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A BIM-integrated Fuzzy Multi-criteria Decision Making Model for Selecting Low-carbon Building Measures

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Abstract

Low-carbon building (LCB) has been regarded as an innovative and practical approach to reducing building carbon emissions. The design decision-making for LCBs should consider various criteria which however are often associated with uncertain information. Little research has examined multi-criteria decision making (MCDM) in selecting LCB measures, particularly in high-density subtropical urban environments. That selection process is inhibited by the lack of consensus on assessing the performance of LCB options and of an efficient decision support system. The aim of this paper is to develop a BIM-integrated fuzzy MCDM model for selecting LCB measures. The paper identifies the key criteria and alternatives to systematically assess LCB measures. Five criteria and nine alternatives were identified within the context of high-rise commercial buildings in Hong Kong, which are centralized on technical, economic and environmental aspects of building performance. With the use of BIM and eQUEST, a MCDM model based on Fuzzy PROMETHEE is developed. The developed model is validated utilizing a real project case in Hong Kong. The results will provide design decision-makers with a consolidated tool for selecting LCB measures.

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Keywords: Low-carbon building measures; Building information modeling; Fuzzy PROMETHEE; Decision-making.

1. Introduction

Recently, there has been a transition towards a low carbon built environment and increasing attention to the use of low carbon technologies [1,2]. The construction industry is a key sector expected to support achieving carbon

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emission reductions, as 33% of greenhouse gas (GHG) emissions, 40% of energy consumption and 36% of energy related carbon emissions are concerned with buildings [3]. Also, GHG discharged from buildings in cities is even more serious due to high urban density [1]. For instance, in high-density subtropical urban environments of Hong Kong, buildings' contributions to electricity consumption and GHG emissions are around 90% and 60% respectively [4].

Acknowledging that the rapid development of the construction industry has caused essential impacts on the environment, stakeholders involved have been striving to achieve LCBs within the budget. Thus the approach of LCB has been prompted in many countries and regions. However, the take-up of LCB measures in general is still low, and the full benefits of LCB measures are not realized in many practices. A risk-averse culture often appears in the construction industry and decision-makers trend to reduce financial risks associated with making an early commitment to using innovative LCB measures or technologies. However, an arguably more essential cause is the inability of decision-makers to compare many conflicting building performance factors and achieve trade-offs among multiple decision criteria, which are attributed to a lack of consensus on criteria for assessing the performance of building design options and a paucity of systematic tools to support LCB decision making.

This paper aims to address this knowledge gap by developing a BIM-integrated fuzzy MCDM model for selecting LCB measures. Building information modeling (BIM) was adopted into this research to improve interoperability in the construction industry [5], and aid seamless data exchange and sharing at the software level among diverse applications in the LCB delivery process. LCB measures in this paper encompass all LCB technologies, products and systems, with a focus on applied innovative ones. A digital systematic assessment approach was advocated for value-based comparison among different LCB measures, rather than evaluation ending up as a cost-comparison exercise [6]. A newly method based on fuzzy logic and the PROMETHEE method was adopted, which requires less and straightforward information from customers and makes fuller use of information input to be more objective and efficient to apply [7,8]. The research was carried out with commercial buildings in Hong Kong. As the EMSD [4] reported, commercial buildings account for 65% of the overall energy consumption in Hong Kong, having more possibilities to adopt LCB measures for improving building energy performance due to their straightforward energy using pattern [9] and commercial returns. This paper develops a model of BIM-integrated decision making model using BIM, eQUEST and MCDM applets. The model is then validated utilizing a real-life case of low carbon commercial building in Hong Kong. The implications of the results are discussed, which leads to discussions and conclusions about LCB measures selection.

2. Literature review

2.1. LCB measures

LCB measures are current primary approaches adopted to improve buildings' energy performance and reduce buildings' carbon emissions. The delivery process of LCBs can be simplified into three phases, namely planning, designing, and managing and retrofitting [3]. Previous research has identified and categorized LCB measures. For example, Tymkow et al. [10] divided LCB measures into four groups, including passive design, active design, supply energy efficiency and renewable energy. Heating and cooling demand reduction technologies and renewable energy technologies were also mentioned by Ma et al. [11]. Energy-efficient lighting was added into LCB measures by Malatji et al. [12]. Based on the framework of Malatji et al. and Zhang et al. [3,12], 26 LCB measures in five groups were identified for commercial buildings in Hong Kong as an example of hot and humid subtropical climate.

2.2. The PROMETHEE and Fuzzy PROMETHEE

The PROMETHEE is a type of MCDM outranking methods developed in the 1980s by Brans and others [15]. It is applied to rank a set of alternatives by considering a set of criteria. There are 6 different types of preference functions. The alternatives are ordered based on the size of their net flows. Considering the underlying structure for MCDM problems, the consideration of fuzzy logic combined with MCDM seems to be nearly self-evident [16]. Fuzzy set theory, first developed by Zadeh [13], was used to solve problems with subjective, vague and imprecise information. Literature review reveals that several attempts to integrate fuzzy logic with MCDM are being discussed for the evaluation of objective function and fuzzy information. For instance, Goumas and Lygerou [17] extended the PROMETHEE methods to consider fuzzy inputs with crisp weights. Geldermann et al. [16] made improvements and used fuzzy preference and fuzzy weights to obtain fuzzy scores.

2.3. Building Information Modeling (BIM)

BIM is most frequently perceived as a tool for visualizing and coordinating AEC (architecture, engineering and construction) work. A lot of research has been done in the applications of BIM for construction projects. Chen and Luo [18] developed a BIM-based construction quality management model to integrate the existed POP data structure. Matipa Wilfred et al. [19] adopted BIM to conduct cost planning. Bazjanac [20] simulated the building energy performance with the IFC BIM-based methodology. Previous research reveals that BIM is beneficial in the preparation and management of construction. Research has already been conducted to investigate the combination of BIM and other technologies for management or decision making. For instance, Park et al. [21] used AR (augmented reality) within BIM for quality defect management. Bank et al. [5] integrated BIM with a system dynamics/decision-making tool, AnyLogic^{TM}, to aid decision making process. However, all these research just focus on single aspect of building performance which should consider multiple criteria.

Considering the advantages of utilizing BIM in construction management and decision making, this paper explores the implementation of BIM for LCB measures selection process and proposes to integrate BIM with the proposed MCDM procedure to improve selecting efficiency.

3. Methodology of model development

3.1. Criteria and LCB measures for commercial buildings in Hong Kong

Potential criteria were carefully selected and synthesized from the literature review, with evaluation which is based on a five-level scale. Reliability analysis was conducted. According to this literature review, frequent identified categories of decision criteria for delivering LCB measures and corresponding LCB measures are listed in Figure 1. The criteria can be classified into three dimensions: technical-related, economic-related, and environmental-related, with five criteria included. Meanwhile, nine LCB measures were also carefully selected in the same way.

With all the criteria and LCB measures determined, this research then ascertains the weighting system of criteria according to the interviews conducted with 10 experts belonging to different stakeholder groups, i.e. consultant, developer, architecture and contractor. The weights concerned with decision criteria, Technical reliability (TR), Ease of operation & maintenance (EOM), Initial cost (IC), Payback period (PP) and Potential for operational carbon reduction (PCR) are 11.54%, 8.46%, 20.96%, 51.88% and 7.16% separately [3].

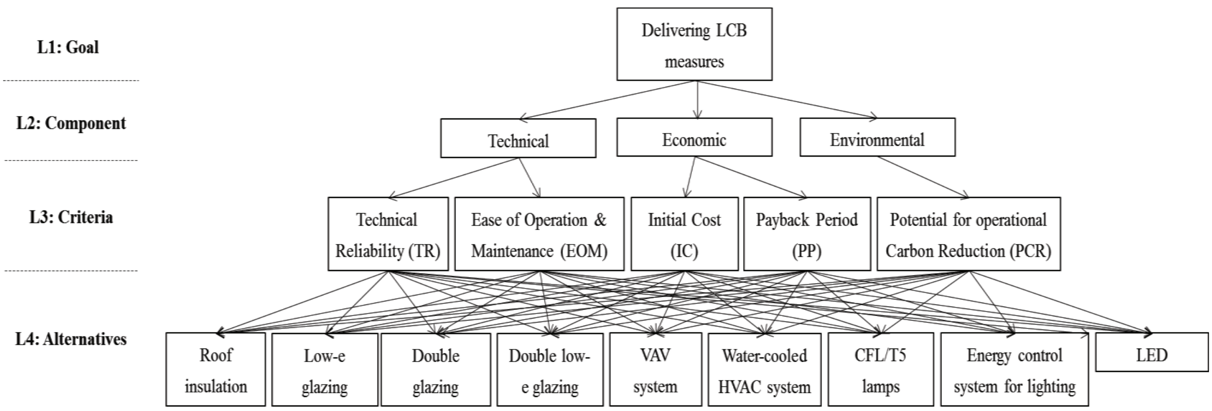

Fig. 1. MCDM criteria and LCB measures [3,10,11,12,14]

3.2. MCDM Model development

MCDM has been widely used to optimize sustainable energy solutions in many areas. Given that the decision regarding the utilization of LCB measures is complex, MCDM can effectively review the problem in accordance with the significance of different criteria and the preferences of the decision-makers.

This research employed the Fuzzy RPOMETHEE method to explore the selection process of LCB measures for commercial buildings in Hong Kong, which allowed decision-makers to have much more freedom to conduct judgments and make decisions. In addition, conventional PROMETHEE method was also used to compare with and evaluate the proposed method in this paper. The proposed model is specified in Figure 2. Four sections of this model are identified, to determine criteria and alternatives, weightings, conduct Fuzzy PROMETHEE and PROMETHEE method, and finally conduct comparison and draw conclusions.

3.3. BIM-integrated MCDM model development

BIM can be adopted in the selection process of LCB measures to improve decision making efficiency. An elementary means of using BIM is simply to reduce the amount of work involved in evaluating multiple alternatives early in the design process [5]. In the process of selecting LCB measures for commercial buildings in Hong Kong, multiple criteria need to be taken into consideration, including technical reliability (TR), ease of operation and maintenance (EOM), initial cost (IC), payback period (PP) and potential for operational carbon reduction (PCR). Some criteria, such as TR, EOM and PP, can be assessed via scoring of experts. Others such as IC and PCR, can be evaluated quantitatively through simulations. All assessment results are regarded as initial inputs of MCDM models, to conduct further analysis. The information flow is shown in Figure 3. The proposed BIM-integrated MCDM model is consisted of four phases, namely input, BIM-integrated simulation, MCDM models and output.

The first step, input phase, is to identify the required information describing the geometry of buildings in the simulation, HVAC systems, materials' properties and LCB measures performance under each criterion. Other design related information such as lighting and electrical systems and their schedules of use, building occupancy, and weather conditions for the simulation, is also needed to be taken into consideration. Weighting system is required for further alternatives ranking and selection [5, 22]. Once inputs are identified, the next step is to incorporate these variables as parameters in the BIM model. The prototype link between BIM and MCDM models is accomplished through Open Studio, eQUEST, and Low Impact Design Explorer (LIDX).

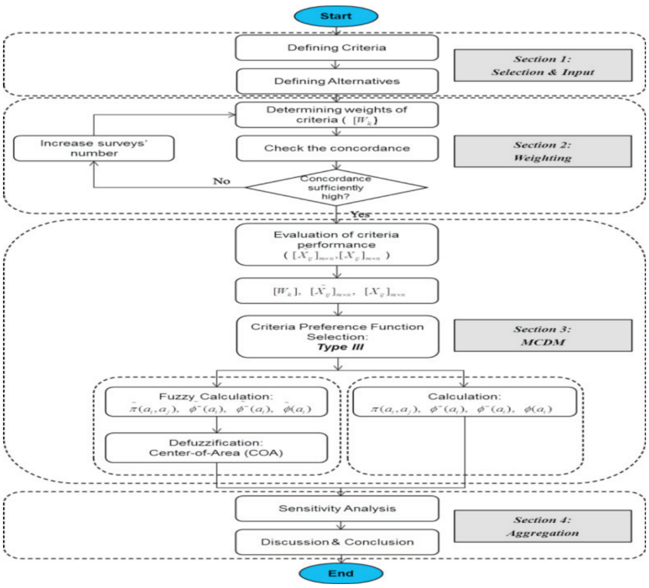

Fig. 2. Proposed MCDM model

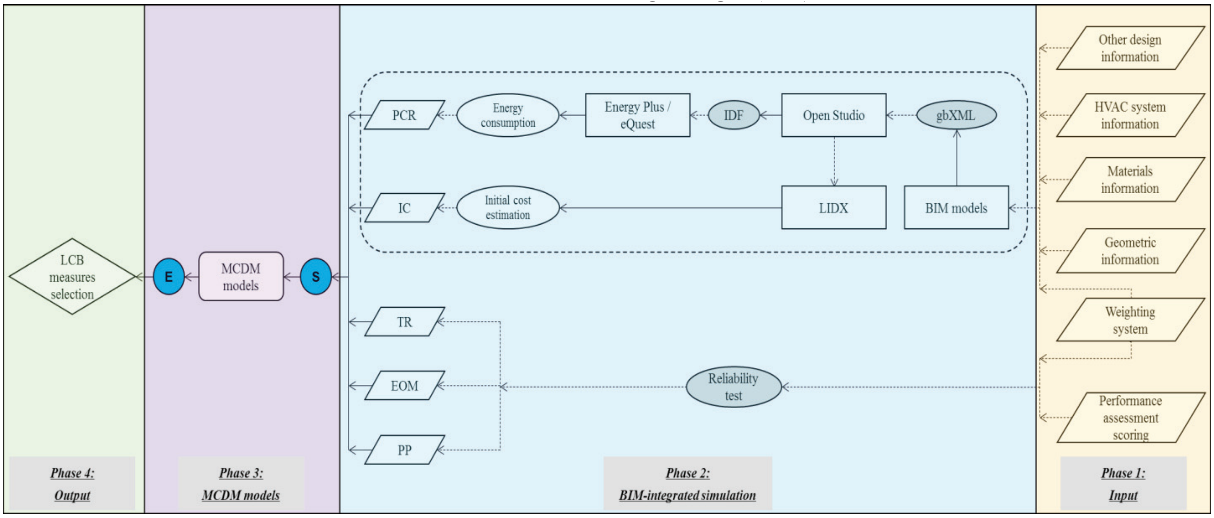

Fig. 3. Framework of proposed BIM-integrated MCDM system

In the second phase, BIM-integrated simulation process, building geometry is developed through BIM, such as AutoDesk's Revit® Architecture. This software requires manual redrawing of target buildings and thermal zone geometry. Then with the output information in Green Building XML (gbXML) format which can be directly imported into Open Studio, manual geometry drawing for complementary revises can be done in Open Studio. After the definition of building geometry information, thermal zone information and materials information, two procedures need to be followed. In the first procedure, data are derived from the Open Studio BIM model in IDF format which is directly imported into eQUEST. The simulation results of energy consumption can be incorporated into the carbon calculation tools provided by the Hong Kong Electric Company. PCR from using these nine LCB measures can thus be calculated. It is similar to using LIDX for the IC estimation. The evolving nature of design is inherent in the ethos of LIDX in that the system assists designers to build SketchUp BIM models to suit the different need in the early stage [23]. Building cost estimations are generated through a built-in automation facility in LIDX that simulates the process of costing-a-design in practice as design develops.

Besides, in terms of TR, EOM and PP factors, Cronbach's alpha (C-alpha) method is applied to improve the reliability and consistency of initial input data. Generally, a C-alpha value which is greater than 0.7 is considered the lowest requirement for conducting a survey and is also applied in this particular research. Once data satisfy the reliability requirements, data flow of these three criteria can move on into the third phase. Outputs from the second phase are incorporated into the input information for the MCDM model described in Figure 2. And final results of LCB measures ranking and selection are delivered in the fourth phase.

The proposed BIM-integrated MCDM model achieves the seamless integration of early stage decision making and design. Accurate simulation process allows the decision-making process more realistic and reliable, other than totally relying in scoring and other subjective assessment methods.

4. Model verification: project case study

4.1. Background

The proposed BIM-integrated MCDM system is demonstrated using data from a typical commercial building in Hong Kong, called project A. Project A is 48 m above ground level and included three office towers, one shopping mall podium, and one skywalk podium. Its total floor area was 47340 m^2. Some variables in this study were simplified for convenience without affecting the final simulation with eQUEST, namely, the interior and exterior decorations and the thermal zones.

4.2. Data collection and simulation process

To generate the simulation model using eQUEST software, required variables related to building design and building services installation were derived from the original design and contract document as necessary. Additional data were mainly obtained through discussions with architects and from building energy codes (BECs). The weather data obtained from the eQUEST database represented the conditions in Hong Kong. In addition, the total electricity consumption of a building indicated energy consumption in this research.

Considering the applicability of 9 LCB measures and the reality of project A together, some revises needed to be done for LCB measures. The HVAC system is simulated as a single-zone air-handling system based on the data. Thus, "Water-cooled HVAC system" does not improve design. LEDs are advantageous in terms of robustness and service life, but are mostly used as lighting for external decorations. As such, they were both excluded from the potential LCB measures. Finally, 7 LCB measures were tested in relation to the improvement of design measures for Project A at the design stage as listed in Table 1.

Using the eQUEST and LIDX, each alternative were assessed under PCR and IC as listed in Table 1. In terms of other criteria assessment, a questionnaire survey distributed by email was conducted, and 25 complete responses were received.

Table.1. PCR and IC values of LCB measures for Project A

LCB Measures	Initial Cost (M HKD)	Potential of Carbon Reduction (t/y)
A1: CFL/T5 lamps	0.64	481.9
A2: Energy controlling system for lighting	0.76	381.7
A3: VAV system	1.9	955.9
A4: Roof insulation	0.39	23.7
A5: Low-e glazing	0.67	252.8
A6: Double glazing	5.35	331.8
A7: Double low-e glazing	8.02	402.9

4.3. MCDM process

PROMETHEE and Fuzzy PROMETHEE were both applied to 7 LCB measures for LCB measures ranking.

The PROMETHEE method utilizes a single number to represent each criteria entry and thus cannot couple uncertain information. However, Fuzzy PROMETHEE allows for the use of data in its available form [3]. In this paper, the associated uncertainties were then incorporated by treating the representative criteria as a triangular fuzzy numbers. A five-scale linguistic variable fuzzy number was used, as in the study by Chen et al. [8] to assess the importance of criteria, TR, EOM and PP, with a fuzzy set. However, PCR and IC were calculated in another fuzzy triangular form $(m^{x_{ij}}, \alpha^{x_{ij}}, \beta^{x_{ij}})$ and $\alpha = \beta = 0.15m$, according to Bazjanac and others [22].

For ranking purposes, the linear preference function Type III [15] was considered reasonable where $d_k = g_k(a_i) - g_k(a_j)$. The parameter p_k can be set as $p_k = g_k(\cdot)_{\max} - g_k(\cdot)_{\min}$, where $g_k(\cdot)$ is the evaluation of all alternatives for criterion k. The result of fuzzy synthetic decision of each alternative is a fuzzy number. Several approaches have been proposed for ranking fuzzy numbers with most of them transforming the fuzzy number into a real number. This paper utilized the Center-of-Area method due to its simplicity and more reasonable results than others [3]. The defuzzified value of fuzzy number can be obtained from:

$$x_{defuzzified} = [(u_{ij} - l_{ij}) + (m_{ij} - l_{ij})]/3 + l_{ij} \tag{1}$$

4.4. Results and analysis

One program in C++ was written to implement the Fuzzy PROMETHEE method. Using the program developed, the preference of each criterion over the others was then evaluated, summed and weighted to obtain the preference indices for each LCB measure. These values are placed in Table 2 (PROMETHEE) and Table 3 (Fuzzy

PROMETHEE) indicating the preference of one measure over the other. The outranking obtained for these 7 LCB measures based on this proposed BIM-integrated fuzzy MCDM model using PROMETHEE and Fuzzy-PROMETHEE methods were the same. However, the net flow values derived by each of the methods were not. This is attributed to more information being incorporated into Fuzzy-PROMETHEE evaluation. Meanwhile, with the help of BIM software, the process can be convenient and reliable.

Table.2. PROMETHEE preference indices

$\pi(A_i, A_j)$	A1	A2	A3	A4	A5	A6	A7	ϕ^+	ϕ_{net}	Rank
A1	-	0.58	0.57	0.24	0.28	0.71	0.92	0.55	0.54	1
A2	0.00	-	0.11	0.03	0.01	0.24	0.35	0.12	-0.13	5
A3	0.04	0.15	-	0.11	0.05	0.18	0.39	0.15	-0.08	4
A4	0.01	0.37	0.41	-	0.12	0.54	0.72	0.36	0.27	2
A5	0.00	0.31	0.31	0.08	-	0.44	0.65	0.30	0.22	3
A6	0.00	0.11	0.00	0.07	0.01	-	0.22	0.07	-0.28	6
A7	0.00	0.00	0.00	0.03	0.01	0.01	-	0.01	-0.53	7
ϕ^-	0.01	0.25	0.23	0.09	0.08	0.35	0.54			

Table.3. Fuzzy PROMETHEE preference indices

$\pi(A_i, A_j)$	A1	A2	A3	A4	A5	A6	A7	ϕ^+	Defuzzified ϕ_{net}	Rank
A1	-	(0.00, 0.16, 0.70)	(0.02, 0.16, 0.71)	(0.03, 0.09, 0.63)	(0.01, 0.08, 0.63)	(0.09, 0.26, 0.81)	(0.14, 0.37, 0.92)	(0.05, 0.19, 0.73)	0.16	1
A2	(0.00, 0.00, 0.44)	-	(0.02, 0.04, 0.60)	(0.02, 0.02, 0.17)	(0.00, 0.01, 0.51)	(0.09, 0.14, 0.69)	(0.14, 0.21, 0.80)	(0.05, 0.07, 0.54)	-0.01	5
A3	(0.02, 0.03, 0.50)	(0.02, 0.07, 0.63)	-	(0.05, 0.08, 0.57)	(0.03, 0.05, 0.57)	(0.08, 0.13, 0.72)	(0.13, 0.23, 0.83)	(0.06, 0.10, 0.64)	0.03	4
A4	(0.00, 0.01, 0.53)	(0.00, 0.10, 0.67)	(0.03, 0.13, 0.69)	-	(0.00, 0.03, 0.59)	(0.10, 0.22, 0.77)	(0.15, 0.31, 0.88)	(0.05, 0.13, 0.69)	0.10	2
A5	(0.00, 0.00, 0.51)	(0.00, 0.08, 0.64)	(0.02, 0.10, 0.67)	(0.01, 0.03, 0.57)	-	(0.09, 0.19, 0.74)	(0.14, 0.30, 0.86)	(0.04, 0.12, 0.67)	0.08	3
A6	(0.00, 0.00, 0.44)	(0.00, 0.03, 0.58)	(0.00, 0.00, 0.57)	(0.02, 0.04, 0.51)	(0.00, 0.01, 0.51)	-	(0.02, 0.11, 0.70)	(0.01, 0.03, 0.55)	-0.12	6
A7	(0.00, 0.00, 0.41)	(0.00, 0.00, 0.55)	(0.00, 0.00, 0.54)	(0.02, 0.03, 0.49)	(0.00, 0.01, 0.48)	(0.00, 0.00, 0.53)	-	(0.00, 0.01, 0.50)	-0.23	7
ϕ^-	(0.00, 0.01, 0.47)	(0.00, 0.07, 0.63)	(0.02, 0.07, 0.63)	(0.03, 0.05, 0.49)	(0.01, 0.03, 0.55)	(0.08, 0.17, 0.71)	(0.12, 0.26, 0.83)			
ϕ_{net}	(-0.42, 0.18, 0.73)	(-0.58, 0.00, 0.54)	(-0.57, 0.03, 0.62)	(-0.44, 0.08, 0.66)	(-0.51, 0.09, 0.66)	(-0.70, -0.14, 0.47)	(-0.83, -0.25, 0.38)			

5. Discussion

The PROMETHEE and the Fuzzy PROMETHEE methods provide the same final ranking of the LCB measures with different net flow values. However, the absolute differences between the traditional methods and fuzzy methods are somewhat significant. This may be due to the size of the dataset and more information can be included in the Fuzzy PROMETHEE method. Besides, the net flow values are much closer between each alternative when Fuzzy PROMETHEE is utilized. This corresponds with the intuitive observations of the initial data where the differences would be minor. Thus, when there is substantial uncertainty in data, the use of Fuzzy PROMETHEE should be preferred. While if all criteria have crisp known values, PROMETHEE should be adopted to save time.

6. Conclusion

This paper has developed a BIM-integrated Fuzzy MCDM model based on Fuzzy PROMETHEE, eQUEST and LIDX for selecting LCB measures. Five criteria for the selection of nine LCB measures were identified, including PCR, IC, TR, EOM and PP, based on the combination of attributes associated with the economic, technical, and environmental factors. The BIM, eQUEST and LIDX were used to simulate the energy consumption and initial cost associated with the LCB measures. Through the analysis based on the developed model, both the PROMETHEE and Fuzzy PROMETHEE methods provided the same final ranking of LCB measures for commercial buildings in Hong Kong: CFL/T5 lamps → Roof insulation → Low-e glazing → VAV system → Energy controlling system for lighting → Double glazing → Double low-e glazing. However, Fuzzy PROMETHEE includes more information and provides more freedom for decision-makers, which should be proposed when substantial uncertainties exist.

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