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Sustainability assessment model for mass housing's interior rehabilitation and its validation to Ekbatan, Iran

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ABSTRACT

Mass housing (MH) buildings from the '60s to the '80s, after decades of continuous use and inadequate maintenance, cause several sustainability issues and need rehabilitation. Most current conventional rehabilitation approaches have long been criticized because they consider neither sustainability requirements nor contemporary building standards. In this regard, the assessment and selection of suitable approaches for rehabilitating MH interiors, from a holistic sustainability viewpoint, is a crucial issue that faces several challenges since this is a multidisciplinary and multi-criteria process. On this subject, the present study develops a novel MCDM model based on the MIVES and Delphi methods for the holistic sustainability assessment of MHs' interior rehabilitation considering involved stakeholders' preferences. This MIVES-Delphi model relies on a comprehensive literature review, experts' seminars, on-site surveying, LCA, BIM, user/expert-based questionnaires, bias reduction, and sensitivity analysis. The model was first applied in the Ekbatan MH case study, the largest MH in Iran, to assess the sustainability of four different interior rehabilitation scenarios, including three common rehabilitation scenarios plus an innovative one. Consequently, the new model was validated, and the most sustainable scenario was selected. The specific results regarding these scenarios' evaluation disclosed that none of the common rehabilitation scenarios could either meet the minimum sustainability target value or serve as proper solutions for MH's interior rehabilitation. Contrarily, the fourth scenario, with a global sustainability index of 0.71, could meet the standard minimum target. This outcome provides a possibility for innovative rehabilitation processes to have positive effects on increasing the sustainability performance in MH buildings.

1. Introduction

Mass housing (MH – Appendix A presents a complete list of abbreviations) refers to dense and repetitive housing [1] that spread out worldwide to tackle the acute shortage of housing in the 1960s and 1970s [2–4]. After operating for decades and receiving improper maintenance, these MHs have been censured in terms of their several social, economic, and environmental negative impacts. For instance, recent studies revealed that most MHs have high energy consumption, CO_2 emissions, and maintenance costs [5]. Furthermore, MHs' present interior conditions do not respond adequately to the current needs of their occupants [2]. On the other hand, according to several investigations, rehabilitating (Appendix B) these MHs is preferable to their demolition due to having less negative sustainability impacts. As Gaspar and Santos (2015) [6] and Alba-rodríguez et al. (2017) [7] pointed out, proper rehabilitation approaches can upgrade aged MHs' interior performance to achieve as high sustainable standards as current new builds.

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However, the current MHs' rehabilitation takes place mainly based on conventional approaches, from which the majority neither fulfill sustainability requirements nor contemporary building standards [8–12]. Furthermore, most existing studies and policies regarding MHs' rehabilitation focus on urban-scale rehabilitation [13–18], while rehabilitation on the dwelling scale and its interior spaces have received less attention. Nevertheless, interior rehabilitation of spaces is a crucial issue due to (i) more than 87% of a person's lifespan in modern society is spent indoors, based on the National Human Activity Pattern Survey [19]. Besides, this number even increased due to the recent Covid-19 Pandemic lockdowns [20,21], and (ii) interior spaces affect different sustainability aspects such as energy consumption, CO_2 emissions, and waste generation in buildings as well as the psychology, behavior, well-being, and productivity of their inhabitants [22–24].

Identifying and assessing proper interior rehabilitation approaches from the holistic sustainability viewpoint are crucial, especially in developing countries such as Iran, where sustainable rehabilitation has rarely received adequate attention [4,25]. This assessment procedure faces several challenges since this is a multidisciplinary and multi-criteria process [26–28]. Therefore, numerous former investigations have applied different building sustainability assessment (BSA) methods and tools. Most BSAs have various shortfalls, such as (i) lacking a holistic approach [12,13,29–37], (ii) neglecting the involved stakeholders' preferences [28,38,39], (iii) being limited to a specific regional context [26,27,37,40], and (iv) employing some predefined sustainability indicators some of which are not adequate, relevant, or even applicable for all projects [25,27,37]. These shortfalls can be overcome by developing new individual models based on multi-criteria decision-making (MCDM) methods [26,27,41].

To the best of the authors' knowledge, heretofore, there is no study regarding a holistic sustainability assessment for MHs' interior rehabilitation. Thus, the main objective of the present article is to contribute to moving forward to more sustainable interior rehabilitation approaches for MHs by following three phases (Fig. 1). *Phase A* establishes a novel MCDM model based on the *Modelo Integrado de Valor para una Evaluación Sostenible* (MIVES) [42,43] and Delphi [44] for the holistic sustainability assessment of MHs' interior rehabilitation. *Phase B* validates this model by applying it to the largest MH in Iran and its four different interior rehabilitation scenarios, including common and innovative ones. The result is the selection of the most sustainable rehabilitation scenario. *Phase C* proves the robustness of the model by conducting a sensitivity analysis. This manuscript has six sections: (a) Section 1 introduces the topic with a brief state-of-the-art; (b) Section 2 presents the employed methods for establishing the new model; (c) Section 3 defines and justifies the case study, sample of study, and rehabilitation scenarios to be assessed by the established model; (d) Section 4 shows the results for the defined scenarios; (e) Section 5 discusses the obtained results and the robustness of the model; (f) Section 6 draws conclusions and presents future projects.

2. Methodology

Phase A follows five stages: (2.1) defining the problems, objectives, and boundaries; (2.2) defining the decision-making tree (DT), (2.3) weighting the DT's components; (2.4) establishing the value functions; and (2.5) explaining indicators' values and the global sustainability indexes (GSIs) calculation methods. Fig. 2 depicts these stages, their main steps, and the methods and resources used to establish this new model.

The MIVES method was introduced for the first time in the 2000s [42,45] based on a combination of MCDM and the multi-attribute utility theory [42,46]. The present project uses MIVES because this method: (a) is a well-known scientific MCDM method that has already been satisfactorily applied in a wide range of previous research studies, especially in the building sector [28,38,39,47–70]; (b)

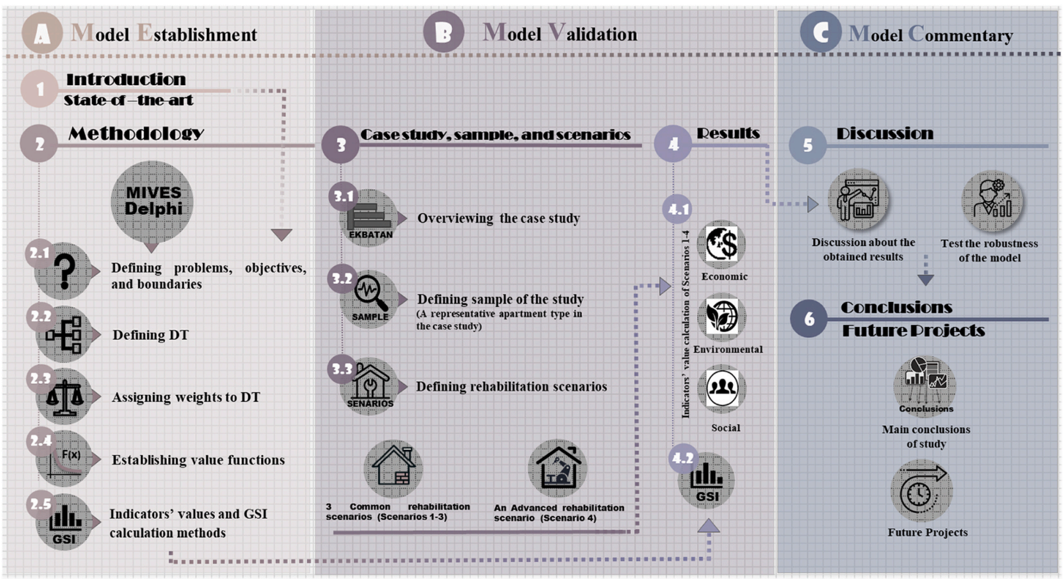

Fig. 1. Schematic framework of the study with its three phases and six sections.

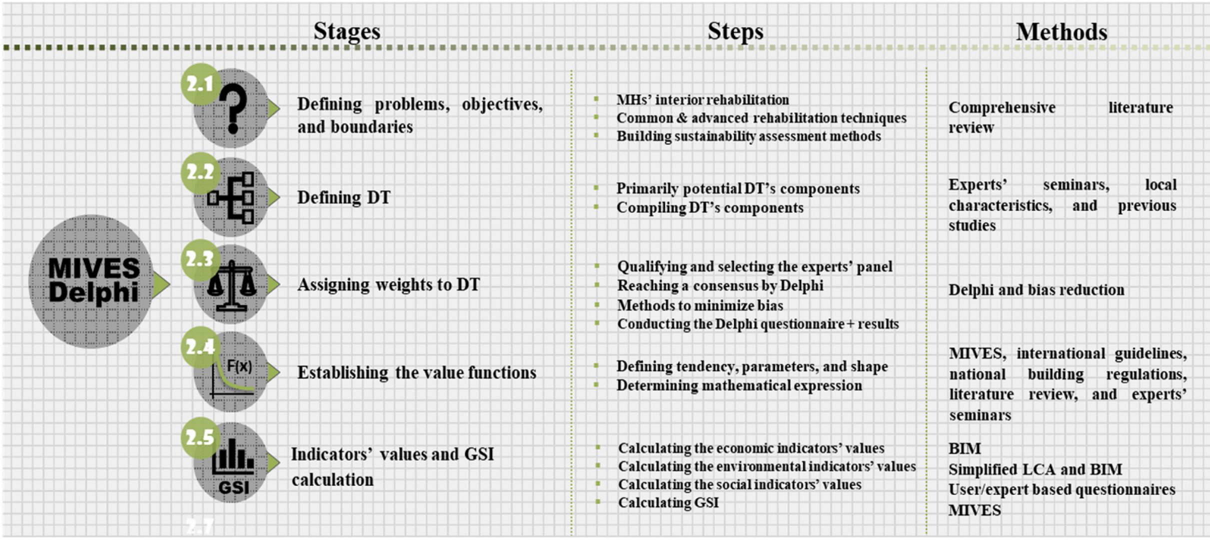

Fig. 2. The process to develop the MIVES-Delphi method.

allows researchers to carry out agile, objective, specific, customizable, and holistic sustainability assessments [47] by considering the essential principles of the sustainability concept – environmental, economic, and social pillars [28]; (c) provides a hierarchical-based DT that enables researchers to easily comprehend, communicate, and implement sustainability models [28,42,47,68]; (d) applies value functions [42,43,66] to measure the satisfaction level of various stakeholders involved in the decision-making procedure [28] and quantify, assess, and normalize both qualitative and quantitative indicators that might have different measurement units and scales [28,47]; (e) is specific for each deterministic or probabilistic case along with homogeneous or heterogeneous assessment [47,71]. Moreover, MIVES can be adapted and applied to different locations with diverse characteristics by considering the geographic contexts, DT's components, and stakeholders' preferences. This MCDM can also (f) be combined with other methods [28,46–49,60] for weighting – e.g., analytic hierarchy process (AHP) and Delphi – and robustness analysis – e.g., sensitivity analysis. Moreover, (g) MIVES calculates the GSI as well as the satisfaction value for each DT's component separately; thus, it enables decision-makers to identify the best alternative – the most sustainable one – through ranking alternatives, identifying their major characteristics, and their strengths and weaknesses regarding each DT's component.

From the vast existing weighting methods such as equal weighting, AHP, factor analysis, and conjoint analysis, this project employed Delphi, which is a systematic method for obtaining a consensus from a group of qualified experts who respond to a questionnaire reiteratively [44]. The reasons to select Delphi are because this method: (a) is a known, reliable, precise, and easy-to-use weighting method that is widely employed in several research studies [44,72]; (b) can be easily adapted and combined with different MCDM methods [44,48], such as MIVES [48]; (c) compiles and qualifies the experts' panel members based on their expertise level regarding a specific topic [44,72]; (d) enables experts to participate in a questionnaire without implying issues, such as scheduling, travel, space requirements, costs, or lengthy discussions; (e) controls and minimizes possible bias, plus enables researchers to obtain reliable data and judgment from an expert regarding a specific topic [44,72].

2.1. Defining problems, objectives, and boundaries of the present study

This MIVES considers the problems and objectives defined in Section 1 and the following boundaries: (i) MHs in Iran built from 1960 to 1980; (ii) rehabilitation at the dwelling scale – including the dwelling's interior spaces and interior façade layers while excluding structural elements, exterior walls, and building's services.

2.2. Defining DT

This stage defines the DT, which includes the most significant sustainability parameters – requirements, criteria, and indicators – regarding the topic of study in a hierarchical structure. This tree can assess the stakeholders' satisfaction and the sustainability of a particular process, system, and product [42,46] in order to: (a) make decisions based on the obtained indicators' values and weights; (b) have a global perspective of the problem; (c) organize the involved ideas; (d) facilitate the comprehension of the model for any stakeholder involved in the decision process; (e) carry out the subsequent mathematical analysis [28]. This DT mostly contains three different levels where the first and second levels – requirements (R_i) and criteria (C_j), respectively – include rather general and qualitative components, while the third level contains quantitative and measurable indicators (I_k) [28,47]. To define a proper DT, the authors followed two steps. The first step identified primary potential and relevant sustainability parameters for assessing MHs' interior rehabilitation in Iran. This step identified three requirements, nine criteria, and 27 indicators relying on a comprehensive literature review and experts' knowledge and expertise. The second step followed MIVES directives, the minimum and exclusively the most significant sustainability parameters should be selected [42,46] to (i) avoid overlapping among sustainability parameters; (ii) eliminate less significant indicators with low relative weights that have low impacts on the final GSI; (iii) prevent time-consuming, complicated evaluation processes, and high uncertainties results [28,73]. In order to do this, the identified sustainability parameters in the first step were refined and compiled using the outcomes of the seminars held by multidisciplinary experts and relavant previous studies alongside considering the case study's local condition. Fig. 3 shows the resulting most representative and independent from each other for three requirements, nine criteria, and 19 indicators.

2.3. Assigning weights to DT

The third stage assigns weights to the defined DT's components by following the Delphi method steps.

2.3.1. Qualifying and selecting the experts' panel

Delphi requires a selection of the experts' panel in a strategic and unbiased manner [44] because experts' opinions have a direct effect on weighting, and consequently, the model's final results [44,72]. Thus, to qualify the experts' panel members, the authors created a set of specific expertise requirements based on the objectives and limitations of this study as follows.

1) Being aware of the local sustainability priorities issues in Iran.
2) Having experience in the field of sustainability assessment methodologies.
3) Having experience in the field of interior rehabilitation of residential buildings, preferably in MHs.

The chosen experts must fullfil all of the three above-mentioned requirementsand should have expertise in one of the following fields: (i) construction practitioners – such as engineers, architects, construction managers, and manufacturers; (ii) academically affiliated experts – mainly engineers and architects; (iii) professionals from municipal organizations such as the Ministry of Housing and Urban Design, the Supreme Council of Architecture and Urban Development, and the Iran Construction Engineering Organization. Table 1 shows the relative point system used to appraise the final qualification of experts, following Delphi suggestions [44,72,74].

This project selected 15 experts who were qualified based on the aforementioned considerations, since several studies suggested 8

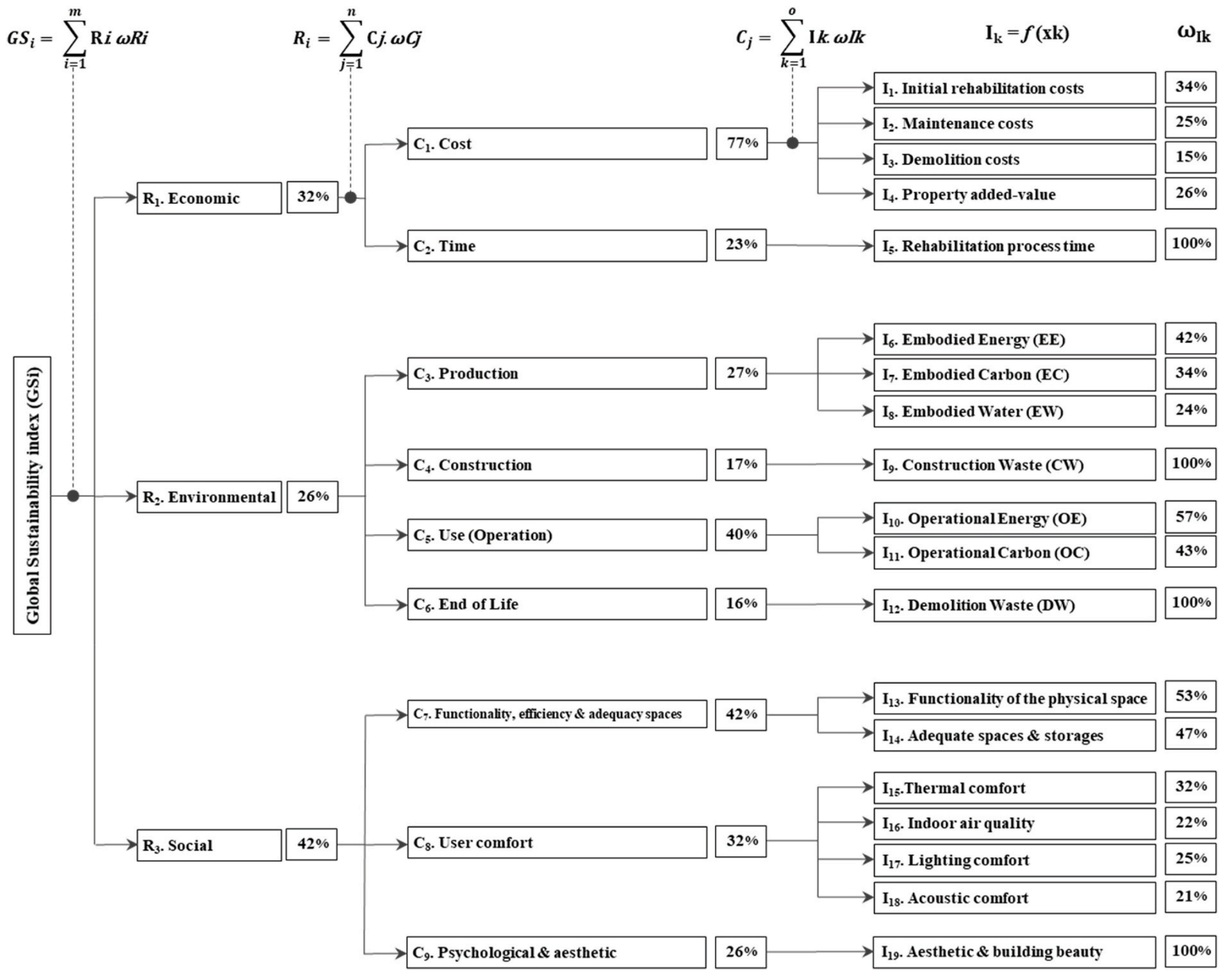

Fig. 3. The defined DT, its corresponding assigned weights, and GSIs' equations.

Table 1
Flexible point system for qualification of experts.

#	Achievement or experience	Level of expertise	Points
1	Professional background importance	Academic experience/year	0.5
		Construction experience/year	1
		Municipal experience/year	0.5
2	Experience in the field of sustainability assessment methods	Medium	2
		High	5
3	Advanced educational degrees	MS	2
		Ph.D.	4
4	Relevant published book/s in the focus area of the research		3
5	Relevant journal publication/s in the focus area of the research		1
6	Relevant patent/s in the focus area of the research		3
7	Licensed Architect from Iran Construction Engineering Organization (IRCEO)	First-grade license	5
		Second-grade license	3
		Third-grade license	1
8	Expert in building constructions rules, regulations, and legislation		3
9	Expert in MHs rules, regulations, and legislation		3
10	Winner of architectural prize/s in the residential building sector		3
11	Interior design/rehabilitation of residential buildings, preferably in MHs project		1.5
12	Expert in the field of advanced construction materials/techniques		4

to 16 panelists to participate in Delphi [44,75,76]. Appendix C explains this selection process.

2.3.2. Reaching a consensus by Delphi

The main objective of Delphi is to reach a consensus from a group of qualified experts by reducing variance in responses [44,72,74,77]. This consensus shall be reached within 1–3 rounds, as suggested by Hallowell and Gambatese (2010) [44] and Dalkey et al. (1970) [78]. Moreover, according to Delphi, a consensus is reached for quantitative studies when the median absolute deviation is less than 1/10 of the range of possible values [44]. In other words, consensus will be reached when the median absolute deviation is less than 10% because weights can adopt values between 0% and 100%. Equation (1) shows the median absolute deviation.

$$\text{Median absolute deviation} = \frac{\sum_{i=1}^{n} |\mathbf{x}_i - \mathbf{median}|}{n} \tag{1}$$

Where: n is the total number of data items; x_i is the data i. Moreover, as recommended by Hallowell and Gambatese (2010) [44], the median absolute deviation is used instead of the standard deviation because it measures variability from the median, which is less likely to be influenced by biased results than the mean [44,72].

2.3.3. Methods to minimize bias

The success of Delphi depends on unbiased experts' judgment. To decrease bias, the authors have considered the suggested points in previous studies [44,72] as follows: (a) selection of experts' panel members that do not know each other; (b) randomize the questions for each panel member and each survey's round; (c) request a brief explanation from each panelist to her/his responses to review their feedback; (d) conduct questionnaires in reiterative rounds – if needed – to reduce variance and bias in responses; (e) calculate the median absolute deviation instead of the standard deviation.

2.3.4. Conducting the Delphi questionnaire and its results

To conduct the Delphi questionnaire for its first round, the qualified experts were provided with (a) a questionnaire and instruction to assign weights to the defined DT's components; (b) a summary of this project to introduce it to them. Through these communications, the experts were asked to fill out the designed questionnaire and provide a brief explanation for their responses. After collecting data from the first round, these data were inserted into SPSS to calculate their median absolute deviation. Table 2 shows the obtained results from Delphi's first round.

As presented in Table 2, during the first round, among all DT's components, two criteria – C_1 Cost and C_2 Time – did not meet the consensus prerequisite. Their weights had median absolute deviations greater than 10% because of present differences among experts' opinions regarding the current economic situation in Iran. Based on the experts' justifications for their assigned weights, some panelists believed that the cost has a significant contribution to the interior rehabilitation of residential buildings – in other words, the cost is more critical than time, while others assigned equal importance to the cost and time. In consequence, the second round of Delphi was required. For this purpose, during this second round, the panelists – that assigned outlier weights – were requested to reconsider their assigned weights only for criteria C_1 and C_2 by providing them the corresponding median for these two criteria. Thus, five panelists reassigned new weights, and the obtained data was inserted into SPSS. Table 3 shows the second round when the experts' weights assignation reached consensus regarding C_1 and C_2, and their median absolute deviations were less than 10%. With the reached consensus and following Delphi instruction, the obtained weights were considered reliable, and no further rounds were required.

2.4. Value function

This fourth stage defines a value function for each defined indicator. MIVES differs from other MCDM methods in large part due to

Table 2
Median, mean, median absolute deviation, and consensus for Delphi's first round.

		Experts' weights (%)															Median (%)	Mean (%)	Median Absolute Deviation	Consensus
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15				
R_1	Economic	35	30	35	40.6	35	15	30	37	30	30	35	30	30	30	30	30	32	3.51	YES
R_2	Environmental	20	20	55	37	20	35	30	21	15	20	30	10	20	40	25	21	26	7.47	YES
R_3	Social	45	50	10	22.4	45	50	40	42	55	50	35	60	50	30	45	45	42	9.04	YES
C_1	Cost	65	75	60	83.3	60	50	70	75	90	85	80	85	60	50	90	75	72	11.55	NO
C_2	Time	35	25	40	16.7	40	50	30	25	10	15	20	15	40	50	10	25	25	11.55	NO
C_3	Production	35	25	25	23.2	25	20	20	35	30	30	40	30	30	20	20	25	27	5.12	YES
C_4	Construction	10	20	25	13.8	20	25	20	12	10	15	10	5	20	40	10	15	17	6.61	YES
C_5	Use (operation)	45	35	30	54.6	45	30	50	40	45	40	30	50	30	20	60	40	40	8.97	YES
C_6	End of Life	10	20	20	8.4	10	25	10	13	15	15	20	15	20	20	10	15	16	4.24	YES
C_7	Functionality, efficiency & adequacy spaces	40	30	40	44.3	50	30	30	55	50	50	30	50	50	40	35	40	42	7.62	YES
C_8	User comfort	35	40	40	38.8	30	30	40	27	25	20	40	25	20	40	35	35	32	6.45	YES
C_9	Psychological & aesthetic	25	30	20	16.9	20	40	30	18	25	30	30	25	30	20	30	25	26	5.01	YES
I_1	Initial rehabilitation cost	40	30	35	48.6	30	25	20	38	35	35	30	35	35	30	45	35	34	5.11	YES
I_2	Maintenance cost	20	30	35	10.8	30	25	35	22	20	25	30	20	25	30	20	25	25	5.15	YES
I_3	Demolition cost	10	15	20	6.3	15	25	10	10	10	10	20	10	10	30	15	10	15	4.91	YES
I_4	Property added-value	30	25	10	34.3	25	25	35	30	35	30	20	35	30	10	20	30	26	6.29	YES
I_5	Rehabilitation process time	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0.00	
I_6	Embodied Energy (EE)	55	35	40	29.7	50	30	20	53	50	50	33.3	50	50	40	40	40	42	8.66	YES
I_7	Embodied Carbon (EC)	35	35	30	54	30	30	40	35	40	25	33.3	40	30	30	30	33.33	34	4.93	YES
I_8	Embodied water (EW)	10	30	30	16.3	20	40	40	12	10	25	33.3	10	20	20	30	25	24	9.00	YES
I_9	Construction Waste (CW)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0.00	YES
I_{10}	Operational Energy (OE)	60	60	60	33.3	60	70	30	65	55	60	50	55	70	60	60	60	57	6.78	YES
I_{11}	Operational Carbon (OC)	40	40	40	66.7	40	30	70	35	45	40	50	45	30	40	40	40	43	6.78	YES
I_{12}	Demolition Waste (DW)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0.00	YES
I_{13}	Functionality of the physical space	60	50	60	50	55	50	50	52	55	60	50	55	50	50	50	50	53	3.13	YES
I_{14}	Adequate spaces & storages	40	50	40	50	45	50	50	48	45	40	50	45	50	50	50	50	47	3.13	YES
I_{15}	Thermal comfort	35	25	40	13.8	50	20	25	43	40	35	30	40	30	25	30	30	32	7.61	YES
I_{16}	Indoor air quality	25	25	20	27.6	10	20	25	25	20	25	30	20	20	25	20	25	22	3.51	YES
I_{17}	Lighting comfort	25	25	25	19.5	30	20	25	20	20	30	20	25	30	25	30	25	25	3.03	YES
I_{18}	Acoustic comfort	15	25	15	39.1	10	40	25	12	20	10	20	15	20	25	20	20	21	6.47	YES
I_{19}	Aesthetic & building beauty	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0.00	YES

Table 3
Median, mean, median absolute deviation, and consensus for Delphi's second round.

		Expert's weights (%)															Median (%)	Mean (%)	Median Absolute Deviation	Consensus
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15				
C_1	Cost	65	75	60	83.3	75	75	70	80	85	85	80	85	80	60	90	80	77	7.22	YES
C_2	Time	35	25	40	16.7	25	25	30	20	15	15	20	15	20	40	10	20	23	7.22	YES

its value function. This function represents the minimal and maximum levels of sustainability satisfaction, which unifies indicators' units on an a-dimensional scale from 0 to 1 [42,43,47,66]. According to Viñolas et al. (2009) [42], Alarcon et al. (2011) [43], and Lombera et al. (2010) [66], establishing the value function follows four steps: (a) determining the value function's tendency (increase or decrease); (b) determining the corresponding points (X_{min} and X_{max}) to the minimum (S_{min}, value 0) and maximum (S_{max}, value 1) satisfaction; (c) determining the value function's shape (linear, concave, convex, and S-shaped); (d) determining the value function's mathematical expression. The first three steps – value function's tendency, parameters, and shape definition –rely on data from international guidelines, national building rules and regulations, scientific literature, the knowledge generated at experts' seminars, experience with previous projects and similar case studies, and the value produced by different rehabilitation scenarios for an indicator [43,59,66]. The fourth step applies the following Equations (2) and (3) [42,43,66]:

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

$$B = \left[1 - e^{-k_i \cdot \left[\frac{|X_{max} - X_{min}|}{Ci}\right]^{P_i}}\right]^{-1} \tag{3}$$

Where: V_i = Non-dimensional value of the evaluated indicator; X_i = The considered indicator abscissa, which generates V_i value. Moreover, the following seven parameters define the behavior of the value function.

A = The response value X_{min} (indicator's abscissa), generally A = 0,
P_i = A shape factor that determines whether the curve is concave, convex, linear, or S-shaped,
C_i = Factor that establishes, in curves with $P_i > 1$, abscissa's value for the inflection point,
K_i = Factor that defines the response value to Ci,
X_{min} = The corresponding point/s to the minimum satisfaction (S_{min} = 0),
X_{max} = The corresponding point/s to the maximum satisfaction (S_{max} = 1),
B = The factor preventing the function from leaving the range (0.00, 1.00); obtained by Equation (3).

More explanations regarding the value function's instruction and its tendencies, parameters, and shapes definition were presented elsewhere, such as [42,43,66]. Table 4 depicts the value functions of all 19 defined indicators with their corresponding tendencies, parameters, and shapes, which are illustrated in Appendix D.

Table 4
The indicators' value functions for the proposed model.

#R	Indicator	Unit	Shape	X_{max}	X_{min}	C_i	K_i	P_i	References
Economic	I_1. Initial rehabilitation cost	€/m^2	DCx	200	50	115	0.05	2.00	[79–85]
	I_2. Maintenance cost	€/m^2.50yrs	DCx	200	70	135	0.10	1.50	[79–85]
	I_3. Demolition cost	€/m^2	DCv	12	8	10	0.15	0.70	[79–85]
	I_4. Property added-value	€/m^2.AU	ICx	26074	0	9017	0.10	1.50	[86–89]
	I_5. Rehabilitation process time	Day	DL	60	20	40	0.0	1.00	[81]
Environmental	I_6. Embodied Energy (EE)	MJ/m^2.50yrs	DCv	1300	7300	3250	0.10	0.80	[90–95]
	I_7. Embodied Carbon (EC)	$kgCO_2$/ m^2.50yrs	DCv	50	450	250	0.60	0.70	[90–95]
	I_8. Embodied Water (EW)	l/m^2.50yrs	DCv	2000	5000	3500	1.00	0.60	[96–99]
	I_9. Construction Waste (CW)	kg/m^2	DCv	10	50	21.86	1.00	0.60	[100–102]
	I_{10}. Operational Energy (OE)	kWh/m^2.yr.	DCx	0	95	47.5	0.05	2.50	[103,104]
	I_{11}. Operational Carbon (OC)	$kgCO_2/m^2$.yr.	DCx	0	75	37.5	0.05	2.50	[103,104]
	I_{12}. Demolition Waste (DW)	kg/m^2	DCv	150	750	450	1.00	0.80	[100–102]
Social	I_{13}.Functionality of the physical space	Points	ICx	5	1	3	0.50	2.50	[105–113]
	I_{14}.Adequate spaces & storages	Points	ICx	5	1	3	0.40	2.00	[110,113]
	I_{15}.Thermal comfort	Points	ICx	5	1	3	0.50	2.00	[25,107,108,114, 115]
	I_{16}.Indoor air quality	Points	ICx	5	1	3	0.50	1.50	[25,107,114,116, 117]
	I_{17}.Lighting comfort	Points	ICx	5	1	3	0.50	1.50	[114,118,119]
	I_{18}.Acoustic comfort	Points	ICx	5	1	3	0.50	1.50	[120,121]
	I_{19}. Aesthetic & building beauty	Points	ICx	5	1	3	0.40	2.50	[22,122–124]

Legend: R: Requirement; DCx: Decreasing Convex; DL: Decreasing Lineal; DCv: Decreasing Concave; ICx: Increasing Convex; AU: Apartment Unit.

2.5. Indicators' values and GSI calculation methods

The fifth and last stage aims to apply and validate the proposed model to the defined scenarios in order to: (i) calculate the indicators' values and GSIs for the defined scenarios and select the most sustainable one; (ii) demonstrate how it enables decision-makers to identify the strengths and weaknesses of interior rehabilitation in MHs from economic, environmental, and social viewpoints.

To calculate the values of the economic indicators, the Quantity Take-Off (QTO) of the applied items – construction materials and building components in this study – was calculated by employing Building Information Modeling (BIM). To do so, each scenario's general and specific data, such as applied items and their relevant parameters – e.g., length, width, height, area, volume, and costs – were collected from the designers, constructors, and stakeholders of these projects. Consequently, the collected data were updated, modified – only for scenario 4 – and inserted in a BIM tool, which is Autodesk Revit 2020 software, and exported using Revit's data-exporting function to obtain the QTOs. Besides the BIM method, international guidelines – [125,126] – national building rules and regulations, scientific literature, and national databases – e.g., the ICMPL for 2019–2020 [79], and [127,128] – were employed to calculate the values of these indicators.

For assessing, measuring, and monitoring environmental sustainability, this study employed the simplified Life-Cycle Analysis (LCA) [129], which is based on the most recognized LCA guidelines and standards published by the International Standards Organization (ISO), ISO 14040 [130], and ISO 14044 [131]. This study retrieved the data for the LCA of each scenario from the QTO of the BIM model.

To evaluate the social sustainability aspect, which is the main driver behind the rehabilitation activities in residential buildings and MHs [8,12,13,132,133], the present project used questionnaire surveys. These surveys are well-recognized and widely accepted methods [134] and scientific approaches for converting qualitative to quantitative data that enable and facilitate statistical analysis [135]. The user-based questionnaire was conducted for value calculation of all defined social indicators – except I_{19}, which is the aesthetic and beauty of the interior space – for scenarios 1 to 3. For I_{19}, the expert-based questionnaire was carried out because this indicator is highly subjective and the user's opinions vary from person to person [136]. Moreover, in the absence of users' experience regarding scenario 4, which is not an actual built project, an expert-based questionnaire was the solution for assessing social sustainability performance [137,138].

GSI calculation follows Equations (4)–(6), which considers two main types of parameters: (a) the non-dimensional values of the defined requirements (R_i), criteria (C_j), and indicators (I_k) obtained from the value functions (Table 4) and the obtained indicators' values – Section 4 –; (b) the weights of requirements (ω_{Ri}), criteria (ω_{Cj}), and indicators (ω_{Ik}) assigned by experts from the Delphi method (Table 2).

$$C_j = \sum_{k=1}^{o} \mathrm{Ik}.\omega\mathrm{Ik} \tag{4}$$

$$R_i = \sum_{j=1}^{n} \mathrm{Cj}.\omega\mathrm{Cj} \tag{5}$$

$$GSI = \sum_{i=1}^{m} \mathrm{Ri}.\omega\mathrm{Ri} \tag{6}$$

Where: indicators non-dimensional value (I_k), criteria non-dimensional value (C_j), requirements non-dimensional value (R_i), indicators' weights (ω_{Ik}), criteria's weights (ω_{Cj}), requirements' weights (ω_{Ri}). Fig. 3 presents the defined DT with its mentioned components and GSI's equations.

3. Case study, sample of the study, and rehabilitation scenarios

Similar to other parts of the world, in Iran, the 1960s and 1970s were marked by MHs construction due to the high demand for housing in urban areas [139–143] because of (i) the migration by people to urban areas [139,141–145], and (ii) the highest birth rates that occurred in these decades [146,147]. More than 500,000 MHs residential units were built from 1960 to 1980 in Iran, of which Ekbatan was among the most significant ones. Over 4.4 million MHs dwellings have been built as of now, making up over 16% of all residential units in Iran [147]. Moreover, the government planned to construct one million houses annually, mainly as MHs projects, based on a strategy known as "the National Housing Action Plan" [103,148]. Therefore, since there are more than 500,000 dwelling units of these MHs that already need to be urgently rehabilitated [103], as well as the other ones that will have the same issue in the near future, *Phase B* validates the novel model by applying it to the four rehabilitation scenarios from the sample and case study.

3.1. Case study

Ekbatan MH (Table 5) was selected as the case study because: (a) it is the largest MH in Iran and one of the largest ones of its kind in the Middle East, (b) it is an MH built in the 1970s, and (c) it has a vast construction area, diverse architectural configuration, high

Table 5
Ekbatan's general characteristics.

Ekbatan	Location	Designed for	Total Population	Total residential units	Land area (m^2)	Total residential substructure (m^2)
Largest MH in Tehran	On the west side of Tehran	Middle/high-class families	80,000	15,593	2,208,570	2,670,000

population density, and unique design.

3.2. Sample of study

The 54 m^2 one-bedroom apartment of Ekbatan called *Aleph-1* was selected as the sample because (i) it is the most repetitive apartment type – with a frequency of 1144 apartment units –; (ii) its architectural plan and space distribution have some similarities with other one-bedroom apartments – being representative of 31% of this MH's apartments – and feasible rehabilitation activities of *Aleph-1* could be easily replicable to all the similar apartments. Appendix E presents the general and specific characteristics of the initial state for *Aleph-1*.

3.3. Rehabilitation scenarios

Among a wide range of feasible interior rehabilitation alternatives, four rehabilitation scenarios were determined, as illustrated in Fig. 4.

a) Three different actual rehabilitation scenarios were selected through on-site surveying of 71 rehabilitated Aleph-1 apartments. Although each apartment has its own characteristics, the experts – interior designers, construction practitioners, and architects – intended to categorize the surveyed apartments into three different groups by considering their characteristics – e.g., architectural plan, space distribution, applied construction materials and techniques, and HVAC systems (Appendix F, Tables F.1 and F.2) – and Iran's construction market. Consequently, from each group, a representative project was selected as named scenarios 1 to 3 in this research. Selecting these scenarios provides an opportunity for a more holistic perspective for the sustainability assessment of different existing MH's interior rehabilitation projects in Iran for two main reasons. First, most of the surveyed Aleph-1 apartments can be categorized into these three groups – 26%, 18%, and 15%, similar to scenarios 1 to 3, respectively. Therefore, these three selected scenarios, with more than 59% of surveyed apartments, represent rehabilitated projects in Ekbatan and Iran. Second, these selected scenarios are different from each other by (i) being rehabilitated partially – scenario 1 – to integrally – scenario 3 –; (ii) their applied rehabilitation activities, construction materials, design, and space distributions.
b) An actual rehabilitation project using innovative rehabilitation approaches was chosen, adapted, and applied to the sample of study – named as scenario 4. A comprehensive overview of several worldwide interior rehabilitation projects selected *LifeEdited-1* due to the following reasons: (i) it is internationally known as a successful rehabilitation project [149–152] which was constantly developed; (ii) consultations with constructors, construction practitioners, and architects concluded that the applied construction technologies on *LifeEdited-1* are available, applicable, and implementable in Iran. Moreover, most of the used construction materials in *LifeEdited-1* already exist in Iran's construction market or can be locally manufactured; (iii) as *LifeEdited*-1 has several similarities with the defined sample, such as their architectural layouts, space distribution, area, and proportion aspects, being easily applied on *Aleph-1* with minor adaptations, as confirmed with experts and the resulting Fig. 5.

Fig. 6 illustrates all defined scenarios 1 to 4, which are explained in detail in Appendix F.

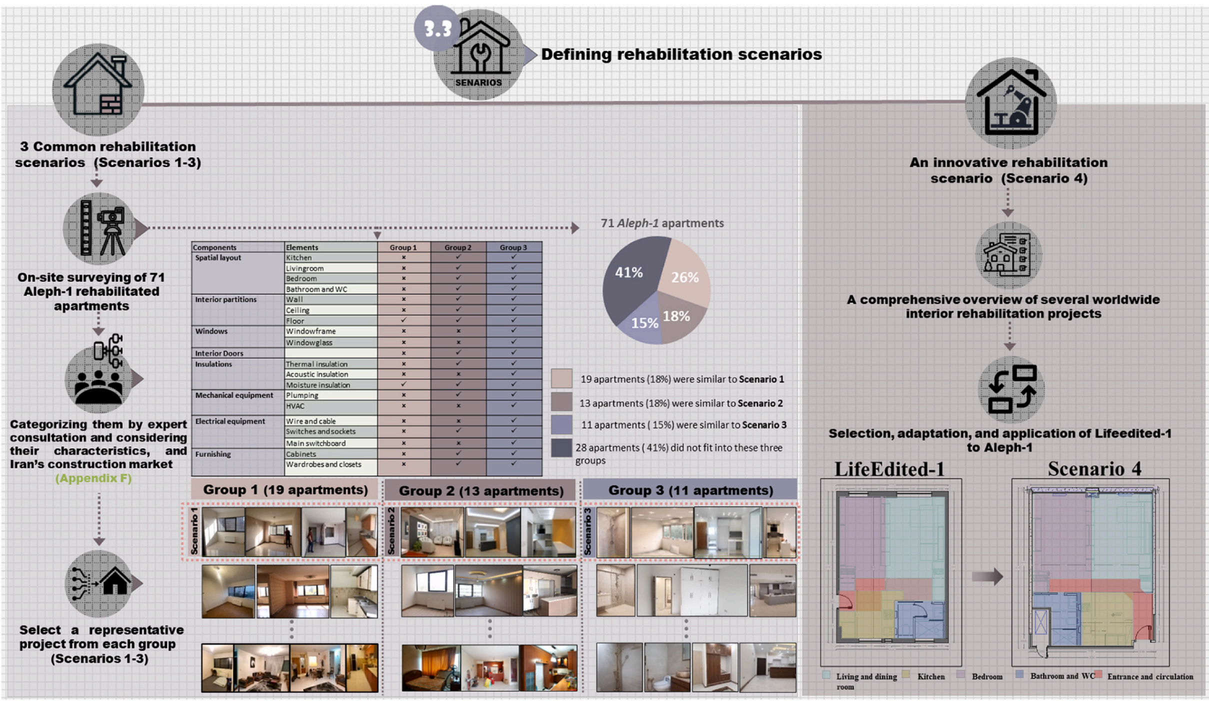

Fig. 4. Defining rehabilitation scenarios.

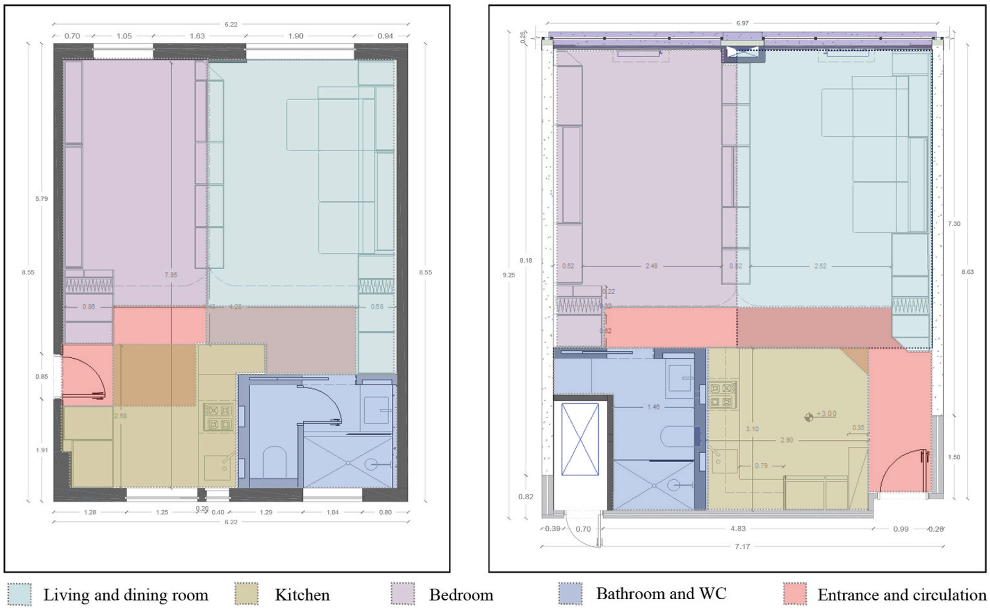

Fig. 5. The *LifeEdited-1* project (Left); The application of *LifeEdited-1* on *Aleph-1* (Right).

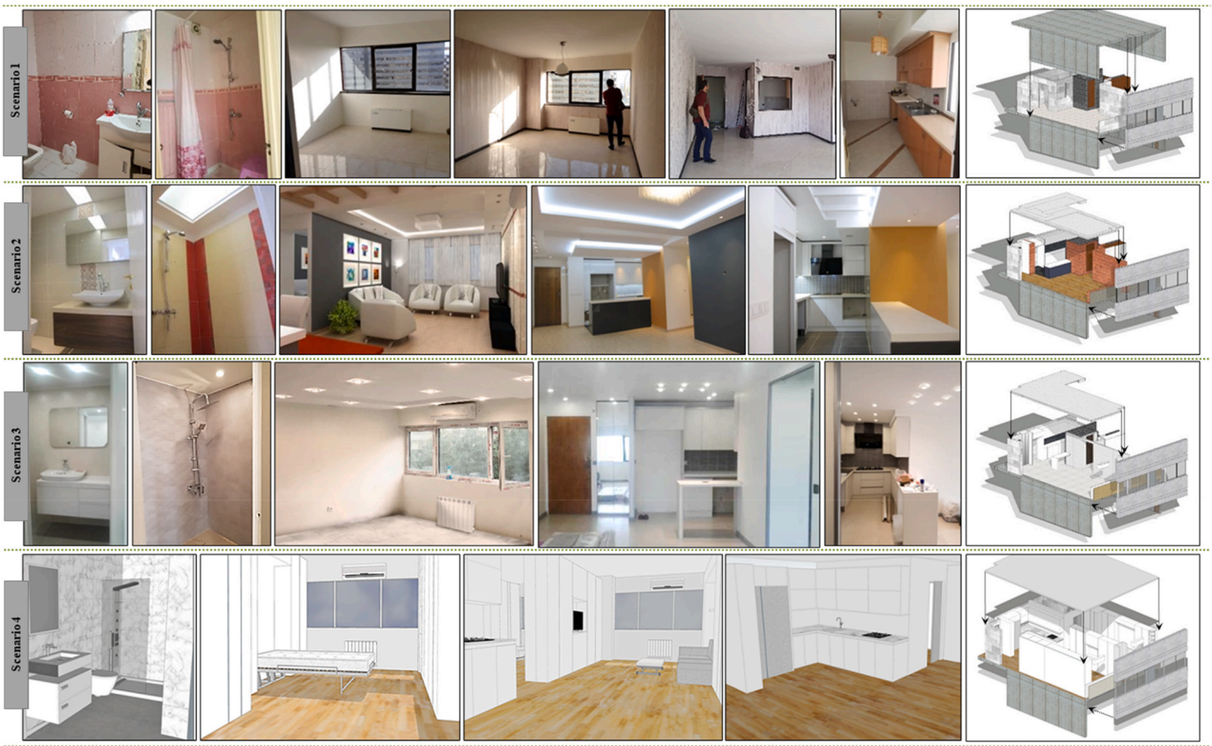

Fig. 6. Images of scenarios 1–4 (Left); Isometrics of scenarios 1–4 (Right).

4. Results

This section presents the results generated by the application of the established model to the defined rehabilitation scenarios to (i) prove the applicability, suitability, and validity of the proposed model; (ii) identify the probabilistic challenges when facing its application; (iii) demonstrate how it enables decision-makers to identify the strengths and weaknesses of MHs' interior rehabilitation from economic, environmental, and social viewpoints and select the most sustainable ones. Section 4.1 and 4.2 calculates the indicators' values for scenarios 1 to 4 and their GSIs, respectively.

4.1. Indicators' values for scenarios 1-4

Table 6 presents the sustainability indicators' values for scenarios 1 to 4, which are explained in Appendix G in more detail.

4.2. GSIs of the defined scenarios 1-4

To calculate the GSI of each defined scenario, the obtained indicators' values – Table 6 – were converted to indicators' non-dimensional values by applying the defined value functions – Appendix D. Consequently, by considering the previously defined DT, its components' weights, and the obtained indicators' non-dimensional values, the GSI of each scenario was calculated through Equations (4)–(6). The GSIs for scenarios 1 to 4 are 0.35, 0.42, 0.53, and 0.71, respectively. The results from this evaluation are GSIs, requirements values (VR_i, i = 1 to 3), criteria values (VC_j, j = 1 to 9), and indicators values (VI_k, k = 1 to 19) for each scenario, as shown in Fig. 7 and Table 7.

5. Discussion

The resulting GSIs for all studied scenarios revealed that the most sustainable rehabilitation scenario for *Aleph-1* is scenario 4. This scenario obtained the highest GSI value of 0.71, which is 0.36, 0.29, and 0.18, greater than the GSIs of scenarios 1 to 3, respectively.

From the economic requirement (VR_1) point of view, these values for scenarios 1 to 4 are 0.48, 0.40, 0.44, and 0.59, respectively. Although the results of all four scenarios mostly fell in the middle-value range, the greatest economic satisfaction value was reached by scenario 4. The authors attribute the superiority of scenario 4 to its higher quality and the durability of the applied materials, improved construction techniques, better design, and less need for repair and maintenance during the building lifespan that caused better performance in maintenance cost (I_2), demolition cost (I_3), and property added-value (I_4). On the other hand, regarding initial rehabilitation cost (I_1) and rehabilitation process time (I_5), scenario 1 obtained the greatest satisfaction values where partial rehabilitation was implemented, which caused the least initial rehabilitation cost and time compared to the other three scenarios. The observed difference in results is due to contrasting values in the defined economic indicators – e.g., scenario 1 needs lower rehabilitation cost (I_1), but it has the highest maintenance cost (I_2) during its lifespan. It is worth mentioning that none of the analyzed scenarios met the minimum standard target value of economic sustainability. The minimum standard sustainability target value has been defined as 0.70 based on an extensive literature review – e.g. Refs. [28,48], – as well as some well-known BSAs [159].

Regarding the environmental requirement (VR_2), scenarios 1 to 4 obtained values of 0.42, 0.42, 0.67, and 0.80, respectively. Scenario 4 attained the highest environmental value – almost double the satisfaction of the two first scenarios and 0.13 more than scenario 3. Although scenario 4 obtained the highest satisfaction values in all the environmental indicators, this scenario has

Table 6
Sustainability indicators' values for scenarios 1 to 4.

Indicator	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	References and Methods
I_1. Initial rehabilitation cost	€/m^2	80.47	98.86	129.80	144.11	BIM [79–85];
I_2. Maintenance cost	€/m^2.50yrs	183.01	135.35	120.37	88.10	BIM [79–85];
I_3. Demolition cost	€/m^2	11.10	11.88	10.84	8.35	BIM [79–85];
I_4. Property added-value	€/m^2.AU	908	9347	15608	19667	Experts-based survey [86–89];
I_5. Rehabilitation process time	Day	26	38	40	36	BIM; Microsoft Project Professional [81];
I_6. Embodied Energy (EE)	MJ/m^2.50yrs	3783	3105	2905	2723	Simplified LCA; BIM [91–95,153–155];
I_7. Embodied Carbon (EC)	$kgCO_2$/ m^2.50yrs	225	141	145	70	Simplified LCA; BIM [91–95,153–155];
I_8. Embodied Water (EW)	l/m^2.50yrs	4551	4638	3493	3361	Simplified LCA; BIM [79,96–99,125,154,155];
I_9. Construction Waste (CW)	kg/m^2.50yrs	44	49	24	13	Simplified LCA; BIM [79,100,102,125,155–158];
I_{10}. Operational Energy (OE)	kWh/m^2.yr.	50.32	48	34.35	21.79	Simplified LCA; DesignBuilder version 6.1.6 and EnergyPlus [103,104];
I_{11}. Operational Carbon (OC)	$kgCO_2$/m^2.yr.	24.41	23.75	18.14	11.97	Simplified LCA; DesignBuilder version 6.1.6 and EnergyPlus [103,104];
I_{12}. Demolition Waste (DW)	kg/m^2.50yrs	645	603	382	215	Simplified LCA; BIM [79,100,102,125,155–158];
I_{13}. Functionality of the physical space	Points	2.59	3.38	3.47	4.43	User-based questionnaire for scenarios 1 to 3; expert-based questionnaire for scenario 4
I_{14}. Adequate spaces & storages	Points	2.69	3.35	3.60	4.64	User-based questionnaire for scenarios 1 to 3; expert-based questionnaire for scenario 4
I_{15}.Thermal comfort	Points	3.01	3.20	3.93	4.07	User-based questionnaire for scenarios 1 to 3; expert-based questionnaire for scenario 4
I_{16}. Indoor air quality	Points	2.40	3.42	3.51	3.67	User-based questionnaire for scenarios 1 to 3; expert-based questionnaire for scenario 4
I_{17}. Lighting comfort	Points	3.15	3.74	3.79	3.87	User-based questionnaire for scenarios 1 to 3; expert-based questionnaire for scenario 4
I_{18}. Acoustic comfort	Points	3.86	3.90	3.89	3.70	User-based questionnaire for scenarios 1 to 3; expert-based questionnaire for scenario 4
I_{19}. Aesthetic & building beauty	Points	1.61	3.37	3.62	4.42	Expert-based questionnaire for all scenarios

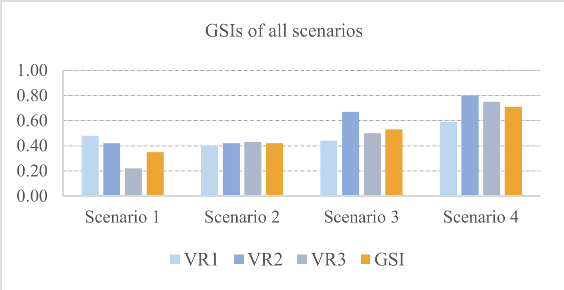

Fig. 7. GSIs of scenarios 1 to 4.

Table 7
The GSIs of all scenarios.

	VI_1	VI_2	VI_3	VI_4	VC_1	VI_5	VC_2	VR_1	VI_6	VI_7	VI_8	VC_3	VI_9	VC_4	VI_{10}	VI_{11}
Weight (ω)	0.34	0.25	0.15	0.26	0.77	1	0.23	**0.32**	0.42	0.34	0.24	0.27	1	0.17	0.57	0.43
Scenario 1	0.64	0.05	0.41	0.01	0.30	0.85	0.85	**0.48**	0.67	0.76	0.42	0.64	0.49	0.49	0.17	0.41
Scenario 2	0.47	0.36	0.11	0.26	0.33	0.55	0.55	**0.40**	0.77	0.89	0.38	0.71	0.19	0.19	0.19	0.42
Scenario 3	0.23	0.49	0.49	0.52	0.41	0.50	0.50	**0.44**	0.79	0.88	0.76	0.81	0.88	0.88	0.36	0.54
Scenario 4	0.14	0.81	0.95	0.71	0.58	0.60	0.60	**0.59**	0.82	0.98	0.79	0.86	0.98	0.98	0.56	0.68

	VC_5	VI_{12}	VC_6	VR_2	VI_{13}	VI_{14}	VC_7	VI_{15}	VI_{16}	VI_{17}	VI_{18}	VC_8	VI_{19}	VC_9	VR_3	GSI
Weight (ω)	0.4	1	0.16	**0.26**	0.53	0.47	0.42	0.32	0.22	0.25	0.21	0.32	1	0.26	**0.42**	
Scenario 1	0.27	0.37	0.37	**0.42**	0.13	0.22	0.17	0.34	0.27	0.49	0.69	0.44	0.01	0.01	**0.22**	**0.35**
Scenario 2	0.29	0.47	0.47	**0.42**	0.34	0.41	0.37	0.40	0.57	0.66	0.70	0.57	0.36	0.36	**0.43**	**0.42**
Scenario 3	0.43	0.80	0.80	**0.67**	0.37	0.49	0.42	0.64	0.59	0.67	0.70	0.65	0.44	0.44	**0.50**	**0.53**
Scenario 4	0.61	0.95	0.95	**0.80**	0.74	0.86	0.80	0.69	0.64	0.70	0.65	0.67	0.76	0.76	**0.75**	**0.71**

significantly better performance in comparison with the other three scenarios in construction and demolition waste (I_9 and I_{12}), operational energy (I_{10}), and operational carbon (I_{11}) due to the improvements in its thermal insulations, applied HVAC systems, applied windows, and the application of more light-weight and eco-friendly materials. Only scenario 4 met the minimum standard target value of environmental sustainability.

In the case of social requirement (VR_3), scenarios 1 to 4 obtained values of 0.22, 0.43, 0.50, and 0.75, respectively. While scenario 4 had tremendously higher social performance – 0.61 satisfaction value more than the first scenario – scenarios 2 and 3 fell in the middle-value range, and scenario 1 had the lowest social performance. Moreover, scenario 4 attained the highest values in all of the social indicators – due to its design that provides more flexible and multifunctional spaces with more unity and integrity, more adequate facilities and amenities, more living and storage spaces, better space distribution, and improvements in its details quality, harmony, and creativity and innovation of design – except the acoustic comfort (I_{18}). Regarding acoustic comfort (I_{18}), scenario 4 attained the lowest value. However, it has slightly better performance in outdoor acoustic comfort due to the application of acoustic insulations in its skin – vinyl layer, 4 mm thickness. However, it has significantly lower performance in indoor acoustic comfort – with a movable wall and magnetized curtains used to separate the living and bedroom spaces – in comparison with the other three scenarios. Remarkably, only scenario 4 met the minimum standard target value of social sustainability.

Up to now, most Ekbatan interior rehabilitation projects have been carried out by owners individually, similar to scenarios 1 to 3 with low sustainability performances. Due to the existence of similar repetitive apartments in MHs, establishing proper, organized, and holistic rehabilitation approaches and policies could encourage owners to take advantage of and participate in these programs. For instance, regarding the economic issues that all studied scenarios face, proper economic policies can reduce the rehabilitation time and costs and encourage owners to rehabilitate their property in a more sustainable way.

5.1. Prove robustness of the proposed MIVES-Delphi model

As the GSI quantification depends directly on the weighting of the DT's components [28,48,49,58], its consistency in different weighing states (WSs) – based on different situations and conditions – proves the relative objectivity and validity of the proposed model. Although employing the Delphi and BIAS reduction techniques could further improve the proposed model [49], applying sensitivity analysis by considering diverse probabilistic WSs enhances the proposed model's robustness. Therefore, this section recalculates and assesses the GSIs of all four scenarios by altering the assigned weights for their requirements (ωR_i) in five different probabilistic WSs. Fig. 8 presents these five WSs: WS1 represents the assigned weights – Ec = 32%, En = 26%, Sc = 42% –, WS2 considers a balanced distribution of weights, in which all three requirements have the same weights – Ec = 33.33%, En = 33.33%, Sc = 33.34% –, in WS3 the greater weight placed on the economic requirement – Ec = 70%, En = 15%, Sc = 15% –, in WS4 the environmental requirement has the greatest value – Ec = 15%, En = 70%, Sc = 15% –, and WS5 consists the greatest social requirement – Ec = 15%, En = 15%, Sc = 70%.

In Fig. 8, the obtained results confirm the predominance of scenario 4 over the other three scenarios and the stability of the GSI values under different weighting states with variations of less than 8%. Therefore, as the GSI variations are less than ±10% [28,48,49,58], the robustness of the proposed MIVES-Delphi model has been achieved. It is worth mentioning that in most weighting states (1, 2, 4, and 5), only scenario 4 attained the minimum standard target value for GSI. The exception is the third weighting state – where the economic requirement was considered with the highest weight – in which none of the four studied scenarios obtained the mentioned

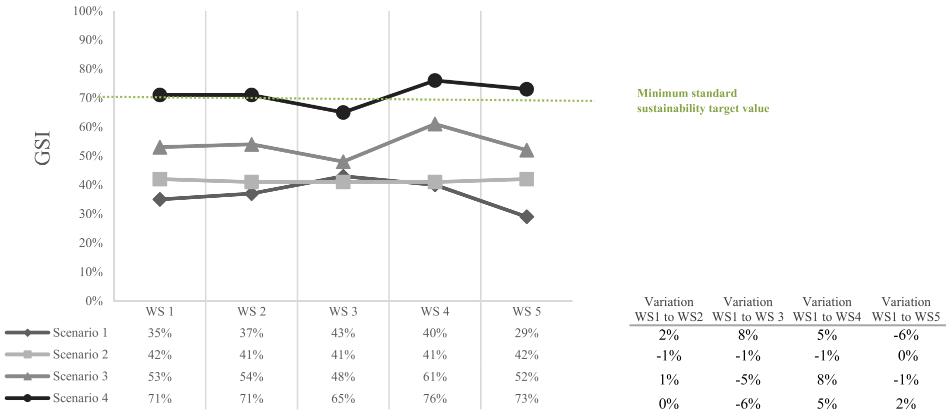

Fig. 8. Sensitivity analysis and variations of each weighting state (WS) for the defined scenarios.

minimum target value. Furthermore, in all weighing states, the trends of GSIs for all scenarios were monotonic, except in WS3, where scenario 2 attained the lowest value.

6. Conclusion and future projects

A novel MCDM model based on the MIVES and Delphi methods for holistic sustainability assessment of MHs' interior rehabilitation was successfully established, validated, and its robustness was proven. The main conclusions regarding this study were drawn as follows.

a) Since the developed model is a combination of MIVES and Delphi methods, it can be considered more comprehensive and rigorous than the former present MIVES tools, although it requires more dedication to be fully developed. Moreover, this model takes advantage of the combination of quantitative and qualitative analyses and methods that use data from different sources and make the established model more hybrid, robust, and reliable.
b) As MIVES can objectively consider local conditions, the proposed model is flexible, adaptable, and applicable for any type of MHs' interior rehabilitation after configuring it to the particularities in each context. Moreover, the developed model could be synthesized with other methods, simulation tools, and building standards and certifications.
c) Since this model was first applied in one of Iran's MHs, it can serve as a framework for the local government, decision-makers, and stakeholders who are dealing with MHs' interior rehabilitation in Iran to facilitate the assessment and selection procedure by considering involved stakeholders' satisfaction.
d) Moreover, assessing three real rehabilitated projects – scenarios 1 to 3 – and a designed rehabilitation project to be constructed – scenario 4 – proved that this developed model can be applied in different building phases, including design, construction, and rehabilitation.
e) Partial interior rehabilitation (scenario 1), which is the most frequent interior rehabilitation approach in the selected case study, could neither fulfill the contemporary building norms nor serve as a solution for sustainable rehabilitation.
f) Common rehabilitation approaches (scenarios 2 and 3) do not serve as proper solutions for interior rehabilitation, and sustainability improvements – especially in their weak points – are required.
g) Considering the fact that only scenario 4 could meet the standard minimum target value, this study concludes that the improved or innovative rehabilitation approaches could positively increase buildings' sustainability performance during their whole lifecycle.

The present study contributes to moving forward to more sustainable interior rehabilitation approaches for MHs, leading to moving toward more sustainable architecture and construction. Moreover, this study opens up opportunities for future research perspectives that could be (a) adaptation and implementation of the developed model to other MHs outside Ekbatan in order to consolidate and strengthen the proposed model; (b) considering other rehabilitation aspects beyond the physical interventions, including security, privacy, residents' attachment to their homes, and cultural and heritage conservation to obtain an even more holistic approach; (c) application of different simulation tools and increasing questionnaires' sample size for quantifying inherently subjective indicators, such as social indicators, in order to reduce human errors and obtain more precise results; (d) involving inhabitants and householders, especially women, in different interior rehabilitation procedures to identify their real needs, experiences, and preferences, as well as encouraging them to rehabilitate their properties in more sustainable rehabilitation ways; (e) combination of the developed model with artificial intelligence and Fuzzy logic to achieve a superior methodology.

Author statement

Seyyed Mohammadreza Zolfaghari: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Oriol Pons:** Conceptualization, Methodology, Supervision, Validation, Writing - review & editing.

Jelena Nikolic: Conceptualization, Methodology, Supervision, Validation, Writing - review & editing.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2022.105685.

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