building systems increases the need for considering multiple and conflicting factors in the decision-making process. The main purpose of this study is to develop a structured and systematic decision-making approach in building maintenance and FM by utilizing the CBA method. CBA provides a practical framework to decision-makers in FM with various backgrounds and benefits FM professionals with a step-by-step decision-making approach considering multiple factors and their advantages to enhance the efficiency of decisions.

CBA aids in identifying the most value generating alternative by considering cost and financial factors as constraints in the process. Therefore, the decision-making problem identified in this study: *"Which building maintenance decision alternative: repair, replace, or do-nothing, is more effective in a resource-constrained environment of FM considered for individual building equipment?"* fits into the concept of CBA, where cost and/or funding availability are traditionally treated as dominant factors. Evaluating the factors without any financial considerations provides the opportunity to determine the values and advantages of these factors for each decision alternative. For instance, the replace alternative might be considered the most favorable one in the absence of financial constraints; however, criteria of factors (duration, scheduling, or strategic business planning) might not align with the replace alternative. Subsequently, CBA provides a transparent process in evaluating the factors in the process with the opportunity to see the impact of each factor on the final decision with the IoA concept.

The main contribution of this study is to support the use of a practical, systematic and structured decision-making approach in building maintenance and FM. The implementation of

CBA in this study was presented with the sole purpose of illustrating the approach and performed within a hypothetical case with the inclusion of only one FM professional. A case study with real data and the participation of multiple stakeholders would increase the opportunity to reveal the benefits of CBA in the decision-making process of building maintenance and FM.

Sensitivity analysis revealed the importance and impact of IoAs in the CBA method by providing two different results in three-point and quartile IoA scale implementations. It is interesting to observe that the quartile IoA scale provided a better opportunity to identify the advantages of medium level attributes. Considering this, different intervals or attributes in the IoA scale might increase the benefits of the CBA method.

While acknowledging the fact that the identified criteria of factors in this study are considered as *"want"* criteria; utilizing *"must"* criteria based on current codes, industry standards, or organization's policy might reveal the potential and benefits of CBA with better accuracy in evaluating attributes with quantitative values.

A brief demonstration of utilizing CBA in multiple equipment cases with limited funding availability indicates that CBA might be a promising method for the resource allocation of building maintenance in FM. Including several pieces of equipment in a building portfolio, prioritizing maintenance needs with limited funds becomes more complex than the decision-making problem of only one piece of equipment, thereby potentially increasing the usefulness of CBA.

As a promising effort in utilizing CBA in FM, this study may lead to several future studies such as comparing the results of CBA and traditional decision-making approaches or other decision-making methods utilized in FM. In light of the results of the sensitivity analysis, the development of an IoA scale in the context of CBA is also an interesting topic to focus on for future implementations of CBA. Even though the consensus of decision-makers is the suggested way of developing IoA scales in the CBA literature, it is worthwhile to explore other possible techniques in similar decision-making studies of other domains. Moreover, different decision alternatives such as defer repair or defer replace may result in additional discussions in the CBA process by providing different results.

As mentioned earlier, CBA considers the advantages of the decision alternatives rather than assigning weights to each individual criterion or conducting pair-wise comparisons. This was identified in the literature (Suhr,1999) as a benefit because it decreases the subjectivity by evaluating each decision alternative with respect to each of the factors. While this is important, it also results in potential challenges in establishing the IoA scale. Future research studies in implementing CBA in building maintenance and FM may consider incorporating weights and/or pair-wise comparisons to the CBA process as part of defining the IoA scale. Particularly in establishing the IoA scale, using weights might benefit the process to obtain a more specific scale for each decision alternative considering that the CBA method is sensitive to IoA values and scales as was shown in the sensitivity analysis presented herein. Given that, it is worthwhile to explore the use of weights or pair-wise comparisons in developing different intervals for IoA values and scales in CBA as part of future research studies.

This study presented a practical MCDM method for building maintenance decisions in FM that supports developing effective maintenance strategies. It also reveals the possibility of using CBA in the context of FM, a topic that has not previously been investigated. The presented step-by-step approach of CBA might benefit FM departments for justifying their budgetary needs as well as prioritizing their maintenance activities. Finally, as an important step utilizing the

CBA method in FM, this study supports the use of a systematic decision-making approach, which aids in improving the outcome of decisions.

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CHAPTER 5: Conclusions, Research Contribution, and Future Research

This dissertation includes three separate but related studies with the goal of developing a systematic and structured MCDM approach for building maintenance practices in a resource-constrained environment in FM. Each study focused on essential pieces of the MCDM approach: (i) identifying fundamental criteria needed for constructing an MCDM model, (ii) developing a resource-efficient and quantitative CA framework, (iii) demonstrating a MCDM method for a systematic approach in building-maintenance decision-making. This chapter summarizes and highlights the significant findings of the three studies that constitute this dissertation with research contributions and recommendations for future research.

The first study incorporated a literature review and a nationwide online survey with FM professionals, including ranking, multiple-choice, and open-ended questions. The online survey targeted members of the IFMA and APPA in the United States. These associations are well known to have a vast majority of professionals involved in corporate and higher education FM practices in the United States and worldwide. The identified criteria in the study are: (1) code compliance, (2) condition, (3) cost, (4) duration, (5) funding availability, (6) health and safety, (7) impact of failure, (8) occupancy, (9) scheduling, (10) sustainability, and (11) strategic business planning. Survey participants were also asked to rank the criteria in the online survey to reveal the importance of these criteria in the decision-making process. The mean importance rankings highlighted the importance of "Health and Safety", "Code Compliance", and "Condition" above "Cost" and "Funding Availability," which were anticipated to be dominant criteria. Even though financial constraints influence FM practices to a large extent, the nature and complexity of building maintenance requires comprehensive criteria, as evidenced by the findings of the first study. The findings also suggest that “Condition” was identified as one of the top criteria in building maintenance decision-making, highlighting the importance of condition information in the decision-making process as well as the need for effective CA practices. Moreover, the findings of the first study revealed that the current decision-making practices in building-maintenance highly depend on past experience and expert opinion where the administrators in the FM industry is aging overall. These findings support the need of systematic processes in the decision-making practices as well.

The second study developed a less subjective and more quantitative CA framework, as an alternative to visual inspections, to obtain a condition rating value for building maintenance in FM. An example of applying the framework to HVAC equipment using a brief case study was presented in the study. MTBF, age-based obsolescence, FCI, occupant feedback, and preventive maintenance cycles were identified variables used to obtain the proposed condition rating value. Along with these variables, fuzzy sets theory, which deals with imprecise, uncertain, and ambiguous judgments with the membership relations, was utilized to obtain a less subjective and quantitative condition rating value. The second study is an important step in utilizing CMMS data for CA practices. It also reveals the possibility of using CMMS data in FM, in addition to tracking daily activities or work orders. The framework does not require additional resources or funding, which is a significant constraint in existing FM practices; it merely requires applying fuzzy sets theory to readily available data to obtain a condition rating. The second study is a promising effort for future applications of fuzzy concepts in CA, building maintenance and FM areas, providing a systematic and mathematical approach to linguistically ambiguous results.

In the third study, CBA, a new generation MCDM method, is utilized to demonstrate the use of a systematic decision-making approach in FM building maintenance. CBA provides a practical framework to decision-makers in FM with various backgrounds and benefits FM professionals with a step-by-step decision-making approach that considers multiple factors and their advantages to enhance the efficiency of decisions in building maintenance activities. Also, CBA aids in identifying the most value-generating alternative by considering cost and financial factors as constraints in the process. The importance of participation and consensus of multiple stakeholders in the process fits into the context of FM. As a promising effort in utilizing CBA in FM, the third study demonstrated the benefits of using a systematic decision-making approach in FM building maintenance.

5.1. Research Contribution

With the results and findings of these three studies, this dissertation achieved the following contributions in the domain of FM:

- Promoting the consideration of multiple criteria in building maintenance decision-making.
- Emphasizing the use of MCDM methods in building maintenance and FM decision-making problems.
- Revealing effective uses of FM data in CA processes with a framework including multiple variables as opposed to a single source of information provided by visual inspections.
- Including CMMS data, expert opinion, occupant feedback, and industry standards in CA processes, which considers failure trends, cost, deterioration, human perspective, and maintenance practices in the process.
- Developing a CA framework that minimizes subjective judgment with fuzzy sets theory providing a systematic and mathematical approach to linguistically ambiguous results.

- Presenting the implementation of CBA in the FM domain as a practical decision-making method.
- Improving the quality of maintenance services with effective resource allocation.
- Assisting facilities management executives and decision-makers at all levels in the decision-making process of maintenance activities.
- Developing a practical decision-making framework that serves FM professionals of various backgrounds with the participation of multiple stakeholders.

It is important to note that the application and value of this research is not limited to a facility type. The methodology and developed framework are applicable to any organization that manages a single building or has facility portfolios, including campuses, school districts, government agencies, and business organizations.

5.2. Future Research

Numerous recommendations were presented in the study chapters as part of addressing the need for a systematic decision-making approach in FM building maintenance. The following is a brief summary of the recommendations for future research stemming from this dissertation.

The findings of the first study suggested that "Condition" was identified as one of the top criteria in building maintenance decision-making, highlighting the importance of CA practices. Further research is required to better reveal the time interval, capacity, and process of CA practices. In addition, documentation and reporting of CA practices are important to get the maximum benefit from outputs, where further studies might reveal the benefit of integrating technological advancements in CA practices. Based on the lower importance ranking of "Sustainability" in the first study, further research on sustainability in FM is necessary to reveal the understanding and current practices of this category in the domain. The aging workforce identified in the survey results highlight the importance of further studies in training, scholarship, and education programs, as well as effective pipeline strategies in FM. The applicability and significance of identified criteria in different FM contexts such as healthcare, industrial, educational, and office should be further investigated. In addition, future studies may reveal the differences in building maintenance and decision-making practices in public and private institutions, as the first study revealed statistically significant differences in the mean rankings of some of the identified criteria between participant groups in public and private organizations.

The developed CA framework in the second study focused on HVAC equipment, where further studies could be extended to include other building equipment in the CA process. The reliability of the obtained condition rating value in the developed CA framework could be further investigated by comparing it to outcomes of traditional CA methods such as visual inspection or expert opinion. Future studies could also focus on if and how the condition rating obtained through the developed framework can be used in conjunction with, and thus supplement, condition ratings obtained through visual inspections and walk-through surveys. Focusing on the fuzzy sets theory implementation in the second study, further studies could focus on the development of the membership functions for the proposed CA framework by including additional experts. The outcome of the different defuzzification methods could be investigated in applications of fuzzy sets theory.

Implementation of CBA in the third study was presented with the sole purpose of illustrating the approach and performed within a hypothetical case with the inclusion of only one FM professional. A case study with real data and the participation of multiple stakeholders will increase the opportunity to reveal the benefits of CBA in the decision-making process of building maintenance and FM. Based on the findings of sensitivity analysis, different intervals in the importance of advantages (IoA) scale regarding the attributes might increase the benefits of the CBA method. The development of an IoA scale in the context of CBA is an interesting topic to focus on for future implementations of CBA. Even though the consensus of decision-makers is the suggested way of developing IoA scales in the CBA literature, it is worthwhile to explore other possible techniques in similar decision-making studies of other domains. It is also worthwhile to explore the use of weights or pair-wise comparisons in developing different intervals for IoA values and scales in CBA as part of future research studies. Moreover, different decision alternatives, such as defer repair or defer replace, may result in altered discussions in the CBA process by providing different results. The decision-making problem of maintenance needs selection of multiple equipment in a set of buildings should be another future study to reveal the benefits of CBA and a systematic decision-making approach in complex building maintenance scenarios.