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Multi-objective interior design optimization method based on sustainability concepts for post-disaster temporary housing units

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ABSTRACT

Temporary housing units (THUs), which are provided after disasters, are crucial in terms of sustainability pillars (economic, social, and environmental). In general, THUs, which are regular houses with minimum space and facilities, incorporate some negative aspects of the building industry. Additionally, as large numbers of THUs are usually provided in a short time and under emergency situations, some negative impacts of these units escalate. In this context, this study aims at reducing some negative impacts of THUs by applying a novel optimization model that maximises sustainability indexes by simulating the design of interior geometries for THUs. This method is based on the coupling of artificial intelligence and a multi-criteria decision-making model for sustainability assessment. The proposed model generates optimal solutions using a backtracking algorithm together with a binary search. To evaluate the sustainability indexes, an Integrated Value Model for Sustainability Assessment (MIVES) is applied. This novel method enables decision makers to automatically generate the most suitable alternative solutions for the early design stage of THUs. The results confirm that small changes in the interior geometric design can remarkably affect the sustainability indexes of THUs.

1. Introduction

The total displaced population (DP) is expected to increase in the near future, owing to increases in both climate-related hazards and social vulnerability [1]. The DP needs somewhere to live while their permanent housing is being reconstructed, or until they find alternative permanent accommodations [2,3]. Temporary housing is often utilised in the social process of recovery programs and associated physical housing [4]. One type of such physical housing is temporary housing units (THUs), such as prefabricated units and on-site masonry units, that are erected after events. THUs have been utilised after many major disasters [4–9]. However, according to Refs. [10–19], THUs have been criticised because of economic, social, and environmental issues. As these researchers discussed, the main problems of THUs are as follows: they require large public expenditures that can be used for permanent housing; they prolong the permanent reconstruction time; they often do not match the culture of the DP; and they involve minimum community participation and negative environmental effects.

Additionally, according to Refs. [[20,21]], the building industry uses considerable amounts of energy, raw materials, and water, and creates CO_2 emissions during the building life cycle. THUs embrace most of the negative aspects of normal buildings. However, the sizes of THUs are usually smaller than normal residential buildings, as providing massive numbers of units could have substantial negative impacts. Furthermore, the life services of THUs are much lower than those of normal buildings. Consequently, THUs could have considerable negative features. In this context, Atmaca [19] mentioned that there could be a major opportunity to reduce resource consumption and greenhouse gas emissions by minimizing the negative impacts of THUs, considering the incremental trend of producing/using these units in recent decades.

Thus, a question that arises is why decision makers provide these units, with negative features, to accommodate the DP. To answer this question, it should be noted that decision makers are forced to choose them based on the special conditions, potential, obstacles, and limitations of the affected area and populations. Therefore, to respond to the needs of the DP and to manage the aforementioned issues, there are two

Abbreviations: THU, Temporary housing unit; TH, Temporary housing; DP, Displaced population; W, Wall; K, Kitchen; B, Bathroom; L, Living room; E, Entrance; DMT, Decision-making tree; SI, Sustainability index; DCx, Decrease convexly; IS, Increase S-shape; DS, Decrease S-shape; IRR, Iranian Rial (Iranian currency); pts., Points; Ec., Economic; S., Social; En., Environmental.

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approaches: (1) finding alternatives that are more suitable to replace the THUs, and (2) decreasing the negative features of the THUs. However, when there are no other alternatives to THUs, to meet all the demands of the DPs found in previous cases, it is necessary to try to minimise the negative impacts of THUs.

A main problem of THUs is the interior architectural design of these units; however, there is very little research on this problem. Evans & McCoy [22] declared that interior architectural dimensions could have an impact on human psychological stress. The importance of this problem is more evident when DPs are forced to live in these units for several years. Additionally, according to Yi & Malkawi [23], a building's geometric variables, including the dimensions and heights that form the area and volume of the building, have an impact on other aspects, such as energy consumption. Moreover, according to Atmaca & Atmac [24], the walls and floors of the THUs comprise a major part of the total construction cost. Thus, the interior design problems of THUs could have a considerable impact on the three pillars of sustainability. In this regard, it is necessary to assess the interior design of THUs to increase the satisfaction of DPs in two areas: (1) to assist in reducing the psychological stress of DPs and to mollify their sufferings, and (2) to avoid the rejection of THUs by DPs, which increases the negative impacts of these units. In addition, it is also desired to decrease the economic and environmental impacts of THUs.

The main objective of this research is to optimise the sustainability index (SI) of THUs by simulating the sizing of interior spaces. Indeed, this study is aimed at minimizing the environmental and economic negative impacts of THUs, while maximizing the satisfaction of social requirements. In other words, this research will permit designers and decision makers to achieve optimal SIs by automatically generating the most suitable sizing for interior spaces, with both the construction technology (materials and process) and plan topology (spatial relations) remaining unchanged.

According to Arvin & House [25], the space-planning problem can be categorised into two groups: topological and geometric problems. This research focuses on geometric problems, especially on the horizontal geometry. Additionally, as the interior design of buildings can embrace a wide range of possible solutions, computational methods for design optimization could assist decision makers in generating and filtering appropriate alternatives. To this end, a combination of artificial intelligence and a multi-criteria decision-making model is applied for the sustainability assessment. Additionally, as the relative importance (weight) of the sustainability pillars could be different for each case, this study uses an indicator-weighting system.

The remainder of this paper is organised into four parts: (1) Section 2, a literature review; (2) Section 3, a case study considering the temporary housing program aftermath of an earthquake in Bam, a city in southeastern Iran, 2003; (3) Section 4, the model design, which presents a newly designed model based on a backtracking algorithm together with a binary search approach and an integrated value model for sustainability assessment (MIVES); and (4) Sections 5–7, the model application and results.

2. Literature review

There are numerous studies focused on the impacts of THUs. However, there is little research to support decision makers in terms of finding an optimal THU [14]. It should be noted that, to the best of the authors' knowledge, there is no research that presents a sustainability optimization method oriented to the design of THUs. However, some researchers have developed optimization tools to solve temporary housing problems, but in other areas (e.g., site location problem). In this case, El-Anwar et al. [26] presented an automated system to assist decision makers by determining optimal temporary housing arrangements. This system was designed to minimise negative socioeconomic impacts. Hosseini et al. [27] applied a combination of a multi-criteria decision-making method (MCDM) called MIVES and a knapsack algorithm to identify the most suitable site locations for THUs by maximizing the SI. El-Anwar & Chen [28] designed a computational model based on a Hungarian algorithm to optimise temporary resettlement problems by focusing on socioeconomic issues, and El-Anwar [29] conducted an optimization process by using genetic algorithms and an integer-programming model to evaluate the socioeconomic benefits of a temporary housing program.

Evins [30] stated that the number of research studies on optimization problems for sustainable building design has considerably increased. Table 1 lists the studies devoted to the optimization of building components and indicators.

According to Table 1, most of the optimization methods have focused on the environmental performance of buildings, especially energy issues. Evins [30] stated that most of the publications considered single-objective problems. Indeed, it must be remarked that the optimization processes in these studies only embrace one or some of the SI indicators, whereas other relevant indicators were disregarded.

Additionally, few studies considered buildings' interior design problems in the context of sustainability. Some studies considered space-planning problems, such as topological and geometric problems. Nonetheless, most of these were studies conducted based on architectural design problems, not sustainability issues. For instance, Balachandran & Gero [40] designed a new multi-criteria optimization methodology for the dimensions of architectural floor plans considering three objectives, including minimizing construction cost, maximizing floor area, and maximizing aspect ratio. Previously, Merrell et al. [41] used linear programming to overcome dimensioning problems of mobile homes. As another example, Merrell et al. [42] presented a new approach to automatically generate residential building design by using the Metropolis algorithm. Nevertheless, Merrell et al. [42] did not consider client-specific factors. Arvin & House [25] designed a prototype system to solve space planning problems by providing designers control of generated solutions. Bahrehmand et al. [43] presented a new model for determining an ideal layout by maximizing quality functions using an evolutionary algorithm. Other research studies considered the 3D space layout of buildings. For instance, Yi et al. [44] suggested a new decision-making method for solving 3D space layout problems. Bao et al. [45] presented an approach to determining the most suitable shape layout of buildings from among possible solutions, based on guidelines and functional quality measures. Finally, other authors have considered the furniture layout system in building interior problems, such as Merrell et al. [46].

3. Case study

On the 26th of December 2003, an earthquake occurred in Bam, a city in Southeastern Iran. Bam's population was approximately 100,000 predisaster [47], in an area of 19,374 km^2 [48]. It is estimated that 80% of the buildings were completely destroyed [49], approximately 30% of Bam's population died [50], and approximately 75,000 people lost their homes [[51,52]]. In the aftermath of the Bam earthquake, THUs were used to accommodate the DP.

In the Bam case, the decision makers had to choose THUs because of the following reasons: (1) a large DP, (2) a lack of other possibilities, (3) climatic conditions, and (4) the cultural conditions of the DP. Therefore, the TH program was performed as an intermediate phase of the Bam recovery that included three phases: (1) tent shelters, (2) intermediate shelter, and (3) permanent housing phase [52]. To this end, contractors were requested to supply a vast number of THUs with different technologies for the DP. According to Refs. [[48,53]], 35,905 units of THUs were built, 26,900 on private properties, and 9005 in 23 camps.

The Iranian government introduced the Housing Foundation of Islamic Republic of Iran (HFIR) and the Ministry of Defence as a responsible for providing the TH. These two organizations provided THUs directly or via hiring contractors [52]. The experts from the HFIR designed eight alternatives for THUs, based on four external walls, two

Table 1
Previous research studies considering the design optimization problem.

Authors	Optimization	Optimization Method	Variable	Simulated Component	Case
Adamski [31],	Construction Cost & Energy Consumption	–	Exterior Partition	Shape of Oval Plan	Residential
Caldas & Norford [32],	Thermal and Lighting Performance	Genetic Algorithms	Windows Features	Envelope	Office
Hasan et al. [33],	Life Cycle Cost	Hooke–Jeeves algorithm	Construction Layers	Envelope	Residential
Jin & Jeong [34],	Thermal Performance	Genetic Algorithms	Top & Bottom Length, Height, Angles	Shape	–
Kämpf & Robinson [35],	Solar Energy Utilization	Hybrid CMA-ES/HDE	Shape Geometry	Urban Form	–
Marks [36],	Construction Cost & Energy Consumption	–	External Wall Features	Shape	–
Ordóñez & Modi [37],	Energy Consumption & CO_2 Emission	–	Floors Number	Shape	Residential
Wang et al. [38],	Life Cycle Cost & Energy	Genetic Algorithms	Construction Layers, Orientation, Material	Shape, Material	Office
Wang et al. [39],	Life Cycle Cost & Energy	Genetic Algorithms	Construction Layers, Orientation,	Envelope	Office
Yi & Malkawi [23],	Energy Consumption	Genetic Algorithms	External Wall Geometry	From	–

roofing technologies, and light steel structures. The designed THUs had 18, 20, and 36 m^2 area alternatives, with different plans.

The wall technologies were (1) autoclaved aerated concrete blocks; (2) concrete masonry units (CMUs); (3) 3D sandwich panels, each of which comprises a polystyrene core sandwiched between two welded steel wire meshes [54]; and (4) a pressed reeds panel that could be covered with different plasters, such as concrete and gypsum plaster, as shown in Fig. 1.

These eight alternatives had already been assessed by Hosseini et al. [55] to determine the SI of each one. The results of the assessment of these alternatives demonstrated that the CMUs obtained the highest SI. Additionally, a considerable amount of this technology had been applied after the Bam earthquake. In this regard, this study considers a CMU of 20 m^2, which is shown in Fig. 2, as a case study.

In addition to the general problems of THUs previously discussed, 10–20% of these THUs were vacant [56], and took a considerable amount of time to be delivered. Furthermore, the TH program cost reached \$60 million [56], and there was no specified plan for a second life for the THUs. Additionally, the DP remained in these units for several years until the construction of the permanent housing was finished. In this case, the THUs played the role of permanent housing for some of the DP.

4. Model design

According to Radford & Gero [57], optimization models for building problems explore all feasible solutions to determine the most suitable ones based on defined goals. Thus, this research presents a novel optimization model that automatically generates alternatives with different geometrical floor plan designs as feasible solutions. The objective is to obtain the optimal SI by varying the horizontal interior dimensions of the THU. The MIVES is applied to evaluate the SIs of the alternatives. The MIVES is a MCDM, and includes a value function based on the utility theory. The main framework of the model is developed based on a

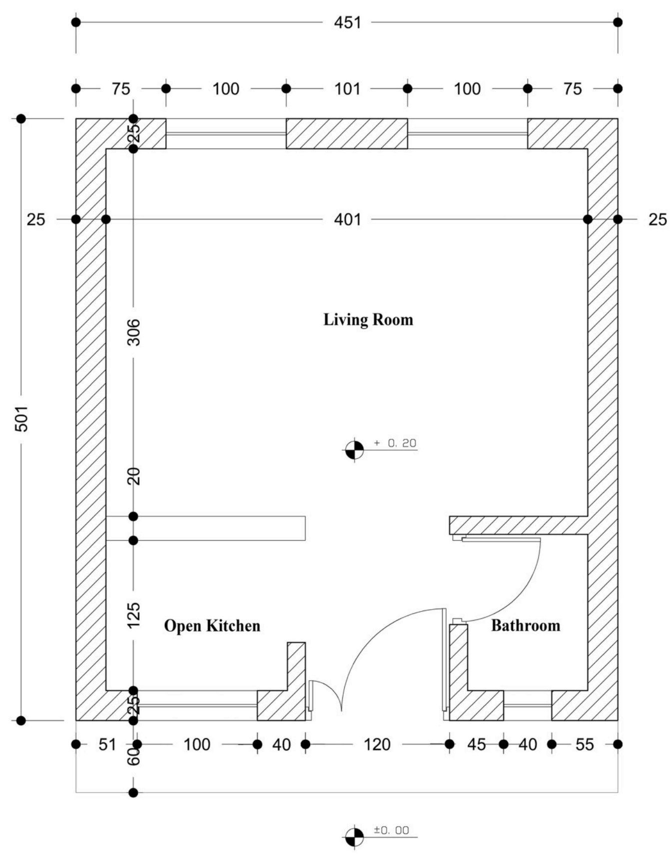

Fig. 2. Plan of a temporary housing unit (THU) (20-m^2 type) constructed in Bam after the 2003 earthquake.

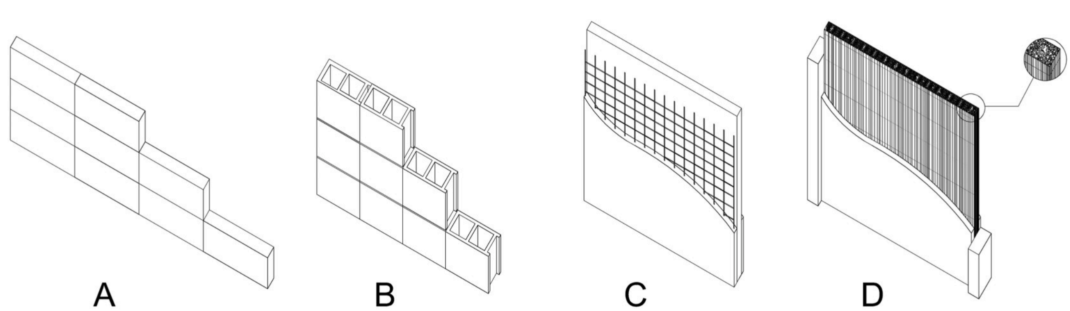

Fig. 1. View of the four wall technologies; (a) autoclaved aerated concrete block, (b) concrete masonry unit, (c) 3D sandwich panel wall, and (d) pressed reeds panel.

backtracking algorithm, which is applied for non-linear and complicated numerical optimization problems (see [[58,59]]). However, other algorithms, such as the shoelace algorithm, are used within the main framework.

4.1. Defining parameters of the temporary housing unit (THU) (case study)

The floor plan of the THU (CMU) applied in Bam was assumed for initializing the layout, to specify parameters. This plan contains four interior spaces surrounded by walls as boundaries (Fig. 2): living room, kitchen, entrance, and bathroom. The parameters to be considered are categorised into *geometry* and *construction materials*.

Solutions with different geometries are generated by sliding walls (see Fig. 3). Codes were assigned to name the walls (W) of each space: entrance (E), kitchen (K), living room (L), and bathroom (B); the indexes refer to the wall number. Additionally, arrows labelled on the edges represent sliding walls and directions. For instance, arrow k_2 indicates that WK_2 can be slid forward and backward. Additionally, as shown in Fig. 3, the nodes on the vertexes of the edges are used to define the geometrical parameters of each edge for the computerised model.

To determine the variation ranges of the walls length parameters, in other words, the possible range of the sliding walls, two approaches have been conducted: (1) using both national and international codes, and (2) interviewing experts. In the first approach, the minimum required areas of the interior spaces are specified based on emergency shelters and normal residential buildings from the national and international codes.

UNHCR [60] considered that the minimum space in an emergency shelter for each person in tropical and warm climate conditions is 3.5 m^2 per person, excluding the kitchen area. The area of this space should be 4.5 m^2–5.5 m^2 per person in cold climate conditions or urban areas; however, this minimum space includes the kitchen. IFRC [61] applied the International Building Code (IBC) and Uniform Building Code (UBC) from the USA to determine the required areas. In this context, in addition to the Iranian National Building Code (INBC) as shown in Table 2, the building codes of the USA and UK were considered. Nevertheless, as IFRC [61] declared, these codes are oriented to permanent housing with

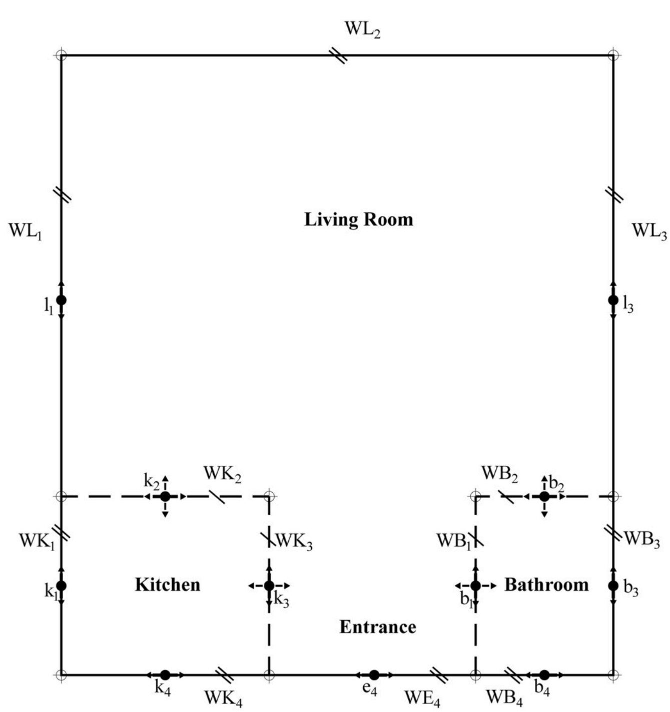

Fig. 3. Simple plan layout of the THU, including sliding walls, directions, and dependent walls.

Table 2
Minimum areas (m^2) of interior spaces for residential buildings.

	Bedroom	Living Room	Kitchen	WC	References
Iran	6.50 & 12.00[a]	12.00[a]	5.50	1.20	[62]
USA	6.50 & 13.9[b]	13.9 & 20.4[b]	–	–	[63]
UK	7.50 & 11.50[c]	–	–	1.60	[64]

[a] The minimum area of the main living room and the main bedroom is 12 m^2, and the minimum areas of the other living rooms and bedrooms are 6.50 m^2.
[b] Each dwelling should have a room with an area of at least 13.9 m^2.
[c] The minimum area of a single bedroom is 7.50 m^2, and the minimum area of a double bedroom is 11.50 m^2.

a service life of 50 years, whilst the design life of TH is usually not considered to be longer than 5 years.

Additionally, areas of THUs are usually different from those of residential units. To this end, the information in Table 2 was normalised by considering the total area of the THU and standards for emergency sheltering. Likewise, it is worth noting that, according to the codes, the differences between THUs and residential units' interior sizes are primarily related to the living room, as this area also plays the role of a bedroom in the former.

For the second approach, 11 professors and researchers from both Shahid Beheshti University and Islamic Azad University (Tehran, Iran) and from the Polytechnic University of Catalonia (Barcelona, Spain) as well as two experts from the HFIR were interviewed. These interviews embraced the THUs interior areas and issues related to this research such as the general indexes, weights of indicators, and wide-ranging interior design problems of THUs.

By merging the results of both approaches, the ranges of variation of the wall lengths were established (Table 3) to fit the recommended aspect ratios assigned to each space. This assignment was carried out by including an indicator that considers the stakeholders' preferences (see Section 4.2.1).

As shown in Table 3, the dynamic design parameters are the dimensions of the sliding walls and floor areas of the four spaces, whereas the static parameters are the height, shape, roof, windows, and doors of the THUs. Table 4 illustrates a dependency matrix (one indicates dependency).

The second group of parameters considered in the sustainability analysis is related to the construction materials of the THU components (see Table 5). Some materials can be used in different components of the THU (e.g. the foundation and roof are the same for all possible solutions); these are noted as *Constant* in Table 5. Put another way, when the interior geometries are changed within the defined range, the amounts of these materials remain constant. However, other construction materials change, based on each floor plan's geometrical design. These are denoted *Continuous* variables in Table 5.

As shown in Table 5, the main continuous components are the exterior and interior walls and floors. When the walls are moved to explore the highest SI, the geometrical properties of the walls and floors are changed. In this context, all of the materials for the floors and two

Table 3
Possible change ranges of walls considering the building codes and interview results.

Space	Partition	Type	Variable Type	Change Range (m)	
				Min.	Max.
Living Room	WL_1	Exterior	Continuous	−0.95	0.15
	WL_2	Exterior	Constant	0.00	0.00
	WL_3	Exterior	Continuous	−0.95	0.30
Kitchen	WK_1 & WK_3	Exterior	Continuous	−0.15	0.95
	WK_2 & WK_4	Interior	Continuous	−0.30	0.50
Bathroom	WB_1 & WB_3	Exterior	Continuous	−0.3	0.95
	WB_2 & WB_4	Interior	Continuous	0.00	0.50
Entrance	WE_4	Exterior	Continuous	−0.20	0.00

Table 4
Dependency matrix of the wall lengths.

	Walls of Spaces											
	WL_1	WL_2	WL_3	WK_1	WK_2	WK_3	WK_4	WB_1	WB_2	WB_3	WB_4	WE_4
WL_1	1	0	0	1	0	0	0	0	0	0	0	0
WL_2	0	1	0	0	0	0	0	0	0	0	0	0
WL_3	0	0	1	0	0	0	0	0	0	1	0	0
WK_1	1	0	0	1	0	1	0	0	0	0	0	0
WK_2	0	0	0	0	1	0	1	0	1	0	0	0
WK_3	0	0	0	1	0	1	0	0	0	0	0	0
WK_4	0	0	0	0	1	0	1	0	0	0	1	1
WB_1	0	0	0	0	0	0	0	1	0	1	0	0
WB_2	0	0	0	0	1	0	0	0	1	0	1	0
WB_3	0	0	1	0	0	0	0	1	0	1	0	0
WB_4	0	0	0	0	0	0	1	0	1	0	1	1
WE_4	0	0	0	0	0	0	1	0	0	0	1	1

Table 5
Main components and construction materials for the temporary housing unit (THU).

Component	Material	Variable Type
Wall/Partition (Exterior & Interior)	Concert Masonry Units (0.40·0.20·0.30 m^3 & 0.40·0.10·0.20 m^3)	Continuous
Wall/Partition (Finishing)	Tile (in), Cement Plaster (out), Gypsum Plaster (in)	Continuous
Floor	lean concrete 150 kg/m^3, the thickness is 0.15 m and Iranian mosaic tile	Continuous
Roof	Corrugated galvanized iron with 4 cm of polystyrene	Constant
Foundation	Strap footing foundation, the height is 0. 35 m	Constant
Structure	Steel hollow square section	Constant
Footing (Plinth)	Brick or block, the height is 0.20 m	Constant
Window	Metal window, the dimension is, type I: 1.00·1.00 m^2 and type II: 0.50·0.30 m^2	Constant
Door	Metal door, the dimension is 2.00·1.00 m^2	Constant
Mortar	Cement mortar 1:6	Continuous

types of walls (interior and exterior) for the interior spaces of the THU are presented in Table 6.

4.2. *Integrated value model for sustainability assessment (MIVES)*

The MIVES method was selected as the approach for assessing the sustainability index (SI) of the plan layout alternatives for the THUs. The MIVES method, as a sustainability assessment approach, has already been used in other fields: (1) post-disaster housing management [[27, 55,65]]; (2) buildings structures [66]; (3) architectural active learning [67]; (4) school edifices [68]; (5) Spanish code of concrete structure [69]; (6) building facades [70]; (7) infrastructures [[71,72]], and others.

The method consists of five steps: (1) designing a requirements tree, (2) specifying minimum (X_{min}) and maximum (X_{max}) satisfaction values for each indicator, (3) determining the tendency and shape of the value function, (4) weighting indicators and requirements (λ_i) and, (5), summing partial satisfaction values (V_i) to compute the SI by using the equation (1).

$$SI = \sum \lambda_i \, . \, V_i \,(x_i) \tag{1}$$

$V_i \,(x_i)$: The value function of each indicator, criterion or requirement.

λ_i : The weight of the indicator, criterion or requirement considered.

Equations (2) and (3) were used to obtain each indicator value. Equation (3) was applied to achieve factor B for equation (2). Equation (3) allows normalizing the indicators' values ($V_i \,(x_i)$) between a range of zero and one.

Table 6
Construction materials for the interior spaces of the THU.

Space	Wall/Partition		Floor
	Type I (Exterior)	Type II (Interior)	
Living Room	• Concrete masonry block • Cement mortar 1:6 • Cement plaster 1:3–1:2 • Gypsum-sand plaster	-	• Lean concrete 150 kg/m^3 • Iranian mosaic tile • Cement mortar 1:6
Kitchen	• Concrete masonry block • Cement mortar 1:6 • Cement plaster 1:3–1:2 • Tile	• Concrete masonry block • Cement mortar 1:6 • Tile • Gypsum-sand plaster • Insulation	• Lean concrete 150 kg/m^3 • Ceramic tile flooring • Cement mortar 1:6 • Insulation
Bathroom	• Concrete masonry block • Cement mortar 1:6 • Cement plaster 1:3–1:2 • Tile	• Concrete masonry block • Cement mortar 1:6 • Tile • Gypsum-sand plaster • Insulation	• Lean concrete 150 kg/m^3 • Ceramic tile flooring • Cement mortar 1:6 • Insulation
Entrance	• Concrete masonry block • Cement mortar 1:6 • Cement plaster 1:3–1:2 • Gypsum-sand plaster	-	• Lean concrete 150 kg/m^3 • Iranian mosaic tile • Cement mortar 1:6

$$V_i = A + B. \left[1 - e^{-k_i \, . \, \left(\frac{\left| X_{Alt_i} - X_{min} \right|}{C_i} \right)^{P_i}} \right] \tag{2}$$

A: The response value X_{min} (indicator abscissa), generally $A = 0$.

X_{Alt_i} : The indicator abscissa that generates the value V_i
P_i : A shape factor that determines whether the curve is concave or convex, linear or S-shaped
C_i : The factor that establishes the value of the abscissa for the inflexion point in curves with Pi > 1.
K_i : The factor that defines the response value to C_i

B: The factor preventing the function from leaving the range (0.00, 1.00); obtained with equation (3).

$$B = \left[1 - e^{k_i \cdot \left(\frac{|x_{max} - x_{min}|}{C_i}\right)^{P_i}}\right]^{-1} \tag{3}$$

4.2.1. Indicator definition

According to the MIVES concept, a decision-making tree (DMT) should include the three pillars of sustainability (T), and those criteria and indicators representative to the case under analysis. The DMT for this research (Fig. 4) was determined based on the local stakeholders' preferences, as identified through seminars and an extensive literature review. The *economic requirement* (R_1) represents the investment required to implement a certain THU layout over its entire life cycle, with the *capital investment* (C_1) being the determining criterion. The *social requirement* (R_2) assesses the effect of each alternative on the DP, as the occupants of units, and third parties potentially affected or involved. The social requirement embraces four criteria: (C_2) *delivery time*, (C_3) *comfort*, (C_4) *safety*, and (C_5) *DP preference*. The *environmental requirement* (R_3) considers the environmental impacts of the overall life cycles of the alternatives by means of (C_6) *resource consumption* and (C_7) *emission* criteria.

The *capital investment* (C_1) encompasses two indicators: the (I_1) *construction cost* of THU alternatives (cost/m^2), and (I_2) *maintenance cost* of those expected repair activities during service. A second life use is assumed to have occurred for most of THUs in Bam. It is assumed that these units are re-used for the same function in the same location for a total extended life of fifty years. In this regard, the service lifespan of the THU and construction materials were determined from the Whitestone

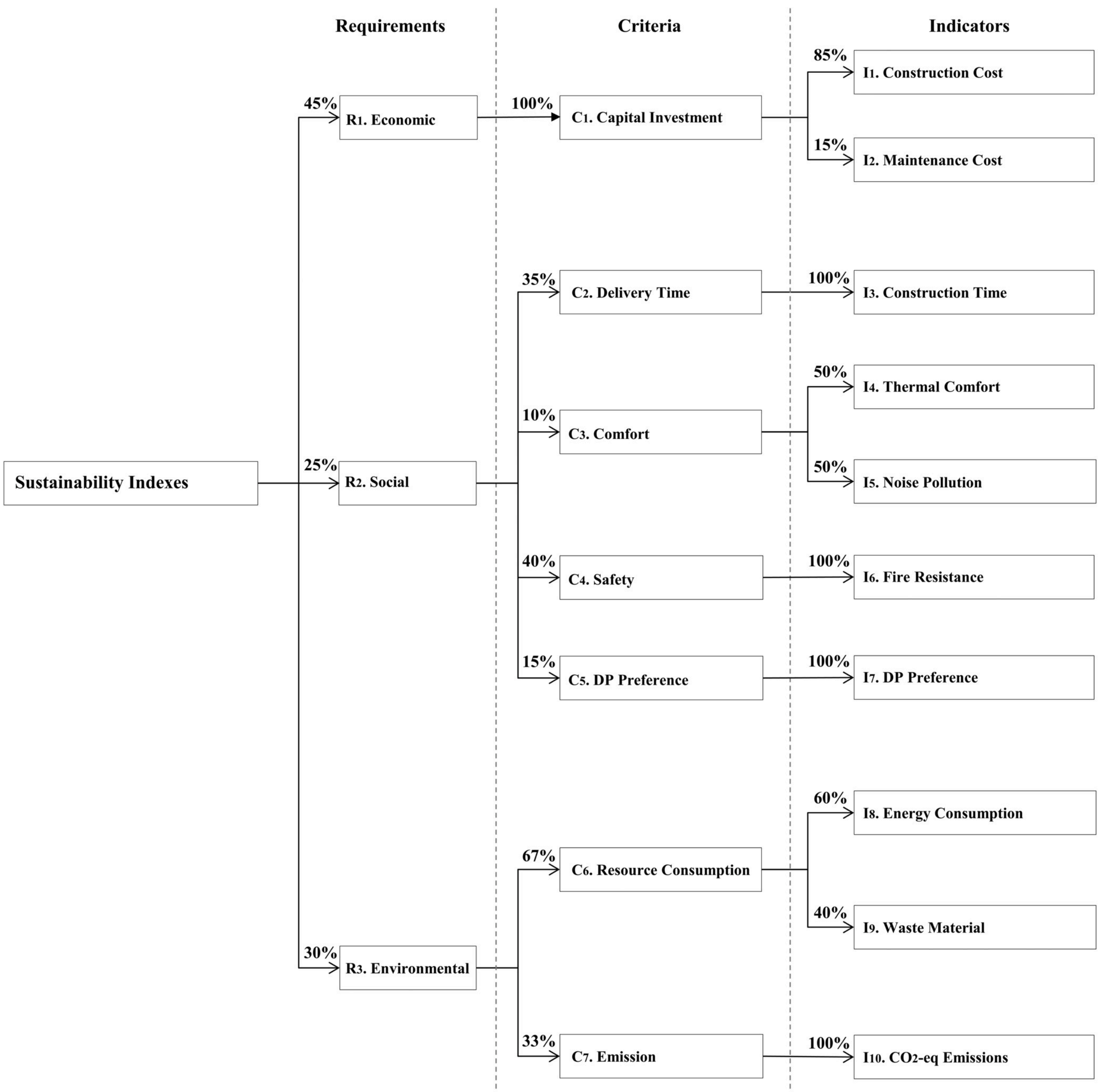

Fig. 4. Requirements tree designed for this model.

Table 7
Lifespan of the THU materials.

Material	Lifespan (year)	
	Abate et al. (2009) [75],[a]	Cochran (2006) [76],[d]
Concrete masonry block	100[b]	75[e]
Tile	75	20
Ceramic tile flooring	50	20
Mosaic tile (Terrazzo)	75	–
Cement mortar	–	75[f]
Cement plaster	75[c]	75[f]
Gypsum-sand plaster	75[c]	–
Insulation	–	–

[a] Frequency of replacing material time are mentioned.
[b] The exterior wall is considered. Frequency of replacing a concrete block of the interior wall is 75 years.
[c] General Plaster (interior).
[d] Typical.
[e] Brick.
[f] Masonry cement.

facility maintenance and repair cost reference 2010–2011 [73] and the Iranian pricing schedule of building 2004 [74]. Additionally, the lifespans of the materials used in the THU are assessed from other sources as well, as shown in Table 7.

The *delivery time* (C_2) includes the *construction time* (I_3) which accounts for the required person-hours for construction; this is quantified based upon the activity type and its amount. Material off-cuts (e.g., mosaics), which could have an impact on the total time, were neglected because they had a minor influence in the case study. Other factors that could have impacts on the delivery time (ex., construction materials availably) were disregarded since those were included in the construction cost indicator.

Comfort (C_3) comprises two indicators: (I_4) *thermal comfort*, which assesses the required thermal transmittances of alternative layouts, and (I_5) *noise pollution*, which considers the environmental noise owing to alternative units. The noise pollution indicator could include two issues: (1) impacts of harmful sounds that have been generated owing to construction activities during the construction phase on labourers and the host area; and (2) the acoustic comfort levels of alternative units for the DP, as occupants, during the operation phase. However, the former was found to be negligible, as the installation of THU units does not require the use of heavy trucks or cranes, or concrete vibrators or soil pneumatic compressors for soil compaction. In this regard, it must be emphasised that the site is considered ready for construction and, hence, the preparation phase is out of the scope of this analysis. Therefore, the acoustic comfort during the operation phase is to be assessed. For this purpose, the acceptable ranges of thermal resistance and acoustics were established from the technical literature (Table 8).

Table 9
Chosen areas of the three spaces by participants.

Participants (%)	Area (m^2)		
	Living Room	Kitchen	Bathroom
47.3	14	3	3
42.1	12	5	2
10.6	Other		

The *safety* (C_4) is meant to assess the occupants' security and safety levels, and includes the indicator *fire resistance* (I_6). Accepted technical codes are used for determining fire-resistance ratings (Table 8).

The criterion *DP preference* (C_5) includes the indicator *DP preference* (I_7) that represents the satisfaction of the DP in terms of usability and adequacy to the users' expectations, including cultural traditions. These items are directly related to the interior geometrical design and spatial distribution. Two approaches were followed to quantify this indicator: (1) questionnaires and interviews; and (2) minimum required areas of interior spaces according to standards (refer to section 4 and Table 2).

To identify the DP preferential factors, 32 interviews were conducted. As the Bam DP from several years ago is inaccessible, the authors interviewed the DP from the earthquake that occurred in 2017 at Kermanshah (western province of Iran). The interview concerned the required interior spaces, the associated areas, and the relative importance (weights) of each interior space. A total of 32 families accommodated in THUs since the aftermath of the earthquake were interviewed. A representative majority of the interviewed people complained regarding sharing restrooms with others, outside of their units. These families preferred a larger living room, divisible into two spaces, to separate private areas for parents and children.

To guarantee a higher statistical representation of the population, an online questionnaire was randomly sent to more than 500 people via a social media application, which is popular in Iran. Through this approach, 181 reliable responses were received. The questionnaire was designed to include two sections: first, the relative importance of each space in the THU was specified and, second, the area assigned to each space among five different area distribution sets was chosen (Table 9). For the first section, 88.9% of respondents ordered (from high to low importance) the internal spaces as: living room, bathroom, and kitchen.

The *resources consumption* (C_6) criterion is aimed at quantifying the natural resources consumed, by means of two indicators. The *energy consumption* (I_8) indicator concerns the manufacturing, construction, and demolition phases. The Inventory of Carbon & Energy (ICE) [84] is also considered as a database. In contrast to most environmental impact analyses on buildings, the energy consumption through the operational phase was not considered in this study case, as (I_4) *thermal comfort* is a representative indicator for energy consumption during the operation

Table 8
Exterior wall standards for residential buildings.

	Exterior wall standards			References
Acoustic range	Iran		Bedroom: R'_w >45; Living room: R'_w >40; Kitchen: R'_w >35	[77]
	USA		Grade 1:STC>55; Grade 2:STC>52; Grade 3:STC>48 (general STC>50)	[78]
	UK		$D_{nT,w} + C_{tr}$ >45	[79]
	Germany*		Class A: R'_w >68; Class B: R'_w >63; Class C: R'_w >57	[78]
Fire resistance (h)	Iran		1	[80]
	USA		1	[81]
Thermal Resistance	Iran **	Light	Group 1: $R > 2.8$; Group 2: $R > 2.1$; Group 3: $R > 1.5$	[82]
		Heavy	Group 1: $R > 1.9$; Group 2: $R > 1.4$; Group 3: $R > 1.0$	
	UK		U-value: 0.3–0.4	[83]

* Row housing.
** Light wall: surface mass < 150 kg/m.^{2}.
** Heavy wall: surface mass > 150 kg/m.^{2}.
R'_w : Weighted sound reduction index (dB); $D_{nT,w} + C_{tr}$: Airborne sound insulation (dB); R: Thermal resistance (m^2.K/W).

Table 10
Percentage of waste material during the construction phase and recycling.

Material	Waste (%)					Recycling Potential
	Solís-Guzmán et al. [85],	Prairie Village [86]	Asgari et al. [87], [e]	Schuette & Liska [88], [f]	Pinto & Agopyan [89], [g]	Saghafi & Teshnizi [90],
Concrete masonry block	2.13 & 5.78 [a]	0.61[d]	18	3.5	–	–
Tile	2.55	1.24	4.80	6.5	9	Landfill
Ceramic tile flooring	0.25 [b]	1.24	4.80	–	7	Landfill
Mosaic tile (Terrazzo)	0.25 [b]	–	5	–	–	Landfill
Cement mortar	–	–	–	3.5	46	Landfill
Cement plaster	0.33[c]	–	–	–	–	Landfill
Gypsum-sand plaster	0.33[c]	–	4.20	–	–	Landfill

[a] Brick exterior and interior walls, respectively.
[b] Floor.
[c] General Plaster.
[d] Cinder block.
[e] Construction and demolition waste.
[f] Cited by Chen et al. [91].
[g] Cited by Bossink & Brouwers [92].

Table 11
Reuse and recycle potential of materials used in the THU.

Material	Viability		
	Reuse in Situ	Reclaimed Material	Recycled-Content Building Product
Concrete masonry block	High	Low	High
Tile	High	High	Medium
Ceramic tile flooring	Low	Low	Medium
Mosaic tile (Terrazzo)	–	–	–
Cement mortar	–	–	–
Cement plaster	Medium	–	–
Gypsum-sand plaster	Medium	–	–
Waterproofing flexible sheets	Medium	Low	Medium

Source: Addis (2012) [94].

phase.

Waste material (I_9) generated in the manufacturing, construction, and demolition phases. Both waste and management aspects are assessed in this indicator. For this purpose, after a thorough literature review was conducted, scarce data on waste material ratios were found. This can be owing to the diverse points of view from which the analyses were performed and the variety of building technologies that were analysed, both aspects leading to data with high variability (see Table 10). The material waste percentages reported in Ref. [74] during the construction phase were considered for this case study.

Additionally, both material reuse and recycling potentials were quantified according to Refs. [[93,94]], Table 11, to assess the waste management rate.

The *emission* (C_7) criterion is represented by the indicator *CO_2-eq emissions* (I_{10}) to quantify the total equivalent CO_2 emissions during the life cycle assessment (LCA). This embraces all greenhouse gases (GHGs) owing to the manufacturing, construction, and demolition phases. The Inventory of Carbon and Energy (ICE) [84] was considered as the reference database for quantifying this indicator.

It should be emphasised that the indicators were identified and determined based upon an extensive literature review (Table 12). Furthermore, although the indicator categorizations were mentioned above, these indicators could have been assigned to other requirement groups simultaneously with regard to their impacts. In other words, there are many interactions between indicators. However, according to the concept of the MIVES method, each indicator is normally considered based on one of its main impacts. The main factors of each are listed in Table 12.

Nevertheless, the different impacts of each indicator are considered in Table 12. Several impacts of each indicator could assist experts and decision makers in assigning a more appropriate weight to each index. In other words, the importance (weights) of the indexes are specified easily and accurately by considering the influential groups of indicators, as shown in Table 12.

4.2.2. Determination of the model's parameters

After defining the DMT (Fig. 4), the parameters for evaluating the values (satisfaction) generated by each indicator were determined. In this step, according to Alarcon et al. [120], the tendency (increase or decrease) and the shape (convex, concave, linear, and S-shaped) of the value function of each indicator (see Fig. 5) were assigned. According to Alarcon et al. [120], a *concave-shaped* function is used when satisfaction decreases slightly or increases quickly. When the satisfaction tendency is contrary to the concave curve, a *convex-shaped* function is the most suitable. A *linear* function is applied when there is a steadily increasing/decreasing satisfaction. If the satisfaction tendency embraces a combination of convex and concave functions simultaneously, an *S-shaped* function is the most representative.

The constitutive parameters of the value functions (Equation (2) and (3)) are presented in Table 13. These parameters, including both tendency and shape, were established based upon the scientific literature, Iranian and International Building Codes, and the background of experts (including professors and HFIR practitioners who attended the seminars, see Table 13).

The weights (see Fig. 4) were assigned based upon the results of a seminar with 11 multidisciplinary experts: professors and researchers from architecture and civil engineering faculties of Iranian universities (Shahid Beheshti and Islamic Azad), from the Polytechnic University of Catalonia (UPC), Barcelona (Spain), and two experts from HFIR. The weighting process followed the well-known analytical hierarchy process (AHP) [125].

4.3. Optimization model

Both the designed MIVES-based model and the *backtracking* algorithm were implemented in C^{++}. The input data includes three different groups:

1. Geometry parameters related to the floor plan design of units. In this case, nodes of spaces, which define edges and consequently boundaries, dimensions, and positions of doors and windows, possible variations of the sliding walls, and dependent/independent parameters belong to this data group (see Section 4.1).

Table 12
Main factors and impacts of the indicators.

Indicator	Factor (Sub-indicator)	Impact	References
I_1. Construction Cost	• Resources (Material, Energy, Water) • Design • Labor • Hazard • Location (Site, Infrastructure, Weather)	• Investors	[95–97]
I_2. Maintenance Cost	• Lifespan of Material • Building Characteristics • Ownership Features	• Investors • Occupants	[98,99]
I_3. Construction Time	• Project (type, Characteristics, Volume, Design, Location, Technology, etc.) • Owner • Contractor • Consultant • Material • Labour • Others (such as Uncertainties, Unpredictable Conditions, Regulations, etc.)	• Occupants' Satisfactions • Construction Cost	[100–103]
I_4. Thermal Comfort	• Occupants' Behavioural Adjustments • Building Features • Climate Conditions	• Occupants' Comfort • Energy Consumption • CO_2 Emission • Operation Cost	[104–106]
I_5. Noise Pollution	• Construction Noise • Acoustic Performance	• Occupants' Comfort • Occupational Disturbance • Environmental Negatively	[107–110]
I_6. Fire Resistance	• Building Fire Response Performance • Occupants' Response • Escape Route	• Occupants' Safety • Investors • Environmental Negatively	[111]
I_7. DP Preference	• Users Preference • Designer (Architect) Preference • Building Standard	• Occupants' Comfort • Construction Cost • Construction Time • Environmental Negatively	[25,112]
I_8. Energy Consumption	• Size & Location • Material • Architectural and Structural Design • Building Services (HVAC, etc.) • Occupants' Behavioural	• Environmental Negatively • Construction Cost • Operation Cost	[113–115]
I_9. Waste Material	• Design • Procurement • Materials Handling • Operation • Lifespan of Material • Reuse & Recycle Potential	• Environmental Negatively • Construction Cost	[91,116,117]
I_{10}. CO_2-eq Emissions	• Manufacturing Material • Material Transportation • Energy Consumption (Construction Activities & Occupants Activities)	• Environmental Negatively • People's Safety	[118,119]

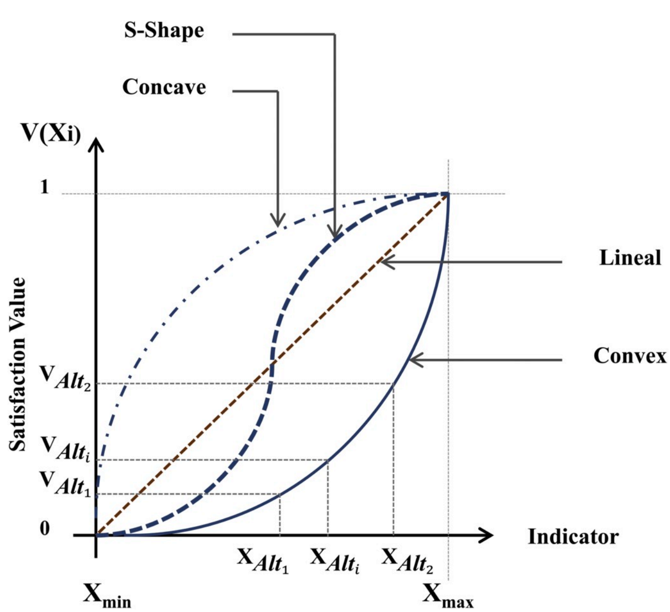

Fig. 5. Value function types, including convex, concave, linear, and S-shaped.

2. Material parameters used for each THU alternative. Once a specific geometry is defined, the amount of materials is quantified, and the properties are transferred to the sustainability assessment model.
3. MIVES parameters (Fig. 4 and Table 13) required to assess the SI of each alternative.

In general, the optimization model, which operates based on a binary search approach, starts by reading the input data. The first step is to calculate the SI of the initial layout (that used in the case study of Bam, with SI = 0.54). From this, the algorithm generates variations and dependencies (new solutions), and both the areas (walls and spaces) and the amounts of required materials for each solution are computed. The areas of components are estimated with the shoelace algorithm. Finally, the SI of each alternative is assessed with the implemented MIVES model.

The algorithm progresses and generates further alternatives by modifying the dimensions and positions of the walls (restricted to compatible variations and dependency conditions). Then, the aforementioned steps are repeated. This loop is repeated until a layout with the maximum SI is determined. However, this research study applies a methodology based on the *backtracking* algorithm, in which the DMT is created by using the *binary search* approach to minimise the design exploration space. Walls are allowed to slide 0.05 m during the iterative process. By this assumption, the number of compatible solutions is greater than 77,000. Nevertheless, the proposed scheme achieves the

Table 13
Parameters and coefficients for each indicator value function.

Indicator	Unit	Xmax	Xmin	C	K	P	Shape	References
I_1	IRR.	$5.4{\cdot}10^6$	$3.5{\cdot}10^6$	$1.2{\cdot}10^6$	0.100	2.00	DCx	[74,121]
I_2	IRR.	$5.2{\cdot}10^5$	$2.8{\cdot}10^5$	$1.4{\cdot}10^5$	0.01	1.50	DCx	[73,74]
I_3	Man-hour	$2.25{\cdot}10^2$	$1.8{\cdot}10^2$	$1.2{\cdot}10^2$	$3.8{\cdot}10^2$	3.50	DS	[74]
I_4	$(W/m^2.K)$	2.35	2.28	0.40	$1.5{\cdot}10^2$	2.20	DS	[82]
I_5	pts. (%)	0.43	0.38	0.15	$3.7{\cdot}10^2$	3.00	IS	[77,122]
I_6	pts. (%)	0.45	0.42	0.35	$3{\cdot}10^2$	1.85	IS	[81,123,124]
I_7	pts. (%)	0.55	0.35	0.40	$0.60{\cdot}10^2$	3.00	IS	[62–64]
I_8	MJ	$2.05{\cdot}10^4$	$1.40{\cdot}10^4$	$1.50{\cdot}10^4$	0.40	1.80	DCx	[84]
I_9	kg	$3.75{\cdot}10^2$	$3.15{\cdot}10^2$	$0.55{\cdot}10^2$	1.80	2.20	DS	[74]
I_{10}	kg CO_2	$1.60{\cdot}10^3$	$1.28{\cdot}10^3$	$1.40{\cdot}10^3$	0.80	1.40	DCx	[84]

Table 14
Change ranges of the walls in the initial and optimal layouts.

Space	Partition	Change Range (m)	
		Initial Layout (Bam)	Optimal Layout
Living Room	WL_1	0.00	+0.15
	WL_2	0.00	0.00
	WL_3	0.00	+0.3
Kitchen	WK_1 & WK_3	0.00	- 0.15
	WK_2 & WK_4	0.00	0.00
Bathroom	WB_1 & WB_3	0.00	- 0.3
	WB_2 & WB_4	0.00	0.00
Entrance	WE_4	0.00	0.00

optimal solution in less than 131 iterations.

5. Result and discussion

The optimal solution is achieved when the areas of the kitchen and bathroom decrease by 0.23 m^2 and 0.30 m^2, respectively, and the area of the living room increases accordingly. As shown in Table 14, this layout presents minimum lengths of WK_1 and WB_2 by decreasing these by 0.15 m and 0.30 m, respectively. Contrarily, the lengths of the dependent walls of the living room (WL_1 and WL_3) are increased, that is, by sliding WK_2 and WB_2 in the direction that permits a minimisation of the kitchen and bathroom areas. The SI (0.66) of the optimal solution generated by the model showed an increase of 12% with respect to that used in Bam (SI = 0.54), with the performances of the economic and environmental requirements being 28% and 42% greater (Fig. 6), respectively. The social requirement value decreased by approximately 1%, owing to a slight reduction in the performances of the I_4 and I_6 indicators (Fig. 7).

However, the optimal solution had higher satisfaction values for the three social indicators, as shown in Fig. 7. Only the satisfaction values for two indicators (I_4 and I_6) are lower than those of the initial layout, as shown in Fig. 7. Thus, the results demonstrate that the model works properly, and generates the optimal solution accurately.

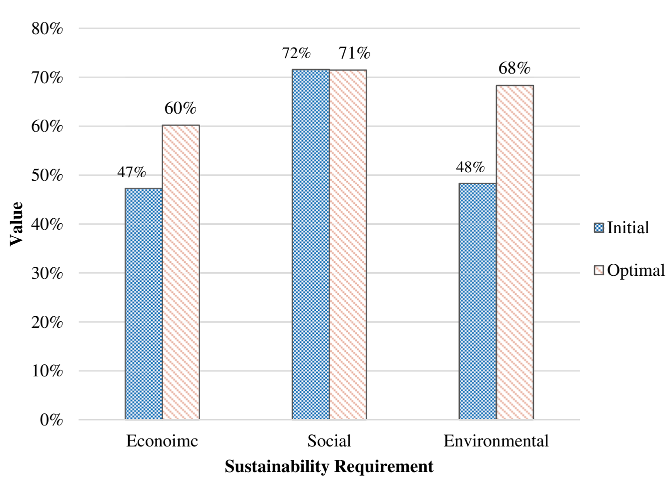

Fig. 6. Satisfaction values of the requirements for the initial and optimal solutions.

Additionally, each one square metre of the construction materials used in the kitchen and bathroom led to more negative impacts in terms of the economic and environmental aspects. There was an expectation before running the model that minimum areas for the kitchen and bathroom would achieve the optimal solution. Finally, the model generated an alternative layout with the minimum areas of these two spaces. In this regard, it could certainly be noted that there is a direct correlation (relation) between the economic value and areas of the kitchen and bathroom. Nevertheless, this relation does not always hold true for the environmental requirement.

The aforementioned fact demonstrates that the kitchen and bathroom areas need to be minimised in THUs as much as possible while respecting the building codes and DP requirements to achieve optimal SIs. In this case, it is possible to have several geometric designs. To this end, in addition to the optimal solution, the top-ten ranked solutions generated by the model are considered, as shown in Table 15. For instance, the second-ranked solution, which has an SI equal to 0.65, has another geometric design. In this solution, the lengths of WK_1 and WK_2 decrease by 0.15 m and 0.05 m, respectively. Furthermore, the lengths of WB_1 and WB_2 are changed by −0.3 m and +0.05 m, respectively, as compared to the same edges of the initial layout.

In general, in all of the top-ten ranked solutions, the kitchen and bathroom areas are smaller than the areas of the same spaces in the initial layout. The highest satisfaction value for the social requirement among all ten solutions belongs to the fourth layout, as shown in Table 15. However, this layout includes lower values of the economic and environmental requirements as compared to the optimal solution. In this solution (fourth one), the decrease in the kitchen area is lower than in the other nine solutions, as shown in Table A.1.

In addition to the consideration of the weights assigned by experts (Fig. 4), other weighting scenarios were analysed, with the purpose of both identifying those requirements that govern the sustainability performance and the layouts derived from each scenario. The weight sets were based on the experts' proposals, including those considered outliers.

On the one hand, the results shown in Fig. 8 confirm that the SI increases for scenarios in which the stakeholders are more sensitive to environmental and social requirements; this was expected because THU costs are commonly covered by public funds. However, it must be noted that, independent of the weights, the model generates the same geometry layout (Table 14) as the optimum. This can be assumed to be an indicator of the robustness of this optimum solution.

Other solutions with greater SIs can be generated by enlarging the ranges of the changes established in Table 3. In this regard, SI = 0.87 if the kitchen and bathroom areas of the initial layout are decreased by 0.975 m^2 and 0.580 m^2, respectively, and 1.296 m^2 are added to the living room. Nevertheless, this layout is not acceptable, because the distribution and minimum area ratios do not meet building code

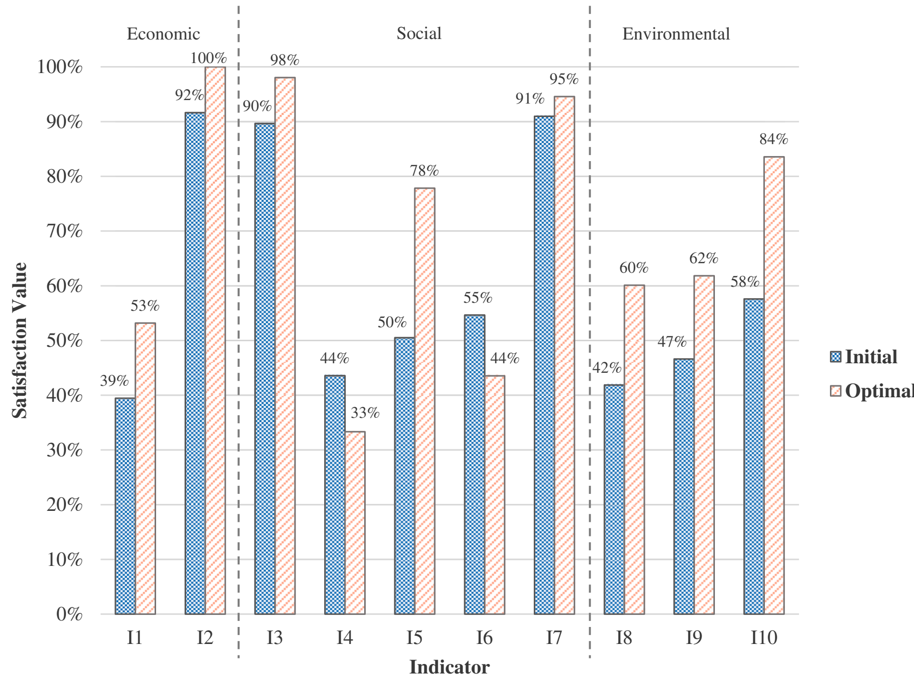

Fig. 7. Satisfaction values of the ten indicators for the initial and optimal solutions.

Table 15
SI of initial layout and top 10 ranked solutions by the model.

Rank	SI	Value			Change the length of the wall (m), compared to the initial one				
		Economic	Social	Environmental	Kitchen		Bathroom		Entrance
					WK_1	WK_2	WB_1	WB_2	WE_4
Initial	0.5367	0.4728	0.7158	0.4832	0.00	0.00	0.00	0.00	0.00
1	0.6551	0.6020	0.7147	0.6830	−0.15	0.00	−0.3	0.00	0.00
2	0.6509	0.6021	0.7003	0.6810	−0.15	−0.05	−0.3	0.05	0.00
3	0.6468	0.6022	0.6858	0.6789	−0.15	−0.1	−0.3	0.1	0.00
4	0.6443	0.5878	0.7261	0.6608	−0.1	0.00	−0.3	0	0.00
5	0.6426	0.6023	0.6714	0.6769	−0.15	−0.15	−0.3	0.15	0.00
6	0.6407	0.5883	0.7122	0.6597	−0.15	0.00	−0.3	0.05	−0.05
7	0.6407	0.5883	0.7122	0.6597	−0.15	0.00	−0.25	0.00	0.00
8	0.6402	0.5879	0.7120	0.6589	−0.1	−0.05	−0.3	0.05	0.00
9	0.6385	0.6038	0.6572	0.6748	−0.15	−0.2	−0.3	0.2	0.00
10	0.6366	0.5885	0.6978	0.6577	−0.15	−0.05	−0.3	0.1	−0.05

requirements. Thus, the geometry layout (Table 14) found with SI = 0.66 is the optimal layout that meets the stakeholders' preferences and the code requirements for the boundary conditions established in Table 3.

6. Conclusions and perspectives

A novel multi-objective sustainability-based approach for optimizing the geometric layout of the floor plans of THUs is presented in this research paper. The sustainability model is based upon the MIVES, which allows the quantification of the most representative indicators belonging to economic, environmental, and social requirements. For this purpose, both the value function concept and AHP processes were implemented to quantify the satisfaction and preferences (weights) of the stakeholders involved in the decision-making process. These methods were calibrated via questionnaires and within the context of experts' seminars and interviews, in which more than 500 people participated. The whole procedure was designed to guarantee the transparency, objectivity, and robustness of the results. However, it should be remarked that this research is based on the assessment of one THU's construction technology and, thus, further cases with more indicators (ex., material off-cuts) should be analysed in order to generalize the outcomes of this study.

An optimization of the SI of the THUs used in the aftermath of the earthquake that occurred in 2003 in Bam (Iran) was conducted with the proposed model. Based on both the analysis of the obtained results and a parametric study, the following conclusions can be drawn:

- The layout that led to the maximum sustainability index (SI = 0.66) consisted of reductions of 0.23 m^2 in the kitchen area and 0.30 m^2 in the bathroom space, with the living room area increasing by 0.53 m^2. This solution represents a 12% sustainability index improvement with respect to the reference layout used in the Bam study case (with SI = 0.54).
- The economic and environmental performances of the optimal solution showed increases of 28% and 42% compared to the reference layout, respectively. The social performance decreased by a negligible 1%. This improvement in both economic and environmental performances, while guaranteeing the same social acceptance, were found to be promising results when considering the number of THUs to be designed and constructed.

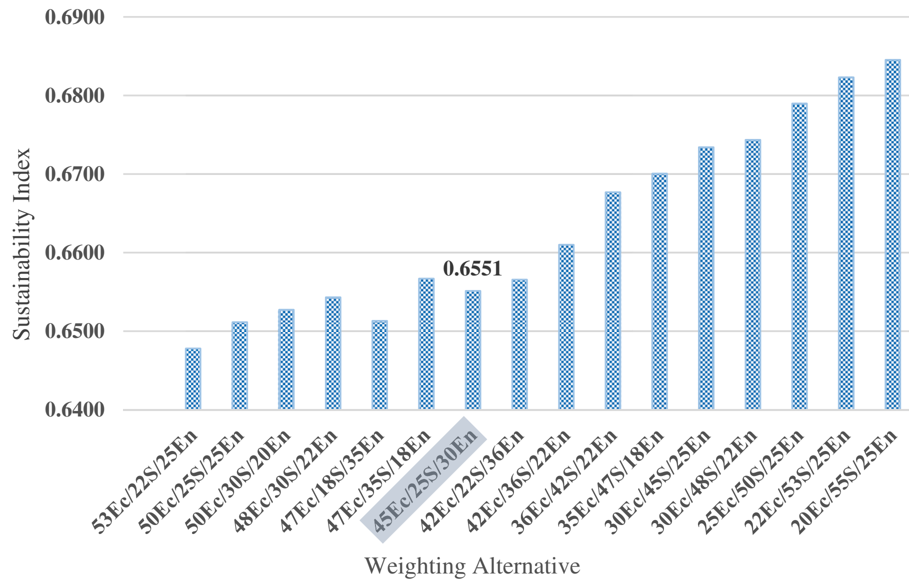

Fig. 8. SIs of optimal solutions generated by the model based on several weighting scenarios.

- The optimal solution detected was proven to be robust in different weighting scenarios (different stakeholders' preferences), and its sustainability performance was greater when social and environmental requirements drove the decision-making process.

The applicability of this approach can be extended to normal residential buildings, offices, and interior spaces with uses other than for THUs. For this purpose, the stakeholders and decision makers ought to include (if necessary) new indicators that prove to be representative of the particular boundary conditions. The weights should be also re-calibrated accordingly.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX

Table A.1
Top 10 ranked solutions, including SIs, satisfaction values of indicators, and areas changes

Rank	SI	Indicator Satisfaction Value										Area change (%) compared to the initial area			
		I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	Kitchen	Bathroom	Entrance	Living Room
Initial	0.5367	0.3946	0.9162	0.8963	0.4356	0.5049	0.5464	0.9097	0.4185	0.4661	0.5759	0%	0%	0%	0%
1	0.6551	0.5317	1.00	0.9803	0.3332	0.7783	0.4355	0.9456	0.6010	0.6183	0.8356	−12%	−23%	−23%	8%
2	0.6509	0.5319	1.00	0.9803	0.3332	0.7857	0.3975	0.9484	0.5986	0.6180	0.8325	−14%	−19%	−23%	8%
3	0.6468	0.5320	1.00	0.9803	0.3332	0.7930	0.3594	0.9511	0.5963	0.6177	0.8294	−17%	−15%	−23%	8%
4	0.6443	0.5152	0.9988	0.9755	0.3444	0.7472	0.4731	0.9392	0.5799	0.6020	0.8073	−8%	−23%	−23%	7%
5	0.6426	0.5321	1.00	0.9803	0.3332	0.8001	0.3215	0.9537	0.5939	0.6173	0.8262	−20%	−12%	−23%	8%
6	0.6407	0.5159	0.9991	0.9756	0.3444	0.7552	0.4355	0.9438	0.5792	0.6016	0.8050	−12%	−19%	−26%	8%
7	0.6407	0.5159	0.9991	0.9756	0.3444	0.7552	0.4355	0.9438	0.5792	0.6016	0.8050	−12%	−19%	−19%	7%
8	0.6402	0.5154	0.9989	0.9755	0.3444	0.7552	0.4355	0.9424	0.5778	0.6017	0.8043	−11%	−19%	−23%	7%
9	0.6385	0.5322	1.00	0.9803	0.3332	0.8071	0.2841	0.9562	0.5916	0.6170	0.8231	−23%	−8%	−23%	8%
10	0.6366	0.5160	0.9991	0.9755	0.3444	0.7630	0.3975	0.9466	0.5768	0.6013	0.8019	−14%	−15%	−26%	8%

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