Research Article

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

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ABSTRACT

Maintenance strategy selection is a challenging process in building maintenance and facility management (FM). In addition to financial constraints, multiple criteria need to be considered to increase the efficiency of maintenance decisions. The purpose of this study is to demonstrate a structured and systematic decision-making approach in building maintenance and FM. For this purpose, a new generation multi-criteria decision-making method, Choosing by Advantages (CBA), is utilized. CBA allows for the consideration of multiple criteria and their advantages. CBA identifies the most-value generating alternative without initially considering cost. Cost, in turn, is defined as a constraint and included later in the process after determining other advantages are established. In addition, CBA facilitates group decision-making. The implementation of the CBA-based decision-making framework is presented using a hypothetical case study. The proposed systematic decision-making approach, which aids in improving the outcome of decisions, is promising in decision-making as well as resource allocation for maintenance needs in FM.

Keywords: Facility management, multi-criteria decision-making, choosing by advantages, building maintenance

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.

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). With rapid changes in the business environment and the increasing attention to cost reduction, decisions have critical impact on the organizations' competitiveness (Ancarani & Capaldo, 2005). Complex building systems require strategic maintenance planning to exceed their designed service with minimum downtime, which lead to a change in the maintenance planning and decision-making in FM (Pun et all, 2017). In addition, the results of a recent survey (Besiktepe et al. 2020) highlighted the aging workforce of decision-makers in FM serving in executive levels such as director, facility manager, and other manager positions. Moreover, almost half of the survey participants identified past experience and expert opinion as their current decision- making practice. These results show that in the future past experience and expert opinion will not be available to lead decision-making processes which is an important indicator of a need of structured decision-making approach in FM. With that, enhancing the decision-making process in FM will not only improve the organizations success, but will increase the longevity of the built environment with better productivity levels.

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.

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 1 chronologically.

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 (Chen et al., 2014; Chou et al., 2008; Ertuğrul & Karakaşoğlu, 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.

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

TABLE 1.—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

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 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.

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 consid-

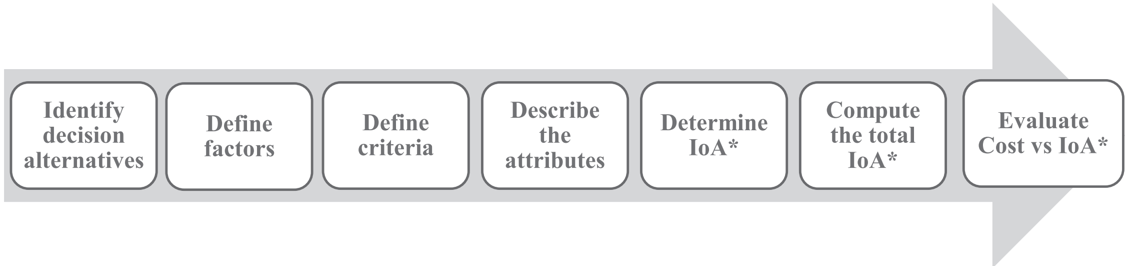

FIGURE 1.—Steps in the CBA Method
*Importance of Advantages: IoA

ering 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.

Research Approach

The comprehensive literature review on facility management decision-making, current efforts in building maintenance strategy selection and MCDM, and CBA provided the relationships and foundation of the methodology in this study. In addition to the literature review, a hypothetical case study is utilized in the methodology with the sole purpose of illustrating the CBA as the proposed decision-making method in building maintenance decisions. It is important to acknowledge that real data with the participation of multiple stakeholders in the case study would increase the effectiveness of investigating CBA in FM. As the preliminary effort of applying CBA in the context of FM, this study provides a practical guideline and illustration of CBA to FM professionals.

Decision-Making with CBA

The quantitative approach of the methodology follows the seven steps of the CBA method (Arroyo et al., 2018; Martinez et al., 2016: Suhr, 1999) to provide a systematic and structured decision-making approach considering multiple criteria. The schematic representation of the methodology is shown in Figure 1. 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 the following subsection.

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).

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.

Step 1: Identify Decision Alternatives: 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.

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

Step 3: Define criteria: 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.

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.

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.

TABLE 2.—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.

- **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 2.

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 3. 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 3.

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 4. 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.

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

TABLE 3.—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**

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 4. 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.

TABLE 4.—Decision alternatives with the total IoAs, cost and funding availability with 3-point IoA scale

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

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 5. 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

TABLE 5.—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**

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. The total IoAs obtained with the quartile scale (25, 50, 75, 100) and cost and funding availability information are presented in Table 6 for each decision alternative.

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.

TABLE 6.—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	-

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.

Practical Steps for Facility Managers new to CBA

The step-by-step approach of CBA provides a practical and easy-to apply structure to its users, yet facility managers may better utilize CBA with some additional guidance. In addition to the steps of CBA outlined herein, identifying the nature of the decision-making problem along with other related dynamics in the organization is essential in the process of utilizing a systematic decision-making approach. For example, the maintenance of a first aid area that requires modifications based on the Occupational Safety and Health Administration regulations, may need extra space for full compliance. The maintenance decision in this case needs the involvement of strategic planning and capital investment. Relation of the maintenance needs to the capital investment as part of the nature of decision-making problem is critical to identify before the application of CBA and/or any decision-making approach.

Another step for facility managers utilizing CBA is to consider the culture of the organization. Even though the trend in the facility management moves towards data-driven systems, a facility manager needs to ensure that the company values the use of systematic approaches as part of their management culture. In the application process of CBA, the participation of the multiple stakeholders such as owner, director, facility manager, project manager, and occupants have a significant and positive impact on the outcome. In other words, the willingness of the stakeholders to participate in the systematic decision-making process is another key item before the application of CBA.

In this study, Microsoft Excel is utilized as a tool for applying the tabular structure of CBA. In addition to its practical structure, CBA does not require a comprehensive training or education for its application. FM professionals can use the guidance of this paper for the fundamental understanding and application of CBA. Wider applications of the CBA method in lean construction provide opportunities for formal trainings of this method with the focus on lean construction and sustainability. However, as mentioned earlier, the practical structure and ease of use are two of the many reasons for applying CBA as a decision-making method in this study.

As a practical next step to be able to start using the framework presented in this study, FM professionals can implement a trial run for a sample decision. In addition to the fundamental decision factors provided in Besiktepe et al.'s study (2020), they can determine any other decision factors that may be relevant to their case. For example, "reliability" can be an additional decision-making factor of CBA for specific HVAC equipment. It is also important to mention that definitions of the decision factors should be identified in each case, such as "sustainability", which has multiple perspectives in social, economic, and environmental principles. Following that, a subset of buildings with maintenance issues and their needs can be identified. Then, stakeholders in the decision-making process should be informed about the terminology and principles of CBA. With the consensus of stakeholders, decision alternatives can be determined such as repair, replace, defer, etc. As an important step in CBA, the stakeholders should also identify the IoA scale based on the factors and decision alternatives. Even though this study provides two IoA scales, it is possible to utilize 6, 7 or even 10-point scale within 0-100. After the implementation of CBA, stakeholders should consider cost and funding availability for selecting the best decision alternative in their problem. By gathering the stakeholders' feedback on this trial run, the implementation of CBA could be customized to the needs of the specific organization. These practical steps, detailed explanation of CBA, and the implementation example in this study provide a good starting point and step-by-step guideline to FM professionals interested in implementing CBA for their decision-making process.

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.

TABLE 7.—Example of multiple equipment's total IoAs vs Cost

	$\sum$ 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

To investigate the potential benefit of CBA in the maintenance decision-making of multiple pieces of equipment, a brief example is presented in Table 7. 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.

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. In addition to the multiple stakeholder involvement, additional techniques such as Delphi study, expert panel, or nominal group technique would increase the effectiveness of the consensus for determining IoA as well as final decision alternative in CBA.

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.

With the guidance provided in this paper, FM professionals can utilize fundamentals of CBA method in their decision-making process. As mentioned earlier, additional focus on identifying factors within quantitative variables and IoA scale would improve the effectiveness of CBA in FM applications and currently under development in researchers' agenda.

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