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Multi-Criteria Decision Analysis for Energy Retrofit in Buildings

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The construction industry is one of the most energy-intensive, resource depleting, and pollution emitting sector in the world. Methods of prolonging the service life and increasing the performance of buildings are heavily explored. This presents an opportunity to improve the performance of existing buildings by incorporating energy-efficient technologies and strategies and either on-site or off-site generation. The ambitious goal would be to transform aged buildings into Net-Zero Energy Buildings (NZEB). Due to economic restrictions and feasibility concerns, energy retrofit strategies must be designed and planned well to achieve the long-term goals of a building. Proposed Multi-Criteria Decision Analysis (MCDA) is developed through the Analytical Hierarchy Process (AHP) and VIKOR for evaluating energy retrofit strategies in buildings that include three performance criteria: environment, economy, and technical. As proof of concept, a case study involving a whole building simulation is considered. The feasibility of a NZEB on an existing university building is achieved, however, based on the results of MCDA, stakeholders gave importance to the initial investment cost rather than the technical performance of retrofit interventions.

1. Introduction

An aggressive construction industry complements economic growth. Construction developments in strategic locations provide a significant impact on economic growth (Huang et al., 2020). This creates significant greenhouse gas (GHG) emissions and is contributors to climate change (Hurlimann et al., 2018). Quality buildings are needed to safely house schools, hospitals, offices, and homes. These buildings demand large amounts of energy during their life span, from construction to demolition. Energy consumption significantly contributes to carbon emissions, which is a major cause of climate change. Due to the limited resources for constructing and operating new buildings, extreme efforts are undertaken by nations around the world in highlighting energy efficiency and low carbon energy into their long-term plans and targets. Energy-saving measures that are efficient, low energy consumptive and reduces GHG emissions is a topic of interest (Xin, 2018). For old buildings, improving the performance is crucial in reducing global energy use and helps promote environmental sustainability.

Old buildings are known to be poor energy performers, these buildings are often found in a state of abandonment and face limited options as they approach the end of life. The decision of whether to retrofit or demolish an aged building is not always straightforward. A typical building requires cost-intensive materials as well as operation and maintenance over a long period along with immense environmental impacts associated with it, and significant efforts towards prolonging its service life are being explored by researchers. A Net-Zero Energy Building (NZEB) is a structure that produces as much renewable energy as it needs. The act of retrofitting buildings is complex in which many criteria are balanced to achieve the long-term goal of a building. In most cases, the economic and environmental performance are usually inversely proportional, and methods to integrate both in an equally weighted manner is essential (Webb, 2017).

Sustainability can be categorized into three dimensions namely ecological, economic, and social**.** To identify opportunities for improving the environmental aspects associated with the construction sector over the complete

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life cycle of the building, tools and assessments are needed such as Life Cycle Assessment (LCA). Retrofit on structures using LCA provides a good analysis in comparing alternatives (Ongpeng et al., 2019). However, it is not enough to analyze the performance of the product or process based on environmental indicators alone (Costa et al., 2019). Decision-making in assessing outcomes of complex situations involving many intangibles is difficult. It is based on the genuine ability of people to make critical decisions (Saaty, 1980). Previous research showed that decision-making tools like Multi-criteria Decision Analysis (MCDA) provided good model results in considering benefits, opportunities, costs, and risks to plan a sustainable city (Saaty and Sagir, 2015). A sustainable building option reduces environmental degradation in an economically viable and socially acceptable manner (Janjua et al., 2019). The ideal decision must consider the triple bottom line (TBL) which brings the trade-off situation to a higher level of complexity (Zanghelini et al., 2018). In addition, building performance as a parameter in evaluating the energy consumption within a building is significant and complex (Fathalian, 2018).

Several studies suggested valid and optimal solutions to satisfy sustainability objectives. Pombo et al., (2016) highlighted the necessity of applying the life cycle method to determine the optimal retrofit solutions. Asdrubali et al. (2019) proposed to evaluate the energy and carbon payback time of different retrofit scenarios, while Salem et al. (2020) presented an energy performance analysis to select individual energy efficiency measures to meet NZEB targets and create retrofit scenarios. In this paper, a MCDA model with three performance criteria: environment, economy, and technical is developed and applied to a case study building. It is to provide a robust comparison between various retrofit strategies through different retrofit scenarios in achieving a compromised retrofit solution that is closest to the ideal condition following the preference of stakeholders.

2. Problem Statement

The demand for improving the energy efficiency of new buildings and exploring retrofit strategies to the existing ones is rapidly increasing. Several studies considered the type of strategy, barriers, complexity, and feasibility (Holopainen et al., 2016). The decision to retrofit is challenging since it involves substantial funding and decision-making from a wide range of stakeholders with constraints, limitations, and assumptions. Considering the environmental efficiency and socio-technical performance further complicates the sustainability dilemma. In most retrofit interventions, the economic optimum does not deliver environmental performance targets. Choosing between alternatives based on multi-attributes especially when the data regarding the alternatives are uncertain, imprecise, and subjective is difficult. MCDA is a form of integrated sustainability evaluation. This study proposes using Analytical Hierarchy Process (AHP) and a distance-to-target method VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje) to measure three performance criteria to attain a compromised solution favorable to decision-makers.

3. Methodology

Shown in Figure 1 is the framework of the proposed model. Numerous retrofit strategies (r_n) of old buildings are considered. Performance criteria on environment, economy, and technical are used for the MCDA.

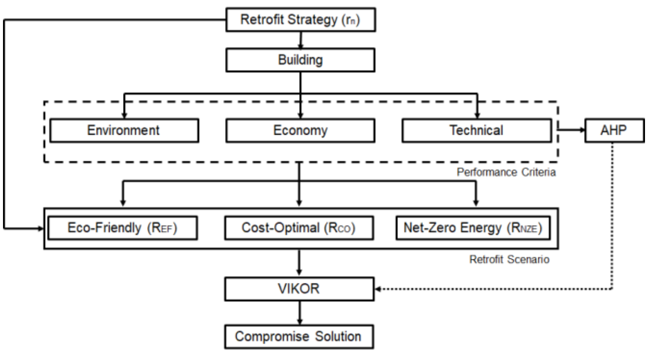

Figure 1: Conceptual Framework of the Study

The steps of the proposed methodology are shown below:

Step 1. Environment performance criteria are done using Simapro software with Eco Indicator 99 as the life-cycle impact assessment method (LCIA). The total environmental load was expressed as a single score in thousands of ecopoints, kPt (Grause, 2018). The case study building as the functional unit and it encompasses a "cradle-to-gate" assessment with its system boundary limited to the manufacture of the construction materials up to the construction processes. The use and end-of-life are omitted.

Step 2. Economic performance criteria are done by collecting commercially available technology and cost with material properties and/or energy consumption. A detailed unit price analysis of each retrofit strategy is done to ensure the accuracy of these criteria.

Step 3. Technical performance criteria are derived using DesignBuilder software. The initial modeling is done using pertinent information such as floor plans, date of construction, number of occupants, material details, utility bills, weather data, and geographic location. Calibration of model is needed to ensure that the model behaves similarly to the actual building. It measures and determine the energy potential: energy saved and generated of energy retrofit strategies. A criterion for calibration with acceptable tolerance is set. For this study, a $\pm$15 % mean bias error is used to compare the monthly usage prediction to the historical monthly utility bill data.

Step 4. After the three performance criteria with models are generated, a questionnaire is prepared for stakeholders. This is to establish the preference weights of each performance criterion used in AHP (Saaty, 1980). The weight of each evaluation criterion is generated by using a series of pairwise comparison.

Step 5. A compromise solution is generated using Vlsekrtuijumska Optimizacija I Kompromisno Resenje (VIKOR) (Opricovic and Tzeng, 2007). In this method, the three retrofit scenarios Eco-friendly (R_{EF}), Cost-Optimal (R_{CO}) and Net-Zero Energy (R_{NZE}) are evaluated. A compromise solution is an acceptable concession after all the alternatives are evaluated according to all established criteria including the decision-makers' characteristics.

4. Case Study

An old aged four-story building in Diliman, Quezon City, Philippines was chosen for the case study. Calibrated model for technical performance criteria modelling from DesignBuilder software is illustrated in Figure 2.

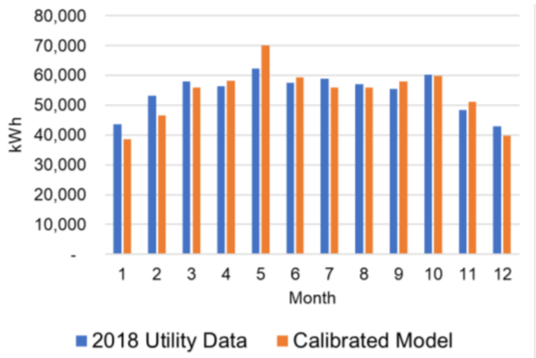

Figure 2: Calibrated model for the technical performance criteria

Table 1: Characteristics of the building systems

Characteristic	Description of the Case Study
Location	Diliman, Quezon City 14.6538°N, 121.0685°E
Energy Use	654,200 kWh
Exterior Wall	200 mm Plastered CHB Wall
Type of Opening	6mm Single glazed in aluminum
Roofing	Clay Tiles without insulation
Lighting	Fluorescent Lamp
Sytem Type	Air-conditioning (COP 2.0)

The calibrated model was the result of multiple simulations and iterations using the 2018 monthly utility data of the building and it is within ±15 % mean bias error. Table 1 shows the characteristics of the building system while Table 2 shows the performance criteria, sub-criteria, and units for the Environment, Economic, and Technical. Energy retrofitting strategies shown in Table 3 were applied separately using the calibrated model on DesignBuilder software. Energy retrofit strategies were grouped into three retrofit scenarios. The Eco-Friendly scenario (R_{EF}) composes of strategies having the least environmental damage while the Cost-optimal scenario (R_{CO}) includes strategies with the least investment cost. Lastly, the Net-Zero Energy Scenario (R_{NZE}) is to achieve an NZEB status that gives a high energy potential.

Table 2: Performance Criteria

Criteria	Sub Criteria	Unit
Environmental	Human Health	kPt
	Ecosystem Quality	kPt
	Resources	
	Investment Cost	kPt
Economic	Energy Potential	PhP
Technical		kWh

Table 3: Energy retrofit scenarios and strategies

Retrofit scenario	Code	Retrofit strategy	Designation	Description of Retrofit Strategy
1 Eco-friendly	r2	Glass-fiber Insulation	Wall	100 mm THK, κ: 0.043 $W \times m^{-1} \times K^{-1}$
Scenario (R_{EF})	r5	Stone Wool Insulation	Roof	100 mm THK, κ: 0.040 $W \times m^{-1} \times K^{-1}$
	r7	Installation of tint	Window	Heat control window film
	r10	Efficient Air-conditioning	Mechanical	Coefficient of Performance: 2.71
	r13	Lighting and Controls	Electrical	LED + 3-stepped control
	r17	330 W Photovoltaic system	Generation	Polycrystalline solar panel
	r1	Expanded Polystyrene	Wall	100 mm THK, κ: 0.035 $W \times m^{-1} \times K^{-1}$
2 Cost-optimal	r6	Glass Wool	Roof	100 mm THK, κ: 0.032 $W \times m^{-1} \times K^{-1}$
Scenario (R_{CO})	r8	Blinds with high reflective slats	Window	Window shading
	r11	Efficient Air-conditioning	Mechanical	Coefficient of Performance: 3.77
	r14	Lighting and Controls	Electrical	LED + Linear Control
	r16	360 W Photovoltaic system	Generation	Monocrystalline solar panel
3 Net-Zero	r3	Rockwool Insulation	Wall	100 mm THK, κ: 0.033 $W \times m^{-1} \times K^{-1}$
Energy	r4	PUR Insulation	Roof	100 mm THK, κ: 0.026 $W \times m^{-1} \times K^{-1}$
Scenario (R_{NZE})	r9	Glazing system	Window	Double glazed with Argon gas gap
	r12	Efficient Air-conditioning	Mechanical	Coefficient of Performance: 3.95
	r15	Lighting and Controls	Electrical	LED + Linear/Off Control
	r18	420 W Photovoltaic system	Generation	Thin-film solar panel

The performance criteria of each retrofit strategy are presented in Figure 3 from the calibrated model.

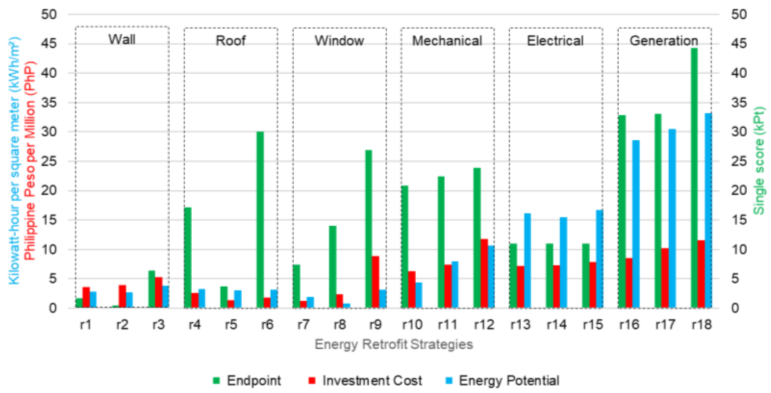

Figure 3: Performance metrics of energy retrofit strategies

It can be observed in the figure that On-site generation strategies account for the largest energy potential, however, the trade-offs are its endpoint damage impact and a high investment cost taken from performance criteria of environment and economy. Building envelope strategies such as wall and roof insulation, and window upgrades exhibit low performance on energy potential, investment cost and environmental damages compared to other strategies. It is quite significant that using efficient lighting such as light-emitting diode (LED) with lighting controls contribute to a considerable decrease in the energy consumption of a building. Replacing existing air-conditioning with a highly efficient system will result in a considerable initial investment cost despite its adequate energy potential.

Numerous retrofit scenarios are possible to achieve the NZE goal, nevertheless, the feasibility of a NZEB was proven through an energy reduction of 52 % and a 48 % on-site energy generation strategy. Energy retrofit strategies were grouped into scenarios and each performance metric was added cumulatively. Normalization was done to determine the impact of each metric for each scenario as illustrated in Figure 4. Beneficial criteria are those with higher values that are desired, alternatively, lower values are preferred for non-beneficial criteria (Giorgetti et al., 2013). In terms of the five sub-criteria, the R_{NZE} scenario performed poorly in all non-beneficial criteria despite displaying significant energy potential. It also produced the most environmental burden in all damage categories. While R_{CO} and R_{EF} are the more economical options as less investment cost was required while showing a comparable 72 % and 69 % energy potential of the R_{NZE}. Alternative scenarios R_{EF} and R_{CO} also displayed lower environmental damage in each environmental metrics.

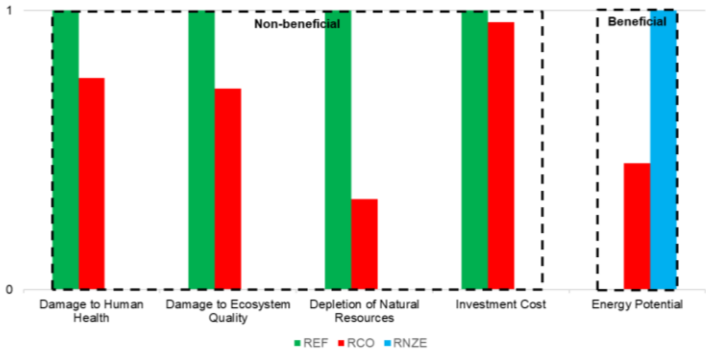

Figure 4: Normalized environmental, economic, and technical performance metrics of energy retrofit scenarios

In addition, AHP was done to determine the weight of each retrofit strategy with respect to the criteria as seen in Table 4. Investment cost was the most important criterion for stakeholders which accounts for 44.40 %, followed by the environmental impacts with a total of 37.35 % and lastly energy potential with 18.25 %. A decision was sought by the stakeholders to determine the alternative with the least investment cost and maximum benefit criteria.

Table 4: Interval decision matrix

	Human Health (kPt)	Ecosystem Quality (kPt)	Resources (kPt)	Investment Cost (PhP)	Energy Potential (kWh)
Weight	15.76 %	11.59 %	10.00 %	44.40 %	18.25 %
R_{EF}	7.05	0.44	0.06	30.0×10^6	476.4×10^3
R_{CO}	8.73	0.39	0.13	30.8×10^6	559.0×10^3
R_{NZE}	13.98	0.87	0.16	47.8×10^6	658.7×10^3

Table 5: S, R, and Q of retrofit scenarios

	Si	Ri	Qi	Rank Order	Acceptable Stability
R_{EF}	0.19	0.18	0.12	2	0.09 < DQ
R_{CO}	0.23	0.10	0.03	1	0.03 < DQ
R_{NZE}	0.82	0.44	1.00	3	0.97 > DQ
	$S^+ = 0.19$	$R^+ = 0.10$	DQ = 0.50		
	$S^- = 0.82$	$R^- = 0.44$			

The economic and technical performance of retrofit strategies are usually inversely proportional. A method to integrate both in an equally weighted manner was done. It can be strongly concluded that a particular alternative is the best one if the difference between the first alternative and the second alternative is DQ = 0.50. In Table 4 and 5, the results show that stakeholders prefer the investment cost when it comes to energy retrofitting. The Si, Ri, Qi and DQ in Table 5 are dimensionless and are ratio of performance criteria.The cost-optimal scenario and eco-friendly scenario ranks 1 and 2, for the compromise alternatives. While the Net-Zero Energy scenario proved feasible, this scenario was not generated as a compromise alternative. This model can be considered by decision-makers when faced with uncertain, conflicting and incommensurable criteria.

5. Conclusions

In this work, a proposed MCDA model using AHP and VIKOR with environmental, economic, and technical performance criteria of retrofit strategies in buildings was developed. This model is capable of aiding the decision maker towards finding the optimum balance for energy retrofitting an existing building by considering three damage categories, investment cost and energy potential of energy retrofit strategies. It is noteworthy that a compromise alternative may differ according to the responses of stakeholders, performance criteria considered, and the number of alternatives examined. The model has been successfully tested on an institutional building and it is found that there is still a scope for improving the model by using other performance indicators, retrofit strategies and scenarios to further refine the model. Studies in the future may explore different types of building with varying occupancy and construction with social aspects of energy retrofitting to provide a holistic sustainability assessment. For the whole life cycle of the building, additional parameters such as maintenance and operations, and life-cycle cost is recommended. Laboratory and actual validations are suggested to further strengthen the information regarding energy retrofit strategies.

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