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Application of Multi-criteria Decision-making in the Design of a Post-disaster Transitional Shelter

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The Philippines is prone to natural disasters due to its location along the Pacific Ring of Fire. Damaged housing is a common occurrence so post-disaster shelters are often constructed. In light of this, the study applied multi-criteria decision-making (MCDM) to enhance the design of a shelter in the Philippines. The suitability of different partitions, namely concrete hollow blocks (CHB), autoclaved aerated concrete (AAC) and rice husk ash composite concrete (RHAC), roofs, namely corrugated galvanized iron (CGI) sheets, and insulated sandwich panels, as well as opening configurations were analyzed. The criteria used in evaluating the shelter were its environmental impact, thermal comfort, and cost. Results showed that the combination of AAC partitions, CGI roof, and additional openings is the best configuration. Compared to shelters with CHB, shelters that use AAC and RHAC have significantly better thermal comfort. The global warming potential (GWP) of the AAC partition is also 31.3 % lower, while the GWP of the RHAC and CHB partitions are almost equal. However, shelters that use AAC and RHAC are at most 23.4 % and 10.6 % more expensive than CHB counterparts. On the other hand, shelters with insulated panels have better thermal comfort over counterparts with CGI roofs, but the sandwich panels have over four times the GWP of CGI sheets and make the shelter at least 37.7 % more expensive. Overall, the original shelter can be improved by adding openings and using either AAC or RHAC partitions, but using insulated sandwich panels is impractical due to its high environmental impact and cost.

1. Introduction

Each year, around twenty (20) tropical cyclones, equivalent to a quarter of all typhoons worldwide, enter the Philippine Area of Responsibility (PAR) (Santos, 2021). As a result, the Philippines is among the most disaster-prone countries in the world. Housing often makes up the largest share in losses from post-disaster damage. One reason is that several Filipinos live in non-engineered houses which are incapable of withstanding tropical storms (Hernandez et al., 2015). Damaged houses are often reconstructed with the same structural vulnerabilities (Stephenson et al., 2018). Therefore, houses keep collapsing, and assisting displaced households through the construction of transitional shelters becomes a recurring concern.

The International Federation of Red Cross and Red Crescent Societies (IFRC) created the B7 Philippine transitional shelter to assist those affected by Tropical Storm Washi. Its partitions are constructed from CHB and plywood, while its roof is formed from CGI sheets. However, studies have shown that similar wall and roof materials provide poor thermal comfort in tropical climates (Hashemi et al., 2015). Matard et al (2019) found that the B7 shelter has the 2nd highest carbon dioxide emission among 81 shelters worldwide.

Since common techniques for improving comfort in warm climates involve altering the walls, roof, ceiling, and windows (Ramírez-Dolores et al., 2020), this study evaluated the suitability of different partition, roof, and opening configurations. Cement accounts for 86.7 % of the GWP of concrete (Liu et al., 2019) and is extensively used in the partitions, columns, and foundations of the B7 shelter. The use of concrete mixtures with lower cement content was evaluated – namely RHAC and AAC. Since rice is among the most widely grown crops in the Philippines, concrete and mortar, with 15 % of its cement replaced with rice husk ash (RHA), were considered. Likewise, AAC, a lightweight concrete made from cement, lime, water, sand, and an aerating agent, uses less cement than ordinary concrete due to the introduction of air pockets. For the roof, CGI sheets were compared to insulated sandwich panels having 50 mm thick polyurethane foam (PUR), while for the openings,

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two 0.5 m x 0.5 m windows were added to the original design. Both these modifications target thermal comfort. Overall, 12 shelter configurations were compared. Each modification is assigned 3 letters which represent its partition, roof, and opening type (Table 1). Apart from environmental impact and thermal comfort, cost was also studied. This is in line with the triple bottom line (TBL) framework, which focuses on the balance of environmental, social, and economic concerns.

Table 1: Shelter Modifications

Letter	Category	Description
C	Partitions	100 mm CHB
A	Partitions	100 mm AAC
R	Partitions	100 mm RHAC
S	Roof	CGI Sheet
P	Roof	Sandwich Panel with 50 mm PUR Insulation
N	Openings	No Additional Openings
W	Openings	Additional 2 Pcs. 0.5 m x 0.5 m Windows

Sustainability, comfort, and cost-effectiveness are common metrics in the design of post-disaster housing; however, the combination of the three criteria in an MCDM analysis is limited. Hosseini et al., (2016) conducted such an analysis on temporary housing units. One weakness of the proposed methodology is the use of thermal resistance of the building materials as the performance indicator for thermal comfort since the suitability of a material varies with location. Thermal comfort simulation tools which consider both environmental and material parameters may be more appropriate.

2. Methodology

The research applied life cycle assessment (LCA), thermal comfort assessment (TCA), and quantity surveying (QS) to evaluate each shelter configuration. These processes yielded the GWP, predicted percentage of dissatisfied (PPD), and cost of the shelters. Compared to other environmental impacts, global warming has a more immediate threat to the environment (Azari et al., 2016). GWP was used as the metric for sustainability. Likewise, PPD was used as the metric for thermal comfort as Fanger's PMV-PPD model is a widely accepted method for measuring comfort and has been applied in international standards. PPD, in particular, estimates how many occupants feel uncomfortable and is often the basis for determining whether thermal comfort conditions are acceptable.

MCDM was applied to identify the best configurations according to stakeholder preference. Criteria weights were determined through the analytical hierarchy process (AHP), while prioritization was done through the technique for order of preference by similarity to ideal solution (TOPSIS). Some researchers have noted that the combination of AHP with other MCDM techniques is preferred over AHP alone (Dewi et al., 2018). AHP-TOPSIS, specifically, is widely used since these are the two most popular MCDM methods (Zyoud and Hanusch, 2017).

2.1 Life cycle assessment

The cradle-to-gate system boundary was used in measuring the GWP of the shelter, as material production is one of the major contributors to GWP for residential buildings (Ansah et al., 2020). The functional unit used to define the quantities throughout the LCA was 1 post-disaster shelter unit, which includes its partitions, roof, structural system, and fixings. Although multiple impact categories were quantified, only GWP had an influence on the environmental performance and ranking of the shelter in the MCDM stage. To quantify this, the ReCiPe midpoint impact assessment method was used.

2.2 Thermal comfort assessment

Thermal comfort simulation software was used in measuring the thermal comfort in the shelter according to the standards of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 55. The simulation involved three key inputs: climate data, material properties, and a building information model (BIM). Climate data were obtained from the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA), a government agency that monitors weather-related phenomena, while the thermal properties of different materials were obtained from scientific journals. A Revit model of the shelter was created using the plans of the IFRC. With these inputs, a convective heat transfer simulation was conducted, and the average PPD was measured. Simulation results validated with field measurements are the most common analytical methods for evaluating thermal comfort (Sibyan et al., 2022), but this study focuses on the early design of post-disaster shelters when field measurements are unavailable.

2.3 Cost analysis

The material and labor costs of the shelter were computed based on rates in the Philippines in 2023. Materials without updated prices were adjusted based on the year-on-year change of the construction materials retail price index in the Philippines. Productivity rates in the Philippines were used in computing the labor cost based on the daily salary of foremen in the Philippines and an 8 h/day work schedule. The costs of specialized products, namely AAC and insulated sandwich panels, were obtained from Philippine suppliers. In computing the total cost, transportation cost was excluded.

2.4 Pairwise comparison

Convenience sampling was applied in conducting the pairwise comparison required for AHP. Surveys were distributed to 10 respondents from government and non-governmental organizations (NGO) in the Philippines. These are the National Housing Authority, a government agency tasked with providing public housing, as well as Habitat for Humanity Philippines, Base Bahay Foundation Inc., and Kawayan Collective, NGOs that design and deploy post-disaster shelters in the Philippines. Architects and engineers from these organizations were chosen due to their experience in shelter design.

3. Results and discussion

3.1 Summary of results

To compare the shelter configurations, the results were normalized using the equation

$$x_{normalized} = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (1)$$

where the minimum (x_{min}) and maximum (x_{max}) computed GWP, PPD, or cost across the 12 shelters were used to compute the normalized value ($x_{normalized}$) of each shelter. In general, a lower normalized value is desired. Normalized results (Figure 1) show that the unmodified B7 shelter (CSN) is the most economical but exhibits the worst thermal comfort. In contrast, the shelter with AAC partitions, insulated panels, and modified openings (APW) is the most comfortable but has the highest cost. This highlights the trade-off that typically exists between the three dimensions of the TBL framework. The shelter with the least environmental impact uses AAC partitions while retaining the CGI roof and opening layout of the original design. These findings highlight the potential of AAC to lessen the environmental impact and to improve the thermal comfort of the post-disaster shelter.

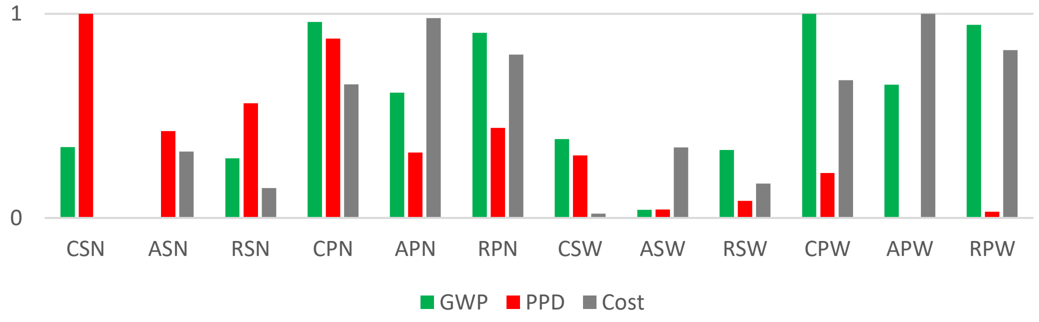

Figure 1: Normalized performance of different shelter configurations

Table 2: Percent reduction in PPD by each modification

Modification	Percent Reduction in PPD	
	Minimum	Maximum
AAC Partitions	34.5 %	43.1 %
RHAC Partitions	29.7 %	33.8 %
Insulated Sandwich Panels	8.1 %	12.3 %
Additional Openings	42.1 %	50.9 %

As seen in Table 2, all four modifications were effective in reducing PPD and improving comfort, the most effective being the addition of windows. This is because the original design only has openings in one of the three rooms. This design causes air to stagnate and leads to thermal discomfort. The placement of windows in each room addresses the issue and causes a 42.1 % to 50.9 % reduction in PPD. The second most effective was the AAC partition, which provides the best comfort among the three concrete types; this is followed by the RHAC partition. The insulated sandwich panels have the least impact on thermal comfort, only lowering PPD by 8.1 % to 12.3 % compared to counterparts with CGI sheets.

Apart from thermal comfort, the AAC and RHAC partitions excel over the CHB partition in terms of GWP. As seen in Figure 2, AAC still performs the best among the three. Its GWP is 31.3 % lower than the CHB partition, given that less steel and mortar are needed. Specifically, this is due to the use of zinc-plated brackets for beam and column connections instead of rebar as well as the use of thin bed adhesive instead of mortar. In contrast to the GWP of the CHB and RHAC partitions which primarily comes from the concrete blocks and mortar, 74.3 % of the GWP of the AAC partition comes from the AAC blocks alone. In fact, its GWP is higher than the CHB and RHAC blocks. The benefit of using RHAC partitions is less significant as GWP is only 4.9 % lower. Despite this, it highlights the potential of RHA replacement in lessening global warming. However, results also show that the RHAC partition is the most damaging in terms of land use, water consumption, and ozone depletion due to rice cultivation.

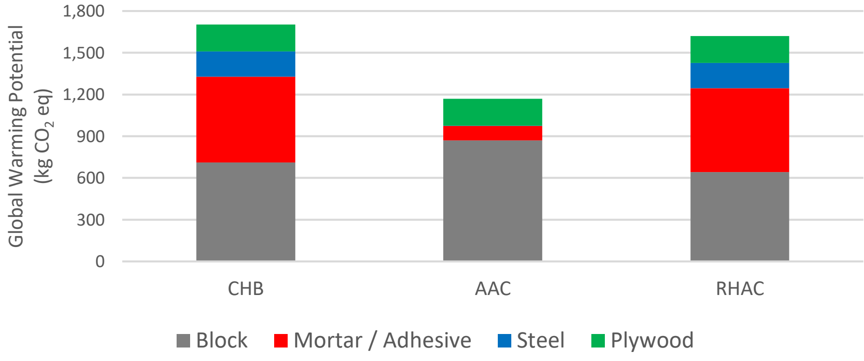

Figure 2: GWP of Different partition types

The insulated sandwich panel is more damaging than the CGI sheet due to the addition of PUR foam. For a single shelter unit, the GWP of the sandwich panels is roughly 1,209.93 kg CO_2 eq. This is about 4.6 times the GWP of the CGI sheets. In fact, it is slightly greater than the GWP of the entire AAC wall system. As seen in Figure 3, the reason for this is the PUR foam, which accounts for 62.4 % of the total GWP. The second most damaging component is steel cladding, accounting for 22.0 % of the GWP. Apart from GWP, the PUR foam is also the most damaging in 11 other environmental impact categories. The only exception is mineral resource scarcity, where steel cladding accounts for 75.7 % of the overall impact. This is due to the extraction of iron ore during steel production.

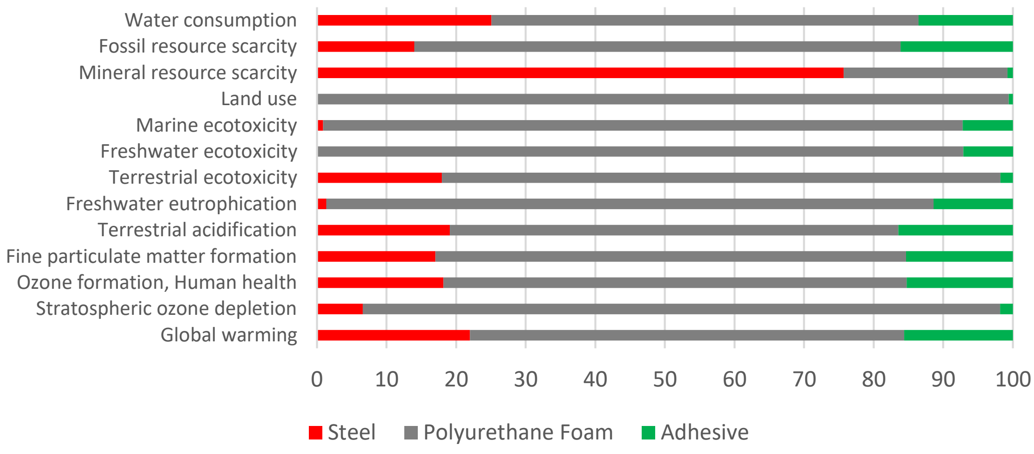

Figure 3: Percentage contribution of insulated sandwich panel components to environmental impact

Results from the cost analysis (Figure 4) show that AAC is the most expensive partition type, followed by RHAC. In terms of material cost, the AAC and RHAC partitions are roughly 3.0 and 1.8 times the price of the CHB partition. Although the faster installation of AAC results in reduced labor costs, it is offset by the added material cost. Considering the shelter as a whole, the price increase for using AAC and RHAC is at most 23.4 % and 10.6 %. This is because only a portion of the partitions is made of concrete, and the structural system accounts for a significant portion of the cost. In fact, the structural system is the most expensive component of the unmodified B7 shelter. On the other hand, the added material cost is even greater from the use of insulated sandwich panels as they are 3.7 times the price of the CGI sheets. Overall, the cost to construct the most comfortable, as well as the most expensive, shelter (APW) is 72.0 % higher than the cost of the unmodified B7 shelter (CSN).

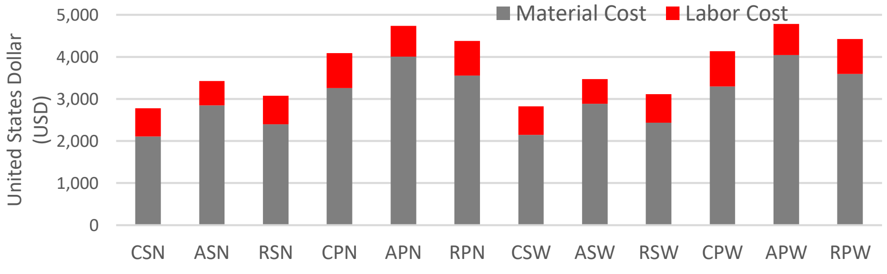

Figure 4: Material & labor costs in USD

3.2 Prioritization and ranking

Results from the pairwise comparison survey revealed that the respondents as a whole prioritize environmental impact the most, followed by thermal comfort then cost. However, segregating the respondents into government agencies and NGOs revealed that priorities vary. As seen in Table 3, the main difference is in cost. While the ranking is the same between the government and combined weights, the respondents from NGOs place greater emphasis on cost such that it outranks thermal comfort but not environmental impact.

Table 3: Computed weights for different groups of respondents

Criterion	Weight		
	Government	Non-Government	Combined
Environmental Impact	0.610	0.433	0.534
Thermal Comfort	0.290	0.261	0.285
Cost	0.100	0.306	0.181

Figure 5: Preference value and ranking of different shelter configurations

The computed preference values seen in Figure 5 determine the ranking of the shelter configurations in which higher values are desired. Results show that the best configuration uses the AAC partitions and modified opening layout while retaining the CGI sheet roof (ASW). The unmodified shelter (CSN) ranks second from the worst, while the most comfortable shelter, which uses AAC partitions and insulated panels (APW), ranks third overall. The ranking of shelters with AAC and RHAC partitions as well as modified openings over their respective counterparts, shows that their benefits to either thermal comfort or environmental impact are worth their added cost. In contrast, the high environmental impact and cost combined with the minimal improvement to thermal comfort means that using insulated panels for roofing is not recommended.

4. Conclusions

Through the integration of the TBL framework with MCDM, buildings can be designed in consideration of the three dimensions of sustainability while prioritizing specific performance metrics depending on stakeholder needs. Additionally, the study promotes digitalization in the construction industry through the use of LCA, BIM, and simulation tools. This approach assists in decision-making during the early design stage, minimizing rework and saving on time and resources. The application of these processes in the study highlighted the worth of adopting more expensive partition and opening configurations for the B7 Philippine transitional shelter to enhance both environmental and social sustainability. Despite the apparent benefits of adding openings, the implications of this must be further examined, specifically on its impact on the strength of the shelter. The use of AAC partitions is ideal for immediate use in post-disaster shelters. From a structural standpoint, commercially available AAC achieves compressive strengths above the 2.1 MPa recommendation of the IFRC (2013). Future work may combine other performance indicators that align with the TBL framework such that a holistic assessment of different design configurations can be conducted.

Acknowledgments

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