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Sustainable Building Technologies for Post-Disaster Temporary Housing: Integrated Sustainability Assessment and Life Cycle Assessment

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Abstract**—**After natural disasters, displaced people (DP) require important numbers of housing units, which have to be erected quickly due to emergency pressures. These tight timeframes can cause the multiplication of the environmental construction impacts. These negative impacts worsen the already high energy consumption and pollution caused by the building sector. Indeed, post-disaster housing, which is often carried out without pre-planning, usually causes high negative environmental impacts, besides other economic and social impacts. Therefore, it is necessary to establish a suitable strategy to deal with this problem which also takes into account the instability of its causes, like changing ratio between rural and urban population. To this end, this study aims to present a model that assists decision-makers to choose the most suitable building technology for post-disaster housing units. This model focuses on the alternatives sustainability and fulfillment of the stakeholders' satisfactions. Four building technologies have been analyzed to determine the most sustainability technology and to validate the presented model. In 2003, Bam earthquake DP had their temporary housing units (THUs) built using these four technologies: autoclaved aerated concrete blocks (AAC), concrete masonry unit (CMU), pressed reeds panel (PR), and 3D sandwich panel (3D). The results of this analysis confirm that PR and CMU obtain the highest sustainability indexes. However, the second life scenario of THUs could have considerable impacts on the results.

Keywords**—**Sustainability, post-disaster temporary housing, integrated value model for sustainability assessment (MIVES), life cycle assessment (LCA).

I. Introduction

AFTER disasters, many people lose their accommodations. According to [1], [2] temporary housing (TH) makes secure and welfare conditions for DP to return to the normal life as before disaster while their permanent houses are reconstructed. Meanwhile, the TH programs have been criticized due to the lack of sensibility towards the integrated view of the sustainability generally [3]-[5]. Therefore, TH has considerable negative impacts especially, those types of TH that are constructed after natural hazards, which are called temporary housing units (THUs), such as prefabricated buildings. Additionally, this type of TH has been rejected by most researchers, such as [1], [2], however, this type has been applied for many previous cases, such as Japan 1995, 2011; Turkey 1999, 2011; Iran 2003, 2012; USA 2005; China 2008; New Zealand 2011 [3], [4], [6]-[15]. Thus, in order to deal with this THUs there are two possible approaches, as shown in Fig. 1. First, it is possible to not to use these types of TH that have considerable negative impacts. In this case, if the number of TH with less negative impacts cannot solve all DP dwelling needs, decision-makers are forced to apply THUs without being able to reduce the negative impacts of THUs by improving these units. On the other hand, if decision-makers avoid using THUs then DP, who need to settle in safe area until the permanent housing process finishes, are forced to live in low-quality shelter. The second approach is to use improved THUs that have had their main endemic problems solved by having assessed and improved their features previously. Therefore, this study aims to design a strategy for assessing sustainability of THUs based on the second approach in Fig. 1. This strategy could determine weaknesses and strengths of THUs in order to assist decision-makers for choosing most suitable alternative, when decision-makers have no other choice except using THUs. In this regard, this study presents an approach for determining the most suitable alternative by considering integration of TH management, emergency conditions, and the sustainability assessment technique, which are already designed by the authors. To this end, this study is broken into the three sections; (1) definition of TH and emergency requirements, (2) explanation of life cycle of TH, especially THUs, and (3) applying the sustainability assessment model to the four THUs alternatives that had been defined by decision-makers after Bam earthquake in Iran, 2003.

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II. Post-Disaster Temporary Housing

To bridge the time gap between the emergency phase and permanent housing, the TH phase is required. However, investment in TH has been questioned by most experts [16]. Nevertheless, this stage is unavoidable because DP need somewhere to live during the permanent housing construction process. There are different residential options during this process that are called TH. In general, post-disaster recovery programs in terms of TH provision can be organized into (1) separate (individual) stages and (2) joint stages, as shown in Fig. 2. In the first approach, a specific accommodation is used for each recovery phase encompassing the emergency, temporary, and permanent housing phases. In this case, some materials of these houses can be reused from a previous housing phase to the next phase. Also, a complete TH unit can be utilized without advanced planning. In the second approach, a settlement that had been used for one of the recovery phases can be operated for other phases with or without modification. For instance, in 2006, after the Lorestan earthquake, decision-makers chose tents for DP until finishing the reconstruction phase [5]. Thus, these tents were used both as emergency settlements and TH in the Lorestan recovery program. Additionally, the core housing (nuclear dwelling), as TH approach that has been praised by experts, is assigned in the joint stages group, as shown in Fig. 2. During construction process of permanent housing, when one of these approaches are followed, choosing the best type of TH is essential for settling DP, as it has been previously said. In this regard, decision-makers sometimes are forced to apply THUs because of some especial conditions, such as lack of other TH options, unsuitable climate conditions, DP features, political issues, etc. However, according to the most researchers, such as [3]-[5], THUs consume a lot of materials and investments, which could have been used for permanent housing. Thus, suitable approach for decision-makers in this case could be to link between THUs and local future requirements. Based on the mentioned limitations and possibilities, it is required to assess life cycle of THUs sensibly. Consequently, considering an appropriate scenario for reusability of THUs could lead to avoid wasting materials and capital investments. In this case, it is possible to consider a progressive process for THUs like the core housing process, which is shown in Fig. 2, instead of discontinues process.

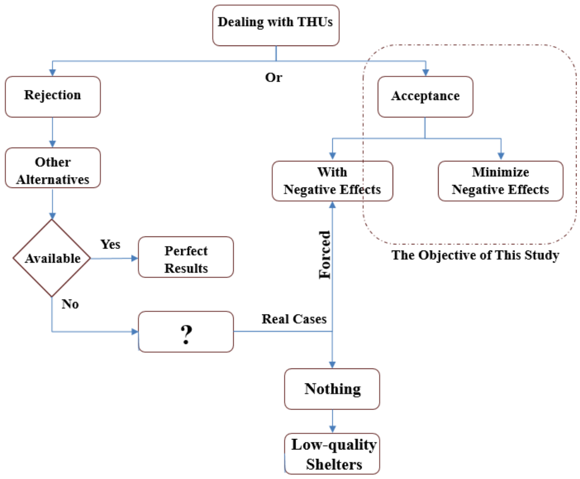

Fig. 1 The two approaches for dealing with THUs

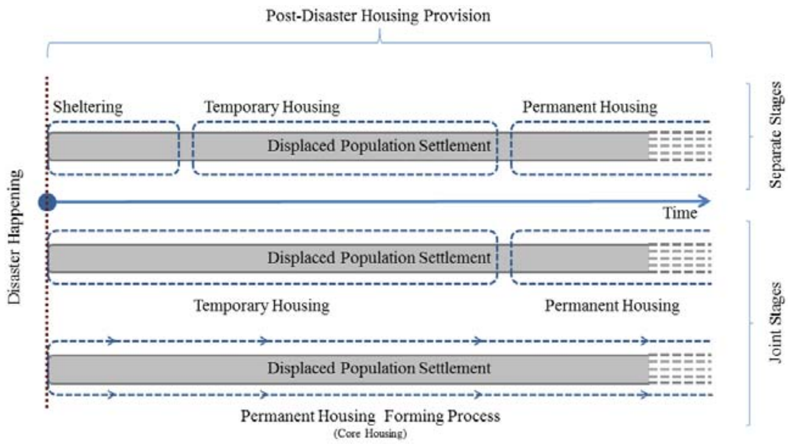

Fig. 2 Stages of post-disaster temporary housing approaches

III. Life Cycle of TH

The life cycle of TH can be organized into four phases: planning, provision or construction, operation, and second life, as shown in Fig. 3. During the planning phase, the initial form of TH is determined by decision-makers and experts to be applied after probabilistic natural hazards. However, this phase was contingent upon the natural disaster in a considerable number of previous recovery cases. Indeed, alternative accommodation types and their requirements were specified. Provision or construction phase usually starts after natural disasters. In this second phase temporary accommodations and required facilities are prepared to be used by DP; to do so, different actions are performed such as: organizing available accommodations, constructing units and site preparation. Theoretically, operation phase lasts from the time DP start living in TH until DP leave. However, it is possible that DP stay in TH for a long time as a permanent housing. In this sense, the present research project considers that this phase embraces all issues during the use of these accommodations as TH, taking into account a maximum of 5 years. Finally, this research study considers the second life phase of THUs, which embraces a period of time from five to fifty years.

According to [16], [17], for the second life of THUs, there are the two possible scenarios, as following: (1) storage for potential use, such as TH for future post-disaster, or (2) reuse with two different approaches: (2.1) complete building and (2.2) component usage. In the first scenario, there are three different main issues to be considered: a) *location* (same or another location), b) *property condition* (THUs can be sold, rented or donated), and c) *function* (same or other function). In the second scenario, the main issue is component usage because THU elements can be used as main building components, raw materials, and recycled materials. Furthermore, according to [2], [11], [17]-[20] the factors involved in TH provision, from planning to second life, are categorized generally, as shown in Fig. 3. However, the importance of indicators could vary for different recovery program scenarios based on different local concerns, requirements, and potentials. Additionally, changing (increasing or decreasing) parameters of indicators could have antithetical impacts on satisfaction values - in other words, the relationships of satisfactions values and indicators always are not based on direct proportionally (linear relationship). To this end, in order to deal with TH properly, it is required to apply a decision-making model, which could consider these two aforementioned aspects.

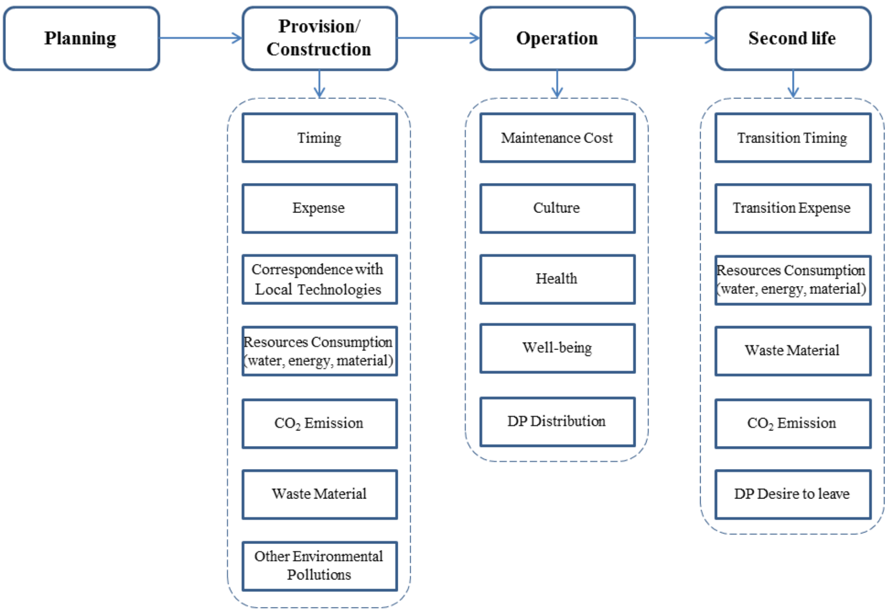

Fig. 3: Life cycle phases of TH from cradle to grave and associated indicators

IV. Sustainability Assessment Technique Based on MIVES

Modelo Integrado de Valor para Evaluaciones Sostenibles (MIVES), a model for sustainability assessment, consists of a multi-criteria decision-making method that incorporates the concept of value function [21]. This model considers the main sustainability requirements (economic, environmental, and social). In addition, by means of the value functions, the satisfaction degree of the involved indicators, which might have different units, can be assessed. According to Alarcon et al., MIVES presents rates satisfaction on a scale from 0 to 1, where 0 indicates minimum satisfaction (Smin) and 1 indicates maximum satisfaction (Smax) [21]. MIVES was developed by three different Spanish institutions (UPC, UPV, and Labein-Tecnalia) and the initial application was for industrial buildings sustainability assessment [21].

MIVES has been used more recently to assess the sustainability and to make decisions in the fields of (1) university professors [22], (2) economic decisions in the Barcelona Metro Line 9 [23], (3) industrial buildings [24], (4) the Spanish Structural Concrete Code [25], (5) sewerage concrete pipes [26], (6) school edifices [27], (7) developing the probabilistic method MIVES–EHEm–Mcarlo for large and complex edifices [28], (8) structural concrete columns [29], (9) wind-turbine supports [30], (10) TH [31]-[33], (11) architectural aspects [34], [35], and (12) assessment of public investment project [36].

According to MIVES, a specific tree, including requirements, criteria, and indicators, is developed to assess the sustainability of alternatives. Then, by determining a value function for each indicator according to MIVES value functions, it is possible to quantify each attribute. The parameters, tendency and shape of each indicator value function are determined from international guidelines, scientific literature, National Building Regulations, and the background of multidisciplinary experts that participated in seminars [32]. In the next step, the value function is obtained based upon the general exponential in MIVES (1).

$$V_i = A + B.\left[1 - e^{-k_i \cdot \left(\frac{|X_{ind} - X_{min}|}{C_i}\right)^{P_i}}\right] \quad (1)$$

A: The response value X_{min} (indicator's abscissa), Generally *A* = 0; X_{ind}: The considered indicator abscissa which generates a value V_i; P_i: A shape factor that determines if the curve is concave or convex; or is linear or shaped as a ''S''; C_i: Factor that establishes, in curves with Pi > 1, abscissa's value for the inflexion point; K_i: Factor that defines the response value to C_i: *B:* The factor that prevents the function from getting out of the range (0.00, 1.00), is obtained by (2).

The sets of indicator values ($V_i\ (x_i)$) that are between 0 and 1, according to the satisfaction range, are generated by (1) as:

$$B = \left[1 - e^{k_i \cdot \left(\frac{|X_{max} - X_{min}|}{C_i}\right)^{P_i}}\right]^{-1} \quad (2)$$

In (3), the indicator value ($V_i(x_i)$) has previously been determined and the weights (λ_i) are assigned to determine the sustainability value of each branch. For the multi-criteria case, the additive formula corresponding to (3) is applied to determine the sustainability value of each level including indicators, criteria, and requirements.

$$V = \sum \lambda_i \cdot V_i\ (x_i) \quad (3)$$

$V_i\ (x_i)$: The value function of each indicator and each criterion; λ_i : The weight of considered indicator or criterion.

In this step, the weights of the requirements, criteria, and indicators (λ_i) are assigned by using the Analytical Hierarchy Process (AHP).

A. Applying MIVES to Bam THU Building Technologies

In September 26, 2003 an earthquake happened in Bam, which had an estimated magnitude of 6.6 by the USGS (United States Geological Survey) [37]. Bam is located in the south-eastern Iran, approximately1000 km southeast of Tehran [38] with 19,374 km[2] area [11]. In the wake of Bam earthquake, 80% of buildings were fully destroyed [39], approximately 30% of Bam population died [37], and about 75,000 people of Bam lost their homes [12], [38].

By then, two approaches were applied to provide THUs: (1) THU provision in public camps, 9,005 in 23 camps and (2) THU provision in private properties, 26,900 units. [11], [13]. Both Housing Foundation o,f Islamic Republic of Iran and Ministry of Defence were responsible for providing THU. These two organizations were involved in providing THU directly or by hiring contractors [12]. The experts of Housing Foundation of Islamic Republic suggested four technologies for wall and two technologies for roof, as shown in Table I and Fig. 4 (see [32] for more complete information).

TABLE I
THE WALL AND ROOF MATERIALS OF THE SUGGESTED ALTERNATIVES

Component	Technology	Wall	Abbreviation
Wall	Alternative 1	autoclaved aerated concrete blocks	AAC
	Alternative 2	Concrete masonry unit	CMU
	Alternative 3	Pressed reeds	PR
	Alternative 4	3D sandwich panel	3D
Roof	Alternative 1	Corrugated galvanized iron	-
	Alternative 2	Sandwich panel	-

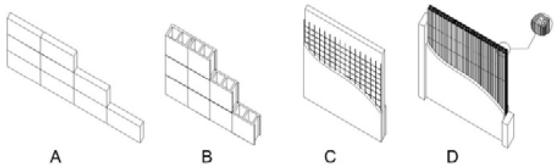

Fig. 4 View of the four wall technologies; (a) autoclaved aerated concrete block (AAC Block), (b) concrete masonry unit (CMU), (c) 3D sandwich panel wall, and (d) pressed reeds panel

This research project analyses eight alternatives in order to select the most sustainable technology. To do so, this project designed a new sustainability assessment model based on MIVES with a simplified Life Cycle Assessment (LCA). As, the suggested materials for the roof, celling, and structure were almost the same, the sustainability assessment model was applied to the four technologies used for walls. In this regard, one square meter of each alternative was studied in depth. First, this project defined a requirements tree following MIVES methodology, which is described in the previous section. To do so, the previous works [2], [11], [18], [19], [40], [41] were taken into account in order to define and organize indicators and criteria in three main groups, as shown in Table II.

Equations (1) and (2) present the associated parameters, tendency, and shape of the value functions of this research model indicators and sub indicators. The ten functions have the following shapes: six decrease convexly (DCx), and four increase, including two S-shape (IS) and two increase convexly (ICx). Furthermore, X_{min} and X_{max} of each indicator are determined based on the national and international guidelines, standards, and previous studies (see [32] for more complete information).

During seminars, multidisciplinary professors and experts of Housing Foundation of Islamic Republic of Iran assigned these weights using AHP. Table II also shows these requirements, criteria and indicators weights. Third, sustainability indexes were determined applying (3). This process was accomplished for each alternative in order to obtain sustainability index of each one, as shown in Table III.

V. DISCUSSION

The results of the present sustainability assessment are: CMU and PR obtain maximum sustainability index while 3D and AAC obtain the minimum sustainability index. However, ACC and 3D would have had higher sustainability indexes, if the model was designed for permanent housing.

As shown in Fig. 5, PR has the maximum satisfaction value of the environmental requirement and CMU has the maximum satisfaction value of the social requirement. Nevertheless, the construction time of CMU is the highest. Additionally, 3D achieves high satisfaction values for social indicators, except the Compatibility one. This is because 3D was a very new and unknown technology on that time, especially for DP. In terms of the economic requirement, ACC achieves the highest satisfaction value.

TABLE II
REQUIREMENTS TREE WITH ASSIGNED WEIGHTS

Requirements	Criteria	Indicators	Sub-indicators
R_1. Economic **(45%)**	C_1. Implementation Cost **(85%)**	I_1. Building Cost **(100%)**	
	C_2. Maintenance Cost **(15%)**	I_2. Reusability Cost **(100%)**	
R_2. Social **(25%)**	C_3. Safety **(60%)**	I_3. Construction Time **(36%)**	
		I_4. Risk Resistance **(42%)**	S_1. Natural Disaster Risk **(50%)**
			S_2. Fire Resistance **(50%)**
		I_5. Comfort **(22%)**	S_3. Acoustic **(50%)**
			S_4. Thermal Resistance **(50%)**
	C_4. Customization **(40%)**	I_6. Compatibility **(100%)**	S_5. Cultural Acceptance **(45%)**
			S_6. Skilled Labour **(30%)**
			S_7. Flexibility **(25%)**
R_3. Environmental **(30%)**	C_5. Resources Consumption **(67%)**	I_7. Energy Consumption **(47%)**	
		I_8. Water Consumption **(18%)**	
		I_9. Waste Material **(35%)**	
	C_6. Emissions **(33%)**	I_{10}. CO_2 Emissions **(100%)**	

TABLE III
SUSTAINABILITY INDEX (I), REQUIREMENTS (V_{RK}), CRITERIA (V_{CK}), INDICATOR (V_{IK}), AND SUB-INDICATOR (V_{SK}) VALUES FOR THE FOUR ALTERNATIVES

	I	V_{R1}	V_{R2}	V_{R3}	V_{C1}	V_{C2}	V_{C3}	V_{C4}	V_{C5}	V_{C6}
AAC	0.50	0.76	0.39	0.20	0.74	0.87	0.43	0.34	0.25	0.11
CMU	0.53	0.62	0.39	0.49	0.63	0.59	0.29	0.55	0.48	0.51
PR	0.53	0.55	0.19	0.79	0.55	0.52	0.21	0.15	0.74	0.9
3D	0.36	0.28	0.38	0.46	0.32	0.06	0.61	0.02	0.43	0.52
	V_{I1}	V_{I2}	V_{I3}	V_{I4}	V_{I5}	V_{I6}	V_{I7}	V_{I8}	V_{I9}	V_{I10}
AAC	0.74	0.87	0.2	0.83	0.04	0.34	0.1	0.55	0.3	0.11
CMU	0.63	0.59	0.11	0.41	0.36	0.55	0.79	0.03	0.3	0.51
PR	0.55	0.52	0.37	0.18	0.01	0.15	0.87	0.98	0.44	0.9
3D	0.32	0.06	0.52	0.65	0.7	0.02	0.33	0.66	0.44	0.52

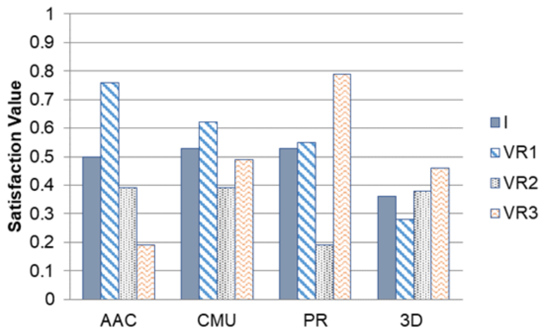

Fig. 5 Requirement values for the four alternatives

It should be mentioned that satisfaction values for the environmental requirement vary substantially for the four alternatives. In this case, ACC technology has the minimum satisfaction value and PR has the maximum. AAC obtained this result because of its high energy consumption. CMU has the lowest satisfaction value in the water consumption indicator, as shown in Fig. 6. Nonetheless, as the water consumption during the manufacturing is very low compared to the operation phase, it would be possible to assign even a lower weight to this indicator. Therefore, AAC and 3D technologies have been rejected because of the lowest satisfaction value of the environment requirement and low sustainability index. Consequently, CMU and PR, which have the highest sustainability indexes, need to be compared in order to determine most suitable one based on different scenarios of the requirements' weights. Additionally, a sensitivity analysis in order to examine the obtained results by the designed method is required. To this end, 16 scenarios of the requirements' weights have been considered based on the all assigned weights to the indicators during the several seminars. As shown in Fig. 7, CMU could obtain highest sustainability indexes almost in all different scenarios. Thus, it could be concluded that CMU is the most sustainable alternative among the four assessed alternatives.

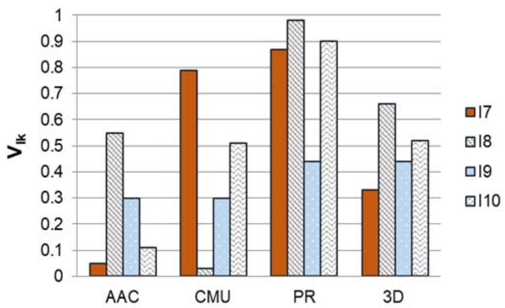

Fig. 6 Environmental indicator values for the four alternatives

These results are obtained only based on applying the LCA and MIVES methods in the emergency situation. However, it is vital to consider second life of THUs as well. In this regard, all alternatives could have very low sustainability indexes, if decision-makers needed to reuse the units in other locations, after finishing the TH phase. Additionally, assuming that units were used as permanent housing with minimum modifications in the same location, the result could change noticeably. In this case, 3D achieves highest social satisfaction values while PR obtains minimum social satisfaction values. This is because PR alternative has important weaknesses to be used as permanent housing. Therefore, besides decision-making model, it is necessary to consider second life scenarios of THUs and local conditions and requirements in order to analyse different technologies suitability.

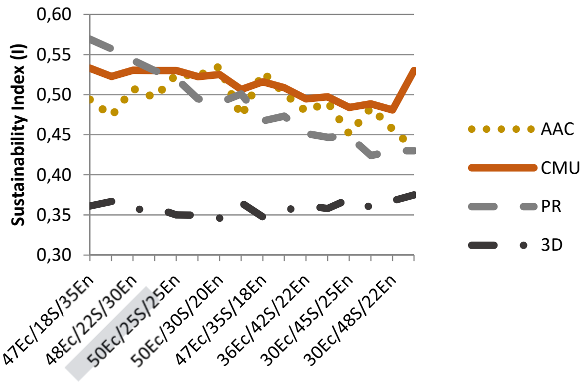

Fig. 7 Sustainability indexes of the four technologies with different requirement weights (economic (Ec), social (S), and environmental (En))

VI. Conclusion

This research project presents a strategy for choosing the most suitable THUs. This strategy, which leads to increase the suitability of RH programs, combines LCA and MIVES and is based on post-disaster conditions. This project faced the information uncertainty about the local exist potential and conditions after disasters as the main limitation for post-disaster recovery programs.

The research proves that the use of decision-making methods to deal with the recovery programs could be insufficient. However, by applying these methods some facts could be demonstrated for decision-makers although these facts could be very diverse from the predictions. In this regard, some technologies such as CMU were considered unsuitable to build THUs because of their weaknesses have obtained high sustainability indexes when assessed by this project MIVES model. Thus, it should be noted that all types of TH could be sustainable, provided all weaknesses are considered and improved, from very early stages of planning phase until end life of alternatives based on local characteristics including material and immaterial aspects. To this end, second life scenarios of THUs could play an important role in sustainability index range. Therefore, it is required to decide for each recovery program based on the local requirements and future plans by appropriate decision-making methods. Furthermore, appropriate decision-making methods have ability to be customizable by assigning weight systems. Finally, in future studies, it is essential to consider more strategies in order to reduce negative impacts of THUs, which are undeniable for some recovery programs based on some special conditions.

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