Design and Construction Technique for Low Embodied Energy Building: An Analytical Network Process Approach

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Highlights:

- The analytical network process can be used as an important decision-making tool in the construction sector.
- Reducing the amount of cement will help to reduce energy accumulation in buildings.
- Creating knowledge modeling can help build sustainable practices.

Abstract. Energy performance in the construction industry is one of the significant features to be assessed in order to achieve sustainability in the built environment. There is a limited amount of literature on the analytical network process (ANP) in achieving sustainability towards reducing embodied energy. The aim of this study was to achieve buildings with less embodied energy through design, construction techniques and automation using ANP in order to promote sustainable construction. Data collection was primarily done by way of a well-structured questionnaire and an expert opinion survey. The responses retrieved from the questionnaire were analyzed using descriptive statistics and ranked accordingly. An ANP model was developed using multi-criteria decision-making based on the expert survey and used to prioritize and assign an important weighting for the identified criteria. The findings showed that multi-criteria decision-making with ANP when effectively employed will help in achieving sustainable buildings with low embodied energy. Reducing the amount of cement through design and building information modeling is the most significant factor towards achieving buildings with less embodied energy.

Keywords: *analytical network process; construction; design; embodied energy; survey*.

1 Introduction

Presently, ecological involvement in construction processes is relatively small. There is a need for the construction industry to change its traditional ways of operating in response to developing awareness about environmental damage as a

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result of consumption of non-renewable resources, ecological degradation and global warming [1]. Numerous endeavors are currently being coordinated toward sustainable building in the construction industry.

The focal point of the construction industry is currently moving from ecological awareness as only a small part of building procedures to having advanced procedures being consolidated as part of a much more extensive effort to protect the environment. Sustainable improvement is a value-laden articulation [2]. Likewise, du Plessis [3] has examined different approaches of sustainable development and sustainable construction. Accomplishing sustainability in the construction industry is of vital significance. In Malaysia, non-renewable energy sources are required to be utilized in the production of construction materials with high embodied energy [4]. The energy utilized in building operations can promptly be determined but the embodied energy contained in a building is hard to measure. In spite of the Malaysian government having ordered contractors to increase the use of industrialized building systems (IBS), construction practice in Malaysia is as yet based on the customary practice of casting in situ [5].

The impact on the environment from the construction industry is huge, accounting for 42% of total energy utilization, around 35% of ozone depleting substance outflow and around 32% of waste transportation [6]. The construction sector's demand for materials in South East Asia cannot be supplied by local production of building materials. Several constraints are faced by countries producing cement, particularly in the supply of the source materials caused by demand fluctuation and lack of capital. Cement production is the largest contributor to greenhouse emission, while the most important factors contributing to climate change are concrete and steel production. The concrete mix is composed of about 12-14% cement, however, transportation, production of aggregates and manufacturing also contribute to embodied energy. When used in construction, masonry, which is the world's most common building technique and exists in various forms, such as bricks, blocks, adobe, and concrete masonry, is energy-efficient [7].

2 Sustainable Construction in Malaysia

Sustainability initiatives in construction have been promoted by Malaysian government since the year 2000, which has subsequently led to several pilot projects. The Malaysian government has committed to adopting a voluntary reduction of about 40% of GDP in terms of emission intensity by the year 2020 compared to the 2005 levels. The administration of Malaysia as of late has presented the National Green Technology Policy together with a proposed RM 1.5 billion (USD 500 million) Green Technology Financing Scheme to advance green and sustainable technologies [7]. In any case, for the construction sector, the National Green Technology Policy supplements the past push to embrace industrialized building systems (IBS) to create buildings and to diminish the dependence of the sector on migrant labor. Fiber reinforced polymers (FRB) for strengthening and repairing reinforced concrete and masonry use composite materials that are environmentally friendly and sustainable [8].

2.1 Embodied Energy in the Design and Construction Stages

Embodied energy is the energy expended during the production, construction, demolition and disposal of building materials [9]. During the design process, the building's size, structure, direction and presentation are taken into account to make a structure that from the earliest stage will generate low warming, cooling and lighting loads. To this, 'impassive' design measures are added to also include lower energy burdens and additional alleviation levels. Several factors can be considered in the design stage to minimize embodied energy [10-14].

According to Foraboschi [15], optimizing the design of floors can improve the design and construction with a high span-thickness ratio that meets the desired specification. Load bearing system design has been proposed as a sustainable and efficient alternative approach for the construction sector [16].

2.2 Analytical Network Process

The analytical network process (ANP) is a decision-making method proposed in [15,16]. ANP is an extension of the analytical hierarchy process (AHP). AHP, developed in 1980, is one of the most widely used multi-criteria decision-making methods. AHP breaks down problems into numerous levels making up a hierarchy, whereby each decision element is independent [17]. ANP has significant power in decision making when an extensive number of factors are involved. It allows for a more complex inter-relationship among decision elements by substituting the hierarchy in AHP with a network.

Basically, there are two categories of multi-criteria decision-making (MCDM) problems: multiple-criteria discrete alternative problems and multiple-criteria optimization problems. Among the methods proposed for solving discrete alternative problems are modeling based on multiple-attribute utility theory (MAUT) [18] and ANP [16]. Numerous studies have been conducted using ANP to solve various MCDM problems, including leveling and resource allocation [17], sustainability assessment and urban planning [18], risk assessment and decision analysis [19], and allocating resources [20]. According to Chung, *et al.*[21], ANP has been used in solving numerous complicated decision problems. They used ANP for selecting the product mix for efficient manufacturing in semi-conductor fabrication.

3 Methodology

This study adopted a quantitative method to gather in-depth data about developing sustainable buildings with low embodied energy with the help of ANP in the Malaysian construction industry. Figure 1 illustrates the essential steps taken in this research methodology.

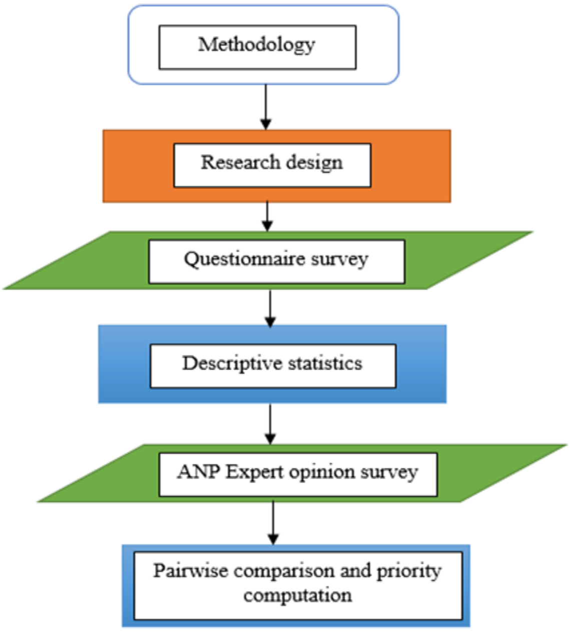

Figure 1 Methodology flowchart.

3.1 Data Collection and Sampling

Data collection was performed through a questionnaire survey. This is a quantitative methodology and was undertaken to demonstrate existing theories and to reinforce research findings with theories and findings of previous researches. The questionnaires were of two different types. The variables used to develop the first questionnaire were obtained from the literature [15,22]. The first questionnaire was designed using a Likert scale of 1-5 to examine the respondents' knowledge on design and construction strategies to achieve sustainable buildings. The survey respondents included civil engineers, architects, quantity surveyors, M&E and others (building designers and interior designers) associated with public and private construction organizations.

A sample size of 357 was obtained from a total respondent population of 5232, based on Czaja and Blair [23]. The questionnaire data generated were imported to an SPSS version 22 database.

3.2 Analytical Network Process

ANP using the multi-criteria decision-making approach was applied by using the feedback from the expert questionnaire survey. The ANP made a pairwise correlation of options from the responses received with respect to the strategies of achieving sustainable buildings with less embodied energy. The three basic steps of ANP are: model development, pairwise comparison, matrix computation and priorities.

3.2.1 Model Development

The model was developed with minimizing embodied energy as the goal, followed by the criteria to form three (3) clusters: design, construction and automation, and alternatives comprising of nine (9) nodes. The connections between the different clusters and nodes were defined within the network. The multi-criteria model was created as per the response of the experts, as shown in Figure 2. This step was used to classify clusters and generate the ANP model network topology for the problem being explored [24].

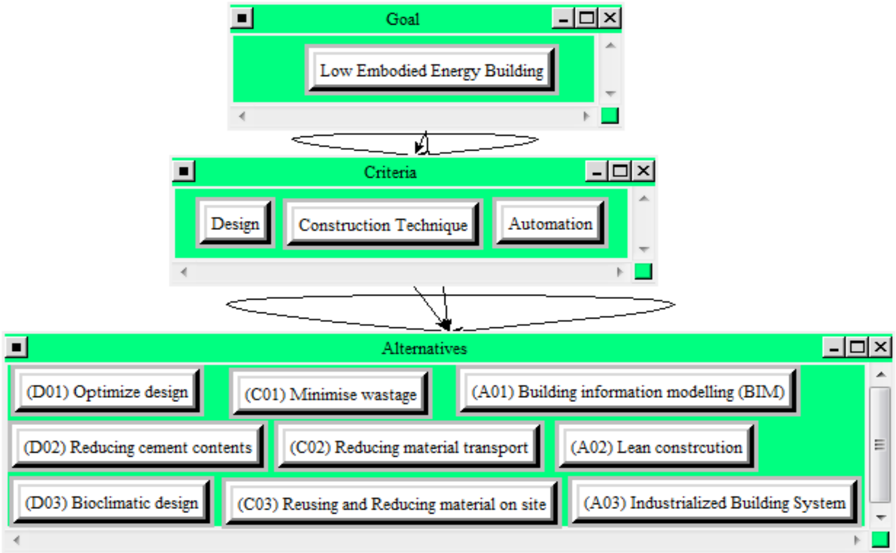

Figure 2 ANP model.

3.2.2 Pairwise Comparison

The next step was to arrange the results in a matrix for a pairwise comparison. This matrix was then normalized by dividing each entry to get a standardized matrix by summing its corresponding column. The standardized matrix rows were then averaged to consider the priority vector for each element. ANP uses a scale of 1-9 based on this measurements and derives the relative weights. The pairwise comparison can be seen in Figure 3, showing each alternative compared to the rest with respect to design.

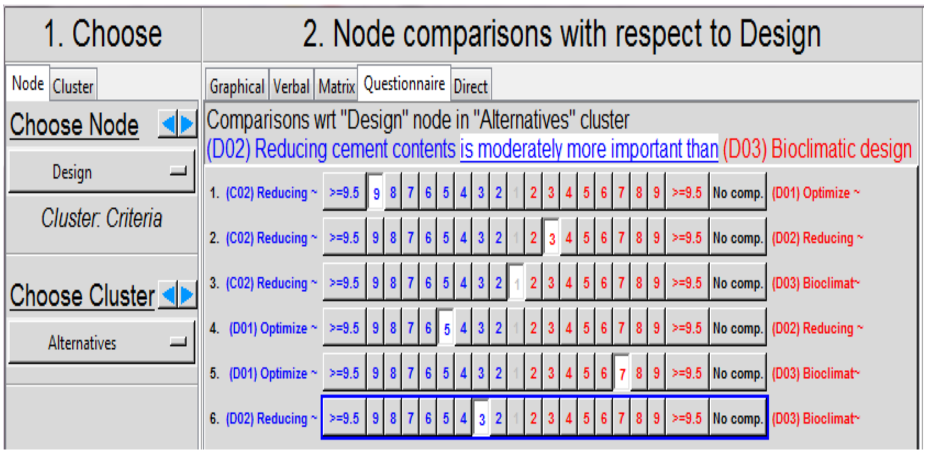

Figure 3 Pairwise comparison.

3.2.3 Priorities Vectors and Weight

Priorities are the values of any limit matrix column. They are displayed in two ways: the limit matrix gives the limit values. The standardized cluster values are obtained by standardizing the priorities for each component to sum up to 1.0. Priorities are obtained for each respondent and then aggregated.

4 Result and Discussion

4.1 Demographic Analysis

Classification of the respondents showed that 30% were civil engineers, 22% were architects, 19% were quantity surveyors, 17% were mechanical and electrical engineers, while the remaining 12% includes other professionals like interior designers, developers and project managers. The responses demonstrate that the greater part of the respondents work in the private sector (64%) while the public sector accounted for 36% of the respondents, 39% had a bachelor's degree, while 32%, 14%, and 15% had a master's degree, PhD, and diploma respectively; 42% of the respondents had 5 to 10 years of work experience or more.

4.2 Descriptive Statistics

Descriptive statistics was employed to obtain the mean and standard deviation of the individual factors and sorted likewise. This study adopted the use of an internal consistency reliability test using Cronbach's alpha value. Table 1 shows that a Cronbach alpha value of 0.976 was obtained from the reliability test, which indicates excellent reliability. Pallant [25] indicates that this statistic provides an indication of the average correlation among all the items that make up the scale. The values range from 0 to 1, with $\alpha \geq 0.9$ indicating *excellent*, $0.7 \leq \alpha < 0.9$ indicating *good* while $0.6 \leq \alpha < 0.7$ indicates *acceptable*, $0.5 \leq \alpha < 0.6$ indicates *poor*, and $\alpha < 0.5$ indicates *unacceptable* [26].

Table 1 Reliability results.

Cronbach's Alpha	No. of variables
0.976	33

The responses acquired from the study were analyzed by descriptive statistics and multi-criteria decision-making was also used using pairwise comparison to determine the priorities based on expert opinion. Table 2 shows the descriptive statistics of different design strategies for embodied energy minimization. The results are arranged from the highest to the lowest in terms of mean score and standard deviation.

Design optimization, cement content reduction and bioclimatic design were ranked highest among the factors considered, with mean values of 4.3524, 4.3429 and 4.1810, respectively. On the other hand, low maintenance design, layout plan optimization, and design consideration of load bearing structures were ranked low, with mean values of 3.6381 and standard deviation of 0.85624, 0.88929, and 0.87841, respectively.

Table 3 shows the construction techniques used in construction by Malaysian construction companies toward minimizing embodied energy in buildings. Minimizing wastage, decreasing transportation of building materials to the building site, reusing and reducing materials at the building site were ranked highest among the different factors considered, with mean estimations of 4.2952, 4.2762 and 4.2476, respectively.

On-site generation of energy from renewable sources, maximizing the use of local skills, and using new innovations in construction were the techniques considered during construction toward achieving sustainability in embodied energy minimization, with mean values of 4.0000, 3.9810 and 3.9333, respectively.

Table 2 Design strategies.

Items	Mean	Standard deviation	Ranking
Design optimization	4.3524	.72032	1
Cement content reduction	4.3429	.74458	2
Bioclimatic design	4.1810	.74396	3
Use of recyclable materials	4.1524	.84103	4
Design for durability	4.1429	.69929	5
Selection of low embodied energy materials	4.0667	.75021	6
Use of local materials	4.0667	.78773	7
Use of fewer finished materials	3.9333	.84656	8
Specification of low carbon concrete mixes	3.9238	.76831	9
Use of lightweight materials	3.8857	.83567	10
Designing for low end of life impact	3.7810	.88775	11
Increasing the use of prefabricated elements	3.7619	.81481	12
Optimization of the structural system	3.7333	.86898	13
Design for deconstruction	3.6952	.86740	14
Design for flexibility	3.6952	.78598	15
Low maintenance design	3.6381	.85624	16
Optimization of layout plan	3.6381	.88929	17
Design consideration of load bearing structures	3.6381	.87841	18

Table 3 Construction techniques.

Factors	Mean	Standard deviation	Ranking
Minimize wastage	4.2952	.69232	1
Reduction of transportation of building materials to the construction site	4.2762	.79051	2
Re-using and reducing materials on the construction site	4.2476	.78178	3
On-site water treatment	4.1429	.80178	4
Procuring green power on the construction site	4.0571	.84157	5
Light-weight construction	4.0095	.74026	6
On-site generation of energy from renewable sources	4.0000	.77211	7
Maximizing the use of local skills	3.9810	.79640	8
Using new innovations in construction	3.9333	.72413	9

As shown in Table 4, building information modeling (BIM), lean construction, and industrialized building systems (IBS) were ranked highest among the other variables by the respondents with mean estimations of 4.4286, 4.2857 and 4.0190, respectively. This means that adoption of BIM toward environmentally friendly building is of great importance. BIM supports a more prominent coordinated effort using task data, enabling one to practice and grow progressively in carrying out structural models.

BIM adds additional measurements to a building model by gathering 'insight' as data are calculated, captured, investigated, and shared. BIM information takes three additional measurements into consideration compared to a conventional 3D building model [27]. Benchmarking and concurrent engineering on the other hand were ranked low, with mean and standard deviation values of 3.7714, 3.5026 and 0.74003,0.72836, respectively.

Table 4 Automation construction.

Factors	Mean	Standard deviation	Ranking
Building information modeling (BIM)	4.4286	.70516	1
Lean construction	4.2857	.64621	2
Industrialized building systems (IBS)	4.0190	.73355	3
Modular engineering	3.8216	.81166	4
Benchmarking	3.7714	.74003	5
Concurrent engineering	3.5026	.72836	6

4.3 Priorities

As shown in Figure 4, considering design strategies, out of the priorities obtained from expert respondent one (1), reducing cement content, with a normalized cluster of 0.53725 and a limiting value of 0.179083, is most important toward achieving a sustainable building with low embodied energy, followed by building information modeling and minimizing wastage, with normalized clusters of 0.52561 and 0.40421, respectively. Reusing and reducing materials on-site was the least important according to respondent 1, with a normalized cluster of 0.10671 and a limiting value of 0.035571.

The priorities obtained from respondent 2, as shown in Figure 5, indicate that bioclimatic design had the highest priority ranking with a normalized cluster of 0.56369. It was followed by building information modeling, with a normalized cluster and limiting value of 0.52800 and 0.049899, respectively. Design optimization and reducing cement content were the most importance strategies to be adopted in the design stage. This can be seen from the normalized cluster and limiting values of 0.44907 and 0.318622. Reusing and reducing materials on-site was the least mentioned, with a normalized cluster of 0.10187.

Figure 6 also shows that reducing cement content and lean construction having a normalized cluster of 0.50760 and 0.50270 are more significant compared to other factors.

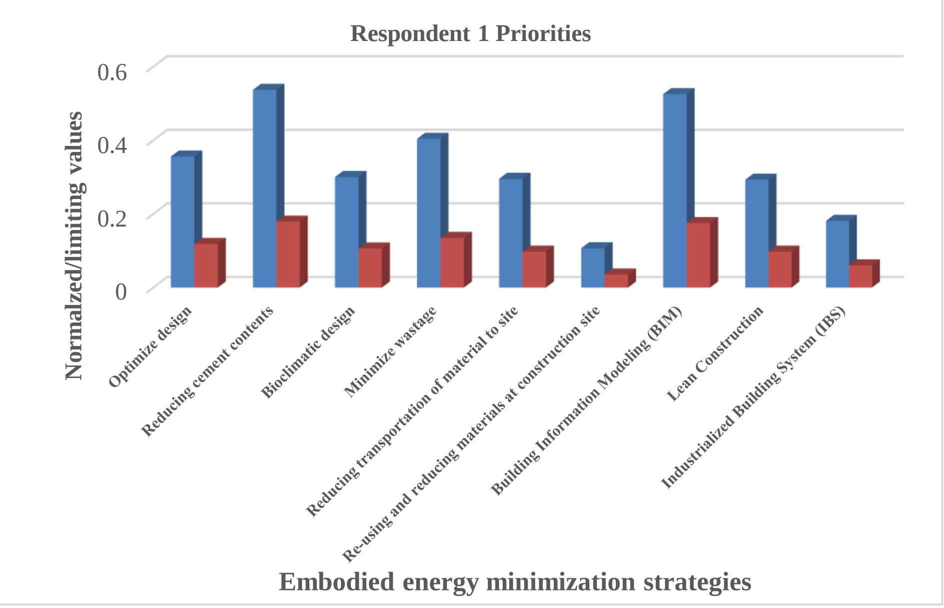

Figure 4 Priorities of respondent 1.

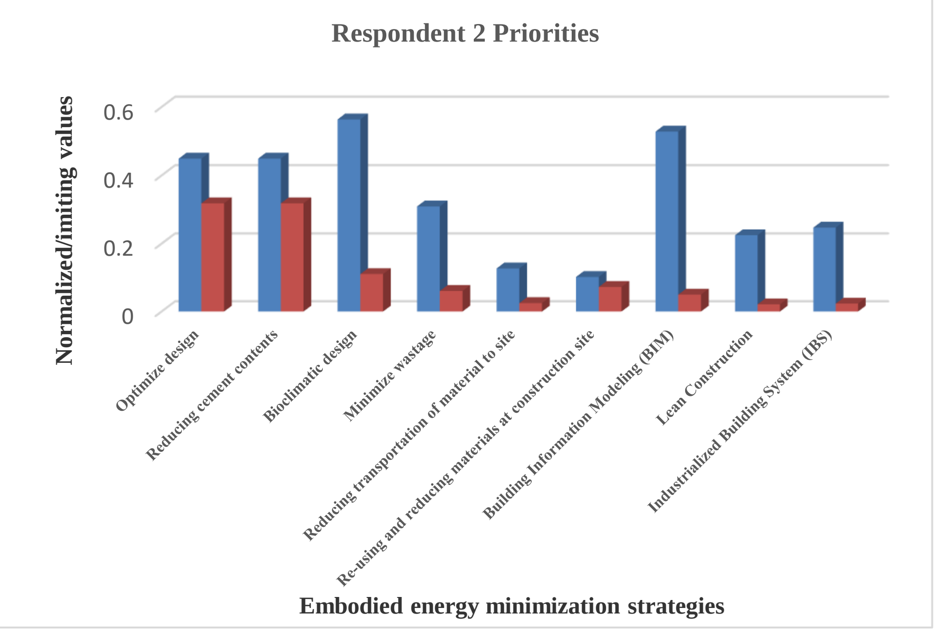

Figure 5 Priorities of respondent 2.

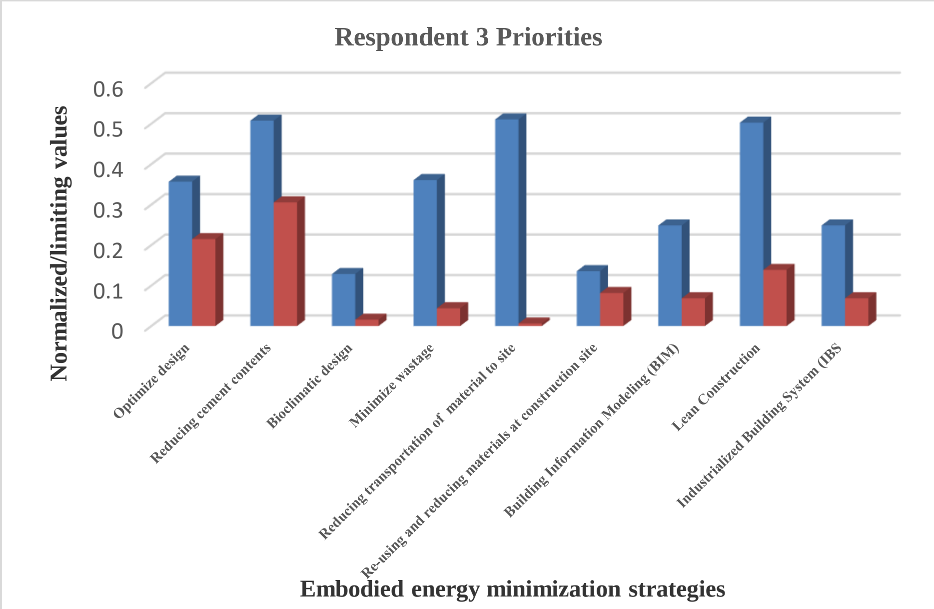

Figure 6 Priorities of respondent 3.

4.4 Aggregated priorities

The geometric mean of the expert opinions was obtained as shown in Table 5 and Figure 5, with (D02) reducing cement content by the most significant amount.

Using:

$$(R1)(R2)(R3) \ldots \ldots .(Rn)^{1/n} \qquad (1)$$

where R = individual score and n = number of criteria, n = 3, 1/n = 0.3333

Table 5 Geometric mean calculation from expert opinion.

Strategies	R1	R2	R3	Aggregate
D01	0.35604	0.44907	0.35677	0.38498
D02	0.53725	0.44907	0.50760	0.49663
D03	0.30033	0.56369	0.12866	0.27930
C01	0.40421	0.30937	0.36078	0.35603
C02	0.29546	0.12695	0.51056	0.26757
C03	0.10671	0.10187	0.13563	0.11384
A01	0.52561	0.52800	0.24865	0.41020
A02	0.29320	0.22473	0.50270	0.32118
A03	0.18118	0.24728	0.24865	0.22337

The aggregated priorities of the three respective expert opinions, respondent 1 (R1), respondent 2 (R2), respondent 3 (R3) and the aggregates of the respondent priorities are shown in Table 5. It indicates that reducing cement content in the design stage, building information modeling in the automation cluster, and design optimization in the design cluster were found to be the most important strategies towards achieving sustainable buildings with less embodied energy, with aggregated priorities of 0.49663, 0.41020 and 0.38498, respectively. The least significant factors considered were: reducing materials transportation (C02) and reusing and reducing materials on-site (C03) with aggregated priorities of 0.26757 and 0.11384, respectively.

The respective priorities of the respondents, including the aggregated priority, can be seen clearly in Figure 7. The figure shows a plot of the priorities with respect to the factors indicated by the respondents to minimize energy embodied in buildings.

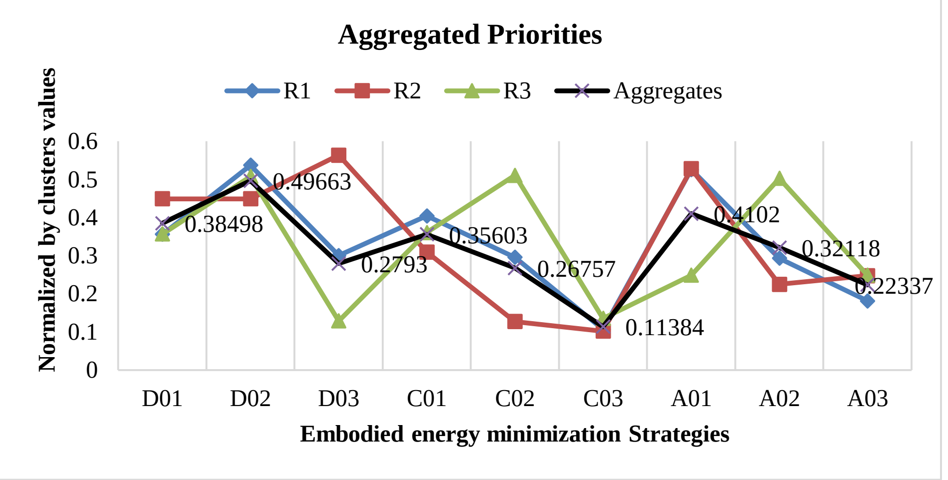

Figure 7 Aggregated respondent priorities.

5 Conclusion

This study explored the potential to minimize embodied energy through the analytical network process (ANP) in design, construction and automation techniques by reviewing the literature, conducting surveys and the development of a multi-criteria decision-making model. The most significant finding was the limited adoption of ANP in the construction industry. No previous attempt has been done to adopt ANP in embodied energy minimization, while the results obtained show that the application of ANP can help to achieve sustainable buildings with low embodied energy in design, construction and automation, according to criteria, which include cement content reduction, minimizing wastage of materials on site, and adoption of building information modeling, respectively. Design optimization and lean construction can also be considered by construction professionals in the Malaysian construction industry in order to achieve energy efficiency in buildings.

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