Aggregation of Fuzzy Weights for Sustainable Buildings: Application of Multi-Criteria Extent Analysis and Geometric Mean Process Towards Risk Mitigation Management Schema

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***Abstract*—Energy consumption requires natural resources, and the construction industry is one of its major contributors. The Green Building concept reduces its negative impacts and creates more energy-efficient buildings. The green building momentum is continuing to grow and so determining the appropriate standard of care is necessary. This paper includes a Hierarchical Risk Breakdown Structure, the Analytical Hierarchy Process, and the Fuzzy Analytical Hierarchy Process to detect and measure risks in Green Building Projects (GBP) in the Philippines. Data were collected and evaluated through 4 phases of risk management process (identification, evaluation, handling, and controlling). As a result, 28 risk factors were established and classified into 11 risk groups, one external risk and ten internal risks. The consistency ratios of the risk groups identified have acceptable values between 0.00 and 0.70. There are three Fuzzy AHP methods utilized in this study: Geometric Mean method, Extent Analysis method, and Arithmetic Mean method. A comparison was made through a Kolmogorov-Smirnov test in choosing the final criterion weights to be used among the three FAHP methods. A further comparative analysis between the parameter weights results from the AHP and the FAHP to even further reinforce the rank of the risks identified in GBPs as per the level of impact. This research also offers 11 risk reduction strategies that were included in the establishment of a risk management framework and may support the Philippines accomplish its sustainability objectives by guaranteeing the effective implementation of GBPs.**

***Index Terms*—construction management, fuzzy analytical hierarchy process, green building, risk assessment**

I. INTRODUCTION

RAPID community growth and development have a substantial environmental impact. The use of natural resources during the construction and operation phases of a building is accountable for global warming and climate change. Green Building projects reduce these negative impacts, and the increase of the general public's environmental awareness has influenced the construction industry to design and build by green principles.

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Although there have been several studies on GBPs and their benefits, there are only very few addressing their risks and how they can be managed. Since the Philippine construction industry is still young, only a few stakeholders are aware of the implications correlated with green building projects. The green building sector is booming and establishing the appropriate standard of care is becoming more significant.

The purpose of this research is to analyze and assess GBP risks in the Philippines. This formulates a risk management framework with underlying mitigation strategies that will address these uncertainty risks. This aims to answer the following objectives: (1) identify risks, present in green building projects, by utilizing the hierarchical risk breakdown structure, which also serves as a guideline in determining the scope of the identified risks; (2) assess the identified risk factors through the Analytic Hierarchy Process or AHP and quantifying it further by incorporating fuzzy logic (FAHP) on the criterion weights from the data collected for each risk factor, ranking it according to its level of impact on green building projects; (3) propose mitigation strategies on targeted risk groups level to eliminate risk, its probability, and its impact on a project; (4) develop a framework addressing uncertainties on a project using five risk management strategies particularly to avoid, mitigate, transfer, and accept the identified risk factors.

Risk groups and risk factors were adapted from the case of Singapore [1], an active advocate of green building projects. The framework suggested and developed in this study is only limited to the case of the Philippines. Macroeconomic risk, contract disputes, client-related risk, design problems, safety risk, operation complexity, technical problems, human resource risk, material/equipment concerns, project team risk, and cost overrun risk are all taken into consideration. In developing countries, participating in sustainable projects constitute challenges and financial barriers as there are fewer funds allocated for it [2]. Major schedule delays in construction projects are also experienced which are caused by contract modification and changes in specifications [3]. Unclear requirements from the client can be classified as risks too. Clients are accountable for decision-making during the construction and the implementation of sustainable designs in the project [4]. Unlike traditional buildings that are built with the compliance of requirements, green buildings must achieve better performance and must also comply with the requirements for the certification of green building status [5]. According to a study, the various aspects of the design elements, as well as the means and methods of construction in LEED-certified buildings, have an impact on worker safety [6]. Since document management, utility, and control are main factors in all project phases, delays in the issuance of documents such as reports have become a burden in recent decades in the construction industry [7,8]. Also, the innovative and complicated green technologies may need additional testing and inspection compared to traditional buildings [9]. And selecting appropriate sustainable building materials is one of the key requirements in achieving sustainable construction goals [10].

There is still an unknown role of individual workers in contributing to sustainable development. Individual employees also perform an uncertain role in contributing to long-term growth. To manage the diverse and innovative techniques and infrastructure, the green project needs a dynamic workforce of more comprehensive experts [11]. Cost overrun is linked to inaccurate cost-estimation procedure [12] and expensive technologies, products, materials associated with Green buildings may add up to the construction project's budget [13] which may eventually lead to overlooked initial costs for the project.

As the country pushes for sustainability and at the same time deals with rapid demand for urbanization, policymakers can utilize this research for effective policymaking from the academic perspective. For studies relevant to the industry, this may also promote the use of a multi-criteria decision-making (MCDM) strategy, specifically the fuzzy AHP. The development of a risk management system may also aid in the effective completion of GBPs in the Philippines. Ultimately, this research project offers new insights into the country's current situation in terms of achieving long-term construction goals.

II. Methodology

A. Risk Identification

Understanding the key concepts of green building projects and conducting an extensive literature review on its potential risk factors is the first step in risk identification on green projects. As a risk identification tool, the Hierarchical Risk Breakdown Structure (HRBS) enables risk categorization into internal and external resources [14].

B. Risk Evaluation

Non-nominal types of responses were measured through the 5-point Likert scale. This quantitative scale is converted to a 9-point AHP fundamental scale to get each criterion's relative weight through the pairwise comparison matrix. The qualitative scale conversion into the AHP scale [15] is shown in Table I. For pairwise judgment, the data transformation scheme is shown in Table II.

TABLE I
QUALITATIVE SCALE OF CONVERSION INTO AHP SCALE

Qualitative Scale	Quantitative Scale	AHP Fundamental Scale Intensity	AHP Fundamental Scale Definition
VL	1	1	EI
L	2	3	MI
M	3	5	SI
H	4	7	VSI
VH	5	9	EI

VL – Very Low, L – Low, M – Moderate, H – High, VH – Very High, EI – Equal Importance, MI – Moderate Importance, SI – Strong Importance, VSI – Very Strong Importance, EI – Extreme Importance

TABLE II
DATA TRANSFORMATION SCHEME TO PAIRWISE JUDGMENT

Scale	Linguistic Scale Term	Paired Comparison of Criteria
1	E	1:1
2	E to MD	2:1 3:2, 4:3, 5:4, 6:5, 7:6, 8:7, 9:8
3	MD	3:1, 4:2, 5:3, 6:4, 7:5, 8:6, 9:7
4	MD to SD	4:1, 5:2, 6:3, 7:4, 8:5, 9:6
5	SD	5:1, 6:2, 7:3, 8:4, 9:5
6	SD to VSD	6:1, 7:2, 8:3, 9:4
7	VSD	7:1, 8:2, 9:3
8	VSD to ED	8:1, 9:2
9	ED	9:1

E – Equal, MD –Moderately Dominant, SD – Strongly Dominant, VSD – Very Strongly Dominant, ED – Extremely Dominant

By attaining the rules of reciprocity and transitivity for all its elements, the matrix $a_{i,j}$ is consistent. Below shows the equation for transitivity (1) and reciprocity (2):

$$a_{i,j} = a_{i,k} \cdot a_{k,j} \tag{1}$$

$$a_{i,j} = \frac{1}{a_{i,j}} \tag{2}$$

For the pairwise comparison matrices, the example of consistent matrix and matrix formation is shown in (3):

$$A = \begin{bmatrix} A_{11} & \cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ a_{nl} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \vdots & \vdots \\ w_n/w_1 & \cdots & w_n/w_n \end{bmatrix}$$

$$\begin{bmatrix} w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \vdots & \vdots \\ w_n/w_1 & \cdots & w_n/w_n \end{bmatrix} \times \begin{vmatrix} w_1 \\ \vdots \\ w_n \end{vmatrix} = n \begin{vmatrix} w_1 \\ \vdots \\ w_n \end{vmatrix}$$

$$A * W = nW \tag{3}$$

The number of comparisons for a consistent reciprocal matrix is equal to λmax. The weight of the corresponding criterion is given by the arithmetic average of each row of the normalized matrix, and the criterion's total weight must equal 1 by summing each column element of the pairwise matrix and then dividing each column element with the sum of the respective column.

The consistency ratio (4) should be less or equal to 0.10, it will determine if the inconsistency of judgment is acceptable or needs revision. Random index is the value depending on the number of elements as proposed by Saaty. Equation 5 shows the consistency index.

$$CR = \frac{CI}{RI} \tag{4}$$

$$CI = \frac{\lambda \max - n}{n-1} \tag{5}$$

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Representation for pairwise comparison matrix can be through a fuzzy set linked with a fuzzy scale [16]. A type-1 fuzzy set (triangular fuzzy numbers) and a 9-level fuzzy scale are used in this analysis. Table III shows the transformation of the linguistic scale to a fuzzy scale, and Fig. 1 shows the 9-level fuzzy scale described by a collection of fuzzy sets.

TABLE III
LINGUISTIC SCALE OF IMPORTANCE

Linguistic Scale	AHP Scale	Triangular Fuzzy Scale	Triangular Fuzzy Reciprocal Scale
Equal Importance	1	(1, 1, 1)	(1, 1, 1)
Intermediate 1	2	(1, 2, 3)	(1, 0.20, 0.33)
Moderate Importance	3	(2, 3, 4)	(0.50, 0.33, 0.25)
Intermediate 2	4	(3, 4, 5)	(0.33, 0.25, 0.20)
Strong Importance	5	(4, 5, 6)	(0.25, 0.20, 0.167)
Intermediate 3	6	(5, 6, 7)	(0.20, 0.167, 0.143)
Very Strong Importance	7	(6, 7, 8)	(0.167, 0.143, 0.125)
Intermediate 4	8	(7, 8, 9)	(0.143, 0.125, 0.111)
Extreme Importance	9	(9, 9, 9)	(0.111, 0.111, 0.111)

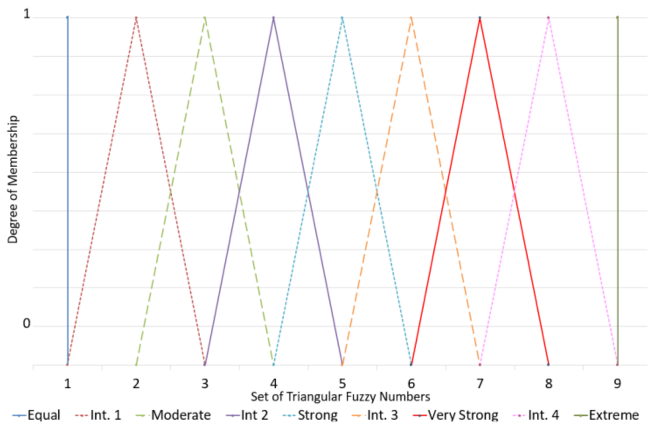

Fig. 1. 9-Level Fuzzy Scale

To obtain results from the pairwise comparison matrix, aggregation methods are used. This involves methods for deriving fuzzy weights. For type-1 fuzzy set (TFN), this paper used the extent analysis method [17] and the mean methods: geometric mean [18] and arithmetic mean. For the defuzzification, these methods utilized the centroid method and the EAM through the degree of possibility. For consistency measurements, methods used the crisp consistency principle which was Saaty's consistency ratio.

The following equation is used in the EAM to calculate the value of fuzzy synthetic extent in reference to S_i and the ith object:

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \times \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right] \quad (6)$$

The degree of possibility, $M_2 = (l_2, m_2, u_2) \geq M_1(l_2, m_2, u_2)$, is then expressed, as shown in Equations 7 and 8, where is the ordinate of the highest intersection point D between μ_{M2} and μ_{M1}.

$$V(M_2 \geq M_1) = \sup_{y \geq x}\left[\min(\mu_{M1}(x), \mu_{M2}(y))\right]y \quad (7)$$

$$V(M_2 \geq M_1) = hgt(M \cap M_1) = \mu_{M2}$$

1 if $M_2 \geq M_1$

0 if $l_2 \geq \mu_2$

Otherwise: $$d = \frac{l_1 - \mu_2}{(m_2 - \mu_2) - (m_1 - l_1)} \quad (8)$$

In the case of $d(A_i) = \min V(S_i \geq S_k)$, k = 1,2,..., n; k 1. The weight of the vector, where Ai is the number of components.

$$W' = [d'(A_1), d'(A_2), \ldots, d'(A_n)]^T \quad (9)$$

The equations below can be used to generate normalized weight vectors, where W is a non-fuzzy number:

$$d(A_i) = \frac{d'(A_i)}{\sum_{i=1}^{n} d'(A_i)} \quad (10)$$

$$W = [d(A_1), d(A_2), \ldots, d(A_n)]^T \quad (11)$$

The summation value of $\tilde{r}$ can be obtained using (12) and the reciprocal using the Geometric Mean method (13).

$$\tilde{A}_1 \otimes \tilde{A}_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 * l_2, m_1 * m_2, u_1 * u_2) \quad (12)$$

$$\tilde{r} = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \ldots \otimes \tilde{a}_{in})^{\frac{1}{n}}, i = 1,2,\ldots,n \quad (13)$$

For each criterion of the fuzzy number, the relative fuzzy weight $\tilde{W}_i$ can be obtained by multiplying $\tilde{r}_i$ with the reciprocal using (14). For non-fuzzy weights (M_i), relative weights undergo defuzzification using Equation 15. Each criterion is then normalized to determine its weight using Equation 16.

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \otimes \tilde{r}_2 \otimes .. \tilde{r}_n)^{-1} = (lw_i, mw_i, uw_i) \quad (14)$$

$$M_i = \frac{(lw_i \otimes mw_i \otimes uw_i)}{3} \quad (15)$$

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \quad (16)$$

Equation 17 and 18 are applied, using the Arithmetic Mean method, in obtaining weight vectors.

$$\tilde{C}_i = \frac{1}{n}(\tilde{C}_{i1} \oplus \tilde{C}_{i2} \oplus \ldots \oplus \tilde{C}_{in}) \quad (17)$$

$$\tilde{W}_i = \frac{\tilde{c}_i}{\sum_{j=1}^{n} \tilde{c}_j} \quad (18)$$

C. *Risk Handling*

The Friedman test (19) is used to rank the efficacy of the proposed risk reduction steps.

$$F_R = \frac{12}{nk(k+1)} \sum R_i^2 - 3n(k+1) \quad (19)$$

D. *Risk Controlling*

The final part of risk management is risk control, but it does not mean that it ends here. The design and development of a risk management framework to continue to ensure the assessment and mitigation are effective, and the monitoring process is still required. If any of these handling processes were ineffective, then identified risks may undergo re-assessment/s and re-analyzation, or new strategies that may be adopted.

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III. Results and Discussion

A. Risk Identification

This is the first step in the risk-management procedure. Risks to GBPs were discovered through a study of the literature. It was defined further by its scope with the aid of the HRBS (Fig. 2). As shown below, only 1 risk group was identified as an external factor: Macroeconomic Risk. The rest were identified as internal risk factors.

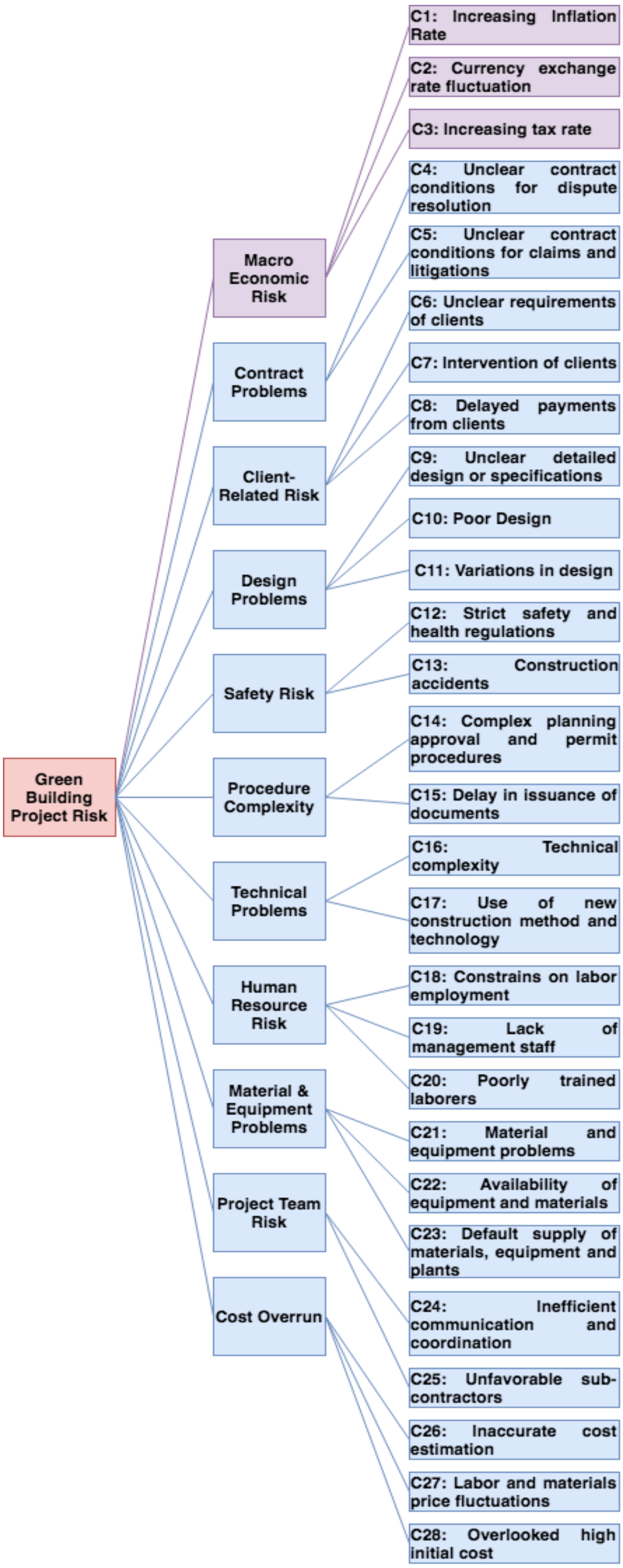

Fig. 2. Hierarchical Risk Breakdown Structure – Green Building Projects

B. Risk Evaluation

Here lie the technical aspects of the risks identified, it can be assessed through the AHP and the FAHP. Using Cronbach's alpha, identified risk groups were internally consistent with results greater than 0.70. Proposed risk mitigation measures' value of alpha is 0.919. After the pairwise comparison matrix and obtaining weight criterion using AHP, the consistency ratio for every risk group was obtained to be consistent. The only external factor, Macroeconomic Risk, obtained a 0.07 consistency ratio while the rest of the risk groups obtained a 0.00 value. Table IV displays the risk factor parameters weights calculated using the three FAHP methods.

TABLE IV
Comparison of FAHP Methods

Risk Group	Risk Factors	Geometric Mean Method	Extent Analysis Method	Arithmetic Mean Method
(1) Macroeconomic Risk	C1	0.54	0.29	0.47
	C2	0.08	0.36	0.08
	C3	0.38	0.36	0.45
(2) Contract Problems	C4	0.20	0.73	0.20
	C5	0.80	0.27	0.80
(3) Client-Related Risk	C6	0.33	0.33	0.33
	C7	0.33	0.33	0.33
	C8	0.33	0.33	0.33
(4) Design Problems	C9	0.43	0.47	0.43
	C10	0.15	0.04	0.14
	C11	0.43	0.47	0.43
(5) Safety Risk	C12	0.89	0.00	0.89
	C13	0.11	1.00	0.11
(6) Procedure Complexity	C14	0.64	1.00	0.66
	C15	0.36	0.00	0.34
(7) Technical Problems	C16	0.25	0.00	0.25
	C17	0.25	1.00	0.75
(8) Human Resource Risk	C18	0.75	0.00	0.25
	C19	0.25	0.50	0.25
	C20	0.25	0.00	0.50
(9) Material/ Equipment Problems	C21	0.49	0.50	0.12
	C22	0.12	1.00	0.64
	C23	0.64	0.00	0.24
(10) Project Team Risk	C24	0.25	1.00	0.25
	C25	0.75	0.00	0.75
(11) Cost Overrun	C26	0.25	0.09	0.25
	C27	0.49	0.68	0.50
	C28	0.26	0.22	0.25

In choosing the final FAHP criterion weight among methods utilized, the geometric mean method was used from the results of the Kolmogorov-Smirnov test [19]. Figures 3a, 3b, and 3c are the Quantile-Quantile Plots which show that data from the geometric mean method, EAM, and arithmetic mean method are normally distributed.

In Table V, the risk factors' criterion weights from AHP and FAHP were compared. The results for the criterion weights are almost identical. Based on the FAHP results, the following are the risk groups with its highest risk factor/s: Risk Group 1 – C1, Risk Group 2 – C5, Risk Group 3 – C6/C7/C8, Risk Group 4 – C9/C10, Risk Group 5 – C12, Risk Group 6 – C14, Risk Group 7 – C17, Risk Group 8 – C20, Risk Group 9 – C22, Risk Group 10 – C25 and Risk

Group 11 – C27.

C. *Risk Handling*

Through the Friedman test with 58 blocks and 11 treatments, the null hypothesis was rejected. All 11 risk mitigation measures proposed (Table VI) do not have the same probability distribution. This means that at least 2 measures differ from each other. The table shows the ranking of the proposed measures according to its level of effectiveness on GBPs. The most effective risk mitigation measure is "S6: Extensive planning and research, using references of successful green building projects". And the least effective risk mitigation measure is "S2: Precise contract language and give provision to limit each parties' liabilities".

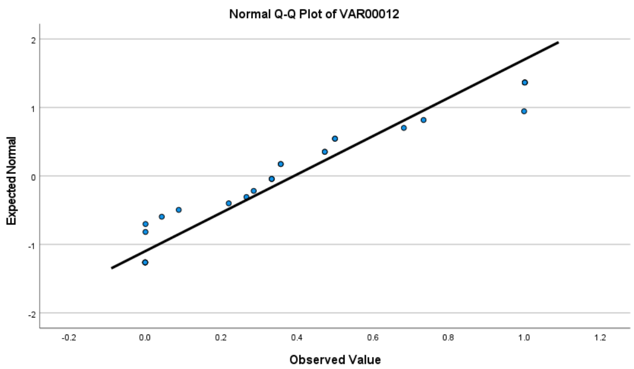

Fig. 3(a). Q-Q Plot of K-S test for Geometric Mean Method

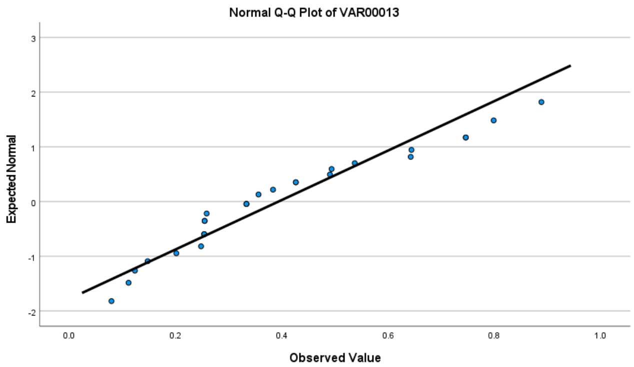

Fig. 3(b). Q-Q Plot of K-S test for Extent Analysis Method

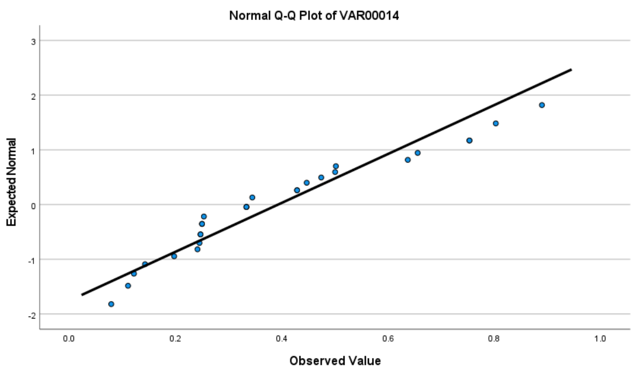

Fig. 3(c). Q-Q Plot of K-S test for Arithmetic Mean Method

TABLE V
COMPARISON OF CRITERION WEIGHTS OF AHP & FAHP

Risk Group	Risk Factors	AHP Values	FAHP Values
Macroeconomic Risk	C1	0.55	0.54
	C2	0.08	0.08
	C3	0.37	0.38
Contract Problems	C4	0.20	0.20
	C5	0.80	0.80
Client-Related Risk	C6	0.33	0.33
	C7	0.33	0.33
	C8	0.33	0.33
Design Problems	C9	0.43	0.43
	C10	0.14	0.15
	C11	0.43	0.43
Safety Risk	C12	0.89	0.89
	C13	0.11	0.11
Procedure Complexity	C14	0.67	0.64
	C15	0.33	0.36
Technical Problems	C16	0.25	0.25
	C17	0.75	0.75
Human Resource Risk	C18	0.25	0.25
	C19	0.25	0.25
	C20	0.50	0.49
Material/Equipment Problems	C21	0.12	0.12
	C22	0.65	0.64
	C23	0.23	0.23
Project Team Risk	C24	0.25	0.25
	C25	0.75	0.75
Cost Overrun	C26	0.25	0.25
	C27	0.50	0.49
	C28	0.25	0.26

TABLE VI
PROPOSED RISK MITIGATION MEASURES

Code	Risk Mitigation Measures	Rank
S1	Contingency funds in case of emergency	10
S2	Precise contract language and give provision to limit each parties' liabilities	11
S3	Understanding the client's goal for green building rating system	5
S4	Utilizing an integrated design process	9
S5	Implementation of safety, health regulation, and inspection of design quality	3
S6	Extensive planning and research using references of successful green building projects	1
S7	Ensuring sound project design and early briefing	7
S8	Developing training programs to improve employee's knowledge and skills	2
S9	Inspection of quality frequently with a detailed checklist and investing in research on green building materials	6
S10	Enhance communication toll for better collaboration and development of education programs for team members	8
S11	Establishing a proactive cost contingency plan and insurance at risk allocation	4

D. *Risk Controlling*

The framework (Fig. 4) shows the proposed risk management process for GBPs. This highlights the following: Identify, Assess, Handle, and Control. Identifying the sources of risk, as the first step, by conducting a risk registry and categorizing it using the HRBS. The next step is to "Assess" to evaluate the magnitude of impact using

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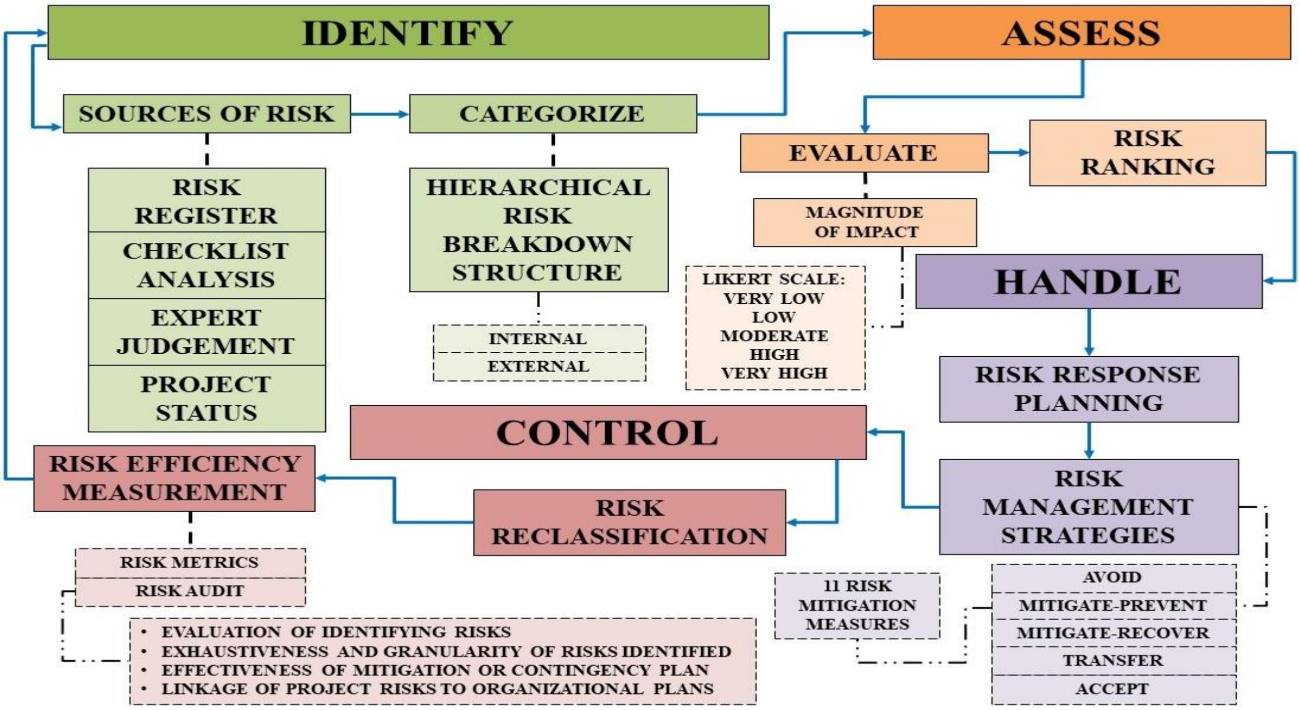

Fig. 4. Proposed Risk Management Framework

the Likert scale and rank the risk. Next is to "Handle" by conducting risk response planning and applying risk management strategies: avoid, mitigate-prevent, mitigate-recover, transfer, accept. The last part is to "Control" using risk reclassification and risk efficiency measurement.

IV. Conclusion

Understanding risk management process helps in identifying, analyzing, and creating responses for project risks. This research has carried out an extensive literature review on green building projects and its risks.

There are 11 risk groups and 28 risk factors identified which have acceptable values between 0.00 - 0.70 for the consistency ratio by applying the AHP. The quantification of linguistic variables and applied scales through a survey was further established by allowing respondents to include fuzziness in decision-making on predetermined factors. Through the FAHP, this study was able to determine the criterion weights of each risk factors and rank them among its corresponding risk category based on its level of effect on green building projects. A comparison between the criterion weights calculated from the AHP and FAHP showed that there is little to no difference in the values obtained which validates the ranking of the identified risks.

Furthermore, this study was able to design a schema for risk management that can be utilized by project stakeholders. This may contribute not only to the success of future Green projects, but also in achieving sustainability goals in the Philippines.

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