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Sustainability Assessment Model of Mass Housing's Interior Rehabilitation

Economic, environmental, and social impacts of interior rehabilitation scenarios in Iranian MHs. The case of Ekbatan, Tehran, Iran

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Abstract

The construction of mass housings (MHs) solved high demands for housing in urban areas in the 1960s and 1970s worldwide. After decades of continuous use and inadequate maintenance, these MHs have been censured due to their several social, economic, and environmental negative impacts. For instance, recent surveys and studies revealed that most MHs cause high energy consumption, CO_2 emissions, and maintenance costs. Furthermore, MHs present interior conditions do not respond adequately to the current needs of their occupants. These mentioned MH's deficiencies require MH interior rehabilitation. In Iran, this rehabilitation is currently based mainly on traditional and conventional construction technologies and techniques, most of which neither follow sustainability requirements nor contemporary building standards.

In this regard, assessment and selection of proper MHs' interior rehabilitation procedures, from a sustainability point of view, is a crucial issue that faces several challenges since this is a multidisciplinary and multi-criteria process. To overcome this challenge, several existing studies and investigations applied different building sustainability assessment (BSA) methods and tools. Most BSAs have various shortfalls such as (i) lacking a holistic approach, (ii) neglecting the involved stakeholders' satisfaction, (iii) being limited to a specific regional context, and (iv) employing some predefined sustainability indicators some of which are not adequate, relevant, or even applicable for all projects. These BSA's shortfalls lead numerous researchers to develop individual models based on multi-criteria decision-making (MCDM) methods to fulfill their projects' objectives.

The present thesis aims to develop a novel MCDM model based on the MIVES and Delphi methods for holistic sustainability assessment of interior rehabilitation of MHs. This MIVES-Delphi model relies on a comprehensive literature review, seminars composed by experts, on-site surveying, LCA, BIM, user- and expert-based questionnaires, bias reduction, and sensitivity analysis. The model was first applied to the Ekbatan MH case study, which is the largest MH in Iran. Moreover, the author has applied this novel model to assess the sustainability of four different interior rehabilitation scenarios, including three common rehabilitation scenarios plus an innovative one. Consequently, the new model has been validated and the most sustainable rehabilitation scenario has been selected. The whole procedure has been designed to guarantee the transparency, objectivity, and robustness of its results.

This validation proves that the developed model can objectively quantify the holistic sustainability assessment of interior rehabilitation in MHs in Iran by considering the involved stakeholders' preferences. Additionally, this model has flexibility, adaptability, and applicability for any type of interior rehabilitation procedure in MHs in different geographical contexts as well as different construction phases including design, construction, and rehabilitation. The specific results regarding the rehabilitation scenarios' evaluation disclosed that none of the studied three common conventional rehabilitation scenarios could either meet the minimum sustainability target value or serve as proper solutions for interior rehabilitation. On the other hand, the fourth scenario, with a global sustainability index of 0.71, could meet the standard minimum target. This proves the assumed hypothesis and provides a possibility for innovative rehabilitation processes to have positive effects on increasing the sustainability performance in MH buildings.

This thesis aims to contribute to moving forward to more sustainable rehabilitation techniques for interior rehabilitation in MHs as well as moving towards more sustainable architecture and construction. Moreover, this thesis opens up opportunities for future research perspectives that could be (i) adaptation and implementation of the developed model to other MHs beyond Tehran in order to consolidate and strengthen the proposed model, and (ii) combination of the developed model with Fuzzy logic to reach a superior methodology.

Keywords: *MHs' interior rehabilitation, Common rehabilitation techniques, Advanced rehabilitation techniques, Sustainability assessment, MIVES, Delphi*

Resum

La construcció d'habitatge massiu (HM) va resoldre les grans demandes d'habitatge a les zones urbanes dels anys seixanta i setanta a tot el món. Després de dècades d'ús continuat i un manteniment inadequat, aquest HM ha estat majoritàriament censurat pels seus diversos impactes negatius socials, econòmics i ambientals. Per exemple, enquestes i estudis recents van revelar que la majoria dels HMs provoquen un alt consum d'energia, emissions de CO_2 i costos de manteniment. Així mateix, els HMs presenten condicions interiors que no responen adequadament a les necessitats actuals dels seus ocupants. Aquestes deficiències esmentades dels HMs demanen la rehabilitació interior dels HM. A l'Iran, aquesta rehabilitació es basa actualment principalment en tecnologies i tècniques de construcció tradicionals i convencionals, la majoria de les quals no segueixen els requisits de sostenibilitat ni els estàndards de construcció contemporanis.

En aquest sentit, l'avaluació i selecció dels procediments adequats de rehabilitació interior dels HM, des del punt de vista de la sostenibilitat, és un tema crucial que s'enfronta a diversos reptes, ja que es tracta d'un procés multidisciplinari i multicriteri. Per superar aquest repte, diversos estudis i investigacions existents han aplicat diferents mètodes i eines d'avaluació de la sostenibilitat de l'edifici (BSA). La majoria de BSA tenen diversos dèficits, com ara (i) manca d'un enfocament holístic, (ii) descuidar la satisfacció de les parts interessades implicades, (iii) limitar-se a un context regional específic i (iv) emprar alguns indicadors de sostenibilitat predefinits, alguns dels quals no són adequats, rellevants ni aplicables a tots els projectes. Aquestes mancances dels BSA porten a nombrosos investigadors a desenvolupar models individuals basats en mètodes de presa de decisions multicriteri (MCDM) per assolir els objectius dels seus projectes.

La present tesi pretén desenvolupar un nou model MCDM basat en els mètodes MIVES i Delphi per a l'avaluació holística de la sostenibilitat de la rehabilitació interior de HM. Aquest model MIVES-Delphi es basa en una revisió exhaustiva de la literatura, seminaris formats per experts, enquestes in situ, BIM, qüestionaris basats en usuaris i experts, reducció de biaixos i anàlisi de sensibilitat. El model es va aplicar per primera vegada al cas d'estudi d'HM d'Ekbatan, que és l'HM més gran de l'Iran. A més a més, l'autor ha aplicat aquest nou model per avaluar la sostenibilitat de quatre escenaris diferents de rehabilitació interior, inclosos tres escenaris de rehabilitació comuns més un innovador. En conseqüència, s'ha validat el nou model i s'ha seleccionat l'escenari de rehabilitació més sostenible. Tot el procediment ha estat dissenyat per garantir la transparència, objectivitat i robustesa dels seus resultats.

Aquesta validació demostra que el model desenvolupat pot quantificar objectivament l'avaluació holística de sostenibilitat de la rehabilitació d'interiors en HM a l'Iran, tenint en compte les preferències de les parts interessades implicades. A més a més, aquest model té flexibilitat, adaptabilitat i aplicabilitat per a qualsevol tipus de procediment de rehabilitació d'interiors en HM en diferents contextos geogràfics, així com diferents fases de construcció, incloent el disseny, la construcció i la rehabilitació. Els resultats específics sobre l'avaluació dels escenaris de rehabilitació van revelar que cap dels tres escenaris de rehabilitació convencionals comuns estudiats no podia assolir el valor mínim de l'objectiu de sostenibilitat ni servir com a solucions adequades per a la rehabilitació interior. D'altra banda, el quart escenari, amb un índex de sostenibilitat global de 0,71, podria complir l'objectiu mínim estàndard. Això ofereix la possibilitat que els processos de rehabilitació innovadors tinguin efectes positius en l'augment del rendiment de sostenibilitat als edificis d'HM.

Aquesta tesi té com a objectiu contribuir a avançar cap a tècniques de rehabilitació més sostenibles per a la rehabilitació d'interiors en HM, així com avançar cap a una arquitectura i construcció més sostenibles. A més a més, aquesta tesi obre oportunitats per a futures perspectives de recerca que podrien ser (i) l'adaptació i implementació del model desenvolupat a altres HM més enllà de Teheran per tal de consolidar i reforçar el model proposat, i (ii) la combinació del model desenvolupat amb lògica Fuzzy per arribar a una metodologia superior.

***Paraules clau**: Rehabilitació interior d'habitatge massiu, Tècniques convencionals de rehabilitació existents, Tècniques de rehabilitació millorades, Avaluació de Sostenibilitat, MIVES, Delphi*

Resumen

La construcción de vivienda masiva (VM) resolvió las grandes demandas de vivienda en las zonas urbanas de los años sesenta y setenta en todo el mundo. Tras décadas de uso continuado y un mantenimiento inadecuado, esta VM ha sido mayoritariamente censurada por sus impactos negativos sociales, económicos y ambientales. Por ejemplo, encuestas y estudios recientes revelaron que la mayoría de los VMs provocan un alto consumo de energía, emisiones de CO_2 y costes de mantenimiento. Asimismo, los VM presentan condiciones interiores que no responden adecuadamente a las necesidades actuales de sus ocupantes. Estas deficiencias citadas de los VMs piden la rehabilitación interior de los VM. En Irán esta rehabilitación se basa actualmente principalmente en tecnologías y técnicas de construcción tradicionales y convencionales, la mayoría de las cuales no siguen los requisitos de sostenibilidad ni los estándares de construcción contemporáneos.

En este sentido, la evaluación y selección de los procedimientos adecuados de rehabilitación interior de los VM, desde el punto de vista de la sostenibilidad, es un tema crucial que se enfrenta a varios retos, puesto que se trata de un proceso multidisciplinar y multicriterio. Para superar este reto, varios estudios e investigaciones existentes han aplicado distintos métodos y herramientas de evaluación de la sostenibilidad del edificio (BSA). La mayoría de BSA tienen varios déficits, como (i) carencia de un enfoque holístico, (ii) descuidar la satisfacción de las partes interesadas implicadas, (iii) limitarse a un contexto regional específico y (iv) utilizar algunos indicadores de sostenibilidad predefinidos, algunos de los cuales no son adecuados, relevantes ni aplicables a todos los proyectos. Estas carencias de los BSA llevan a numerosos investigadores a desarrollar modelos individuales basados en métodos de toma de decisiones multicriterio (MCDM) para alcanzar los objetivos de sus proyectos.

La presente tesis pretende desarrollar un nuevo modelo MCDM basado en los métodos MIVES y Delphi para la evaluación holística de la sostenibilidad de la rehabilitación interior de VM. Este modelo MIVES-Delphi se basa en una revisión exhaustiva de la literatura, seminarios formados por expertos, encuestas in situ, BIM, cuestionarios basados en usuarios y expertos, reducción de sesgos y análisis de sensibilidad. El modelo se aplicó por primera vez al caso de estudio de VM de Ekbatan, que es el mayor VM de Irán. Además, el autor ha aplicado este nuevo modelo para evaluar la sostenibilidad de cuatro escenarios distintos de rehabilitación interior, incluidos tres escenarios de rehabilitación comunes más un innovador. En consecuencia, se ha validado el nuevo modelo y seleccionado el escenario de rehabilitación más sostenible. Todo el procedimiento se ha diseñado para garantizar la transparencia, objetividad y robustez de sus resultados.

Esta validación demuestra que el modelo desarrollado puede cuantificar objetivamente la evaluación holística de sostenibilidad de la rehabilitación de interiores en VM en Irán, teniendo en cuenta las preferencias de las partes interesadas implicadas. Además, este modelo tiene flexibilidad, adaptabilidad y aplicabilidad para cualquier tipo de procedimiento de rehabilitación de interiores en VM en distintos contextos geográficos, así como distintas fases de construcción, incluyendo el diseño, construcción y rehabilitación. Los resultados específicos sobre la evaluación de los escenarios de rehabilitación revelaron que ninguno de los tres escenarios de rehabilitación convencionales comunes estudiados podía alcanzar el valor mínimo del objetivo de sostenibilidad ni servir como soluciones adecuadas para la rehabilitación interior. Por su parte, el cuarto escenario, con un índice de sostenibilidad global de 0,71, podría cumplir el objetivo mínimo estándar. Esto ofrece la posibilidad de que los procesos de rehabilitación innovadores tengan efectos positivos en el aumento del rendimiento de sostenibilidad en los edificios de VM.

Esta tesis tiene por objetivo contribuir a avanzar hacia técnicas de rehabilitación más sostenibles para la rehabilitación de interiores en VM, así como avanzar hacia una arquitectura y construcción más sostenibles. Además, esta tesis abre oportunidades para futuras perspectivas de investigación que podrían ser (i) la adaptación e implementación del modelo desarrollado a otros VM más allá de Teherán para consolidar y reforzar el modelo propuesto, y (ii) la combinación del modelo desarrollado con lógica Fuzzy para alcanzar una mayor metodología.

Palabras clave: *Rehabilitación interior de vivienda masiva, Técnicas convencionales de rehabilitación existentes, Técnicas de rehabilitación mejoradas, Evaluación de Sostenibilidad, MIVES, Delphi*

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List of Abbreviations

Abbreviation	Complete name
ACWR	Average Construction Waste Rate
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
AU	Apartment Unit
BIM	Building Information Modeling
BOD	Benefit of the doubt approach
BREEAM	Building Research Establishment Environmental Assessment Method
BSA	Building Sustainability Assessment
CA	Conjoint Analysis
CBI	Central Bank of Iran
C	Criteria
COPRAS	Complex Proportional Assessment
CW	Construction Waste
Cω	Contribution weight
DC_p	Demolition Cost of the product
DCU_p	Demolition Cost of product per unit
DCv	Decreasing Concave
DCx	Decreasing Convex
DL	Decreasing Lineal
D_p	Density of product
DS	Decreasing S-shape
DW	Demolition Waste
EC	Embodied Carbon
ECC	Embodied Carbon Coefficient
EE	Embodied Energy
EEC	Embodied Energy Coefficient
ELECTRE	ELimination Et Choice Translating REality
EL_p	Expected Lifetime of product
EPDs	Environmental Product Declarations
EW	Embodied Water
EWC_p	Embodied Water Coefficient of product
EWC	Embodied Water Coefficient
FA	Factor Analysis
GDP	Gross Domestic Product
GSi	Global Sustainability index
HAPM	Housing Association Property Mutual Ltd
HRLPs	Housing Rehabilitation Loan Programs
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
ICE	Inventory of Carbon and Energy
UBICE	University of Bath's Inventory of Carbon and Energy
ICEO	Iran Construction Engineering Organization
ICMPL	Iran Construction Material Price List
IC_p	Implementation Cost of the product
ICU_p	Implementation Cost of the product per unit
ICv	Increasing Concave
ICx	Increasing Convex
IEQ	Indoor Environmental Quality
I_k	Indicator
IL	Increasing Linear
IRCEO	Iran Construction Engineering Organization
IRCEO	Licensed Architect from Iran Construction Engineering Organization
IRMTO	Iran Road Maintenance and Transportation Organization
IS	Increasing S-shape
ISIRI	Institute of Standards and Industrial Research of Iran
ISM	Individual Sustainability Model

ISO	International Standards Organization
ITeC	Institut de Tecnologia de la Construcció de Catalunya
LCA	Life-Cycle Assessment/Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCU_p	Labor Cost for demolition of product
LEED	Leadership in Energy and Environmental Design
MAUT	Multi-Attribute Utility Theory
MCDM	Multi-Criteria Decision Making
MH	Mass Housing
MIVES	Modelo Integrado de Valor para una Evaluación Sostenible
M_p	Mass of product
NAHB	National Association of Home Builders
NFTAI	National Freight and Transportation Association of Iran
NHAPS	National Human Activity Pattern Survey
NMR_p	Numbers of required rehabilitation and replacement of product
OA	Optimization Algorithm
OC	Operational Carbon
OE	Operational Energy
OSB	Oriented Strand Board
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
QTO	Quantity Take-Off
R	Requirement
SBRCSs	Sustainable Building Rating and Certification Systems
SCI	Statistical Center of Iran
SP	Study Period
SPSS	Statistical Package for the Social Sciences
TCW	Total Construction Waste
TDC	Total Demolition Cost
TDW	Total Demolition Waste
TEC	Total Embodied Carbon
TEE	Total Embodied Energy
TEW	Total Embodied Water
TLCD	Total Labor Cost for Demolition
TMC	Total Maintenance Cost
TM_p	Total Mass of product
TMW	Total Mass of generated Waste
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions
TWDC	Total Waste Disposal Cost
TWMO	Tehran Waste Management Organization
UCNNR	International Union for Conservation of Nature and Natural Resources
UNCED	United Nations Conference on Environment and Development
UNEP	UN Environment Program
VC	Criteria Value
VICOR	Licence Agreement VlseKriterijumska Optimizacija I Kompromisno Resenje
VI	Indicators Values
V_p	Volume of product
VR	Requirements Values
WCED	World Commission on Environment and Development
WDC	Waste Disposal Cost
WPM	Weighted Product Met
WSM	Weighted Sum Method
WSSD	World Summit on Sustainable Development
X_{max}	The corresponding point/s to the maximum satisfaction (S_{max}=1)
X_{min}	The corresponding point/s to the minimum satisfaction (S_{min}=0)
ωR	Requirement’s weight
ωC	Criteria’s weight
ωI	Indicator’s weight

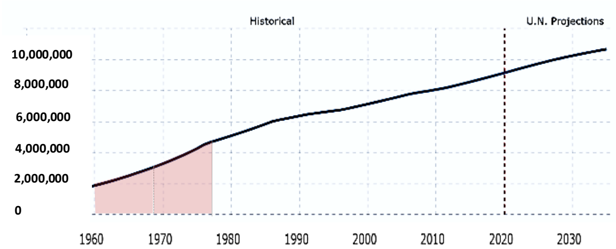
CHAPTER 1

Introduction

Chapter 1: Introduction

1.1. Introduction to this thesis topic of study

At the end of the nineteenth century, following socio-economic and political transformations in many parts of the world, the housing layouts changed radically to respond to the increasing demand for housing (Sarica, 2012; Esentepe, 2013; Sarvari *et al.*, 2020). One of these new housing layouts was Mass Housings (MHs), which aimed to tackle the existed urgent need for housing (Mehta, R.; Bridwell, 2005; Arku, 2006; Hadjri, 2013; Heravi *et al.*, 2014; Anthony, Daniel and Olusegun, 2017; Sarvari *et al.*, 2020). In later years, during and after World Wars (WW1 and WW2), since many buildings were demolished, MHs became shelters for homeless people and spread out in several parts of the world (Alao, 2009; Esentepe, 2013; Kwofie *et al.*, 2014; Eurofound, 2016; World Economic Forum, 2019; Sarvari *et al.*, 2020). Similar to other parts of the world, in Iran, the 1960s and 1970s were marked by MHs construction due to **high demand for housing in urban areas** (Ziari and Gharakhlou, 2009; Moosavi, 2012; Felli, 2016; Ziari *et al.*, 2016; Sedighi, 2018) because of (1) the **immigration of people** from rural to urban areas seeking job opportunities and to increase their living standards caused by Iran's oil boom that provided an opportunity for the government to create several job positions and better services in the big cities such as Tehran (Ziari and Gharakhlou, 2009; Moosavi, 2012; Babak Soleimani, 2014; Al-Saif, 2015; Felli, 2016; Sedighi, 2018), and (2) **the highest birth rates** that occurred in the **1960s** and **1970s** (https://www.amar.org.ir/, www.macrotrends.net/cities/21523/tehran/population) – e.g. Tehran's population grew from 1.5 in 1956 to 4.5 million in 1976 as shown in Figure 1.1. Consequently, more than 500,000 MHs residential units were built from 1960 to 1980 in Iran, from which over 250,000 are located in Tehran (Salek, 2007; Habibi and Meulder, 2015; Sedighi, 2018). Table 1.1 and Figure 1.2 present some of these MHs built in the 1960s and 1970s.



Tehran - Historical Population Data		
Year	**Population**	**Growth Rate**
1956	1,481,000	6.01%
1966	2,663,000	6.05%
1976	4,503,000	5.38%
1986	6,004,000	2.83%
1996	6,744,000	0.85%
2006	7,762,000	1.44%
2016	8,667,000	1.31%

Figure 1.1. Tehran population 1950-2020

Table 1.1. Some examples of MHs that were constructed in Iran in the 1960s and 1970s

Mass Housing	Location	Year of construction	Designer/constructor	Total residential units	Total Population
Ekbatan	Tehran	1974	American & South-Korean firms	15,593	70,000
Ati-Saz	Tehran	1978	Italian firm	2,290	10,000
Omid	Tehran	1976	French firm	1,946	8,500
Gharb (Qods)	Tehran	1978	American firm	1,496	7,000
Behjat-Abad	Tehran	1966	American firm	2,150	10,000
Zomorrod	Tehran	1974	American firm	6,000	27,000
Apadana	Tehran	1977	French firm	2901	11,800
High-rise apartments MH	Mashhad	1973	Italian and French firms	600	2,700
600 Dastgah	Mashhad	1969	Italian firm	600	2,300

Figure 1.2. Some examples of MHs that were constructed in Iran in the 1960s and 1970s

After decades of continuous use and inadequate maintenance, the present conditions of these MHs mostly do not respond to the current needs of their occupants (Kamalipour, Yeganeh and Alalhesabi, 2012; Moosavi, 2012; Mahdavinia, Mamaghani and Goudarzi, 2014; Asasdpoor, 2015; Yadollahi, Mahdavinia and Ghiai, 2015; Abbaszadeh, 2016; Publications, Qodsi and Soheili, 2016; Shoohanizad and Haghir, 2016; Kaja, 2017; Saiedlue *et al.*, 2017). Consequently, the dichotomy of **whether to demolish or rehabilitate** these MHs have become very important in the last decades (Power, 2008; Gaspar and Santos, 2015; Alba-rodríguez *et al.*, 2017). Numerous research studies such as those by Empty Homes Agency, English Heritage, the Building Research Establishment, and the Prince's Foundation proved the advantages and potential of MHs rehabilitation compared to demolishing them (Ohemen, 1998; Dong, Kennedy and Pressnail, 2005; Power, 2008; Crawford, Johnson and Davies, 2014; Gaspar and Santos, 2015; Alba-rodríguez *et al.*, 2017). This potential is due to the following reasons: (1) MHs structures are mostly precast or poured on-site concrete and therefore they have high durability and are difficult to demolish, and (2) the demolition of MHs causes several negative sustainability impacts (Figure 1.3) such as high cost and time-taking process of demolition and reconstruction of MHs as negative economic impacts; the production of large quantities of solid waste, CO_2 emissions, energy consumption, as well as material consumption as negative environmental impacts; and resettlement of residents in new places during the reconstruction process beside missing residents' attachment to their apartments as negative social impacts. Therefore, **upgrading existing MHs** with sustainable rehabilitation actions is **more preferable**, considering once upgraded, they can achieve as high sustainable standards as current new builds (Gaspar and Santos, 2015; Alba-rodríguez *et al.*, 2017).

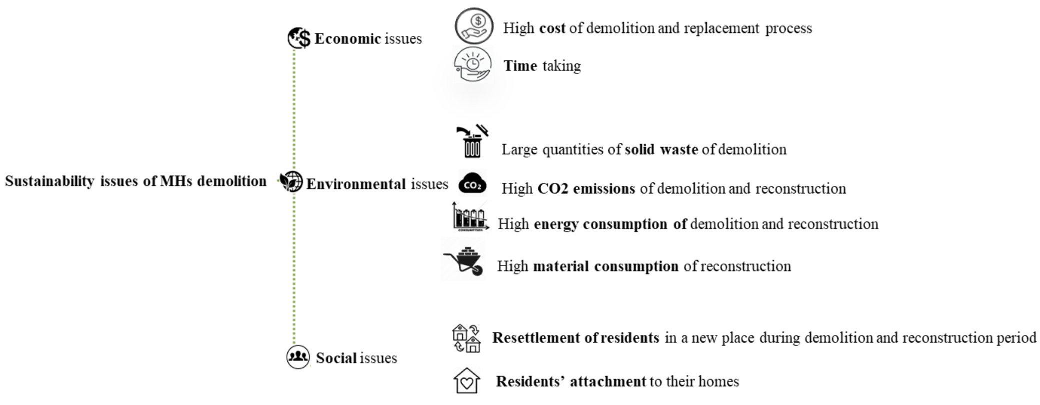


Figure 1.3. Sustainability issues of MHs demolition

In this regard, **the identification of proper rehabilitation activities and techniques** from the **sustainability point of view** is **a crucial issue**, especially in developing countries such as Iran that sustainable rehabilitation activities and techniques have been rarely received proper attention (Zarghami *et al.*, 2018; Sarvari *et al.*, 2020). In this respect, the present doctoral dissertation intends to **contribute to promote more sustainable rehabilitation techniques for interior rehabilitation in MHs**. It does so for Iran as well as thinking on its future application in other countries.

1.2. Problem definition and motivation for this study

This section explains the importance of the present doctoral dissertation and identifies the main existing problems, shortages, deficiencies, and drawbacks regarding this thesis research topic.

1) Based on the last survey by the Statistical Center of Iran (SCI) (https://www.amar.org.ir/) conducted in 2016, among the total 27 million residential units in Iran, **more than 4.4 million** – 16% – **of them were built as MHs** such as *Mehr* MHs – with more than three million residential units in different parts of this country – and the existing MHs in one of the main municipal regions of Tehran which is called *22nd municipal region* – whose buildings are specifically dedicated to MHs construction with more than 150.000 apartment units. According to the recent survey conducted by the Iranian Ministry of Roads and Urban Development (https://www.mrud.ir/, 2019), the **present interior conditions** of more than 250.000 residential units of these MHs **do not respond to** the current **needs of their occupants** and most of them have several **sustainability issues** (Kamalipour, Yeganeh and Alalhesabi, 2012; Moosavi, 2012; Mahdavinia, Mamaghani and Goudarzi, 2014; Asasdpoor, 2015; Yadollahi, Mahdavinia and Ghiai, 2015; Abbaszadeh, 2016; Publications, Qodsi and Soheili, 2016; Shoohanizad and Haghir, 2016; Kaja, 2017; Saiedlue *et al.*, 2017) as indicated in Figure 1.4.

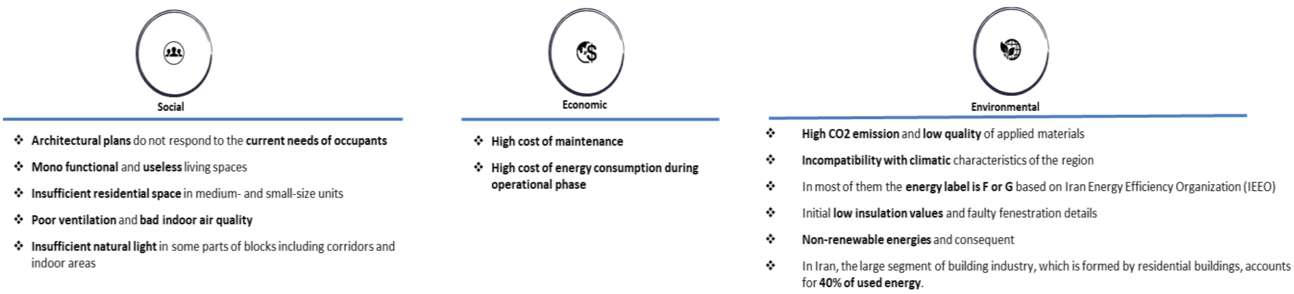


Figure 1.4. Present sustainability issues of Iranian MHs

Moreover, according to several surveys conducted by the Iranian Ministry of Roads and Urban Development in 2019 (https://www.mrud.ir/, 2019), over one million dwelling units are needed to respond to the increasing need for housing in Iran. In this regard, in 2021, by proposing a plan named as "the National Housing Action Plan" (https://www.tehrantimes.com/news/465043/First-step-to-start-one-million-housing-project-to-be-taken-by), the government got obligated to construct **one million houses annually** – mostly as MHs projects – across the country (https://iranwire.com/en/features/10245).

Therefore, since there are a lot of MHs that already need to be urgently rehabilitated as well as the other ones that will have the same issue in the near future, the present thesis intends to contribute moving forward to more sustainable rehabilitation techniques for interior rehabilitation in Iran's MHs.

Due to all abovementioned MHs' issues, this thesis focuses on rehabilitation of MHs instead of other residential buildings to take advantage of the existence of similar repetitive apartment units in these MHs to (1) evaluate the sustainability performance of the rehabilitated apartment units in MHs more rigorously through a wider sample size, particularly for social indicators, and (2) provide an opportunity to reduce their rehabilitation time, consumed materials, and costs of rehabilitation process of these repetitive apartments and encourage owners to rehabilitate their property in a more sustainable way.

2) Most existing studies and policies regarding the rehabilitation of MHs **focus on urban scale** rehabilitation (Pedro, Silva and Duarte, 2018; Karji *et al.*, 2019a), while **rehabilitation in dwelling scale** and its interior spaces **has received less attention**. Nevertheless, **interior rehabilitation of spaces is a crucial issue** due to (a) more than 87% of a person's lifespan, in modern society, is spent indoors based

on the National Human Activity Pattern Survey (NHAPS) (Klepeis *et al.*, 2011). In addition, this number even increased due to the recent Covid-19 Pandemic lockdowns (Jones, Philippon and Venkateswaran, 2020; Kramer and Kramer, 2020), and (b) interior spaces effect on different sustainability aspects such as energy consumption, CO_2 emissions, and waste production in buildings as well as psychology, behavior, well-being, and productivity of their inhabitants (Megahed and Gabr, 2010; Lindenthal, 2020).

3) There are numerous **interior rehabilitation techniques and building processes**, from which most of them – such as traditional and conventional ones – **have long been criticized** because of their low productivity, poor quality and safety records, long-lasting construction time, and large quantities of waste generation (Meijer, Itard and Sunikka-Blank, 2009; Stenberg, Thuvander and Femenias, 2009; Thuvander *et al.*, 2012; Dobson *et al.*, 2013; Rieradevall i Pons, 2014). Furthermore, these techniques **do not satisfy contemporary building standards** regarding mobility, flexibility, accessibility, multi-functionality, assembly or disassembly, and performance parameters among others (Stenberg, Thuvander and Femenias, 2009; Thuvander *et al.*, 2012). These parameters are crucial for sustainability due to their direct relation with social, economic, and environmental aspects. In this regard, **replacing** the traditional and conventional techniques **with new or improved rehabilitation** ones **can be a solution to the aforementioned lack**.

4) For Building Sustainability Assessment (BSA), there are two different types of BSA methods, (1) *sustainable building rating and certification systems (SBRCSs)* such as LEED, BREEAM, LEAN, BEAM, DGNB, VERDE, CASBEE, SBTool, and (2) *individual sustainable models (ISMs)* that are mostly based on Multi-Criteria Decision Making (MCDM) methods (Bragança, Mateus and Koukkari, 2010; Mahmoud, 2017). Regarding ***SBRCSs***, **they have some weak points** that make them **inapplicable** for sustainability assessment of MHs in **Iran**. Some of these weaknesses are as follows: (i) lacking a holistic approach (Meijer, Itard and Sunikka-Blank, 2009; Davoodi, Fallah and Aliabadi, 2014; Gould, Missimer and Mesquita, 2017; Karji, Woldesenbet and Khanzadi, 2017; Xiahou *et al.*, 2018; Zarghami, Fatourehchi and Karamloo, 2019a; Karji *et al.*, 2019a; Liu and Qian, 2019; Olakitan Atanda, 2019; Shirazi and Keivani, 2019; Olawumi *et al.*, 2020), (ii) neglecting the involved stakeholders' satisfaction (Hosseini, De la Fuente and Pons, 2016; Hosseini, Fuente and Pons, 2016; Gilani, 2020), (iii) being limited to a specific regional context (Bragança, Mateus and Koukkari, 2010; Banani, Vahdati and Elmualim, 2013; Mahmoud, 2017; Zarghami, Fatourehchi and Karamloo, 2019a), and (iv) employing some predefined sustainability indicators some of which are not adequate, relevant, or even applicable for all projects (Bragança, Mateus and Koukkari, 2010; Zarghami *et al.*, 2018; Zarghami, Fatourehchi and Karamloo, 2019a). These BSA's shortfalls lead numerous researchers to develop individual sustainable models (ISMs) based on multi-criteria decision-making (MCDM) methods to fulfill their projects' objectives.

5) As most of the architectural, structural, mechanical, and technical data for MHs that were built in the 1960s and 1970s in Iran **are not accessible**, categorized, organized, or in digital format, there is a **lack of precise and reliable database** regarding these buildings. In this respect, providing an integrated database can be used as a foundation for the present thesis as well as a benchmark for future MHs studies.

1.3. Hypothesis of this thesis

The present doctoral dissertation assumes the following hypothesis:

Innovative, improved, or advanced interior rehabilitation techniques are more sustainable alternatives – have lower environmental impacts, lower costs, and higher social acceptances – than other common existing interior rehabilitation techniques; when integrally interior rehabilitating MHs by taking into account the building's whole lifecycle.

1.4. Aims and objectives

As previously mentioned in the problem definition section – section 1.2 –, since MHs account for 16% of the residential sector in Iran and the rehabilitation of these MHs have rarely received proper attention from the sustainability point of view in this country, the main objective of the present doctoral dissertation is **contributing moving forward to more sustainable rehabilitation activities and techniques for interior rehabilitation of MHs**. To achieve this main objective, this thesis defines the following specific objectives:

1) **Developing a new Multi-Criteria Decision Making (MCDM) model for sustainability assessment of MHs' interior rehabilitation scenarios during their whole lifecycle**. This model could be a framework for governments, decision-makers, and stakeholders who are dealing with interior rehabilitation of MHs to facilitate the assessment and selection process.
2) **Particularizing** this new MCDM model to **Iran** and applying it for **the first time** to one of Tehran's MHs. This first application validates the model and assesses the sustainability of the case study in this present thesis – Ekbatan MH – which is the largest one in Iran.
3) Contributing to collect, organize, classify, and digitalize the general and technical information for the selected case study and **providing an integrated database** that can be used as a foundation for the present thesis as well as a benchmark for future MHs studies.
4) Overviewing **common existing interior rehabilitation** activities and techniques in Iran besides **new or improved ones in the world** to **compare and assess** these techniques through the developed MCDM model from the economic, environmental and social point of view and **identifying the most sustainable one**.

1.5. Boundaries and limitations of this thesis

This section includes two main parts. The first part establishes and describes **the boundaries and scope of the study** – section 1.5.1 – and the second part expresses **the limitations and barriers** that the author has faced to achieve the thesis objectives – section 1.5.2.

1.5.1. Boundaries and scope of this thesis

The author has limited the study by defining the following scope and boundaries to study more in-depth the topic of the present thesis.

1. **The post-war MHs** that were built from **1960 to 1980** – the 1960s and 1970s, see section 2.1 – **in Iran** have been selected due to their applied latest construction technologies in that era, their durability of the structure, and their urgent need for interior rehabilitation.
2. **A case study** which is **Ekbatan MH** in Tehran, Iran has been selected 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 a post-war MH built in the 1970s, (c) it has a vast area of construction, diversity of architectural configuration, high population density, and unique design, and (d) it is located in author's country; therefore, collecting information about this case study has been much more feasible and accessible.
3. Additionally, the author has limited this doctoral dissertation to rehabilitate the **interior spaces** and **interior façade layers** of the case study, **excluding the structure** and **building's services**.
4. Furthermore, the author has limited this thesis to the technical and technological aspects of rehabilitation at the **dwelling scale**. Meanwhile, **rehabilitation at the urban scale** – e.g., the neighborhood, community interaction, finance, and urban management – has been put aside due to the fact that **it is another complex subject**.

1.5.2. Limitations and barriers of this thesis

The limitations and barriers of the present thesis can be categorized into (1) **technical** and (2) **operational** limitations.

The technical limitations are as follows:

1. According to the technical literature, most of the investigations regarding the sustainability performance of residential buildings and MHs focused mostly on the environmental aspect instead of having a holistic approach (Meijer, Itard and Sunikka-Blank, 2009; Davoodi, Fallah and Aliabadi, 2014; Gould, Missimer and Mesquita, 2017; Karji, Woldesenbet and Khanzadi, 2017; Xiahou *et al.*, 2018; Zarghami, Fatourehchi and Karamloo, 2019a; Karji *et al.*, 2019a; Liu and Qian, 2019; Olakitan Atanda, 2019; Shirazi and Keivani, 2019; Olawumi *et al.*, 2020). Moreover, despite the fact that **the social aspect** is the **most crucial** one for residential buildings sustainability since it is the main reason for interior rehabilitation (van der Flier and Thomsen, 2006; Meijer, Itard and Sunikka-Blank, 2009; Thuvander *et al.*, 2012; Ahmad and Thaheem, 2017a), it was the **most ignored** one and rarely investigated (Davoodi, Fallah and Aliabadi, 2014; Gould, Missimer and Mesquita, 2017; Karji, Woldesenbet and Khanzadi, 2017; Xiahou *et al.*, 2018; Karji *et al.*, 2019a; Liu and Qian, 2019; Olakitan Atanda, 2019; Shirazi and Keivani, 2019; Zarghami, Fatourehchi and Karamloo, 2019a; Olawumi *et al.*, 2020). Therefore, to the best of this thesis author's knowledge, heretofore, since **there is no study regarding the holistic and integrated sustainability assessment of rehabilitation in MHs** and this topic is novel, there is a lack regarding the research background.

2. For sustainability assessment of the construction industry – especially for the environmental aspect –, there is a lack of **precise written national databases** and **technical building codes** in **Iran**.

3. Since the required data from the case study – architectural layouts, mechanical layouts, structural layouts, construction details, and regulations – were mostly **not accessible** or **not in digital format**, the author had to collect these data from the designers, stakeholders, and constructors of this MH as well as competent authorities and public entities – e.g., Tehran municipality. Consequently, to prepare all the required data for this doctoral dissertation, this data had to be digitalized and that made the process of data collection highly time-consuming.

The operational limitations are as follows:

1. As the selected case study is located in Tehran, Iran, while the author resides in Barcelona, there were some limitations for collecting required data – e.g., on-site surveying. To do so, the author intended to collect these data during five trips to Iran in different periods.
2. For collecting required data through on-site surveying – e.g., interviewing and filling out the questionnaires from Ekbatan's residents, visiting and surveying apartments, and physical measurements – the author faced some difficulties due to the specific introverted socio-cultural and socio-religious nature of Iranian society. Thus, on-site surveying required permissions from different public and private entities as well as apartment inhabitants.

1.6. Structure and methodology of the thesis

The present doctoral dissertation has been organized into two main parts: (1) **descriptive** and (2) **operational**, as shown in Figures 1.5 and 1.6.

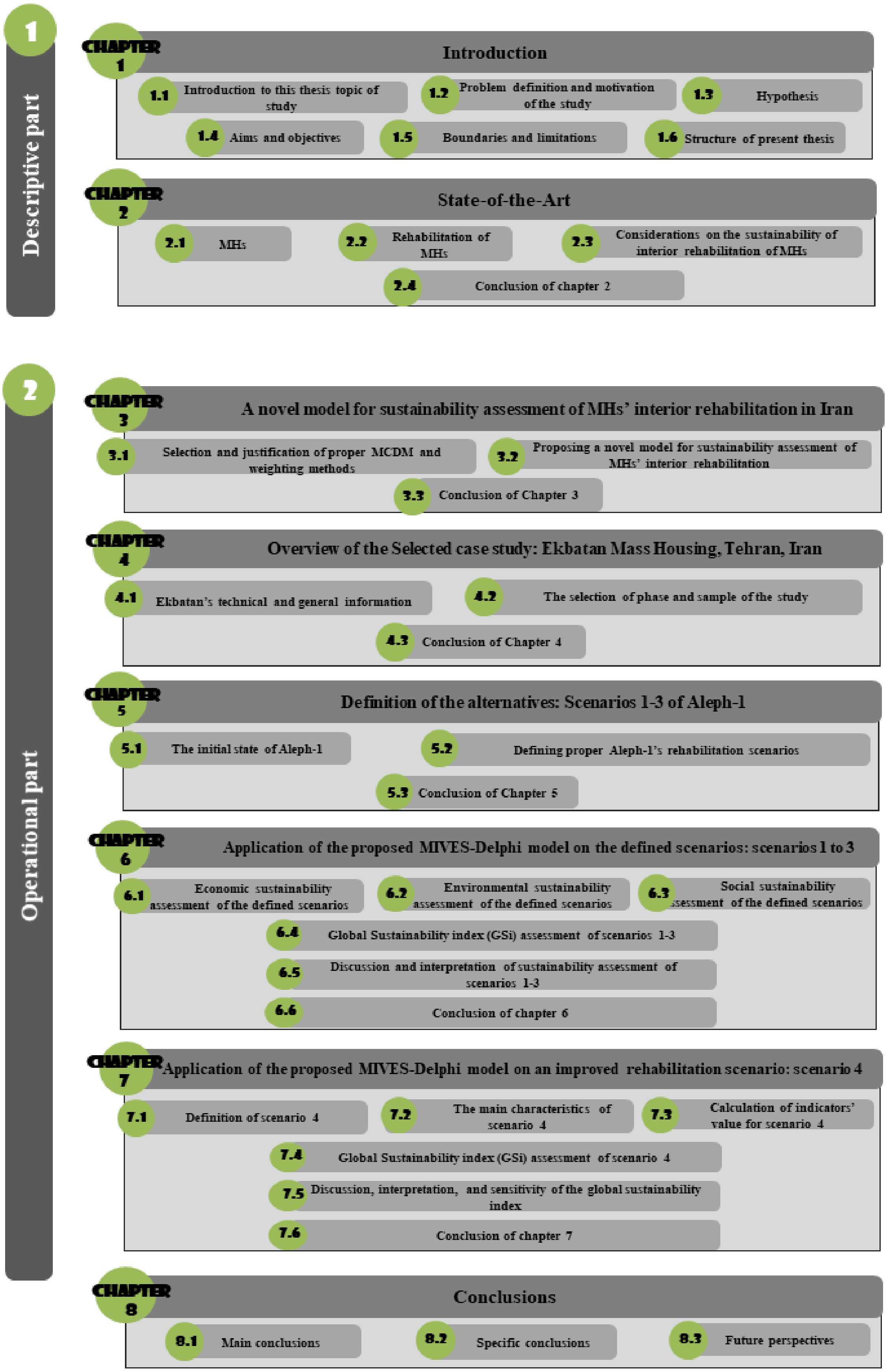


Figure 1.5. The structure of the present thesis

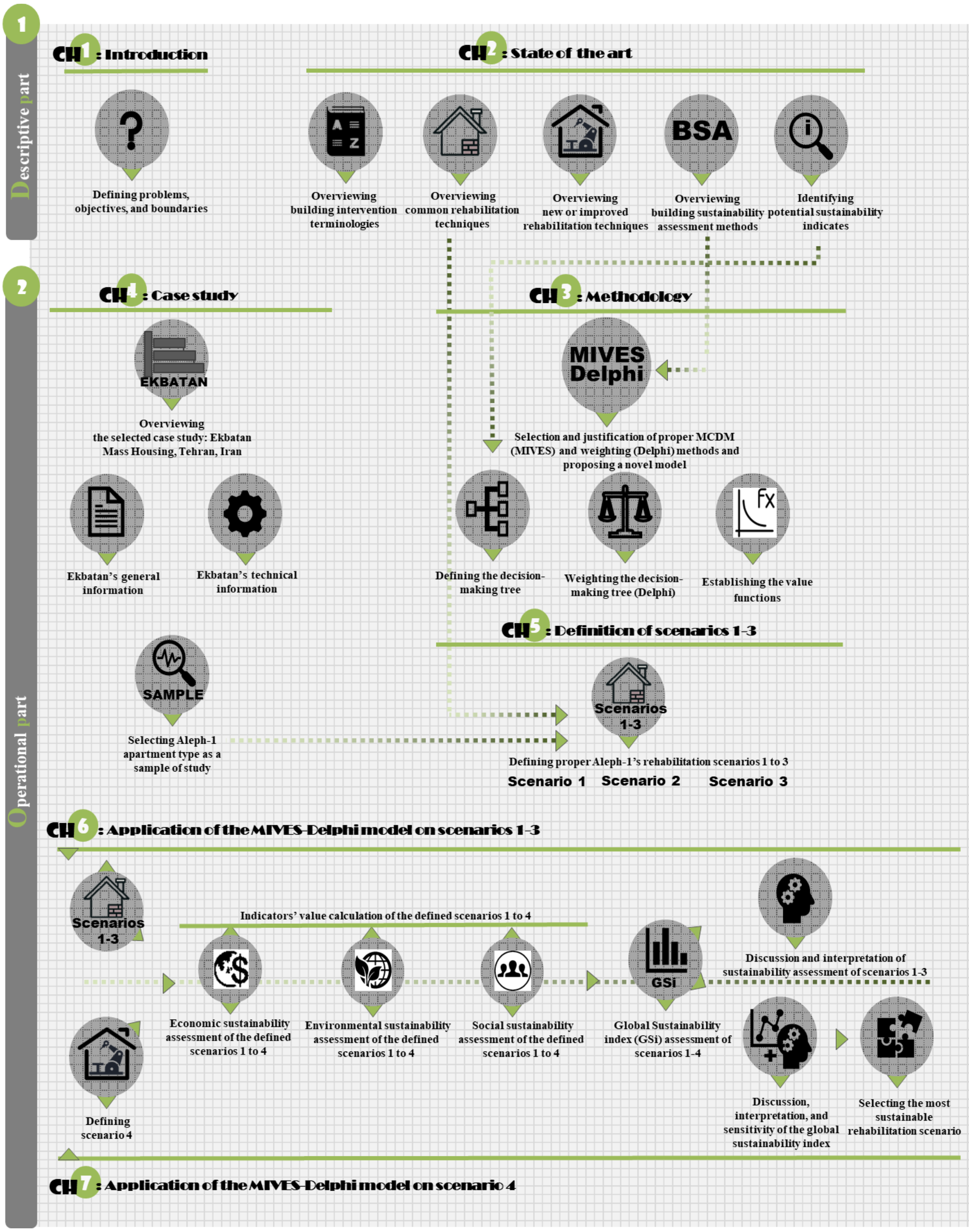


Figure 1.6. Schematic structure of the present thesis

The **descriptive part** embraces two chapters – chapters 1 and 2 – that, in general, describes the introduction and state of the art of this research respectively.

Chapter 1 defines and explains the existing problems and gaps, the importance and motivations, the hypothesis, the aims and objectives, and the structure of the present thesis.

Chapter 2 mainly reviews and analyses previous literature in order to identify gaps in knowledge and form a research foundation to achieve the defined aims and objectives, specifically the first objective – see section 1.4. This chapter is broken down into three main parts: the first part overviews MHs including the definition of MH, the history and different periods of MHs construction in Iran, besides the characteristics of the built MHs in each period. The second part takes into account the rehabilitation of MHs, comprising relevant building intervention terminologies, common existing interior rehabilitation techniques in Iran, significant examples of interior rehabilitation projects constructed with new or improved technologies in the world, and rehabilitation policies and regulations in Iran. The third part provides information regarding the importance of incorporating sustainability principles in the design, assessment, and selection procedure of MHs' interior rehabilitation. This chapter also critically reviews and analyzes the previous BSA tools and methods besides their relative sustainability assessment parameters – requirements, criteria, and indicators.

The **operational part** presents a novel MCDM model by designing and developing the mentioned model, applying it for the defined case study and its corresponding rehabilitation scenarios, and the sustainability assessment of these scenarios. This part includes five chapters – chapters 3 to 7.

Chapter 3 defines the research methodology for developing a proper MCDM model for sustainability assessment of interior rehabilitation of MHs. In this regard, first, the most appropriate MCDM and weighting method regarding the thesis topic are identified, selected, and justified; second, a novel model based on the selected MCDM is developed through its seven stages.

Chapters 4 and ***5*** define the case study, sample, and its different rehabilitation scenarios to validate the proposed model in chapter 3. In chapter 4, by overviewing the case study – Ekbatan – in the neighborhood scale, the sample of study among the different types of Ekbatan's apartment units is defined and justified. Moreover, to fulfill the third specific objective of this thesis – section 1.4 –, the general and technical information of the selected case study is collected, organized, classified, and digitalized. Chapter 5 defines three different rehabilitation scenarios that are the most frequent and representative rehabilitation activities and techniques in Iran. Moreover, the characteristics of mentioned defined scenarios are explained in this chapter.

Chapter 6 presents the first application of the proposed MCDM model – chapter 3 – on the defined rehabilitation scenarios – named as scenarios 1 to 3, chapters 4 and 5 –, in order to (1) prove the applicability, suitability, and validity of the proposed model, (2) identify the challenges when facing its application, and (3) demonstrate how it enables decision-makers to identify the strengths and weakness of interior rehabilitation from economic, environmental and social points of view to improve the sustainability of these rehabilitation activities and select the most sustainable ones.

Chapter 7 presents the second application of the proposed MCDM model on a rehabilitation project – named as scenario 4 – constructed with new or improved rehabilitation techniques in order to (1) prove the applicability, suitability, and validity of this proposed model, (2) identify the challenges when facing its application, (3) identify the strengths and weaknesses of this new scenario from economic, environmental, and social points of view, and (4) compare this improved rehabilitation scenario with other three existing rehabilitation scenarios in Ekbatan to find the most sustainable rehabilitation solution – to validate the defined hypothesis and the fourth objective, see sections 1.3 and 1.4 – for decision-makers who are dealing with interior rehabilitation of MHs.

Chapter 8 draws specific and general conclusions from all chapters as well as future works, which are expected to be followed in future research projects.

CHAPTER 2

State-of-the-Art

Chapter 2: State-of-the-Art

Introduction

In this chapter, the author has reviewed and analyzed the previous related literature to the topic of the present thesis to **identify gaps in knowledge** and **form a research foundation**. This chapter is divided into four main sections as follows – Figure 2.1:

1) First section – section 2.1 – is about **MHs in Iran** and overviews the definition of MH, the history and different periods of MHs construction in Iran, besides the characteristics of the built MHs in each period – their reasons of emergence, target population, and strengths and weaknesses.

2) Second section – section 2.2 – explains the **rehabilitation of MHs**, including relevant building intervention terminologies, common existing interior rehabilitation techniques in Iran, significant examples of interior rehabilitation projects constructed with new or improved technologies in the world, and rehabilitation policies and regulations in Iran.

3) Third section – section 2.3 – provides information regarding **considerations on the sustainability of interior rehabilitation of MHs**. This section includes describing the importance of considering sustainability principles in the design, assessment, and selection procedure of MHs' interior rehabilitation, overviewing several sustainability evaluation methods regarding the thesis topic, and identifying relevant and potential sustainability parameters for sustainability assessment of MHs' interior rehabilitation in Iran.

4) Fourth section – section 2.4 – concludes the previous sections.

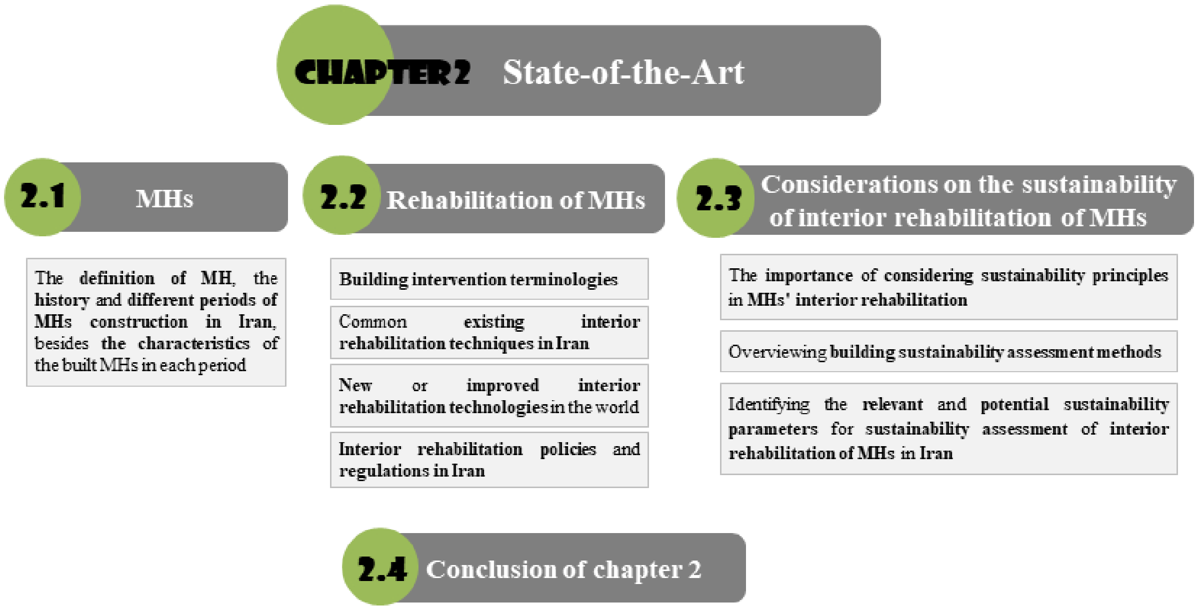


Figure 2.1. The structure of chapter 2

2.1. Mass Housings (MHs) in Iran

The concept of Mass Housing (MH) that refers to dense and repetitive housing (https://www.igi-global.com/dictionary/background/75453) emerged for the first time at the end of the nineteenth century, through radical changes of housing layouts in different parts of the world for responding to the increasingly high demands for housing (Sarica, 2012; Esentepe, 2013; Sarvari *et al.*, 2020). In history, there are three significant movements or events, which were the Industrial Revolution, Communism Movement, and World Wars – WW1 and WW2 – that initiated the important construction of MHs in the world (Esentepe, 2013). On the other hand, similar to other parts of the world, in Iran, MHs construction spread out during **three different periods**: (1) from 1960 to 1980, (2) from 1980 to 2000, and (3) from 2000 until the present (Ziari and Gharakhlou, 2009; Moosavi, 2012; Felli, 2016; Ziari *et al.*, 2016; Sedighi, 2018). The constructed MHs during each mentioned period have their own characteristics – reasons of emergence, target population, construction systems, and strengths and weaknesses – as described more in detail in the following paragraphs.

1) During **the first period** that occurred during 1960 to 1980, as Iran had **the highest birth rates** (https://www.amar.org.ir/, www.macrotrends.net/cities/21523/tehran/population) and **the highest people immigration to urban areas** (Ziari and Gharakhlou, 2009; Moosavi, 2012; Babak Soleimani, 2014; Al-Saif, 2015; Felli, 2016; Sedighi, 2018), the urban population grew radically, especially in big cities – e.g., Tehran's population grew from 1.5 in 1956 to 4.5 million in 1976 (https://www.amar.org.ir/, www.macrotrends.net/cities/21523/tehran/population). During this period, the country's GDP significantly increased because of Iran's oil boom and provided a new lifestyle in well-equipped MHs for the middle- and high-income people (Salek, 2007; Babak Soleimani, 2014; Sedighi, 2018). Due to the booming construction market, insufficient domestic technical knowledge, the demand for new ideas, and the close economic and political relationship with other countries (Salek, 2007; Babak Soleimani, 2014; Sedighi, 2018), foreign consultants constructed more than 500,000 MHs residential units **with the latest construction technologies** of that period (Honar-e Memari Magazine, no.27, 2011). Some of the significant constructed MHs in this period are Ekbatan, Omid, Gharb, and Ati-Saz.

Figure 2.2. MHs constructed in the first period (1960 to 1980)

2) During and after the **Iran-Iraq war**, the second era started in 1980 and continued till 2000 (Habibi & Meulder, 2015; Salek, 2007). Because of this war, a huge number of buildings were demolished and increased the number of homeless people. Consequently, many people started to immigrate to safer places, and several MHs were constructed to become shelters for these homeless people (Salek, 2007). In that period, as Iran was facing **economic issues** besides **high pressure for quick** and **cheap housing** for homeless people, it brought forth the construction of thousands of similar dwellings in MHs – such as

Apadana, Khayyam, and 600 Dastgah – with **minimal requirements in function**, **size**, and **inhabitants' comfort** (Felli, 2016).

Figure 2.3. MHs constructed in the second period (1960 to 1980)

3) Due to the high demand for housing that Iran was facing since 2000 – the highest birth rates in the 1960s and 1970s caused a young generation seeking housing in 2000 –, **the third era** began by establishing **a series of programs and policies by Iran's government** to overcome this issue (Zanganeh Shahraki, Ahmadifard and Farhadikhah, 2020). One of the most important policies in the housing sector was the *Mehr* MHs project established in 2007. Mehr MHs project was proposed to provide appropriate and affordable housing for low-income people through: (1) allocation of low-cost lands for reducing the land price from housing costs, (2) assigning long-term and low-interest loans, and (3) applying prefabricated and low-cost construction materials (Karji *et al.*, 2019b; Zanganeh Shahraki, Ahmadifard and Farhadikhah, 2020). Bypassing more than a decade, **more than three million** dwellings of Mehr MHs have been constructed. Although there are some successful Mehr MHs projects such as Parand and Pardis, **most of Mehr MHs have been criticized** in several investigations (Ivani and Rostami, 2014; Barzegaran and Daroudi, 2015; Karji *et al.*, 2019b; Zanganeh Shahraki, Ahmadifard and Farhadikhah, 2020) because of not considering **the regional context** such as the social, environmental, cultural, and economic parameters.

Figure 2.4. MHs constructed in the third period (2000 until the present)

Table 2.1. Different periods of MHs construction in Iran

	Reasons of emergence	Target population (Constructed for)	Strengths and weaknesses	Examples
1960 to 1980	**High birth rates** and **high immigration of people to urban areas**	**Middle-** and **high-income** people	**Durable structure** and mostly **do not have structural issues**. However, they have **an urgent need** for **interior rehabilitation**.	Ekbatan, Omid, Gharb, and Ati-Saz
1980 to 2000	A huge number of buildings were demolished in the **Iran-Iraq war**	**Homeless people**	**Minimal requirements in function**, **size**, and **inhabitants' comfort**	Apadana, Kayyam, 600 dastgah
2000 until present	**High birth rates** in the **1970s caused by the young generation seeking housing in 2000**	**Low-income people**	**Most Mehr MHs do not respond to their corresponding regional context**	Mehr MHs (Pardis, Parand, Kermanshah)

As previously mentioned in the boundaries and limitations – section 1.5 –, the present doctoral thesis has been **limited to overview and study the MHs constructed during the first-mentioned period** – 1960 to 1980. As these mentioned MHs were constructed with the latest construction technologies of that era, their structures are durable and they mostly **do not have structural issues**. However, based on the recent survey conducted by the Ministry of Roads and Urban Development of Iran (https://www.mrud.ir/, 2019) and numerous investigations (Kamalipour, Yeganeh and Alalhesabi, 2012; Moosavi, 2012; Mahdavinia, Mamaghani and Goudarzi, 2014; Asasdpoor, 2015; Yadollahi, Mahdavinia and Ghiai, 2015; Abbaszadeh, 2016; Publications, Qodsi and Soheili, 2016; Shoohanizad and Haghir, 2016; Kaja, 2017; Saiedlue *et al.*, 2017), the present interior conditions of these MHs do not respond to the current needs of their occupants and most of them have several sustainability issues – see Figure 1.4. Therefore, these MHs have **an urgent need for interior rehabilitation** to improve their sustainability performance. To do so, in the next sections – sections 2.2 and 2.3 –, the author has overviewed the different interior rehabilitation activities and techniques – the common existing techniques and new or improved ones – besides different scientific and well-known sustainability assessment methods to propose a novel model for assessing these rehabilitation techniques and selecting the most sustainable ones.

2.2. Rehabilitation of MHs

This part consists of four main sections that overviews: (1) relevant building intervention terminologies to define the most proper term regarding the thesis topic – 2.2.1; (2) common existing interior rehabilitation techniques and activities in Iran – 2.2.2; (3) significant examples of interior rehabilitation projects constructed with new or improved techniques and technologies in the world – 2.2.3; and (4) interior rehabilitation policies and regulations in Iran – 2.2.4.

2.2.1. Building intervention terminologies

Building intervention encompasses various construction activities that improve existing building conditions and extend the effective building lifespan (Shahi *et al.*, 2020). Common building adaptation terms such as rehabilitation, refurbishment, renovation, retrofitting, remodeling, and restoration were considered as the relevant terms based on the author's experience in the field of building adaptation. These terms are often used **interchangeably with overlapping definitions**, causing a lack of clarity in the addressed scope of the study (Access *et al.*, 2019; Shahi *et al.*, 2020). Moreover, through a comprehensive analysis conducted by Shahi *et al.*, 2020, it was concluded that the technical terminologies related to building adaptation and project scopes **have been changed significantly over time**. In this regard, to select the most proper term for the present thesis, this part intends to define, clarify, and compare the different technical terminologies regarding this field by overviewing the relevant literature as shown in Table 2.2.

Table 2.2. Summary of building adaptation terminologies

#	Term	Definition	Scope	References
1	**Restoration**	Set of actions to preserve and reveal the aesthetic, cultural, and historical values of the project, based on the original applied materials and authentic documents.	❖ Repair ❖ Maintenance ❖ Preserve the historical values of the project	(Access *et al.*, 2019), Carta de Veneza, 1964. http://portal.iphan.gov.br/uploads/ckfinder/arquivos/Carta%20de%20Veneza%201964.pdf , https://everydayoldhouse.com/restoration-vs-remodel-vs-renovate-vs-rehabilitate-whats-the-difference/
2	**Renovation**	Alteration of the existing building conditions, aiming at recovering, improving or increasing its habitability, usability or safety conditions, with or without a change of function, other than maintenance. Renovation is moving forward and modernizing, while restoration is going back in time.	❖ Remodel ❖ Energy efficiency ❖ Aesthetic appearance ❖ Interior design	(Access *et al.*, 2019),Associação Brasileira De Normas Técnicas. NBR 16280: Reforma emedificações - Sistemade gestão de reformas - Requisitos. Rio de Janeiro, Brasil, 2015. https://everydayoldhouse.com/restoration-vs-remodel-vs-renovate-vs-rehabilitate-whats-the-difference/
3	**Remodeling**	Remodeling refers to convert the structure or form of a building.	❖ Remodel ❖ Convert the structure or form	https://everydayoldhouse.com/restoration-vs-remodel-vs-renovate-vs-rehabilitate-whats-the-difference/
4	**Retrofitting**	1. It consists of the union of the term "retro", from Latin, which means to move backward, and of the English term "fit", which means to adjust, resulting in the concept of "reconversion". That is about the renovation of a building, an intervention on an estate so that the old one is reformulated into a new one. 2. Retrofitting refers to applying new technologies to old structures. The old structures may be vulnerable or maybe not. It can be used to increase efficiency or make it economical.	❖ Replacing or reinforcement of structure, envelope, and mechanical equipment ❖ Deteriorating systems, envelopes, and openings ❖ Damaged structure	Conselho Brasileiro de Construção Sustentável (CBCS). Retrofit: Requalificação de edifícios e espaços construí- dos, 2013. http://www.cbcs.org.br/_5dotSystem/userFiles/ comitetematico/projetos/CBCS_CTProjeto_Retrofit_folder.pdf,
5	**Refurbishment**	Building refurbishment is the process of improving the existing conditions of a building for the existing use. It can include the restoration of the previously acceptable conditions or making improvements to the existing systems, including the addition of energy-efficient strategies and renewable energy production.	❖ Repair ❖ Maintenance ❖ Operating costs ❖ Energy efficiency	(Shahi *et al.*, 2020) (Ghose et al., 2017; Institute of Historic Building Conservation, 2019a; Passer et al., 2016)

		Refurbishment is mainly involved in improving the environmental and operating costs of existing buildings. 2. Institute of Historic Building Conservation, 2019 defined refurbishment as "returning the building, or its systems, to their original condition, addressing the forces of physical obsolescence".	❖ Environmental issues	
6	**Rehabilitation**	Building rehabilitation involves the process of repairing, altering, or adding to a deteriorating building to make it compatible for use. Rehabilitation always involves elements that are damaged or deteriorating and sometimes includes the structure but can involve system, building openings, and envelopes.	❖ Reforming and renovation ❖ Repair and maintenance ❖ Retrofitting ❖ Sustainability concept	(Shahi *et al.*, 2020), (Brás et al., 2017; Garrido et al., 2016), Marques de Jesus, C. R. M. Análise de Custos para Reabilitação de Edifícios para Habitação. 2008. Dissertação (Mestrado) – Es- cola Politécnica da Universidade de São Paulo, Universidade de São Paulo, São Paulo, 2008

After overviewing the adaptation terminologies, the **"rehabilitation"** term has been selected due to:

1) As illustrated in Figure 2.5, rehabilitation refers to **a wider range of the intervention activities** and actions – such as restoration, remodeling and reform, renovation, maintenance, and retrofitting – which seek to recover and improve existing building conditions and extend their effective building lifespan (Access *et al.*, 2019; Shahi *et al.*, 2020).

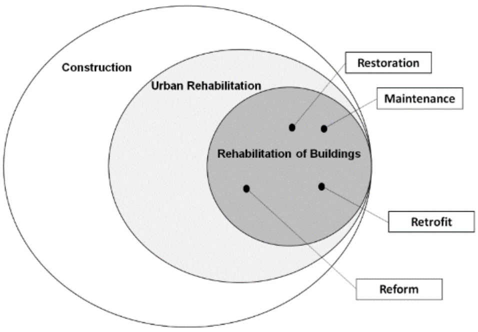


Figure 2.5. Rehabilitation of buildings in the construction sector and its activities, adopted from Marques de Jesus et al., 2008.

2) The rehabilitation processes **have an alignment with the sustainability concept** (Access *et al.*, 2019), which is more relative to the topic of the thesis.

Therefore, in the present doctoral dissertation, the "interior rehabilitation" term has been selected that consists of the rehabilitation of the interior spaces and interior layer of the façade, excluding the structure and building's services.

2.2.2. Overviewing common existing interior rehabilitation techniques and activities in Iran

There is a wide range of construction activities, techniques, and building processes for interior rehabilitation of MHs due to the variation in: the growing number of construction techniques and technologies, materials, designs, market trends, and stakeholders' opinions. Moreover, based on **overviewing the existing interior rehabilitation projects in Iran** through Iran's construction market, on-site surveying of the rehabilitated apartment units in the defined case study, and consulting with experts – architects, designers, engineers, and construction practitioners –, it is revealed that these projects were rehabilitated **partially** or **integrally**. For instance, some owners simply have done partial rehabilitation such as applying wallpapers, painting walls, changing ceramics or toilet tiles, while others have applied more significant changes in spaces and rehabilitated their apartment integrally by demolishing one or several walls, changing architectural plan – proportion, size, shape, and function of space/s –, changing the functional layouts, improving heating or cooling systems and so on. In this regard, in the following figures, some rehabilitated real examples of one of the apartment types in the defined case study have been presented in order to figure out different implemented rehabilitation techniques and activities.

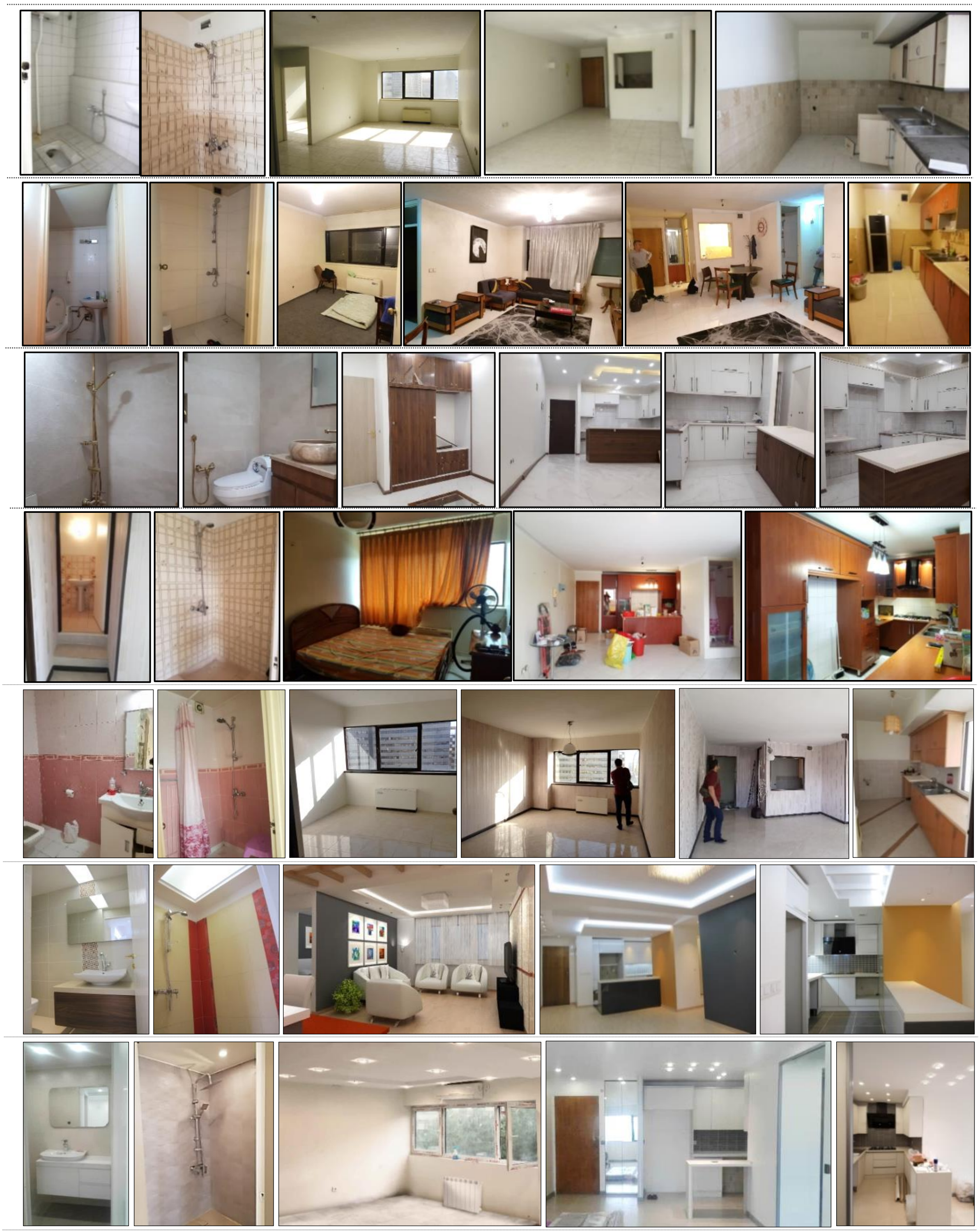


Figure 2.6. Some rehabilitated real examples of one of the apartment types in the defined case study

Based on the conducted questionnaires – see section 6.3 –, the obtained results expressed that most of the implemented interior rehabilitations – as some of them have been illustrated in Figure 2.6 – do not fulfill the current needs of their occupants. Moreover, most of the **existing interior rehabilitation techniques and activities** – such as traditional and conventional ones – **have long been criticized** because of their low productivity, poor quality and safety records, long-lasting construction time, and large quantities of waste generation (Meijer, Itard and Sunikka-Blank, 2009; Stenberg, Thuvander and Femenias, 2009; Thuvander *et al.*, 2012; Dobson *et al.*, 2013; Rieradevall i Pons, 2014). Furthermore, the aforementioned techniques **do not satisfy the contemporary building standards** regarding mobility, flexibility, accessibility, multi-functionality, assembly or disassembly, and performance parameters (Stenberg, Thuvander and Femenias, 2009; Thuvander *et al.*, 2012). These parameters are crucial for sustainability due to their direct relation with social, economic, and environmental aspects (Thuvander et al., 2012). In this regard, **replacing** the traditional and conventional interior rehabilitation techniques **with new or improved** ones **can be a solution to the lack mentioned above**.

To do so, in the following section, the author has overviewed some **existing significant examples** of **interior rehabilitation projects constructed** by **advanced**, **improved**, **or innovative techniques and technologies** to (1) get familiar with their applied construction systems and mechanisms, architectural characteristics, applications, and the opportunities that they provide for their interior spaces, and (2) test and validate the assumed hypothesis – see section 1.3.

2.2.3. Overviewing significant examples of interior rehabilitation projects constructed with new or improved techniques and technologies in the world

This section studies eleven examples as follows: (1) LifeEdited-1, Graham Hill, 2010; (2) Small Home Smart Home, LAAB architects, 2014-2015; (3) YO! Home, Simon Woodroffe, 2012; (4) 24 Rooms Tucked into One, Gary Chang, 2012; (5) The POP-UP House in Madrid, Spain, TallerDE2, 2014; (6) CityHome, MIT Media Lab's, 2014 ; (7) MJE House, PKMN architectures, 2014; (8) "All I Own House", Madrid, PKMN architectures, 2013; (9) Barcode Room, Studio-01, 2012; (10) The Smart Zendo, Sim-Plex, 2019; and (11) Transformer Apartment, Vlad Mishin, 2014.

Example 1. LifeEdited-1, Graham Hill, 2010

LifeEdited-1, also known as "6 rooms into 1", was designed to upgrade and rehabilitate a 50-year-old apartment. In this project, by applying movable and transformable elements and furniture, its designers intended to provide 6 different architectural layouts in a 42 m^2 apartment. Moreover, for designing this project, the designers made an effort to create more living and storage spaces that were more efficient and functional for better responding to its occupants' needs (https://lifeedited.com/about/, https://www.dezeen.com/2018/08/09/lifeedited2-tiny-new-york-apartment-graham-hill-functions-like-one-twice-its-size/, https://www.businessinsider.com/graham-hill-lifeedited-apartment-2013-3#heres-the-bathroom-its-split-into-a-separate-shower-and-toilet-area-the-fixtures-are-from-fluid-and-caroma-designed-the-sink-and-toilet-12, https://faircompanies.com/videos/6-rooms-into-1-morphing-apartment-packs-1100-sq-ft-into-420/, https://lifeedited.com/very-brief-history-of-lifeedited/, https://www.jovoto.com/projects/lifeedited/ideas/10288?page=1&scope2=team_ideas&scope=rating, https://inhabitat.com/this-amazing-420-square-foot-transforming-apartment-can-be-yours-for-995000/lifeedited-graham-hill-apartment-lead/). A movable wall – partition – which was located between the living room and bedroom, not only separates these two spaces, but also includes some furniture such as study desk, dining table, home office desk, TV, home theater with a digital projector, and closets. By moving this wall, the living room and bedroom spaces can be expanded to provide an integrated area or shrunk when needed (Figure 2.7). Also, two murphy beds – one of them in the bedroom and the other one in the living room – were designed to transform/convert this apartment into a two-bedroom apartment. Furthermore, to provide more visual and acoustic privacy for these two spaces, two magnetized curtains were designed and applied. In general, the aforementioned features permitted this space to be used, one at a time, as a living/lounge area for 8 people, a dining area for 6 people, and two bedrooms for 2 couples (https://lifeedited.com/about/).

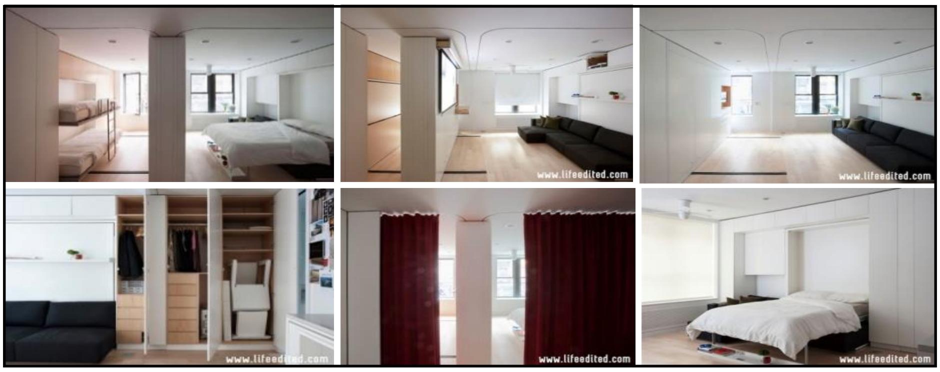


Figure 2.7. The LifeEdited-1 project, Graham Hill, 2010

Example 2. Small Home Smart Home, LAAB architects, 2014-2015

Small Home Smart Home was designed by LAAB architects for a young couple with their 3 cats that needed a large kitchen, guest bedroom, full-size bathtub, home cinema, gym, and cat-friendly features all in an apartment of 31 m^2 (https://www.do-shop.com/blogs/interior-spaces/122291779-small-home-smart-home-by-laab). An ingenious design scheme rehabilitated and transformed the minuscule space into a high-tech multi-functional living machine (https://www.do-shop.com/blogs/interior-spaces/122291779-small-home-smart-home-by-laab). In this project (Figure 2.8), the best part of an entire wall was dedicated to the kitchen, but to avoid blocking the windows – natural light, natural ventilation, and view – the cabinets can be retracted into the ceiling space by pushing a button (https://www.designboom.com/architecture/laab-architects-small-home-smart-home-hong-kong-flexible-interiors-04-26-2016/). Also, an enormous TV screen slides out of the wall that transforms this space into a home cinema, where guests can lounge on two levels' seats (https://www.designboom.com/architecture/laab-architects-small-home-smart-home-hong-kong-flexible-interiors-04-26-2016/). Moreover, the new rehabilitated apartment provides two sleeping areas for two couples (https://newatlas.com/laab-small-home-smart-home-hong-kong/42637/). The architects tried to make the most of this tiny space apartment, by applying sliding panels and high-tech and smart technologies to create more efficient and functional living and storage space and provide more natural light, natural ventilation as well as improving visual comfort (https://newatlas.com/laab-small-home-smart-home-hong-kong/42637/; https://www.do-shop.com/blogs/interior-spaces/122291779-small-home-smart-home-by-laab; https://www.designboom.com/architecture/laab-architects-small-home-smart-home-hong-kong-flexible-interiors-04-26-2016/).

Figure 2.8. Small Home Smart Home, LAAB architects, 2014-2015

Example 3. YO! Home, Simon Woodroffe, 2012

Architect Simon Woodroffe rehabilitated an 80 m^2 apartment by introducing the first prototype of *YO!Home* in 2012 (https://laughingsquid.com/yo-home-transforming-apartment-inspired-by-stage-scenery-design/). The main idea of this project was the application of movable and transformable architectural elements – ceiling, walls, and floors – and furniture to optimize the living and storage spaces (https://www.dezeen.com/2012/09/20/yo-home-at-100-design/; https://yo.co.uk/). In this project (Figure 2.9), the applied 12 moving parts enable the transformation of a one-bedroom apartment into a much bigger one with two bedrooms, two living rooms, a cinema, an office, a kitchen and dining room, a bathroom with a hot tub, and a wine cellar (https://laughingsquid.com/yo-home-transforming-apartment-inspired-by-stage-scenery-design/). In later years, the second prototype of *YO!Home* was developed to rehabilitate a 40 m^2 apartment by following the first concept. This second prototype was developed by improving the prefabrication and modularity concept of the project by constructing 24 different apartments that optimized its rehabilitation cost and time, functionality of spaces, and building aesthetic (https://www.dezeen.com/2012/09/20/yo-home-at-100-design/; https://yo.co.uk/).

Figure 2.9. YO! Home, Simon Woodroffe, 2012. Top: the first prototype of YO!Home, bottom: the second prototype of YO!Home.

Example 4. 24 Rooms Tucked into One, Gary Chang, 2012

24 Rooms Tucked into One is an apartment built in the 1960s in Hong Kong that was rehabilitated by architect Gary Chang in 2012. By innovative open-plan design and applying sliding walls and panels besides transformable furniture, this architect transformed a 32 m^2 apartment into 24 different architectural spaces such as a living room with a hammock, a guest room, a dressing room, a bathroom, a study room, a kitchen and stand bar, an enclosed dining area, and lots of storage spaces (spacehttp://www.meldrenachapin.com/blog/wordpress/2012/05/04/living-smaller-24-rooms-tucked-into-one/; https://www.jebiga.com/hong-kong-micro-apartment-gary-chang/;https://www.nytimes.com/2009/01/15/garden/15hongkong.html). In this way, the architect injected more efficient and functional living and storage spaces to this apartment. Moreover, since the apartment's initial state was facing poor natural lighting and indoor air quality, this new design improved lighting comfort and indoor air quality. Also, according to the BBC report (https://www.bbc.com/news/world-asia-china-21973486), the property value of this rehabilitated apartment increased significantly – more than two times – in comparison with its initial price. As indicated in ArchDaily (https://www.archdaily.com/59905/gary-chang-life-in-32-sqm), *24 Rooms Tucked into One* represents a remarkable example of interior rehabilitation (Figure 2.10).

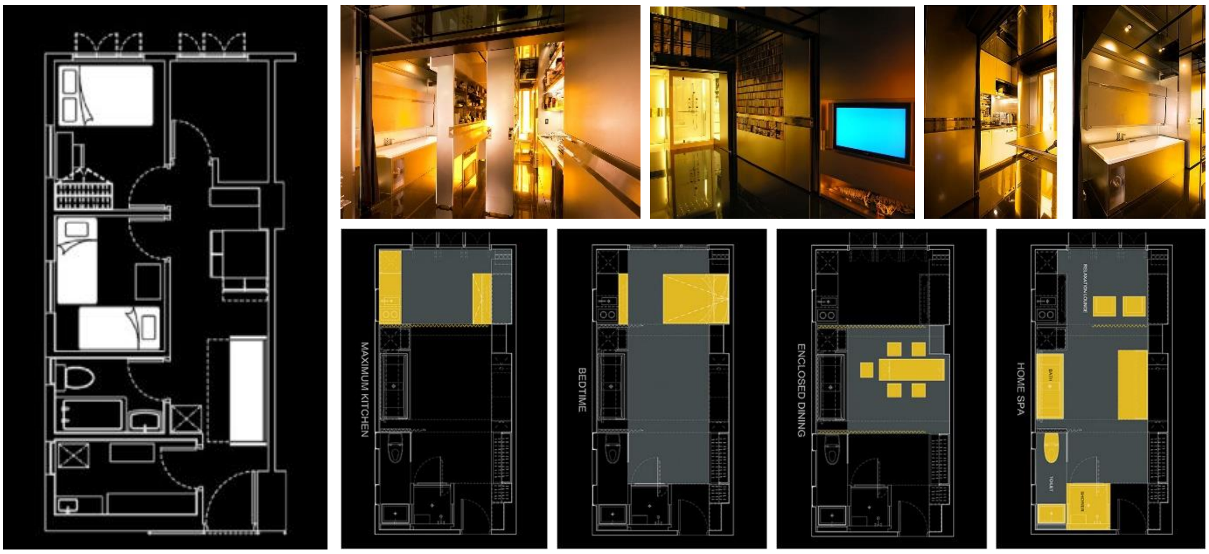


Figure 2.10. 24 Rooms Tucked into One, Gary Chang, 2012. Left: the initial state of the apartment, right: after interior rehabilitation of the apartment

Example 5. The POP-UP House in Madrid, Spain, TallerDE2, 2014

The POP-UP House is an integral rehabilitated residential apartment from the mid-20th century in Madrid (https://www.plataformaarquitectura.cl/cl/758987/the-pop-up-house-tallerde2-arquitectos). Inspired by an old set of traveling trunks, the architects, *TallerDE2*, employed 54 modular divider units made from recycled OSB boards and custom-built space-saving furniture to rehabilitate a small and ordinary apartment into a unique and spacious bachelor pad (https://www.metalocus.es/es/noticias/la-casa-pop-por-tallerde2-arquitectos). These architects removed all dividing walls to provide an additional 27 percent of usable floor space (https://www.plataformaarquitectura.cl/cl/758987/the-pop-up-house-tallerde2-arquitectos). In this way, it is intended to not only provide more functional and efficient spaces but also apply eco-friendly and low-cost materials (Figure 2.11) (http://www.tallerde2.com/projects/built/the-pop-up-house; http://inhabitat.com/tallerde2s-pop-up-house-reinvents-the-bachelor-pad-with-modular-osb-units/tallerde2-arquitectos-transformable-osb-units-pop-up-house 7/;https://www.plataformaarquitectura.cl/cl/758987/the-pop-up-house-tallerde2arquitectos). Moreover, the unique and integrated design of this project improved the aesthetic and visual comfort of interior spaces (https://www.metalocus.es/es/noticias/la-casa-pop-por-tallerde2-arquitectos).

Figure 2.11. The POP-UP House in Madrid, Spain, TallerDE2, 2014

Example 6. CityHome, MIT Media Lab's, 2014

In 2014, the MIT Media Lab team introduced a "home in a box" rehabilitation project known as *CityHome* by applying high-tech devices and technologies that can make a 20 m^2 space feel like a room three times larger (http://inhabitat.com/watch-this-mit-researcher-triple-the-size-of-a-200-foot-apartment-using-minority-report-like-gestures/). The CityHome fits a bed, a workspace, a dining table for six persons, a kitchen counter, a stovetop, and a multipurpose storage space all within a large closet-sized module (Figure 2.12) (https://www.businessinsider.com/cityhome-apartment-in-a-box-2014-5). The designed low-friction rollers in this box provide easily sliding around the apartment. Moreover, interior spaces can be expanded or shrunk by gestures, touch, and voice commands to respond to the occupants' needs (https://www.fastcompany.com/3030991/mits-cityhome-is-a-house-in-a-box-you-control-by-waving-your-hand).

Figure 2.12. CityHome, MIT Media Lab's, 2014

Example 7. MJE House, PKMN architectures, 2014

MJE House is an innovative flexible 70 m^2 apartment that is located in Spain and was rehabilitated by PKMN architectures as a home for a couple in 2014 (http://inhabitat.com/rotating-walls-and-transformable-furniture-make-two-rooms-vanish-in-the-little-big-mje-house/; https://www.metalocus.es/en/news/mje-house-little-big-houses). The main design concept of this project relies on providing different architectural distributions based on its users' needs (https://www.metalocus.es/en/news/mje-house-little-big-houses). In this regard, by the application of mobile and transformable elements – e.g., patriations and furniture –, the configuration of interior spaces can be changed radically (Figure 2.13) (https://www.plataformaarquitectura.cl/cl/774674/casa-mje-pequenas-grandes-casas-number-2-pkmn-architectures). For instance, the dynamic wall located in the central part of this apartment enables adding either one or two bedrooms in less than a minute. Moreover, to provide more visual and acoustic privacy for bedrooms' spaces, sliding panels were designed and applied (https://www.designboom.com/architecture/pkmn-architectures-casa-mje-house-pequenas-grandes-casas-spain-asturias-10-04-2015). Also, its architects maximized natural light by choosing white walls and surfaces (http://inhabitat.com/rotating-walls-and-transformable-furniture-make-two-rooms-vanish-in-the-little-big-mje-house/; https://www.metalocus.es/en/news/mje-house-little-big-houses).

Figure 2.13. MJE House, PKMN architectures, 2014

Example 8. "All I Own House", Madrid, PKMN architectures, 2013

"All I Own House" project was designed by PKMN architects to rehabilitate a single-story house constructed in 1942 in Madrid (https://docplayer.es/17950692-All-i-own-house-madrid-espana-pkmn-architectures.html). 15 m^2 of this 50 m^2 house was allocated to create four main architectural spaces – kitchen, study room, bedroom, and bathroom – by applying three wooden, suspended, mobile and transformable containers (Figure 2.14). These containers were built from OSB and suspended by a simple industrial railing system from the ceiling that can be easily rearranged in seconds (http://inhabitat.com/sliding-modular-dividers-effortlessly-transform-a-tiny-interior-into-a-multifunctional-apartment-in-madrid/all-i-own-house-by-pkmn-architectures-4/; https://www.metalocus.es/en/news/all-i-own-house-yolandas-house-pkmn). These containers were equipped with space-saving furniture including a foldaway bed, work surface, dining table, and storage space. The first and slimmest unit comprises furniture for kitchen and workspace, while the second unit contains a foldaway bed, additional storage, and sliding panels that can be extended for privacy. The third unit, located opposite the bathroom, serves as a dressing room and contains most of storage space. Its architects made an effort to design this project not only with low-cost and eco-friendly materials but also with respect to the occupant's personal belongings and needs (http://inhabitat.com/sliding-modular-dividers-effortlessly-transform-a-tiny-interior-into-a-multifunctional-apartment-in-madrid/all-i-own-house-by-pkmn-architectures-4/;https://www.metalocus.es/en/news/all-i-own-house-yolandas-house-pkmn). Also, this innovative design provides more natural light for all spaces of this house (http://inhabitat.com/sliding-modular-dividers-effortlessly-transform-a-tiny-interior-into-a-multifunctional-apartment-in-madrid/all-i-own-house-by-pkmn-architectures-4/).

Figure 2.14. "All I Own House", Madrid, PKMN architectures, 2013

Example 9. Barcode Room, Studio-01, 2012

One of the successful interior design projects is *Barcode Room* designed and constructed by Studio 01 architectural firm, which was the winner of a design competition (https://www.thecoolist.com/transforming-interiors-designs-modular-smart-homes/). The concept of this project is based on designing a set of furniture-walls (bars) – that seems like a barcode – that can move freely from one side to another, allowing the user to customize the size of the space to adapt to a variety of uses (https://www.thecoolist.com/transforming-interiors-designs-modular-smart-homes/). Its architects designed 12 different furniture-walls or bars that contain different architectural components like closet, table, or chair that can be pulled out or unfolded as needed (Figure 2.15). Different combinations of bars result in different spaces and layouts such as living room, kitchen, study room, dining room, and bedroom (https://www.thecoolist.com/transforming-interiors-designs-modular-smart-homes/). The ingenious design of this project not only provides the dynamic quality of the size and the changing continuity of this space that generates a feeling of connectedness and enlargement of the small area but also creates more functional layouts and storage spaces (https://www.plataformaarquitectura.cl/cl/615576/barcode-room-un-espacio-minimo-y-flexible-a-traves-de-muebles-dinamicos). Moreover, by the application of prefabricated modular architectural elements in this project, its construction time and costs decreased significantly (https://www.plataformaarquitectura.cl/cl/615576/barcode-room-un-espacio-minimo-y-flexible-a-traves-de-muebles-dinamicos). Its architects applied eco-friendly materials to improve the environmental sustainability performance of this project (https://www.plataformaarquitectura.cl/cl/615576/barcode-room-un-espacio-minimo-y-flexible-a-traves-de-muebles-dinamicos).

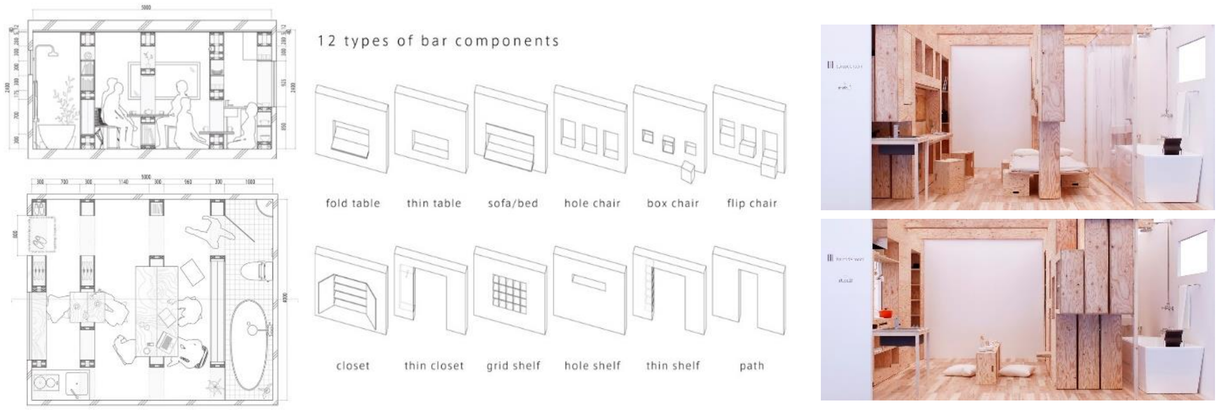


Figure 2.15. Barcode Room, Studio-01, 2012

Example 10. The Smart Zendo, Sim-Plex, 2019

The Sim-Plex is an architectural firm expert in interior rehabilitation of residential buildings that by using smart technologies, space-saving architectural elements, and flexible and transformable architecture could provide multi-purpose and multifunctional spaces (SIM-PLEX (sim-plex-design.com); Smart Zendo: A Hong Kong Apartment with Clever Storage + Smart Tech (design-milk.com)). One of their innovative projects is *the Smart Zendo apartment* which has a 45 m^2 area. In this project, by considering the traditional Chinese philosophies of Zen and Feng Shui besides the proper application of smart technologies, transformable architecture, and space-saving furniture, these designers provided not only multifunctional spaces but also improved the harmony, aesthetic, and beauty of the interior spaces (Figure 2.16) (SIM-PLEX (sim-plex-design.com)). Also, these designers tried to use low-cost and eco-friendly local materials in this project (SIM-PLEX (sim-plex-design.com); Smart Zendo: A Hong Kong Apartment with Clever Storage + Smart Tech (design-milk.com)).

Figure 2.16. The Smart Zendo, Sim-Plex, 2019

These architects designed this project living room on top of an elevated modular wooden platform that allows the transformation of this area into a dining room, playroom, cinema, or guest bedroom as well as providing a lot of storage spaces (SIM-PLEX (sim-plex-design.com)). In this living room, a hidden central dining table pops up from its platform, transforming this space into a dining area in a matter of seconds. Also, in this space, a large floor-to-ceiling window provides natural lighting and ventilation. Adjacent to this multi-purpose living room, there is a modern kitchen complete with quartz stone benchtops, additional seating for casual dining, and flat-screen wall-mounted television (SIM-PLEX (sim-plex-design.com); Smart Zendo: A Hong Kong Apartment with Clever Storage + Smart Tech (design-milk.com)). The living room can be closed off from the open kitchen area with a lightweight sliding folding door as a separation wall that allows the living room to be transformed into a guest bedroom with the added benefit of privacy (Hong Kong micro apartment packs smart tech into transformable spaces (newatlas.com)). Other sections of this project include a master bedroom, with ample built-in wardrobe space, storage and a hidden dressing table, study desk, and wooden platform for additional storage; and the main bathroom with marble tiles and melamine waterproof cabinetry. This project was also equipped with several smart technologies and remote-control features – including voice-activated synthesizers, automatic blinds, automatic lifting dining table, lighting and air-conditioning, electronic hidden projection screen, and electronic door locks – (Hong Kong micro apartment packs smart tech into transformable spaces (newatlas.com)).

Example 11. Transformer Apartment, Vlad Mishin, 2014

A Russian interior designer, Vlad Mishin, in one of his projects known as *Transformer Apartment*, rehabilitated a 62 m² apartment by the application of several transforming elements that can change the entire configuration of the apartment according to its users' needs (https://projects.archiexpo.com/project-29886.html; http://www.home-designing.com/2013/04/unique-transformer-apartment-concept). A rotating wall located between living room and bedroom enables both separate on and integration of space as well as the usage of TV for these two spaces when needed (https://www.thecoolist.com/transforming-interiors-designs-modular-smart-homes/). A continuous geometrical patterned wall made of plywood added more unity, integrity, and harmony to improve interior spaces' aesthetic (Figure 2.17) (https://projects.archiexpo.com/project-29886.html). In this bedroom, a bed nook with a lot of storage space and a styling workspace were designed (https://projects.archiexpo.com/project-29886.html).

Figure 2.17. Transformer Apartment, Vlad Mishin, 2014

2.2.4. Interior rehabilitation policies, laws, and regulations in Iran

For interior rehabilitation of residential buildings and MHs in Iran, the following **hierarchical policies and regulations** (Figure 2.18) have been established by different organizations and entities: the National Building Regulations, building laws and regulations of the municipality, the law of the establishment of settlements, and the law of ownership of apartments.

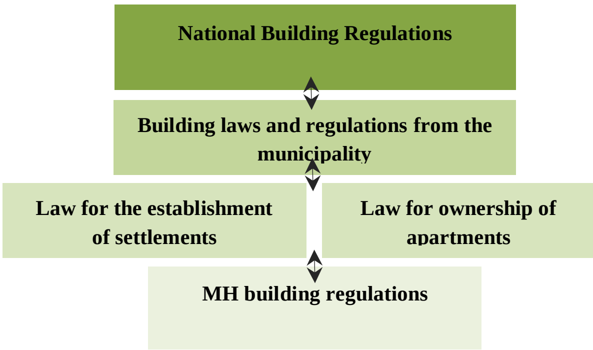


Figure 2.18. Hierarchical building policies, laws, and regulations in Iran

Among these regulations and policies, the **most important** are the **National Building Regulations** established by the Ministry of Road and Urban Development in 1973 (https://www.mrud.ir/en). These National Building Regulations have been codified and categorized into 22 different topics regarding technical, administrative, and legal regulations for designing, supervising, and executing construction activities, rehabilitation and renovation, and demolition (https://www.mrud.ir/en). It is worthy to note that the 22nd topic of these regulations deals with the maintenance and rehabilitation of buildings (http://www.nbri.ir/مباحث-مقررات-ملی-ساختمان).

Besides these National Building Regulations, there are other building regulations such as building laws and regulations from municipalities (https://en.tehran.ir/) – established by each city's municipality, the law for the establishment of settlements – established in 1981 by the Islamic Parliament of Iran (https://en.parliran.ir/) –, and the law for ownership of apartments – established in 1965 by the Parliament of Iran (https://en.parliran.ir/; https://rc.majlis.ir/fa/law/). Moreover, each MH has its own building regulations regarding maintenance and rehabilitation activities established by its central board of directors based on the aforementioned superior regulations.

2.3. Considerations on the sustainability of interior rehabilitation of MHs

This part is divided into three main sections as follows: firstly, section 2.3.1. describes the importance of considering sustainability in the assessment and selection process of interior rehabilitation of MHs; secondly, section 2.3.2. overviews several well-known sustainability evaluation methods regarding this thesis topic; thirdly, section 2.3.3. overviews the relevant and potential sustainability parameters for sustainability assessment of interior rehabilitation of MHs in Iran.

2.3.1. Importance of considering sustainability in the assessment and selection process of interior rehabilitation of MHs

Since the 1980s, the sustainability concept has emerged as a new concept in the building and construction industries, with the aim to achieve the sustainable development goal (Sadineni et al., 2011; Bragança et al., 2010). Over the last three decades, a great deal of efforts – numerous regulations, directives, events, and initiatives such as World Conservation Strategy by UN Environment Program, World Wildlife Fund, International Union for Conservation of Nature and Natural Resources (UNEP/WWF/IUCNNR, 1980); World Commission on Environment and Development (WCED,1987); United Nations Conference on Environment and Development (UNCED, 1992); Goodland, 1995 (Goodland, 1995); and, World Summit on Sustainable Development (WSSD, 2002) – have intended to establish and improve this sustainability framework. In general, the sustainability concept consists of three main pillars – also named as aspects – that are economic, environmental, and social (Pitney, 1993; Spence and Mulligan, 1995; Hill and Bowen, 1997; Ofori and Chan, 1998; Bourdeau, 1999; Ofori et al., 2000; Ding, 2008; Abidin, 2010). In other words, **this sustainability concept** intends to **increase economic and social performance** and **decrease**

negative environmental impacts over the life cycle of a building (Shen et al., 2010) as well as **contribute to establishing a balance among these three pillars** (Kamali, Hewage and Milani, 2018).

Based on several studies and reports (IIASA, 2012; IPCC, 2007, 2014; Mckinsey, 2009; Ürge-Vorsatz, Harvey, Mirasgedis, & Levine, 2007; UNEP, 2009, 2011; UNEP, 2016; WEC, 2013, Eurostat databases, 2016, UN Environment and International Energy Agency,2017; Worldwatch Institute, 2016; Heravi & Abdolvand, 2019; Pombo, Rivela, & Neila, 2019; Zarghami, Fatourehchi, & Karamloo, 2019b), the large segment of the building industry, which is formed by residential buildings, accounts for 40% of global energy consumption, 35% of CO_2 emissions, 16% of global water consumption, 60% of global material resource consumption, and, 40% of global solid waste generation. Moreover, the building industry accounts for a major share of the world's economy, up to 45% (Rhodes, 2015). Therefore, **considering the sustainability concept in all construction phases** – design, implementation, maintenance and rehabilitation, and demolition and building end of life – **should receive more attention**, especially in developing countries where sustainability requirements are mostly ignored (Zarghami *et al.*, 2018).

Although there exists a vast amount of literature about buildings' sustainability, to the best of this thesis author's knowledge, heretofore, there is **no study regarding a holistic** and **integrated sustainability assessment of interior rehabilitation of MHs**. Moreover, the existing studies employed different sustainability evaluation methods with different sustainability parameters – requirements, criteria, and indicators – which most of them are **not applicable for the topic of the present thesis and the selected case study** – see sections 1.2, 1.4, 1.5, and 2.3.2. In this regard, section 2.3.2 overviews several sustainability evaluation methods to identify the most proper one regarding this thesis topic, and section 2.3.3 studies relevant and potential sustainability parameters – requirements, criteria, and indicators – to identify the most appropriate ones for sustainability assessment of interior rehabilitation of MHs.

2.3.2. Overviewing previously used methods for sustainability assessment of interior rehabilitation of MHs

Over the last three decades, a great deal of effort has been made in various construction industry sectors related to Building Sustainability Assessment (BSA) (Sadineni et al., 2011; Bragança et al., 2010). Consequently, several BSA systems, tools, and methods have been established that can be categorized into (1) ***Sustainable Building Rating and Certification Systems (SBRCSs)*** such as LEED, BREEAM, LEAN, BEAM, DGNB, VERDE, CASBEE, SBTool –, and (2) ***Individual Sustainability Assessment Models (ISAMs)*** that are mostly based on **Multi-Criteria Decision Making** (MCDM) methods (Bragança, Mateus and Koukkari, 2010; Mahmoud, 2017). As previously mentioned in section 1.2, the ***SBRCSs*** **have some weak points** that make them **inapplicable** for sustainability assessment of MHs in **Iran**. Some of these weaknesses are as follows:

a) Most of these ***SBRCSs*** are **limited to a regional context** like climate, geographical features, types of building stocks, local policies, regulations and standards, and their historical features and culture value (Bragança, Mateus and Koukkari, 2010; Banani, Vahdati and Elmualim, 2013; Mahmoud, 2017; Zarghami, Fatourehchi and Karamloo, 2019a). Therefore, most of these *SBRCSs* can only represent their own local or regional scales and by applying them to Iran, no precise result would be obtained (Banani, Vahdati and Elmualim, 2013). Also, there are a few global-scale rating systems, but they are still not applicable to developing countries like Iran (Zarghami *et al.*, 2018).
b) Also, these *SBRCSs* mostly – almost 90 percent – **focus on one or two aspects of sustainability** instead of a holistic sustainability evaluation (Zarghami *et al.*, 2018; Gilani, 2020). According to numerous investigations, most of these systems **neglect the social aspect** of sustainability (Meijer, Itard and Sunikka-Blank, 2009; Davoodi, Fallah and Aliabadi, 2014; Gould, Missimer and Mesquita, 2017; Karji, Woldesenbet and Khanzadi,

2017; Xiahou *et al.*, 2018; Zarghami, Fatourehchi and Karamloo, 2019a; Karji *et al.*, 2019a; Liu and Qian, 2019; Olakitan Atanda, 2019; Shirazi and Keivani, 2019; Olawumi *et al.*, 2020) which is the main reason for interior rehabilitation (van der Flier and Thomsen, 2006; Meijer, Itard and Sunikka-Blank, 2009; Thuvander *et al.*, 2012; Ahmad and Thaheem, 2017a). Moreover, the existing *SBRCSs* **rarely evaluate stakeholders' satisfaction** (Hosseini, De la Fuente and Pons, 2016; Hosseini, Fuente and Pons, 2016; Gilani, 2020).

c) **The weight of each indicator** in the aforementioned rating systems is **predefined** according to local socio-cultural, environmental, and economic contexts (Bragança, Mateus and Koukkari, 2010; Mahmoud, 2017) that should be redefined according to Iran's sustainability requirements.

d) These rating systems evaluate sustainability performance through numerous indicators and tens of parameters across the different sustainability aspects (Bragança, Mateus and Koukkari, 2010; Zarghami *et al.*, 2018; Zarghami, Fatourehchi and Karamloo, 2019a). As **many of these indicators** are **not relevant** or **adequate** to evaluate the sustainability performance of MHs' interior rehabilitation, they are not applicable in the present doctoral dissertation.

e) These abovementioned rating systems mainly focus on evaluating a Global Sustainability index (GS_i); however, **the effect of every single indicator** on sustainability performance **is ignored** (Hosseini, Pons and De la Fuente, 2018; Gilani, 2020).

All of these shortfalls regarding *SBRCSs* lead numerous researchers (Mateus and Bragança, 2011; Mahmoud, 2017; Mahmoud, Zayed and Fahmy, 2018; Zarghami *et al.*, 2018) to develop *ISAMs* to fulfill their project's objectives. Since developing *ISAM* is a multi-criteria and multi-participant procedure, several researchers employed MCDM methods (Moghtadernejad, Chouinard and Mirza, 2018). Multi-Criteria Decision-Making (MCDM) methods, as a branch of operational research, are gaining importance as potential tools for analyzing and solving complex problems due to their inherent ability to evaluate different alternatives, by considering various criteria, for possible selection of the best alternative (Chakraborty et al., 2015).

There are numerous available MCDM methods. In order to select the most appropriate one regarding the topic of the present thesis, the author has overviewed several well-known MCDM methods, their application area, and their strengths and weaknesses as described in Table 2.3.

Table 2.3. Summary of the common MCDM methods

Methods	Description	Application area	Strengths	Weaknesses	References
Weighted Sum Method (WSM)	The earliest, simplest, and most commonly used MCDM approach for evaluating a number of alternatives in terms of a number of decision criteria. WSM determines an average weighting for each alternative through the addition of the contribution of each attribute multiplied by its weights.	Structural optimization and energy planning	WSM generates the most suitable results in single-criteria problems. Simple computation	Only a basic estimate of designer's preferences. Difficulty in multi-dimensional problems where the criteria units are different, and their numerical values are occasionally several orders of magnitude apart.	(MacCrimon,1968;Triantaphyllou, 2000; Kolios, Mytilinou, & Lozano-minguez, 2016; Moghtadernejad et al., 2018; Sierra, Yepes, & Pellicer, 2018)
Weighted Product Method (WPM)	Very similar to WSM and creates a ranking of alternatives based on a multiplicative measure. It was proposed as an alternative to overcome the single-dimensionality problem of the WSM.	Optimization	It is dimensionless and can be used in single or multi-dimensional decision-making problems.	It priorities or deprioritizes the alternative which is far from average. The normalization approach considers only two performance values, i.e., minimum (for non-beneficial attributes) and maximum (for beneficial attributes), and does not include all the significant values.	(Triantaphyllou, E. & Mann, S.H., 1989; Triantaphyllou,2000; Moghtadernejad et al., 2018; Zavvadskas, Turskis, & Antuchevicien, 2012)
Elimination and Choice Translating Reality (ELECTRE)	An outranking method that uses pairwise comparisons to evaluate the degree of preferences between available alternatives. It selects the alternatives that are favored over most of the criteria and do not have an unacceptable performance in any of the other criteria. Also, the method applies a positive and negative assessment for each alternative and creates a ranking in relation to the decision weights.	Energy management, building structures and seismic retrofitting	Deals with both quantitative and qualitative criteria. Final results are validated with reasons. Deals with heterogeneous scales. Takes uncertainty and vagueness into account.	Time consuming and Complex application. Despite having 4 revisions it is still not perfect, and sometimes cannot identify an optimal alternative. It only provides a better view of the available alternatives by discarding the less favorable ones.	(Roy, Bernard,1968)

Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS)	An alternative to the ELECTRE method and is based on the concept that the best alternative for a multi-criteria decision-making problem is the one closest to a positive ideal solution and farthest from a negative ideal solution. It is a method of compensatory aggregation that compares a set of alternatives through the weights of their criteria and standardized scores.	Building structures, energy management, construction technologies, demolition, and seismic retrofitting	Works with fundamental rankings and makes full use of allocated information. Easy to use. Clearness. Simple mathematical form.	Since it uses Euclidian distances it does not consider the correlation of attributes. Difficult to weight and keep consistency of judgment.	(Kucukvar et al., 2014; Triantaphyllou, 2013; Velasquez and Hester, 2013)
Preference Ranking Organization Method (PROMETHEE)	Belonging to the methods of the outranking family and based on the selection of a preference function for each alternative that is part of the multi-criteria decision-making issue. This method is based on the pairwise comparison between alternatives to establish a relationship of outranking of one over another. The method applies a positive and negative assessment for each alternative and creates a ranking in relation to the decision weights.	Risk analysis, building structures and seismic retrofitting	Possibility of group-level decision-making. Deals with qualitative and quantitative information. It can incorporate uncertain and fuzzy information.	It does not structure the criteria properly. The difficulty of assigning weights and complexity of the process. It is time-consuming and dependent on the presence of experts. Lack of consideration of interactions and correlations among criteria.	(Gervasio and Da Silva, 2012)
Licence Agreement VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)	It ranks the alternatives based on their distance from the ideal solution. It can generate multiple solutions instead of one; which occurs when none of the alternatives stands out, and there are several alternatives as close to the ideal solution as the one that is the closest.	Energy policy and seismic retrofitting	An updated version of TOPSIS. It has become more interactive and allows the decision-maker to adjust the weights via the information generated by a trade-off analysis.	It needs some modifications as it is sometimes difficult to model a real-time model. The difficulty of dealing with conflicting situations. Lack of consideration of interactions among criteria.	Opricovic, 2007; (Curiel-Esparza et al., 2016) (Moghtadernejad, Chouinard and Mirza, 2018; Sierra, Yepes and Pellicer, 2018)
Spanish Integrated Value Model for Sustainability Assessment (MIVES)	This method is capable of specialized, holistic and integrated sustainability assessment by considering the main sustainability requirements (economic, environmental and social) to obtain global sustainability indexes. One of the main characteristics of MIVES that makes it unique among other MCDM methods is the use of value functions to measure the satisfaction grade of various stakeholders involved in the decision-making procedure.	Sustainable building and construction technologies	Allows minimizing the subjectivity in the assessment. Adaptability, specificity, and the inclusion of multiple data inputs. Measuring the satisfaction grade of various stakeholders involved in the decision-making procedure.	The difficulty of assigning weights and complexity of the process which depends on the input from a panel of experts. Time-consuming.	(Vinolas et al., 2009; Pons, de la Fuente, & Aguado, 2016)
Complex Proportional Assessment (COPRAS)	A step-by-step method by ranking alternatives based on several criteria by using criteria weights and utility degree of alternatives. The selection of the best alternative is based on considering ideal and anti-ideal solutions.	building construction and retrofitting, construction contract	Evaluating both maximizing & minimizing criteria values separately. Simple computation process. Less computational time. Ranking alternatives in terms of significance.	Less stable than other methods in the case of data variation. Results obtained by COPRAS depend on the number of minimizing criteria.	(Zavadskas and Kaklauskas, 1996; zavadskas et al. 1994; Podvezko, 2011; Ayrim, et al., 2018; Moghtadernejad et al., 2018)

This comprehensive overview of MCDM methods indicates that one of the main steps of multi-criteria decision-making procedures is assigning weights to the components of these MCDM models (Meadows, 1998; Juwana et al., 2012). As Saisana and Tarantola, 2002; Wilson and Wu, 2017; and Morse et al., 2001 mentioned, the process of assigning weights is inherently subjective, selecting an appropriate weighting method is challenging (Gan *et al.*, 2017). In this regard, based on peer-reviewed journal articles, books, and reports by international organizations and research institutions, the author has selected and classified some well-known and commonly used assigning weights methods, as shown in Table 2.4.

Table 2.4. Common methods for indicators' weighting

Methods	Type	Strengths	Weaknesses	Examples
Equal weighting	Equal weighting	Simple, replicable, and straightforward	No insights into indicator relationships; risk of double weighting.	Human Development Index (UNDP, 1990); Genuine Savings (WorldBank, 1999)
Analytic hierarchy process (AHP)	Public/Expert opinion-based	It has a hierarchical structure that is in line with the structure of sustainability frameworks. Simple and flexible. Providing consistent verification operation. Available for both quantitative and qualitative data.	Requirement of a high number of pairwise comparisons. Inconsistency and cognitive stress may exist if there are too many indicators in each cluster.	Composite sustainability performance index (Singh et al., 2007); Index of Environmental Friendliness (Puolamaa et al., 1996)
Conjoint analysis (CA)	Public/Expert opinion-based	Results can be easily used for making sustainability plans. Available for both quantitative and qualitative data.	Requires a large sample of respondents. Has a complicated estimation process.	Indicator of quality of life in the city of Istanbul (Ülengin et al., 2001)
Delphi Method	Public/Expert opinion-based	Allows use of a "committee" with fewer drawbacks (scheduling, travel/space requirements, costs, time, lengthy discussions). Anonymity reduces the impact of dominant individuals and helps reduce peer pressure to conform, and allows opinions to be considered in a non-adversarial manner. Responses are weighted equally so no one person can shift the opinions of the group. Providing controlled feedback on the group opinion, reduces noise, and allows participants to reconsider based on others' rankings.	lack of clear methodological guidelines. Continued commitment is required from participants who are being asked a similar question multiple times. Does not allow participant discussion and there is no opportunity for participants to elaborate on their opinions. The existence of a consensus does not necessarily mean that the correct answer, opinion, or judgment has been found, it merely helps to identify areas that one group of participants or experts consider important in relation to that topic.	New sustainability assessment model for Intelligent Façade Layers when applied to refurbish school buildings skins (Habibi, Pons and Pena, 2020)
Benefit of the doubt approach (BOD)	Statistic-based	The processes of weighting, aggregation, and index construction are efficiently integrated. Weights are selected to maximize the index for each unit.	Results may not be comparable and lack transparency. A multiplicity of solutions exists.	Meta-index of Sustainable Development (Cherchye and Kuosmanen 2004) Macro-economic performance evaluation (Melyn and Moesen 1991)

Factor Analysis (FA)	Statistic-based	Reduces the risk of double weighting, classifying ungrouped indicators.	Dimensions of sustainability are unpredictable, and weights may differ from reality.	(Hermans, Bossche and Wets, 2008)

Common weighting methods, primarily based on Nardo et al. (2005), OECD (2008), Hermans et al. (2008), Gan et al. (2017), and Mikulić et al. (2015).

After a comprehensive overview of the aforementioned MCDM and weighting methods, this thesis chapter 3 defines and justifies the most appropriate one regarding the topic of the present thesis.

2.3.3. Overviewing the potential sustainability parameters for sustainability assessment of MHs' interior rehabilitation

The previous overview of *ISAMs* – section 2.3.2 – reveals that **most of these ISAMs developed a bottom-up model** by considering **a hierarchical-based approach** to evaluate sustainability (Ahmad and Thaheem, 2017a, 2017b). This hierarchical-based approach develops a hierarchical decision-making tree that contains the most significant sustainability parameters which normally are categorized into three different levels: requirements, criteria, and indicators (Ahmad and Thaheem, 2017a, 2017b; Gilani, 2020). The first and second levels – requirements and criteria – include parameters that are rather general and qualitative, whereas the third level contains specific aspects by means of defining indicators that are quantitative and measurable (Gilani, 2020).

To identify the relevant and potential sustainability parameters regarding interior rehabilitation of MHs of Iran, a comprehensive literature review has been conducted. Table 2.5 illustrates these identified sustainability parameters.

Table 2.5. The relevant and potential sustainability parameters regarding the interior rehabilitation of MHs of Iran

R#	Requirements	C#	Criteria	I#	Indicators	References
R_1	**Economic**	**C_1**	**Cost**	**I_1**	**Initial rehabilitation costs**	(M. Almeida & Ferreira, 2017; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari et al., 2017; Pan et al., 2012)
				I_2	**Maintenance costs**	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari et al., 2017; Pan et al., 2012, Alwaer & Clements-croome, 2010)
				I_3	**Demolition costs**	(Chen et al., 2010)
				I_4	**Property added-value**	(Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Persson & Persson, 2015)
				I_5	**Affordability**	(Ahmad & Thaheem, 2018; Mulliner, 2015; Persson & Persson, 2015) (Ahmad & Thaheem, 2018)
		C_2	**Time**	**I_6**	**Rehabilitation process time**	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Pan et al., 2012)
				I_7	**Demolition time**	(M. Almeida & Ferreira; Pan et al., 2012)
R_2	**Environmental**	**C_3**	**Production phase**	**I_8**	**Embodied Energy (EE)**	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kono, Ostermeyer, & Wallbaum, 2018; Kylili et al., 2016; Pan et al., 2012; Yahya & Ibrahim, 2012; Yu et al., 2018; Zarghami et al., 2018)
				I_9	**Embodied Carbon (EC)**	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kono et al., 2018; Kylili et al., 2016; Yahya & Ibrahim, 2012; Yu et al., 2018; Zarghami et al., 2018)
				I_{10}	**Embodied Water (EW)**	(Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kono et al., 2018; Kylili et al., 2016; Yu et al., 2018)
				I_{11}	**Toxic contents**	(Yahya & Ibrahim, 2012; Yu et al., 2018)
		C_4	**Construction phase**	**I_{12}**	**Construction Waste (CW)**	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Yu et al., 2018; Zarghami et al., 2018)
		C_5	**Use (operation) phase**	**I_{13}**	**Operational Energy (OE)**	(Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kono et al., 2018; Kylili et al., 2016)
				I_{14}	**Operational Carbon (OC)**	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kono et al., 2018; Kylili et al., 2016)
		C_6	**End-of-life phase**	**I_{15}**	**Recyclability**	(Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Zarghami et al., 2018)
				I_{16}	**Demolition waste (DW)**	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Yu et al., 2018; Zarghami et al., 2018)
R_3	**Social**	**C_7**	**Functionality, efficiency, and adequacy of spaces**	**I_{17}**	**Functional performance of physical space**	(M. Almeida & Ferreira, 2017; Alwaer & Clements-croome, 2010; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari, Corrao, & Henning, 2017; Kylili, Fokaides, Amparo, & Jimenez, 2016; Persson & Persson, 2015; Shamsabadi, Researchers, Club, & Branch, 2018; Wandahl & Lund, n.d.; Yu, Cheng, Ho, & Chang, 2018)
				I_{18}	**Adequate spaces and storages**	(Kamari et al., 2017) (Yu et al., 2018)
		C_8	**Health, safety, and security**	**I_{19}**	**Thermal comfort**	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari et al., 2017; Zarghami et al., 2018)
				I_{20}	**Indoor air quality (IAQ)**	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari et al., 2017; Zarghami et al., 2018)
				I_{21}	**Lighting comfort**	(C. P. Almeida, Ramos, & Silva, 2018; Alwaer & Clements-croome, 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari et al., 2017; Pan et al., 2012; Zarghami et al., 2018)
				I_{22}	**Visual comfort**	(Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015)
				I_{23}	**Acoustic comfort**	(M. Almeida & Ferreira, 2017; Kamari et al., 2017; Monzón & López-Mesa, 2018; Zarghami et al., 2018)
				I_{24}	**Workforce health and safety**	(Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015)
				I_{25}	**Neighbors' safety and noise nuisances**	(Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015)
		C_9	**Psychological, cultural, and aesthetic**	**I_{26}**	**Aesthetic and beauty of the building**	(M. Almeida & Ferreira, 2017; Alwaer & Clements-croome, 2010; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari et al., 2017; Persson & Persson, 2015)
				I_{27}	**Cultural and heritage conservation**	(Alwaer & Clements-croome, 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Yu et al., 2018)

After identifying these relevant potential sustainability parameters regarding interior rehabilitation of MHs in Iran, in the present thesis chapter 3, the author has compiled, selected, and justified the most relevant ones through informal interviews, holding a seminar, and author expertise – see section 3.2.

2.4. Conclusion of chapter 2

This chapter has overviewed related literature to the topic of the present dissertation in three main sections. The conclusions regarding each section have been drawn separately in the following paragraphs.

The first section – section 2.1 –, through overviewing different periods of MHs construction in Iran, concludes that the MHs constructed in **the first period** – from 1960 to 1980 – have mostly several **interior performance issues** and **do not respond to** the current **needs of their occupants**.

The conclusions derived from the second section – section 2.2 – are:

a) The most proper building intervention term regarding this thesis topic is **"rehabilitation"** because it refers to a wider range of intervention activities and is aligned with the sustainability concept.

b) Most **common existing interior rehabilitation activities and techniques in Iran** have some fundamental problems such as **not responding to their occupants' needs**, having **several sustainability issues**, and **not fulfilling the contemporary building standards**.

c) By overviewing existing significant examples of interior rehabilitation projects constructed with **new or improved techniques and technologies** in the world, it can be concluded that these new techniques can **improve the sustainability performance of interior spaces** and **can be a solution for interior rehabilitation** of buildings.

From the third section – section 2.3 –, the author draws the following conclusions:

a) Considering the **sustainability concept** in the design, assessment, and selection procedure of MHs' interior rehabilitation is a crucial issue that **should receive more attention**, especially in developing countries where sustainability issues are mostly ignored.

b) This section's holistic and comprehensive literature review regarding the sustainability performance of residential buildings and MHs, reveals that more than **60% of these investigations focused on the environmental aspect**, while **only 10%** of the available literature **incorporated all three sustainability pillars** – economic, environmental and social.

c) Although there exists a vast amount of literature regarding the sustainability of buildings, there is **still a lack of study regarding the sustainability assessment of interior rehabilitation of MHs**. Moreover, among the studies that investigated this sustainability assessment of interior rehabilitation of MHs, most of them focused on the rehabilitation of MH **in the urban scale** – e.g., neighborhood, community interaction, urban regeneration, and urban management – **not in dwelling scale** – e.g., interior rehabilitation.

d) Social aspects are the most crucial issues for the sustainability of residential buildings since it is the main reason for interior rehabilitation. However, **social** sustainability is the **most ignored** pillar, which is **rarely investigated** and **needs to receive more attention** to fill the mentioned gap.

e) This third section's comprehensive review and analysis of the existing building sustainability assessment methods figured out that most of these methods **neglected the evaluation of stakeholders' satisfaction**.

f) Several shortfalls – see section 2.3.2 – of the existing *Sustainable Building Rating and Certification Systems (SBRCSs)* lead numerous researchers to develop *Individual Sustainability*

Assessment Models (ISAMs) – that are mostly based on Multi-Criteria Decision Making (MCDM) methods – to fulfill their projects' objectives.

g) This section comprehensive overview of different scientific and well-known MCDM methods and several weighting methods, concluded that each method has its own application area, strengths, and weaknesses. In this regard, in this thesis chapter 3, the author defines and justifies the most proper methods regarding the thesis topic.

CHAPTER 3

A novel model for sustainability assessment of MHs' interior rehabilitation in Iran

Chapter 3: Methodology for developing a novel model for sustainability assessment of MHs' interior rehabilitation in Iran

Introduction

As previously explained in section 2.3.1, to the best of this thesis author's knowledge, heretofore, there is **no model regarding a holistic** and **integrated sustainability assessment of interior rehabilitation of MHs**. Moreover, the applications of *Sustainable Building Rating and Certification Systems (SBRCSs)* have some weak points – see section 2.3.2 – that make them inapplicable regarding this thesis topic. Therefore, this chapter is dedicated to defining the main methodologies of the present thesis for establishing and developing a novel model for the sustainability assessment of interior rehabilitation of MHs. Moreover, this model has been particularized and applied, for the first time, to the selected case study – Ekbatan MH. In this regard, as illustrated in Figure 3.1, this chapter is divided into the three following sections:

1) Section 3.1 selects and justifies the most appropriate MCDM and weighting methods for the present dissertation according to the holistic overviews on MCDM and weighting methods conducted in section 2.3.2 – see Tables 2.3 and 2.4.

2) Section 3.2 develops and explains a novel model based on the selected MCDM and weighting methods through defining seven stages.

3) Section 3.3 concludes the previous sections 3.1 and 3.2.

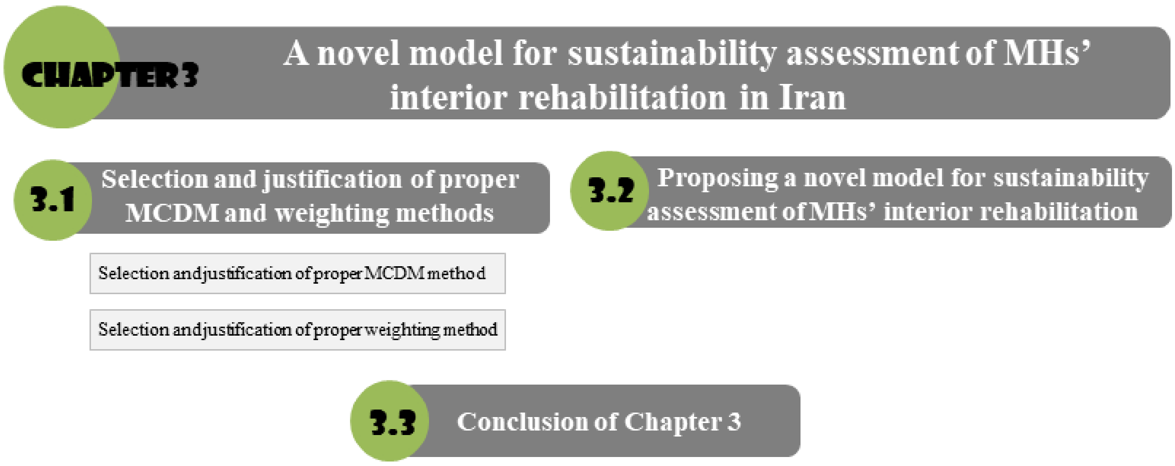


Figure 3.1. Structure of chapter 3

3.1. Selection and justification of proper MCDM and weighting methods regarding this thesis's topic

As previously mentioned in section 2.3.2 and Table 2.3, there are numerous available MCDM methods. For selecting the most appropriate one regarding this thesis topic, the application area, strengths, and weaknesses of each mentioned method should be considered (Moghtadernejad, Chouinard and Mirza, 2018). To do so, after comparing and analyzing these methods – see section 2.3.2 –, **the *Modelo Integrado de Valor para Evaluaciónes de Sostenibilidad (MIVES)*** method – which was introduced for the first time in the 2000s (Losada et al. 2006; San José and Josa 2008; Viñolas, Cortés, Marques, Josa, & Aguado, 2009) based on a combination of the Multi-Criteria Decision Making (MCDM) and the Multi-Attribute Utility Theory (MAUT) (Viñolas *et al.*, 2009; Pons, de la Fuente and Aguado, 2016) – has been selected because of the following reasons:

1) MIVES is a **well-known scientific MCDM method** that has already been **satisfactorily applied in numerous research projects** generating holistic sustainability assessment models in a wide range of case studies including architectural, civil engineering, and building fields (Fuente *et al.*, 2016; Gilani, 2020; Banirazi, Pons and Hosseini, 2021) such as: (1) buildings and components (San-Jose Lombera and Garrucho Aprea, 2010; San-José Lombera and Cuadrado Rojo, 2010; Pons and Aguado, 2012; Gilani, Blanco and Fuente, 2017; Gilani, Pons-valladares and De la Fuente, 2019; Maleki *et al.*, 2019; Gilani, 2020; Habibi, Pons and Pena, 2020; Josa *et al.*, 2020; Ledesma, Nikolic and Pons, 2020; Banirazi, Pons and Hosseini, 2021), (2) concrete structures and slabs (Aguado *et al.*, 2012; Pons and De La Fuente, 2013; de la Fuente *et al.*, 2019), (3) infrastructure management (Feldmann *et al.*, 2008; Cartelle Barros *et al.*, 2015; A. de la Fuente *et al.*, 2017; Albert de la Fuente *et al.*, 2017), (4) hydraulic structures (Pardo-Bosch and Aguado, 2015; De La Fuente *et al.*, 2016), (5) post-disaster housing management (S M Amin Hosseini, Fuente, & Pons, 2016; S M Amin Hosseini, Pons, & De la Fuente, 2018; Seyed Mohammad Amin Hosseini, 2016), (6) economic decisions – Barcelona Metro Line 9 – (Ormazabal, Viñolas and Aguado, 2008), and (7) architecture learning processes (Pons, Franquesa and S. M.Amin Hosseini, 2019; Pons, Franquesa and Seyed Mohammad Amin Hosseini, 2019).
2) MIVES allows researchers to carry out **agile**, **objective**, **specific**, and **holistic sustainability assessments** (Banirazi, Pons and Hosseini, 2021) by considering the essential principles of the sustainability concept – environmental, economic, and social pillars (Gilani, 2020).
3) This method provides a **hierarchical-based decision-making tree** that enables researchers to easily **comprehend**, **communicate**, and **implement sustainability models** (Viñolas *et al.*, 2009; Gilani, 2020; Josa *et al.*, 2020; Banirazi, Pons and Hosseini, 2021).
4) One of the **main characteristics of MIVES** that makes it unique among other MCDM methods is the application of **value functions** (Viñolas *et al.*, 2009; San-Jose Lombera and Garrucho Aprea, 2010; Alarcon *et al.*, 2011) to (a) measure the satisfaction level of various stakeholders involved in the decision-making procedure, and (b) quantify, assess, and normalize both qualitative and quantitative indicators that might have different measurement units and scales.
5) This method is specific for each deterministic or probabilistic case along with homogeneous or heterogeneous assessment (Pujadas *et al.*, 2017; Banirazi, Pons and Hosseini, 2021). Moreover, MIVES can be **adapted** and **applied** to **different locations** with **diverse characteristics** by considering the geographic contexts, sustainability requirement tree components, and stakeholders' preferences.
6) This MCDM can be **combined with other methods** for weighting – e.g., AHP and Delphi – and validating and robustness analyses – e.g., sensitivity analysis – (Pons, de la Fuente and Aguado,

2016; Pons, Franquesa and S. M.Amin Hosseini, 2019; Gilani, 2020; Habibi, Pons and Pena, 2020; Ledesma, Nikolic and Pons, 2020; Banirazi, Pons and Hosseini, 2021).

7) This method calculates the Global Sustainability index (GS_i) as well as **the satisfaction value for each component of the decision-making tree separately** – requirements, criteria, and indicators. Moreover, MIVES 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 component of the decision-making tree.

As previously mentioned in section 2.3.2, one of the main steps of multi-criteria decision-making procedures is assigning weights to the components of these MCDM models (Meadows, 1998; Juwana et al., 2012). Since the process of assigning weights is inherently subjective (Saisana and Tarantola, 2002; Wilson and Wu, 2017; Morse et al., 2001), to select an appropriate weighting method regarding this thesis, a holistic overview of several well-known weighting methods has been conducted in section 2.3.2, Table 2.4. As a result, the **Delphi method,** which is a systematic method designed to obtain a consensus from a group of qualified experts who respond to a questionnaire reiteratively (Hallowell and Gambatese, 2010) has been selected because of the following reasons:

1) Delphi is known as a **reliable**, **precise**, and **easy-to-use** weighting method that is widely employed in several studies (Hallowell and Gambatese, 2010; Casanovas-Rubio and Armengou, 2018).
2) The Delphi method can be easily adapted and **combined with different MCDM methods** (Hallowell and Gambatese, 2010; Habibi et al., 2020) such as MIVES. For instance, the combination of MIVES and Delphi methods was already employed in (S. Habibi, Pons, & Pena, 2020) research.
3) This method compiles, refines, and **qualifies the panel members** based on **their expertise level** regarding a specific topic (Hallowell and Gambatese, 2010; Casanovas-Rubio and Armengou, 2018).
4) The Delphi method **enables experts to participate** in a questionnaire **without implying issues** such as scheduling, travel, space requirements, costs, time, or lengthy discussions. Since the defined expert panel members in the present dissertation were mostly composed of local experts in Iran – see section 3.2, stage 3 –, the author selected the Delphi method to overcome the mentioned issues.
5) Moreover, this method **controls** and **minimizes possible bias**, plus enables to obtain reliable data and judgment from an expert regarding a specific topic (Hallowell and Gambatese, 2010; Casanovas-Rubio and Armengou, 2018).

3.2. A new MIVES-Delphi model for sustainability assessment of interior rehabilitation of MHs in Iran

After identification, selection, and justification of the most appropriate MCDM and weighting methods – see section 3.1 –, **this section develops** a **novel model** based on the **MIVES** and **Delphi methods** for sustainability assessment of interior rehabilitation of Iran's MHs. Thus, this section **fulfills the first defined specific objective** – see section 1.4 – of the present thesis. To do so, the following seven stages have been taken into account: (1) defining problems, objectives, and scopes; (2) defining a decision-making tree and its components; (3) assigning weights to the decision-making tree's components; (4) establishing value functions; (5) defining alternatives – named as scenarios in the present thesis –; (6) calculating the Global Sustainability indexes (GSis) of the defined scenarios; and (7) analyzing the validity and robustness of the proposed model. Figure 3.2 illustrates the above-mentioned stages which have been explained in detail in the following paragraphs.

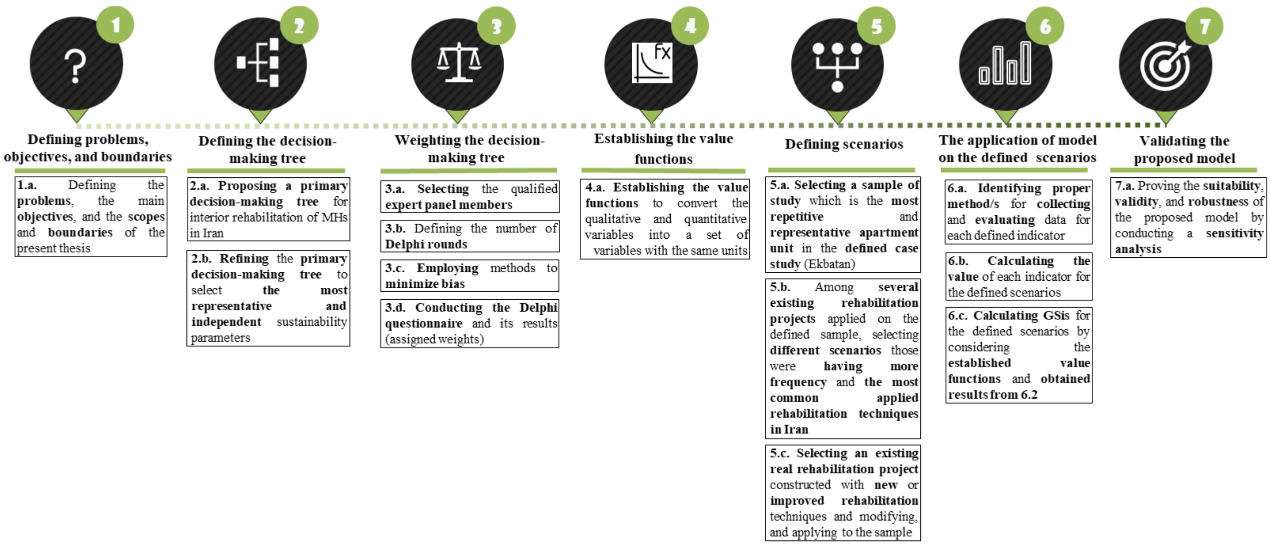


Figure 3.2. Stages of the proposed MIVES-Delphi model for sustainability assessment of MHs' interior rehabilitation

Stage 1) This first stage **defines** the present thesis **problems**, **hypothesis**, **objectives**, and **scopes and boundaries**, which are already described in detail in sections 1.2 to 1.5 respectively.

Stage 2) This stage defines a ***decision-making tree*** – also known as *requirement tree* – that includes the most significant sustainability parameters – requirements, criteria, and indicators – regarding the topic of study in a hierarchical structure. This tree permits the assessment of stakeholder's satisfaction and sustainability of a specific process, system, and product (Viñolas *et al.*, 2009; Pons, de la Fuente and Aguado, 2016) in order to (1) make decisions based on the obtained indicators' values and weights, (2) have a global view of the problem, (3) organize the involved ideas, (4) facilitate the comprehension of the model to any stakeholder involved in the decision process, and (5) carry out the subsequent mathematical analysis (Gilani, 2020). This hierarchical tree mostly contains three different levels where the first and second levels – requirements (R_i) and criteria (C_j) respectively – include parameters that are rather general and qualitative, while the third level contains indicators (I_k) that are quantitative and measurable (Gilani, 2020; Banirazi, Pons and Hosseini, 2021). For defining a proper decision-making tree, the thesis author has followed two steps:

a) The **first** step identified **primary potential** and **relevant sustainability parameters** for sustainability assessment of interior rehabilitation of MHs in Iran. This step relies on a comprehensive literature review and experts' knowledge and expertise – see section 2.3.3, Table 2.5. Consequently, this step **identified 3 requirements**, **9 criteria**, and **27 indicators**.

b) The **second** step followed the MIVES instruction so that the final number of sustainability parameters is the minimum and exclusively the most important ones are selected (Viñolas *et al.*, 2009; Pons, de la Fuente and Aguado, 2016) in order to (1) **avoid overlapping** among sustainability parameters, (2) **discard less important indicators** with low relative weights – namely <5% (Gilani, 2020) – that have low impacts on the final GS_i, and (3) **prevent time-consuming**, **difficult assessment processes**, and **high uncertainties results** (Hosseini, 2016; Gilani, 2020). In this regard, some of the selected indicators of Table 2.5 have been discarded due to the following reasons and justifications. Affordability, recyclability, and visual comfort have been excluded because they would have overlapped with other economic indicators, demolition waste, and building aesthetic respectively. Moreover, as demolition time for interior rehabilitation of an apartment is insignificant, this indicator has been discarded. Furthermore, based on Jensen *et al.*, 2018, the main stakeholders in Sustainable Building Renovation (SBR) can be divided into (i) direct stakeholders with building such as users, occupants, or owners and (ii) indirect ones like constructors, designers, workers, municipality, and so on. Therefore, workers' safety and neighbors' noise nuisances have been considered as the second priority for defining indicators and they have been discarded in the defined requirement tree. Also, cultural and heritage conservation has difficult assessment processes and high uncertainties results. Moreover, security, because it is an issue/concept normally defined and dependent on the neighborhood and building scales (Hamngton-lynn and Pascoe, 1995; Ahmad *et al.*, 2016; Piotr *et al.*, 2016) – not dwelling scale – is out of the scope of the present thesis. In this way, the identified sustainability parameters in the first step were refined and compiled based upon the (1) abovementioned justification based on previous studies and literature, (2) results of the seminars held by multidisciplinary professors and experts, and (3) local characteristics. Consequently, **3 requirements**, **9 criteria**, and **19 indicators were selected as the most representative and independent from each other**, as shown in Figure 3.3. Chapter 6 explains more in detail the final defined sustainability parameters besides their justifications, definitions, collecting data methods, measurement methods and databases, and units and scales.

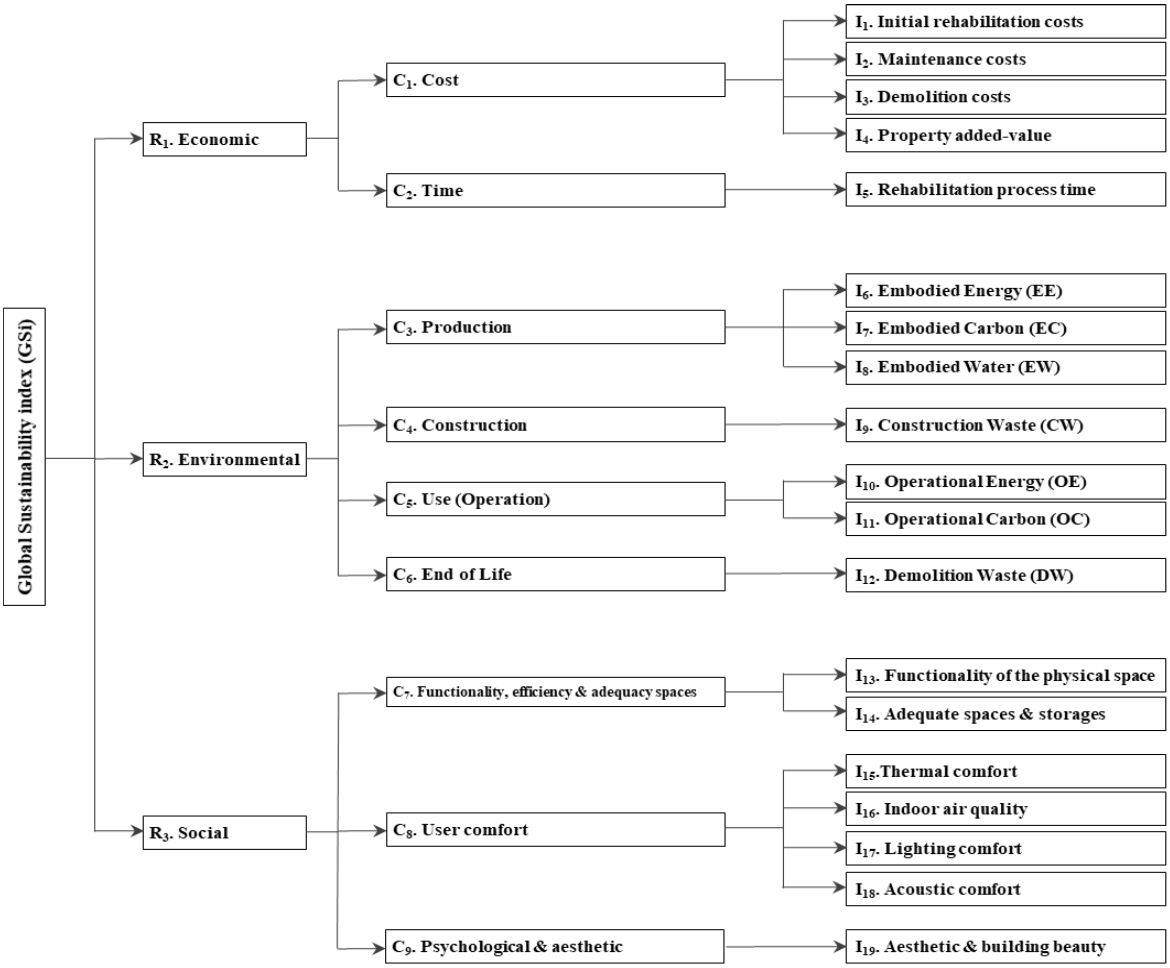


Figure 3.3. Decision-making tree for sustainability assessment of MHs' interior rehabilitation in Iran

Stage 3) The third stage **assigns weights** to the defined components – sustainability parameters – of the established decision-making tree. As previously explained and justified in section 3.1, the present thesis **employs the Delphi method** for **assigning weights** to the mentioned components. Likewise, the Delphi instructions and protocols have been followed:

a) Qualifying and selecting the expert panel members

As experts' opinions have a direct effect on weighting and consequently on the final results of the proposed model (Hallowell and Gambatese, 2010; Casanovas-Rubio and Armengou, 2018), a proper selection of expert panel members in a strategic and unbiased manner is required to be considered in the

Delphi method (Hallowell & Gambatese, 2010). In this regard, to qualify the expert panel members, the author created a set of specific expertise requirements based on the objectives and limitations of this doctoral thesis as indicated in follows:

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

The chosen experts must have (1) all the three above-mentioned expertise requirements simultaneously to lead to a well-qualified, and (2) 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 –, and (iii) professionals from municipal organizations such as Ministry of Housing and Urban Design, Supreme Council of Architecture and Urban Development, and Iran Construction Engineering Organization, which makes policy, standards and general rules for Iranian building construction.

Moreover, to appraise the final qualification of experts, Delphi suggests developing a relative point system (Okoli and Pawlowski, 2004; Hallowell and Gambatese, 2010; Casanovas-Rubio and Armengou, 2018) as shown in Table 3.1.

Table 3.1. Flexible point system for the qualification of expert panelists

#	Achievement or experience		Points
1	Year of professional experience	Academia Construction	0.5 1
		Municipality	0.5
2	Experience in the field of sustainability assessment methodologies	Medium	2
		High	5
3	Advanced degrees	MS	2
		Ph.D.	4
4	Related published Book in the focus area of the research		3
5	Primary or secondary writer of publications in the focus area of the research		1
6	A related patent in the focus area of the research		3
7	Licensed Architect from Iran Construction Engineering Organization (IRCEO)	First-grade license Second-grade license Third-grade license	5 3 1
8	Expert in building constructions' rules, regulations, and legislation		3
9	Expert in mass housings rules, regulations, and legislation		3
10	Winner of architectural prize in the residential building sector		3
11	Interior designing or retrofitting of residential buildings preferably in MHs project		1.5
12	Expert in the field of new construction materials or new construction techniques such as Kinetic or transformable architecture		4

Since several studies Brockhoff, 1975; Boje and Murnighan, 1982; and Hallowell & Gambatese, 2010 suggested between 8 to 16 panelists to participate in the Delphi method, the author selected 15 experts who were qualified based on the aforementioned considerations as the final panel members of the present dissertation, as explained more in detail in Appendix 3.A.

b) Reaching a consensus by Delphi

The main objective of the Delphi method is to reach a consensus from a group of qualified experts by reducing variance in responses (Okoli and Pawlowski, 2004; Hallowell and Gambatese, 2010; Casanovas-Rubio and Armengou, 2018). This consensus shall reach between 1 to 3 rounds as suggested by Hallowell and Gambatese, 2010 and Dalkey et al., 1970. Moreover, according to the Delphi method (Hallowell and Gambatese, 2010), **a consensus is achieved when the median absolute deviation is less than 1/10** of the range of possible values for quantitative studies. As weights can adopt values between 0% and 100%, consensus will be achieved when the median absolute deviation is less than 10%. Equation 3.1 shows the median absolute deviation, which is implemented due to its lower biased impacts.

$$\text{Median absolute deviation} = \frac{\sum_{i=1}^{n} |\mathbf{xi - median}|}{n} \qquad \text{Equation 3.1}$$

Where n is the total number of data items and x_i is the data i.

Moreover, as recommended by Hallowell and Gambatese, 2010, the median absolute deviation – Equation 3.1 – 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 (Hallowell and Gambatese, 2010; Casanovas-Rubio and Armengou, 2018).

c) Methods to minimize bias

The success of the Delphi method depends on the unbiased judgment of experts. **To decrease bias** as far as possible, the author has considered **the suggested points** in (Hallowell and Gambatese, 2010), (Casanovas-Rubio and Armengou, 2018), and (Doyle J et al., 2014) articles as follows:

1) The selection of expert panel members that do not know each other.
2) Randomize the questions for each panel member as well as each round of the survey.
3) Request a very brief explanation and justification from each panelist to his or her responses to control their feedbacks.
4) Conduct questionnaires in different rounds – if needed – to reach a consensus by reducing variance and bias in responses.
5) Calculate the median absolute deviation instead of the standard deviation.

d) Conducting the Delphi questionnaire and its results

To conduct the Delphi questionnaire for the **first round**, the qualified experts were provided with (1) a questionnaire in order to assign weights to the defined requirement tree's components – Figure 3.3 – and relative instructions regarding how to assign these weights, and (2) a brief summary of this doctoral thesis to familiarize them with this study. As the qualified experts were mostly in Iran, the author contacted each one of them through email and online/virtual meetings if it was needed. Through these communications, the experts were asked to fill out the designed questionnaire and provide a brief justification for their responses. After collecting data from the first round, these data were inserted into SPSS to calculate their median absolute deviation based on Equation 3.1. Table 3.2 shows the obtained results from the first round of Delphi.

Table 3.2. Median, mean, median absolute deviation, and consensus for the first round of Delphi.

		Weights of experts (%)															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

As presented in Table 3.2, during the first round of the survey, among all requirement tree's components – requirements, criteria, and indicators –, **two criteria** – C_1. Cost and C_2. Time – **did not meet** the **Delphi consensus prerequisite** – their median absolute deviations were greater than 10%. The variations in the assigned weights were derived because of the existing differences between experts' opinions regarding the current economic situation of Iran. Based on experts' expressions and justifications for their assigned weights, some panelists believed that the cost has a significant contribution to interior rehabilitation of residential buildings – in other words, cost is more important than time –; while others considered the time and cost criteria with the same relative importance – same weights. In consequence, the second round of Delphi had to be conducted.

To do so, 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 of these two criteria. Five panelists reconsidered and assigned new weights to these criteria. After collecting data from this second round, the obtained data were inserted into SPSS. As shown in Table 3.3, in the second round, the experts' opinions about the assigning weights reached consensus regarding C_1 and C_2 as well because their median absolute deviations met less than 10% – 7.22. Since consensus was reached in the second round, based on the Delphi instruction, **the obtained weights** were considered **reliable** and there was **no need to conduct further rounds**. Figure 3.4 illustrates the defined decision-making tree of the proposed model and its assigned weights.

Table 3.3. Median, mean, median absolute deviation, and consensus for the second round of Delphi.

		Weights of experts (%)															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

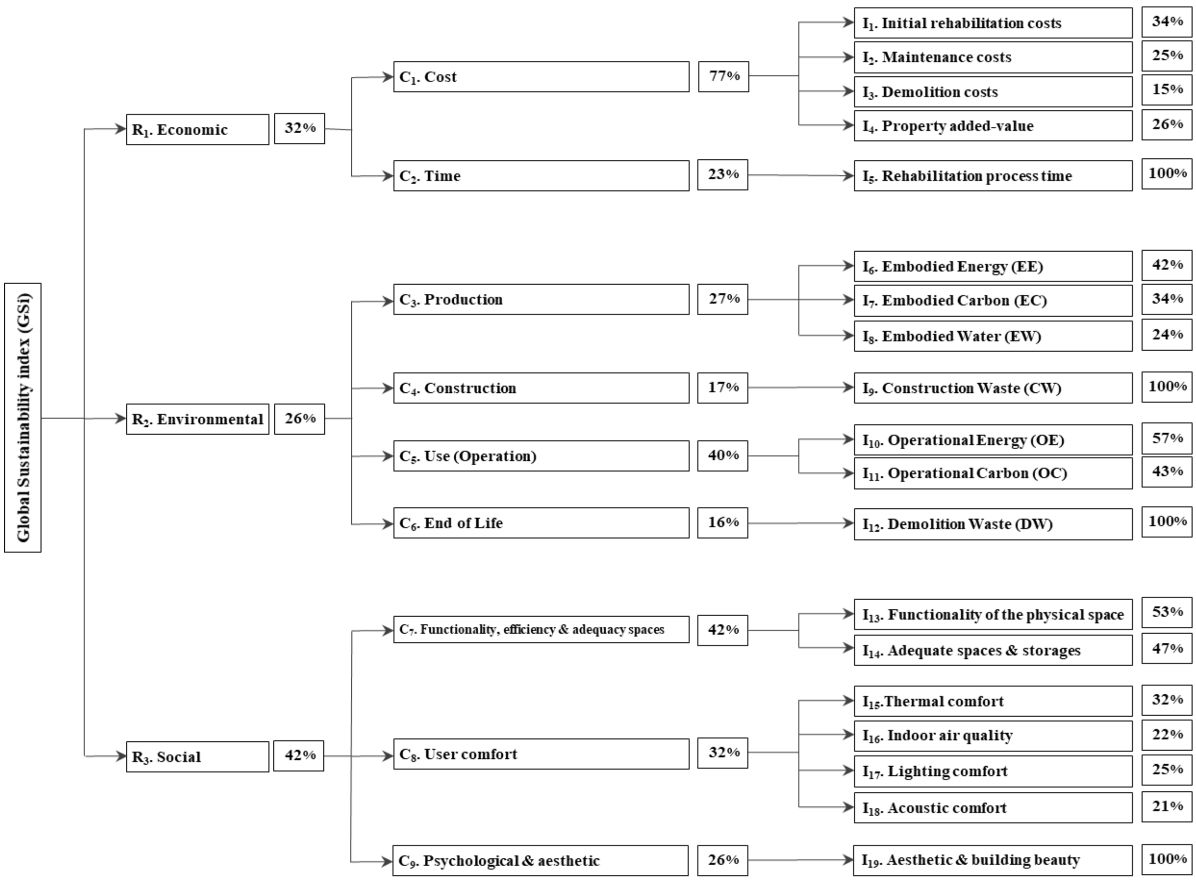


Figure 3.4. The established decision-making tree for sustainability assessment of MHs' interior rehabilitation in Iran and its corresponding assigned weights

Consequently, the contributions of the above-mentioned indicators on the GS_i – in other words, the importance and influence of each indicator on GSi – have been ranked based on their corresponding assigned weights by experts through Equation 3.2:

$$C\omega_{Ik} = \omega_{Ri} \cdot \omega_{Cj} \cdot \omega_{Ik} \qquad \text{Equation 3.2}$$

where $C\omega_{Ik}$ is the contribution weight of each indicator on the GS_i, (ω_{Ri}) is the weight of requirement, (ω_{Cj}) is the weight of criteria, and (ω_{Ik}) is the weight of indicator. Table 3.4 presents the contribution weight of each indicator on the GS_i.

Table 3.4. Contribution weight of each indicator on the GS_i

Rank	Indicator	Indicator name	$C\omega_{Ik}$
1	I_{19}	Aesthetic & building beauty	10.9%
2	I_{13}	Functionality of the physical space	9.3%
3	I_1	Initial rehabilitation cost	8.4%
4	I_{14}	Adequate spaces & storages	8.3%
5	I_5	Retrofitting process time	7.4%
6	I_4	Property added-value	6.4%
7	I_2	Maintenance cost	6.2%
8	I_{10}	Operational Energy (OE)	5.9%
9	I_{11}	Operational Carbon (OC)	4.5%
10	I_9	Construction Waste (CW)	4.4%
11	I_{15}	Thermal comfort	4.3%
12	I_{12}	Demolition Waste (DW)	4.2%
13	I_3	Demolition cost	3.7%
14	I_{17}	Lighting comfort	3.4%
15	I_{16}	Indoor air quality	3.0%
16	I_6	Embodied Energy (EE)	2.9%
17	I_{18}	Acoustic comfort	2.8%
18	I_7	Embodied Carbon (EC)	2.4%
19	I_8	Embodied Water (EW)	1.7%

Legend: $C\omega_{Ik}$ = Contribution weight of each indicator

It is worthy to mention that the established decision-making tree was developed to assess the sustainability of interior rehabilitation of MHs in Iran. To implement this tree in MHs from other cities and countries, it should be adapted by considering projects' problems and boundaries, geographic contexts, sustainability requirements, and assigned weights, as well as stakeholders' preferences.

Stage 4) This fourth stage defines a **value function** for each defined indicator. As previously mentioned, value functions are a MIVES strength compared to other MCDM methods. These functions are a framework for assessing and normalizing the satisfaction degree of the involved indicators, which might have different measurement units Alarcon et al., 2011; San-Jose Lombera & Garrucho Aprea, 2010; Viñolas et al., 2009). In other words, these functions unify indicators' units on an a-dimensional scale from 0 to 1 as the representation of the minimum and maximum degrees of satisfaction in terms of sustainability (Viñolas *et al.*, 2009; San-Jose Lombera and Garrucho Aprea, 2010; Alarcon *et al.*, 2011; Banirazi, Pons and Hosseini, 2021). According to (Viñolas *et al.*, 2009), (Alarcon *et al.*, 2011), and (San-Jose Lombera and Garrucho Aprea, 2010), to establish the value function for each indicator, there are **four steps** to be followed: (1) determine **the tendency** (increase or decrease) of the value function, (2) determine **the corresponding points** (X_{min} and X_{max}) to **the minimum** (S_{min}, value 0) **and maximum** (S_{max}, value 1) satisfaction, (3) determine **the shape** of the value function – linear, concave, convex, and S-shaped –, and (4) determine **the mathematical expression** of the value function.

To conduct the three aforementioned steps – the tendency, parameters, and shape of the value function for each defined indicator –, some data such as 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 the different scenarios for an indicator should be overviewed (Alarcon et al., 2011; S M Amin Hosseini et al., 2018; San-Jose Lombera & Garrucho Aprea, 2010). Figure 3.5 shows the different value function shapes.

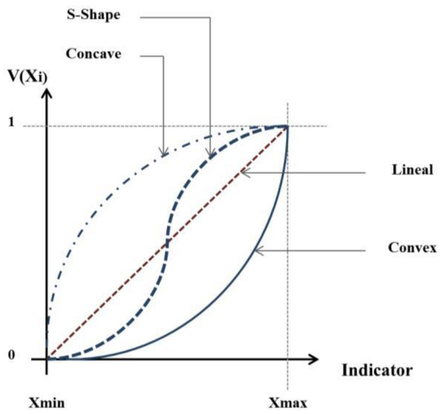


Figure 3.5. Value function shapes (Hosseini, Pons and De la Fuente, 2018)

Also, for conducting the fourth step of the value function, the following equations (Viñolas *et al.*, 2009; San-Jose Lombera and Garrucho Aprea, 2010; Alarcon *et al.*, 2011) should be applied:

$$V_i = A + B.[1 - e^{-k_i \cdot [\frac{|X_i - X_{min}|}{C_i}]^{P_i}}] \qquad \text{Equation 3.3}$$

$$B = [1 - e^{-k_i \cdot [\frac{|X_{max} - X_{min}|}{Ci}]^{P_i}}]^{-1} \qquad \text{Equation 3.4}$$

Where:

V_i= Non-dimensional value of the indicator being evaluated,
X_i= The considered indicator abscissa which generates a value V_i,

And 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 C_i,
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 3.4.

According to (Viñolas *et al.*, 2009), (Alarcon *et al.*, 2011), and (San-Jose Lombera and Garrucho Aprea, 2010), when satisfaction increases rapidly or decreases slightly, a concave-shaped function is the most suitable shape for the defined indicators. Concave value functions present the indicators with less importance and they should be promoted. The P values of less than 1 should be adopted for these types of value functions. On the contrary, in a convex function, when the value of the indicator starts to increase, the satisfaction slightly increases. Unlike the previous case, the convex function is selected when approaching the maximum satisfaction point is more important than moving away from the minimum satisfaction point. In other words, convex value functions present the more crucial indicators. Also, for these kinds of value functions, P values more than 1 should be adopted. A linear function is applied when there is a steadily increasing or decreasing satisfaction and P values equal to 1 should be assigned. If the satisfaction tendency embraces a combination of convex and concave functions simultaneously, a S-shaped function is the most representative. Table 3.5 shows the established value functions of all 19 defined indicators besides their tendencies, parameters, and shapes.

Table 3.5. The established value functions of all 19 defined indicators

Req		Unit	Shape	X_{max}	X_{min}	C_i	K_i	P_i	References
Economic	I_1. Rehabilitation cost	€/m^2	DCx	200	50	115	0.05	2.00	(https://www.cbi.ir/default_en.aspx, https://khedmatazma.com/subservice/building-repairs-and-reconstruction, https://seaart.ir/, https://sanjagh.pro, https://www.jadvalzarb.com/base/tools_119, https://www.arianparax.com/)
	I_2. Maintenance cost	€/m^2.50yrs	DCx	200	70	135	0.10	1.50	(https://khedmatazma.com/subservice/building-repairs-and-reconstruction, https://seaart.ir/, https://sanjagh.pro, https://www.jadvalzarb.com/base/tools_119, https://www.arianparax.com/)
	I_3. Demolition cost	€/m^2	DCv	12	8	10	0.15	0.70	(https://khedmatazma.com/subservice/building-repairs-and-reconstruction, https://seaart.ir/, https://sanjagh.pro, https://www.jadvalzarb.com/base/tools_119, https://www.arianparax.com/)
	I_4. Property added-value	€/m^2.AU	ICx	26074	0	9017	0.10	1.50	(https://ihome.ir/, https://kilid.com/, https://shabesh.com/, https://divar.ir/s/tehran/buy-apartment/)
	I_5. Rehabilitation process time	Day	DL	60	20	40	0.0	1.00	(https://khedmatazma.com/subservice/building-repairs-and-reconstruction)
Environmental	I_6. Embodied Energy (EE)	MJ/m^2	DCx	1300	7300	3250	0.10	0.80	(Dilsiz, Felkner, Habert, & Nagy, 2019; Fernando & Ekundayo, 2018; Hu, 2020; Klemeš, 2015; Monahan & Powell, 2011; Syngros, Balaras, & Koubogiannis, 2017)
	I_7. Embodied Carbon (EC)	kgCO_2/m^2	DCx	50	450	250	0.60	0.70	(Dilsiz, Felkner, Habert, & Nagy, 2019; Fernando & Ekundayo, 2018; Hu, 2020; Klemeš, 2015; Monahan & Powell, 2011; Syngros, Balaras, & Koubogiannis, 2017)
	I_8. Embodied Water (EW)	l/m^2	DCx	2000	5000	3500	1.00	0.60	(McCormack *et al.*, 2007; Choudhuri and Roy, 2015; Bardhan and Choudhuri, 2016; Heravi and Abdolvand, 2019b)
	I_9. Construction Waste (CW)	kg/m^2	DCv	10	50	21.86	1.00	0.60	(Llatas, 2010, 2013; Han *et al.*, 2020)
	I_{10}. Operational Energy (OE)	kWh/m2/yr.	DCv	0	95	47.5	0.05	2.50	The National Regulations for Buildings of Iran (https://www.mrud.ir/en/en-us/), The standard ISIRI 14253(http://standard.isiri.gov.ir/SearchEn.aspx)
	I_{11}. Operational Carbon (OC)	kgCO_2/m^2/yr.	DCx	0	75	37.5	0.05	2.50	The National Regulations for Buildings of Iran (https://www.mrud.ir/en/en-us/), The standard ISIRI 14253(http://standard.isiri.gov.ir/SearchEn.aspx)
	I_{12}. Demolition Waste (DW)	kg/m^2	DCx	150	750	450	1.00	0.80	(Llatas, 2010, 2013; Han *et al.*, 2020)
Social	I_{13}.Functionality of the physical space	Points	ICx	5	1	3	0.50	2.50	(M. Almeida & Ferreira, 2017; Alwaer & Clements-croome, 2010; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari, Corrao, & Henning, 2017; Kylili, Fokaides, Amparo, & Jimenez, 2016; Persson & Persson, 2015; Shamsabadi, Researchers, Club, & Branch, 2018; Wandahl & Lund, n.d.; Yu, Cheng, Ho, & Chang, 2018)
	I_{14}.Adequate spaces & storages	Points	ICx	5	1	3	0.40	2.00	(Kamari et al., 2017) (Yu et al., 2018)
	I_{15}.Thermal comfort	Points	ICx	5	1	3	0.50	2.00	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari et al., 2017; Zarghami et al., 2018)
	I_{16}.Indoor air quality	Points	ICx	5	1	3	0.50	1.50	(M. Almeida & Ferreira, 2017; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari et al., 2017; Zarghami et al., 2018)
	I_{17}.Lighting comfort	Points	ICx	5	1	3	0.50	1.50	(C. P. Almeida, Ramos, & Silva, 2018; Alwaer & Clements-croome, 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari et al., 2017; Pan et al., 2012; Zarghami et al., 2018)
	I_{18}.Acoustic comfort	Points	ICx	5	1	3	0.50	1.50	(M. Almeida & Ferreira, 2017; Kamari et al., 2017; Monzón & López-Mesa, 2018; Zarghami et al., 2018)
	I_{19}. Aesthetic & building beauty	Points	ICx	5	1	3	0.40	2.50	(M. Almeida & Ferreira, 2017; Alwaer & Clements-croome, 2010; Chen et al., 2010; Kamali & Hewage, 2017a; Kamali et al., 2018a; Kamali & Hewage, 2015; Kamari et al., 2017; Persson & Persson, 2015)

Legend: DCx: Decreasing Convex; DL: Decreasing Lineal; DCv: Decreasing Concave; ICx: Increasing convex; IL: Increasing Linear; ICv: Increasing concave; IS: Increasing S-shape; DS: Decreasing S-shape; AU: Apartment Unit.

Appendix 3.B explains in more detail the value functions' characteristics, application, and definition process for all 19 defined indicators. For avoiding repetition, some indicators that have similar value function behavior, have been merged and explained in the same section.

Stage 5) This fifth stage defines some **alternatives to be assessed** – named as **scenarios** in the present dissertation – of interior rehabilitation of MHs in Iran. To do so, **first**, this stage overviews the characteristics of the selected case study – Ekbatan – both in the neighborhood and dwelling scale – see sections 4.1, 4.2, and Appendix 4.A –, to select a **sample of study** which is the most repetitive and representative apartment unit in Ekbatan. **Secondly**, **the proper scenarios** for the defined sample have been selected following these two steps:

a) The scenarios that had a higher frequency of application and the most common applied rehabilitation techniques and activities in Iran were selected, among several existing rehabilitation projects applied on the defined MH sample. To do so, this thesis carried out on-site surveying and experts' interviews – see section 5.2.

b) An existing real rehabilitation project constructed with new or improved rehabilitation techniques was chosen, modified, and applied to the sample of study as explained in sections 7.1 to 7.3 This step relied on the collected data from rehabilitation projects constructed with new or improved technologies all around the world – see chapter 2, section 2.2.3.

Stage 6) The sixth stage aims to **apply** and **validate the proposed model** to the **defined scenarios** in order to (1) calculate the Global Sustainability indexes (GS_is) of the defined scenarios, select the most sustainable one, and consequently test the assumed hypothesis – see section 1.3 –, and (2) demonstrate how it enables decision-makers to identify the strengths and weaknesses of interior rehabilitation of MHs from economic, environmental, and social points of view. To calculate the GS_is, this sixth stage obviously relied on the previously defined decision-making tree, its components' weights, and corresponding indicators' value functions (San-Jose Lombera and Garrucho Aprea, 2010; Fuente *et al.*, 2016; Hosseini, De la Fuente and Pons, 2016; Galant, 2020; Hosseini, Yazdani and De, 2020; Josa *et al.*, 2020; Ledesma, Nikolic and Pons, 2020). In this regard, two main parameters should be taken into account:

1) The non-dimensional values of the defined requirements (R_i), criteria (C_j), and indicators (I_k) obtained from the value functions (Table 3.5) and the obtained indicators' values – from sections 6.1 to 6.3 – and,

2) The weights of requirements (ω_{Ri}), criteria (ω_{Cj}), and indicators (ω_{Ik}) assigned by experts from the Delphi method – see Table 3.2.

Consequently, the global sustainability index (GSi) has been calculated by the following equations:

$$C_j = \sum_{k=1}^{o} I_k . \omega_{Ik} \qquad \text{Equation 3.5}$$

$$R_i = \sum_{j=1}^{n} C_j . \omega_{Cj} \qquad \text{Equation 3.6}$$

$$GS_i = \sum_{i=1}^{m} R_i . \omega_{Ri} \qquad \text{Equation 3.7}$$

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}), Global Sustainability index (GS_i).

Figure 3.6 presents the hierarchy-level decision-making tree with its mentioned parameters and equations.

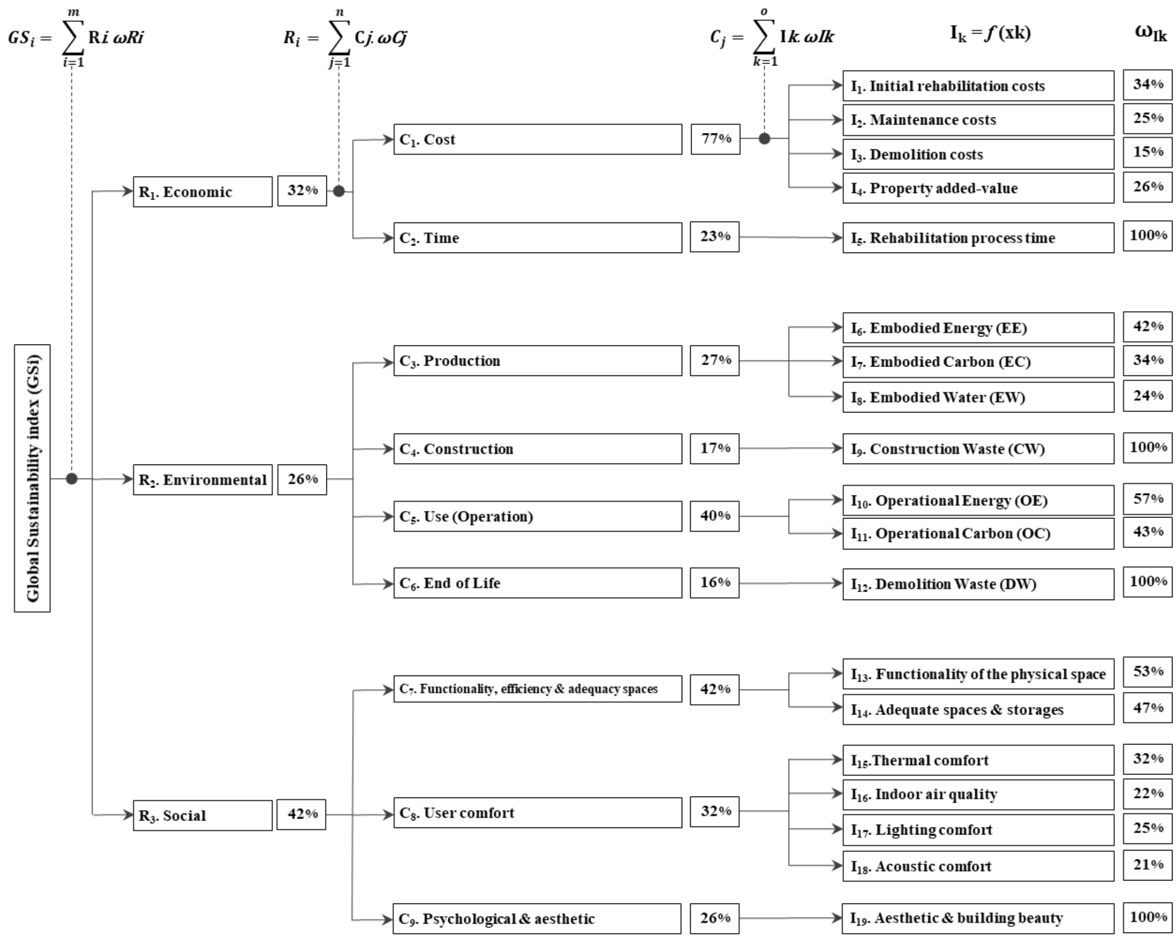


Figure 3.6. The hierarchy-levels decision-making tree, its corresponding assigned weights, and GS_is' equations

Stage 7) This last stage **proves** the proposed model's **suitability**, **validity**, **and robustness** by conducting a **sensitivity analysis** that considered **different probabilistic weighting scenarios** – named as **states** in this thesis – in section 7.5.2.

3.3. Conclusion of chapter 3

This third chapter was dedicated to define the thesis's methodology for developing **a novel model** based on **the MIVES and Delphi methods** – which are well-known and widely accepted in numerous scientific studies – for the sustainability assessment of interior rehabilitation of Iran's MHs. This proposed MIVES-Delphi model, which includes seven main stages – see Figure 3.2 –, is **applicable for any type of MHs' interior rehabilitation** in any country with diverse characteristics. To this end, this model should be adapted by considering the corresponding geographic contexts, sustainability requirement tree components and their assigned weights, and stakeholders' preferences. The seven stages of the proposed model have been concluded as follows:

The **first stage** defined **problems**, **main objectives**, and **scopes and boundaries** regarding the thesis topic to clarify the area of study. The **second stage established a hierarchical decision-making tree** for sustainability assessment of interior rehabilitation of Iran's MHs and its corresponding parameters through selecting 3 requirements (R_i), 9 criteria (C_j), and 19 indicators (I_k) that were the most representative parameters and they were independent of each other. The **third stage assigned weights** to the defined components of the established decision-making tree through conducting two rounds of the Delphi method. The conducted Delphi method enabled the selection of the most qualified experts and decreasing bias for the weighting process. During the **fourth stage**, a **value function** – which is the strength point of the MIVES method – for each defined indicator was established – see Appendix 3.B – by the obtained data from international guidelines, national building rules and regulations, scientific literature, the knowledge generated at experts' seminars, and experience with previous projects and similar case studies. The established value functions measure the satisfaction level of various stakeholders involved in the decision-making procedure as well as quantify, assess, and normalize both qualitative and quantitative indicators that might have different measurement units and scales. Through the **fifth stage** of the proposed model, some **alternatives** – named as **scenarios** in the present dissertation – should be selected to be assessed. To do so, chapters 4, 5, and 7 of the present thesis define the sample of study and consequently some proper scenarios for the defined sample. These defined scenarios include existing real rehabilitation projects in the selected case study – chapter 5 – besides a new and improved one in the world – chapter 7. Chapters 6 and 7 aim to conduct the **sixth stage** of the **proposed MIVES-Delphi model** which is **the application of this model on the defined rehabilitated scenarios** to (1) prove the applicability and validity of this model, (2) calculate the global sustainability index of the defined scenarios and select the most sustainable one, and (3) demonstrate how it enables decision-makers to identify the strengths and weaknesses of interior rehabilitation of MHs from economic, environmental, and social points of view. The **seventh** and the last stage proves the proposed model's **suitability**, **validity**, **and robustness** by conducting a **sensitivity analysis** that considered different probabilistic weighting states.

By conducting the seven aforementioned stages, this **novel model** has been **firstly applied** for the **sustainability assessment of interior rehabilitation of MHs in Iran**. This model would be an appropriate approach for sustainability assessment of interior rehabilitation of Iran's MHs since it **covers the basic principles of the sustainable development concept** through considering the three pillars of sustainability as well as **stakeholders' needs and satisfaction** in the decision-making process. Moreover, since the selection of an optimal sustainable rehabilitation project is a multi-criteria and multi-participant procedure, **this model can serve as a benchmark** for local governments and decision-makers who are dealing with interior rehabilitation of MHs.

CHAPTER 4

Overview of the selected case study: Ekbatan MH, Tehran, Iran

Chapter 4:
Overview of the selected case study: Ekbatan Mass Housing, Tehran, Iran

Introduction

This chapter overviews Ekbatan MH, which is the selected case study, both in the neighborhood and dwelling scales. This overview aims to fulfill the following objectives:

1) **Contribute to collect**, **organize**, **classify**, and **digitalize the general** and **technical information**, of the selected case study to fulfill **the third defined specific objective of the present thesis** – see section 1.4. This objective satisfies an endemic necessity because the required data from the selected case study was mostly not accessible or not in digital format. This first objective that has been fulfilled in section 4.1 aims to: (a) **provide a database** of the selected case study that could be useful for the local government, decision-makers, stakeholders, and relative future studies, and (b) **increase the author's knowledge** regarding the technical information and characteristics of the selected case study to facilitate the selection process of the sample of the study as well as the sustainability assessment of the defined sample more precisely.

To do so, these required data has been collected through (a) contacting with designers, stakeholders, and constructors of this MH, (b) competent authorities and public entities – e.g., Tehran municipality –, and (c) on-site surveying – e.g., interviewing and filling out questionnaires from Ekbatan's residents, visiting and surveying apartments, and carrying out physical measurements. After collecting the aforementioned data, the author has organized, classified, cataloged, and digitalized this information so it becomes more accessible.

2) **Define a sample of study** and consequently **some alternatives** – named as **scenarios** in the present doctoral dissertation – **to be assessed**. This definition is the fifth stage of the established MIVES-Delphi model – see section 3.2. In consequence, to define a proper sample of the study, in section 4.2, the author has selected the most representative apartment unit in Ekbatan as the sample of study based on the obtained data from section 4.1.

Finally, section 4.3 concludes the previous sections 4.1 and 4.2. Figure 4.1 illustrates the structure of chapter 4.

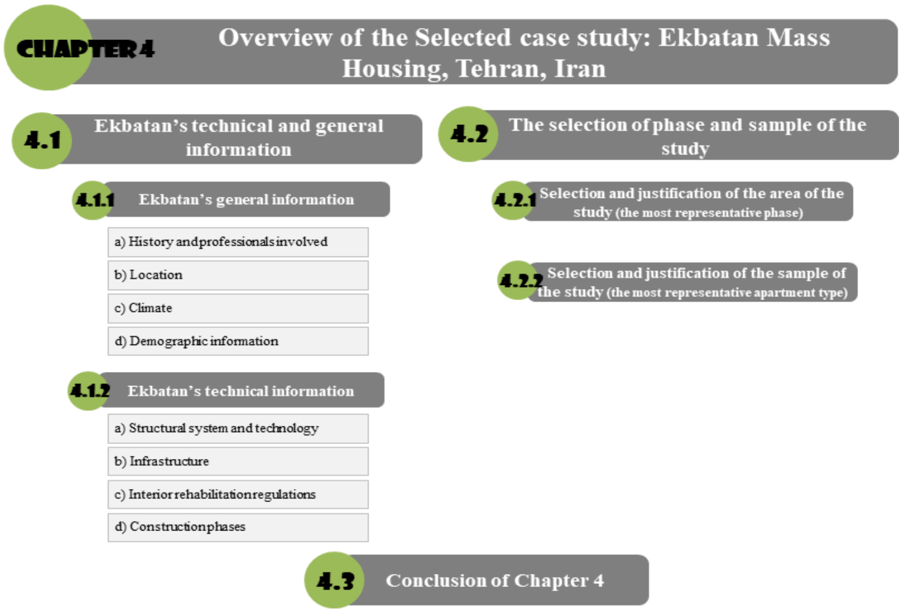


Figure 4.1. Structure of chapter 4

4.1. Ekbatan's general and technical information

This section collects general and technical information of Ekbatan MH to provide a database of this MH, as explained in sections 4.1.1 and 4.1.2 respectively.

4.1.1. Ekbatan's general information

This section overviews the **general information** of Ekbatan including (a) history and professionals involved, (b) location, (c) climate, and (d) demographic information of this MH.

a) History and professionals involved

As previously mentioned in section 2.1, during 1960 to 1980, due to the highest birth rates in Iran (https://www.amar.org.ir/, www.macrotrends.net/cities/21523/tehran/population) and the highest people immigration to urban areas (Ziari and Gharakhlou, 2009; Moosavi, 2012; Babak Soleimani, 2014; Al-Saif, 2015; Felli, 2016; Sedighi, 2018), the urban population grew radically, especially in big cities – e.g., Tehran's population grew from 1.5 in 1956 to 4.5 million in 1976 (https://www.amar.org.ir/, www.macrotrends.net/cities/21523/tehran/population). Due to the significant rise of Iran's GDP, the booming construction market, insufficient domestic technical knowledge, the demand for new ideas, and the close economic and political relationship with other countries (Salek, 2007; Babak Soleimani, 2014; Sedighi, 2018), foreign consultants constructed more than 500,000 MHs residential units with the latest construction technologies of that period (Honar-e Memari Magazine, no.27, 2011) for mostly the middle- and high-income people (Salek, 2007; Babak Soleimani, 2014; Sedighi, 2018).

One of the most significant constructed MHs in that period is **Ekbatan**, which is **the largest MH in Iran**. In 1972, Ekbatan MH construction idea was proposed by Rahman Golzar Shabestani, an Iranian architect. This ambitious architect planned to assign a vacant land with an area of 2.2 million m^2 on the west side of Tehran – about 5 kilometers from the border of this town – to construct over **15,500 apartment units** for around **80,000 inhabitants** with the corporation of foreign firms in **three different construction phases** (Soleimani, 2014; Sedighi, 2018).

Table 4.1. General characteristics of Ekbatan

Ekbatan	Location	Designed for	Total Population	Total residential units	Area of the land (m^2)	Total residential substructure (m^2)
Largest MH estate in Tehran and one of the largest of its kind in the Middle East	On the west side of Tehran	Middle and high-class families	80,000	15,593	2,208,570	2,670,000

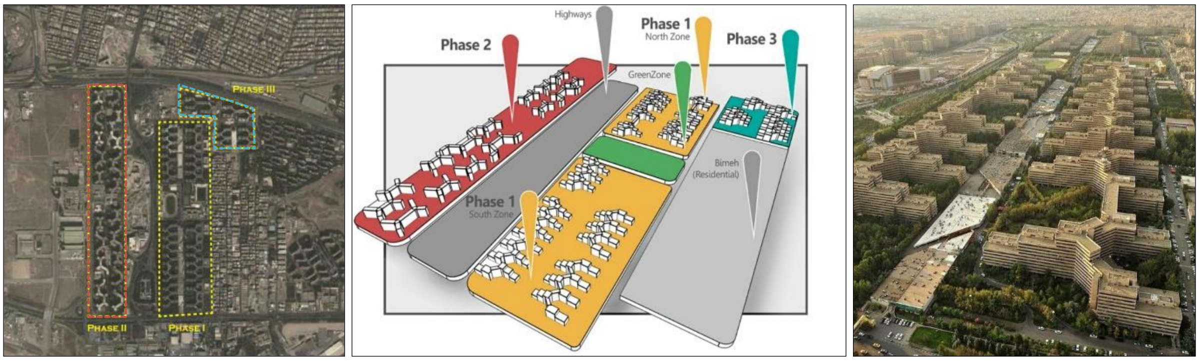


Figure 4.2. Three construction phases of Ekbatan. Source (left): Google earth, (middle): (http://aoapedia.ir/), and (right): Ekbatan MH taken by Saeed Ghazi

The first construction phase of Ekbatan – also named Phase-1 – was designed by Rahman Golzar Shabestari and an American architecture firm – Gruzen and Partners – in 1974 (Gruzen, J and Samton, 2009; Sedighi, 2018). In 1975, another American architecture firm – Starrett Housing Corporation – was being asked to finance and construct over 5600 apartment units in Phase-1 within four years (Figure 4.3) (Pogany, 1996). The first blocks of this phase – blocks *A1* and *C2* – were assigned to civil servants in 1975. Also, other blocks of Phase-1 respectively were assigned before 1979 to government employees (http://www.shahrakekbatan.ir/; http://www.ekbatan.ir/; http://shahrak-ekbatan.ir/).

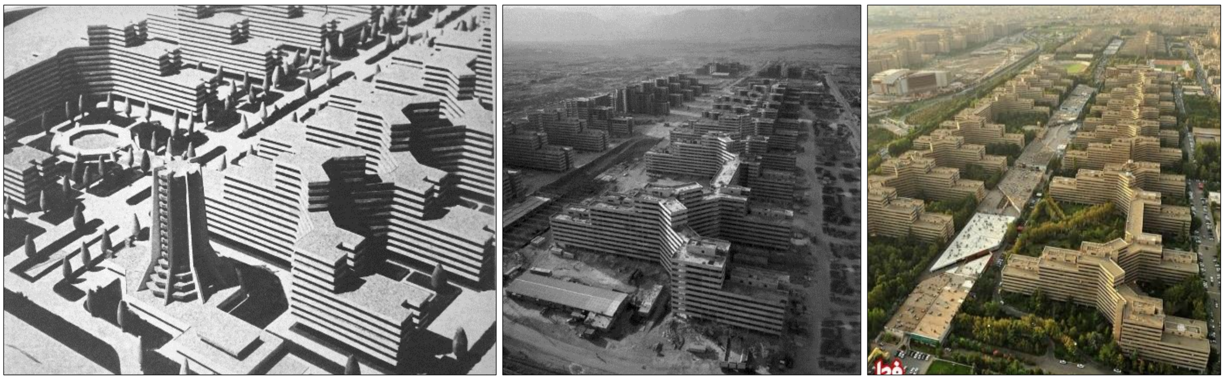


Figure 4.3. (left): The Initial proposed design of Ekbatan’s Phase-1 by Gruzen and Partners, source: Archive of the Ekbatan Redevelopment Company; (middle): Phase-1 of Ekbatan before its completion, source: Honar-e Memari, no. 27, 2011; (right): Phase-1 of Ekbatan after its completion, source: Saeed Ghazi.

In 1976, for **the construction of the second phase** – Phase-2 –, a South Korean architecture firm – Space Group, founded by Kim Swoo Geun – was assigned to design around 8000 apartment units in this phase (Figure 4.4). In the same year, Sherkat-e Omran-e Ekbatan architecture firm – Development Organization of Ekbatan – along with Space Group started the construction of this phase. More than 90% of this phase – except blocks 3 and 5 – was completed before the 1979 Islamic Revolution of Iran (http://www.shahrakekbatan.ir/; http://www.ekbatan.ir/; http://shahrak-ekbatan.ir/, http://ekbatan-2-15.blogfa.com/post/9; Sedighi, 2018; Yasi, 2015). After the mentioned revolution, due to the budget deficit as well as the immigration of foreign firms that were involved in this project, the construction of blocks 3 and 5 of Phase-2 lasted until 1995 (Yasi, 2015).

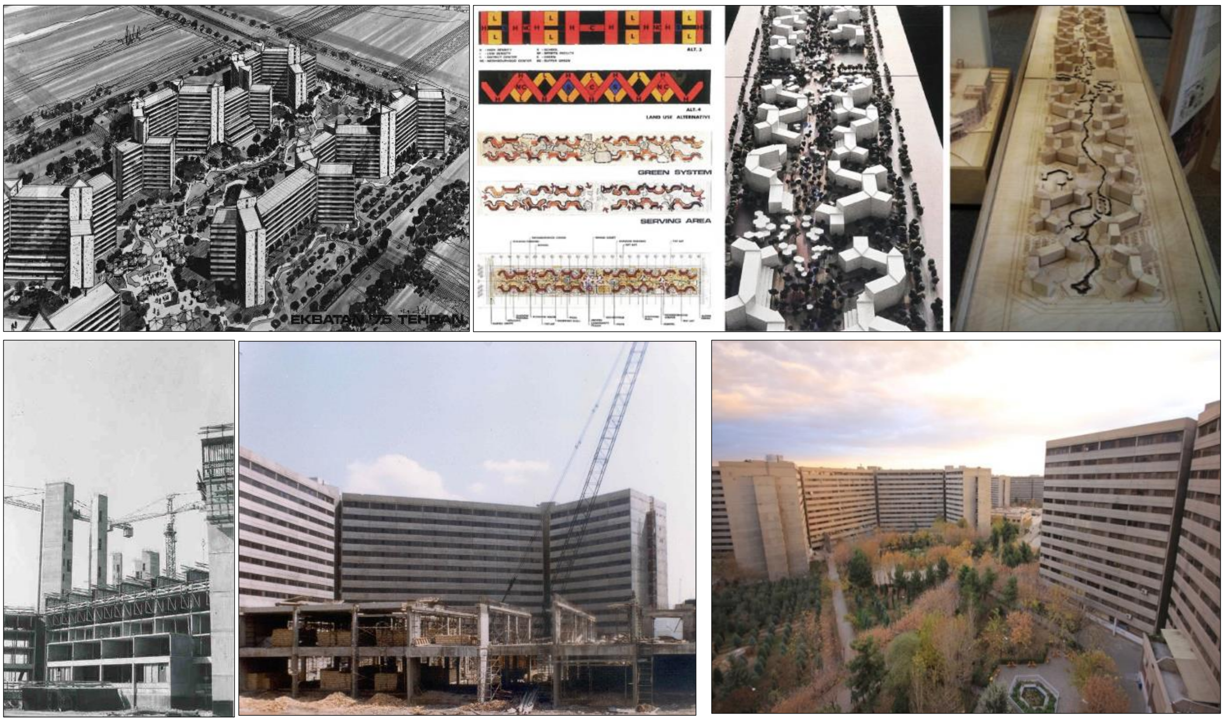


Figure 4.4. (top): Initial proposed design of Ekbatan’s Phase-2 by Kim Swoo Geun architecture firm, source: Kim Swoo Geun architecture firm; (bottom-left): Phase-2 of Ekbatan before its completion, source: Honar-e Memari, no. 27, 2011; and (bottom-right): Phase-2 of Ekbatan after its completion, source: Safa Daneshvar.

In 1985, Sherkat-e Omran-e Ekbatan architecture firm started **the construction of Phase-3**, with more than 2000 apartment units that were successfully built and completed in 1992 (http://www.shahrakekbatan.ir/; http://www.ekbatan.ir/; http://shahrak-ekbatan.ir/) (Figure 4.5).

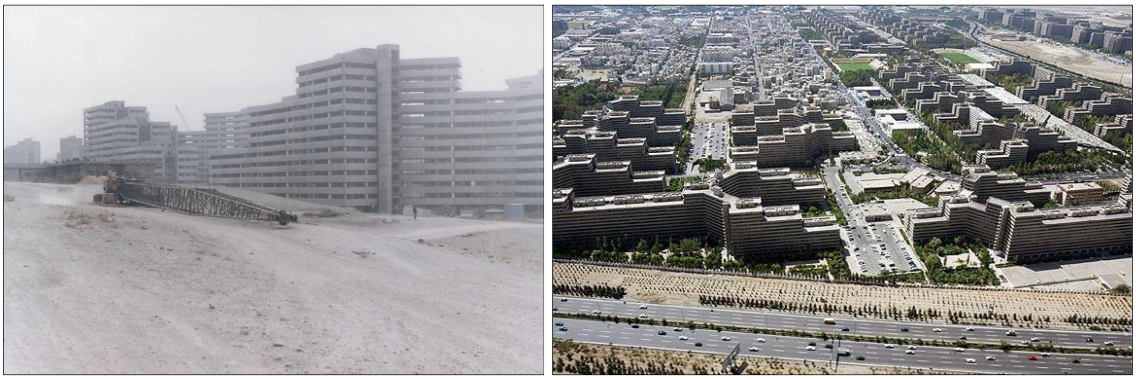


Figure 4.5. (left): Phase-3 of Ekbatan before its completion, source: Honar-e Memari, no. 27, 2011; (right): Phase-3 of Ekbatan after its completion, source: Saeed Ghazi.

Figure 4.6 illustrates schematically the construction time of each part of Ekbatan – phases and blocks.

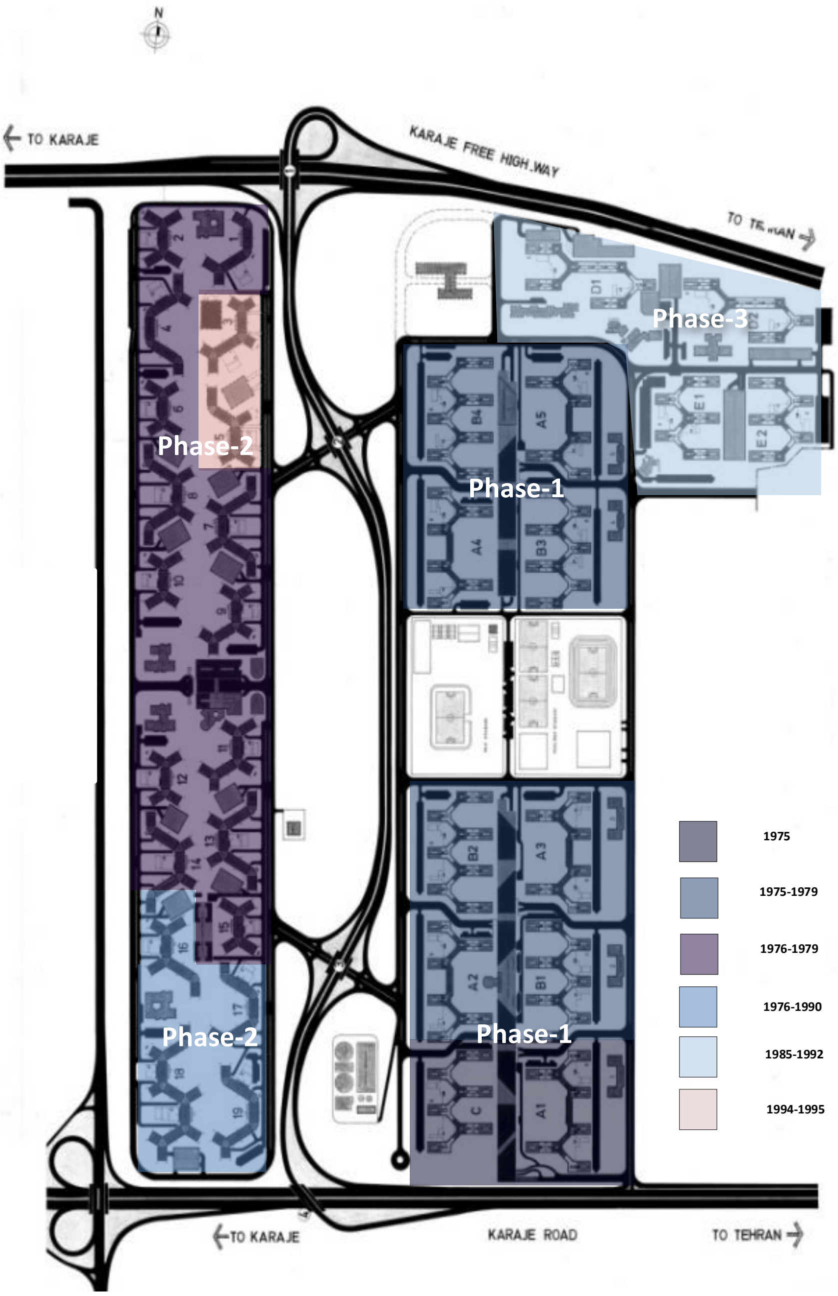


Figure 4.6. Construction time of different parts of Ekbatan, source: Author

b) Location

Ekbatan is located on the west side of Tehran and in the sixth district of the 5th municipality region of this city according to the latest urban division of this metropolitan. This MH has an area of 2.2 million m^2 which is bounded southwards to Mehrabad airport and Shahid Lashkari highway, from the north to the Ferdows neighborhood and Tehran-Karaj highway, from the west to the Aviation Exhibition, and from the east to Apadana and Kooye-e-Bimeh MHs (Figure 4.7).

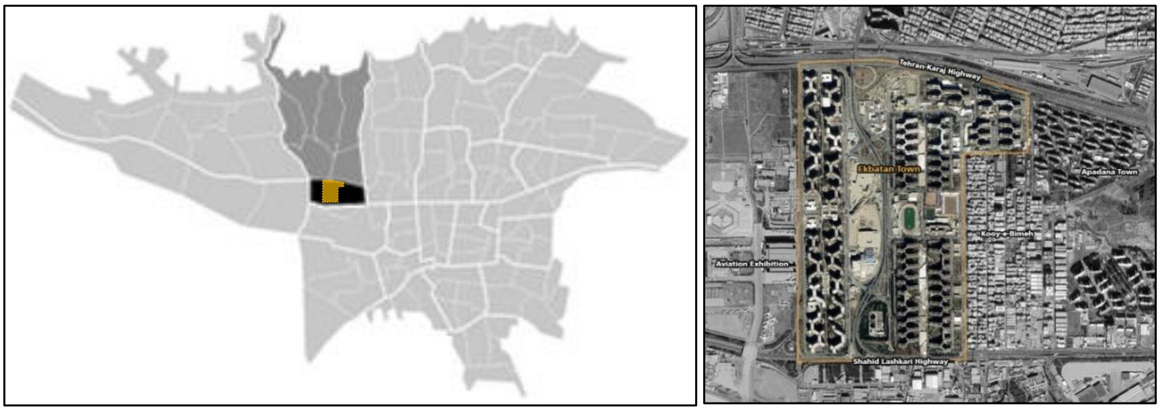
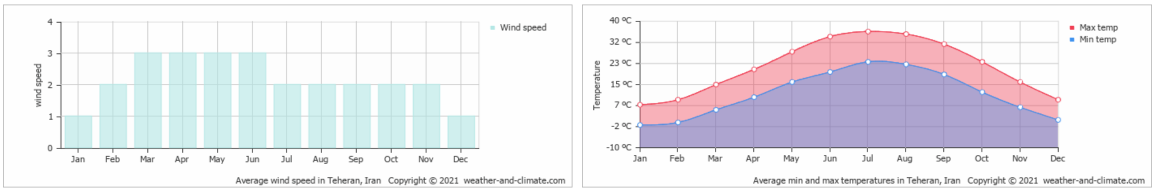


Figure 4.7. Location of Ekbatan in the sixth district of the 5th municipality region of Tehran (left), the urban layout of Ekbatan (right)

c) Climate

Tehran's climate can be generally described as mild in the spring and autumn, hot and dry in the summer, and slightly cold and wet in the winter (https://weather-and-climate.com/average-monthly-Rainfall-Temperature Sunshine,Tehran-ir,Iran; www.timeanddate.com/weather/iran/tehran/climate https://en.climate-data.org/asia/iran/tehran/tehran-198/). Figure 4.8 illustrates the recorded climate data of Tehran during 1988-2018.



Climate data for Tehran, elevation: 1548.2 m or 5079.3 ft, 1988-2018													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	16.4 (61.5)	19.0 (66.2)	23.8 (74.8)	30.6 (87.1)	33.6 (92.5)	37.8 (100.0)	40.8 (105.4)	40.4 (104.7)	39.6 (103.3)	31.2 (88.2)	23.0 (73.4)	19.0 (66.2)	40.8 (105.4)
Average high °C (°F)	6.1 (43.0)	8.1 (46.6)	12.9 (55.2)	19.8 (67.6)	25.0 (77.0)	31.2 (88.2)	33.9 (93.0)	33.5 (92.3)	29.3 (84.7)	22.4 (72.3)	14.3 (57.7)	8.6 (47.5)	20.4 (68.8)
Average low °C (°F)	−1.5 (29.3)	−0.2 (31.6)	4.0 (39.2)	9.8 (49.6)	14 (57)	19.6 (67.3)	22.6 (72.7)	21.9 (71.4)	17.5 (63.5)	11.6 (52.9)	5.4 (41.7)	1.0 (33.8)	10.5 (50.8)
Record low °C (°F)	−11.4 (11.5)	−11.0 (12.2)	−8.0 (17.6)	−1.6 (29.1)	3.0 (37.4)	12.0 (53.6)	15.4 (59.7)	13.5 (56.3)	8.8 (47.8)	2.6 (36.7)	−5.2 (22.6)	−9.6 (14.7)	−11.4 (11.5)
Average precipitation mm (inches)	63.1 (2.48)	66.5 (2.62)	83.3 (3.28)	50.1 (1.97)	27.1 (1.07)	4.0 (0.16)	4.2 (0.17)	3.2 (0.13)	3.4 (0.13)	16.5 (0.65)	41.3 (1.63)	66.3 (2.61)	429 (16.9)
Average rainy days	12.3	10.9	12.3	10.0	8.9	3.3	3.4	1.6	1.3	5.8	8.6	10.7	89.1
Average snowy days	8.9	6.6	2.5	0.1	0.1	0	0	0	0	0	0.6	4.9	23.7
Average relative humidity (%)	67	59	53	44	39	30	31	31	33	44	57	66	46
Mean monthly sunshine hours	137.2	151.1	186.0	219.1	279.8	328.7	336.6	336.8	300.5	246.8	169.4	134.1	2,826.1
Source: Climatological Research Institute													

Figure 4.8.Climate data of Tehran from 1988 to 2018 (www.timeanddate.com/weather/iran/tehran/climate)

d) Demographic information

This section has collected the demographic information of Ekbatan from the Statistical Center of Iran (SCI). Since 1956, SCI has conducted censuses every ten years until 2006, when this center decided to conduct its censuses every five years. It is worthy to note that there is **no exact demographic information of Ekbatan before 1986** because of the two following reasons: (1) census information before 1986 was not recorded digitally, and (2) some of the apartment units in Ekbatan were not completed and assigned and they were occupied gradually. Table 4.2 illustrates the demographic information of Ekbatan from 1996 to 2016 (www.amar.org.ir).

Table 4.2. The demographic information of Ekbatan from 1996 to 2016 (www.amar.org.ir)

Year	Total population	Female population	Male population	Female population rate (%)	Male population rate (%)	Youth population (Under 15 years old)	Elderly population (Over 65 years old)	Dependency rate of the population (Youth and Elderly) %	Number of households	Occupancy rate (%)	Household size
1996	64,257	33,127	31,130	51.55 %	48.45 %	8218 (12.79%)	4131 (6.43%)	19.22 %	12,978	83.37%	4.95
2006	45,244	22,764	22,480	50.32 %	49.68 %	4944 (10.92%)	3778 (8.35%)	19.27%	13,925	89.46%	3.25
2011	44,981	22,702	22,279	50.47 %	49.53 %	3878 (8.62%)	5076 (11.28%)	19.90 %	14,107	90.63%	3.19
2016*	44,125	22,961	21,124	52.03 %	47.87 %	3531 (8.01%)	7290 (16.52%)	24.53 %	14,532	93.36%	3.04

* SCI's censuses conduct each five years. 2021's census is not still reported.

Due to the significant decrease in Iran's birth rate between 1996 and 2006, **the Ekbatan population decreased** as well from 64,000 to 45,000 inhabitants. Moreover, between 2006 and 2016, the population of this MH slightly decreased or even remained constant. Furthermore, between 1996 and 2016, **the Ekbatan occupancy rate** – the percentage of all available units in a residential complex that are occupied at a particular time – **increased** from 12,987 households (83%) to 14,532 households (93%) of the total 15,593 apartment units. Therefore, it can be concluded that the Ekbatan's apartment units were occupied over the years. It is also interesting to know that **the Ekbatan household size has shrunk** over the years. In 1996, the household size in Ekbatan was 4.95 but the results of the Ekbatan census conducted in 2016 show that the average household size is 3.04, which is a meaningful decrease.

Figure 4.9 illustrates the age pyramid of this MH from 2006 to 2016. In 2006, the two major age groups of inhabitants belonged to people between 15 to 24 years old. In 2011, the aforementioned data changed to 20 to 29 years old inhabitants. While these major age groups changed to 25 to 34 years old in 2016. In this regard, it can be concluded that **the Ekbatan population got older over time**. Furthermore, the average number of adults per household has remained constant or even has slightly increased over time.

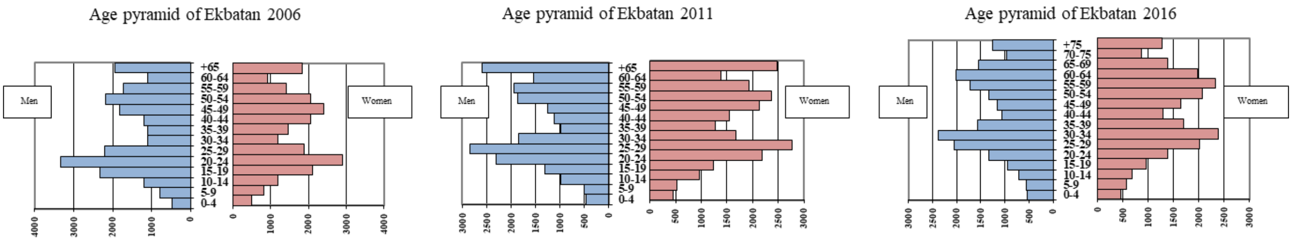


Figure 4.9. the age pyramid of Ekbatan, from 2006 to 2016 (www.amar.org.ir)

4.1.2. Ekbatan's technical information

This section overviews the **technical information** of Ekbatan including (a) structural system and technology, (b) infrastructure, (c) interior rehabilitation regulations, and (d) construction phases and their characteristics.

a) Structural system and technology

MHs used building technologies with high construction speeds. The technology of prefabrication had become applicable to housing projects since the 1970's making precast modules and forms available for an abundance of uses, which was adopted for the construction of MH projects all over the globe. Also in Iran, most of the early residential MHs were constructed utilizing precast and prefabricated elements with the collaboration of foreign consultants (Moosavi 2012; Soleimani 2014).

Nevertheless, Ekbatan MH has load-bearing reinforced concrete structural walls and slabs that were built applying **a semi-tunnel system** with **poured on-site concrete**, which was one of the latest fast construction technologies in the 1970s (Honar-e Memari Magazine, no.27, 2011). The semi-tunnel formwork is a U-shape steel prefabricated mold that allows the wall and the slab to be cast in a single operation (https://www.concretecentre.com/Building-Elements/Walls/Tunnel-form.aspx) (Figure 4.10). These U-shaped pieces created similar cells with a proportion of 7.2 m wide by 21.6 m deep by 3.2 m high which was formed dwellings from 50 to 300 m^2 in this MH (Sedighi, 2018). The space between each U-shape mold was 20 cm in order to place reinforcement concrete walls. Also, the **structure of the façade's main part** is **composed of prefabricated concrete panels**. The Ekbatan structure is highly resistant due to the rapid-hardening concrete and the pre-stressed reinforcement (Kimiaqalam, 2012). The lower floors' structures, as they bear more load, have more reinforcement, but the thickness of all walls and slabs have the same dimensions – 20cm – up to the top. The construction process in Ekbatan was very quick – execution of each floor lasts almost a week – and the daily construction rate was up to 1500 m^3 (Kimiaqalam, 2012; Zolghadr, 2002).

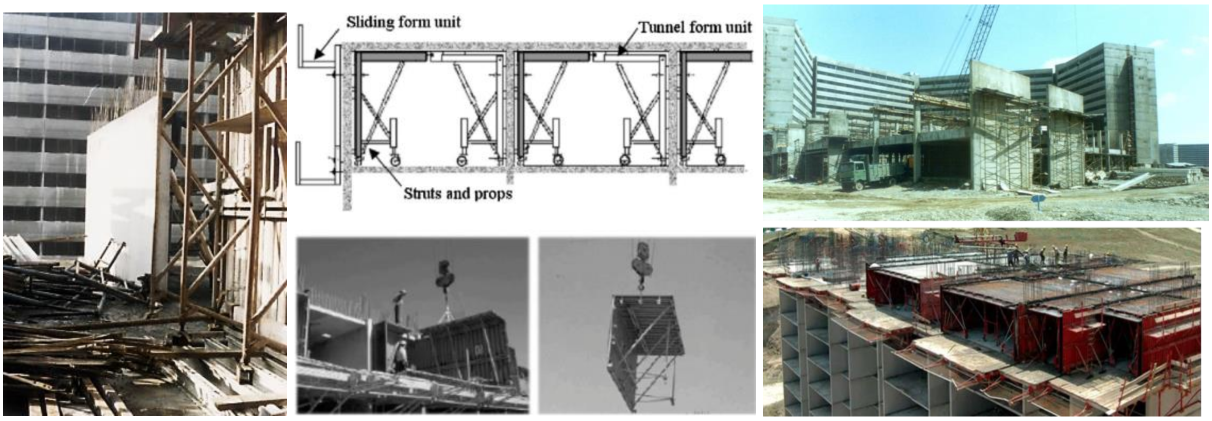


Figure 4.10. Ekbatan construction system and technology, source: (Honar-e Memari Magazine, no.27, 2011)

The operation of the semi-tunnel system in Ekbatan had the following stages: (1) prefabricated wall reinforcement was placed by a crane along with the previous one, (2) two and a half semi-tunnel molds were craned into place and bolted together, (3) the wall concrete was poured, (4) the slab reinforcements were placed and fixed, (5) the slab concrete was placed and with the usage of heaters high temperature was provided for the concrete to reach its strength overnight, and (6) the tunnel-forms were removed by crane after 48 to 72 hours (Figure4.11).

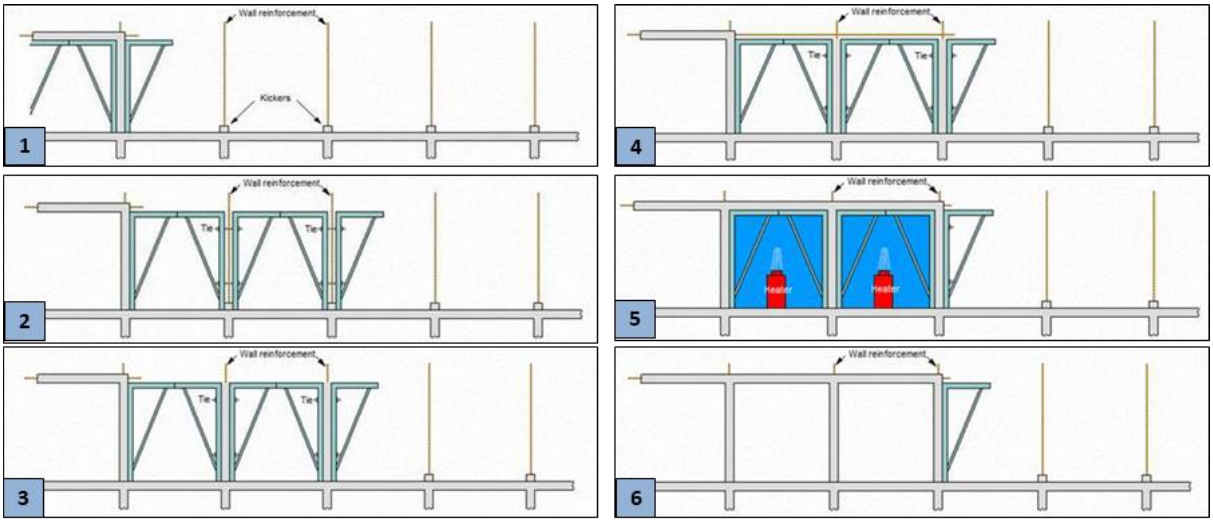


Figure 4.11. The operation of the semi-tunnel system in Ekbatan

The application of **durable materials** and **appropriate construction methods** which were used in Ekbatan MH were two important indicators that caused the structural strength of this MH to withstand an earthquake up to nine on the Richter scale – and thus increase the safety of buildings. Also, based on several references (http://www.shahrakekbatan.ir/; http://www.ekbatan.ir/; http://shahrak-ekbatan.ir/; Felli, 2016; Kimiaqalam, 2012), the useful lifespan of this MH **is estimated up to 300 years**.

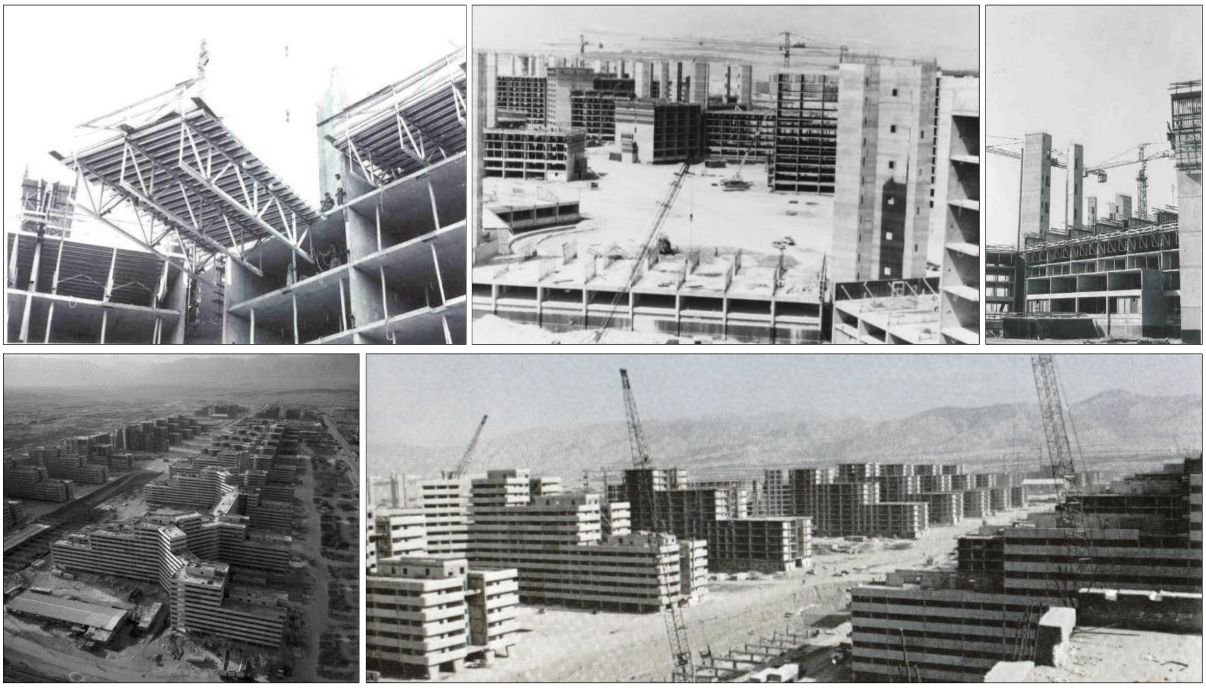


Figure 4.12. Ekbatan construction process (http://www.shahrakekbatan.ir/; http://www.ekbatan.ir/; Honar-e Memari Magazine, no.27, 2011)

b) Infrastructure

Ekbatan is one of the oldest MHs of Iran that was designed and constructed as a large-scale urban project and it is considered as one of Tehran's well-known and prestigious MHs. Due to urban facilities such as high quality of public spaces and vast green areas, building layouts, pedestrian areas, parks, public facilities – shop, mall, school, library, restaurant, mosque, and sports center –, water treatment plants, transportation networks, hospitals, and recreation centers, Ekbatan is considered as a pleasant and peaceful living space by most of its residents (Felli, 2016; Molana, 2016) (Figure 4.12).

Figure 4.13. Ekbatan construction process (http://www.shahrakekbatan.ir/; http://www.ekbatan.ir/; Honar-e Memari Magazine, no.27, 2011)

Besides, Ekbatan was constructed by applying the latest technologies of its own time and prepared facilities and infrastructures such as garbage chute system, escape stairs, and lift with emergency power which were embedded in each block (Felli, 2016; Molana, 2016). Also, this project was unique in terms of energy consumption in its era due to the application of double-glazed windows (Honar-e Memari

Magazine, no.27, 2011). The applied heating and cooling system in this MH is fan coils and cooling towers for cooling and central heating systems for heating.

The total residential infrastructure area in Ekbatan MH is 2,670,000 m^2 (Kimiaqalam, 2012). Since this MH has 15,593 apartment units and 44,125 inhabitants, the average infrastructure for each dwelling unit and each person are equal to 171.1 and 60.51 m^2 respectively. Therefore, based on the aforementioned data, this MH provides an adequate infrastructure area for its inhabitants (Felli, 2016).

c) Interior rehabilitation regulations in Ekbatan

As previously mentioned in section 2.2.4, for interior rehabilitation of MHs' residential buildings in Iran, a hierarchical set of laws and regulations have been established by different organizations and entities: the National Building Regulations, building laws and regulations from the municipality, the law of the establishment of settlements, the law of ownership of apartments, and the specific regulations of corresponding MH. It is worthy to note that since the regulations for general interior rehabilitation in Iran have been explained previously in section 2.24 and Figure 2.18, this section presents the specific regulations for dwellings interior rehabilitation in the case of Ekbatan.

Since 1984, **Ekbatan MH has had its own building regulations** regarding buildings maintenance and rehabilitation that were established by its central board of directors. Since Ekbatan has 33 blocks, the central board of directors of this MH consists of 33 members that each one of them is the director of one block. Moreover, each block has its own board of directors that is chosen by inhabitants of that block every two years (Figure 4.13).

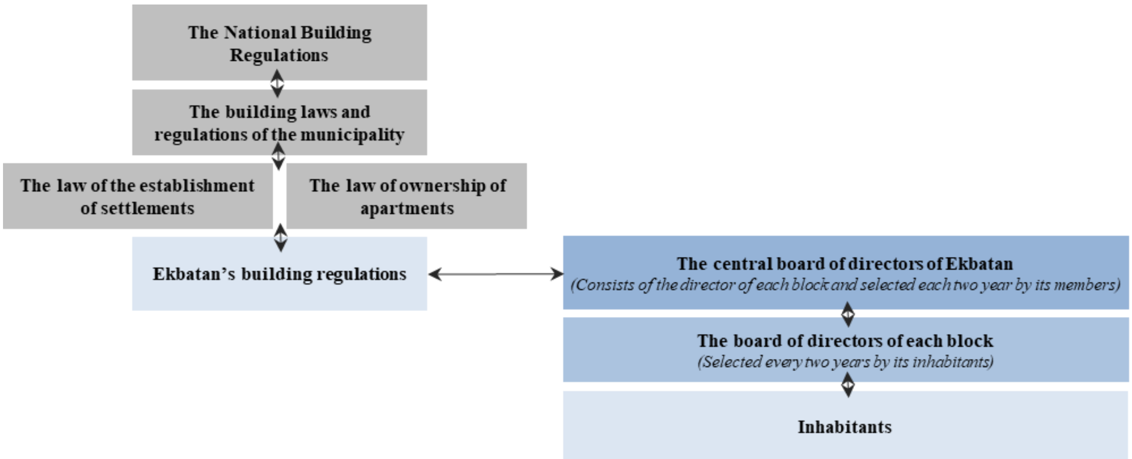


Figure 4.14. Structure of Ekbatan board of directors, source: Author and (http://www.shahrakekbatan.ir/)

Some of the most important and relative specific buildings rehabilitation regulations in Ekbatan are as follows (http://www.shahrakekbatan.ir/; http://www.ekbatan.ir/; http://shahrak-ekbatan.ir/):

- Any kind of building intervention in Ekbatan should follow Iran's building laws and regulations such as the National Building Regulations, building laws and regulations of the municipality, the law of the establishment of settlements, and the law of ownership of apartments.
- Any changes in façade, common or shared spaces – including corridors, doors of apartments, risers, lobbies, etc. – should be based on all abovementioned superior regulations and requires permission from Ekbatan's central board of directors.
- For interior rehabilitation of apartment units in each block, it is obligatory to obtain specific permission from the board of directors of that block.
- Rehabilitation activities must occur during specific day hours – from 8 to 13 and from 16 to 19.
- The utilization of lifts is prohibited for the transportation of construction materials. In this regard, some specific cargo elevators were built next to the emergency stairs of each block.

d) Construction phases of Ekbatan and their characteristics

As previously mentioned, Ekbatan was designed to be constructed in three different construction phases called Phase-1, Phase-2, and Phase-3. Also, each phase was planned to contain categorized independent buildings named as blocks (Figure 4.14) (Ranjipoor, 1390). In total, this MH has thirty-three blocks (Kimiaqalam, 2012). The following paragraphs describe the characteristics of each phase and its blocks more in detail.

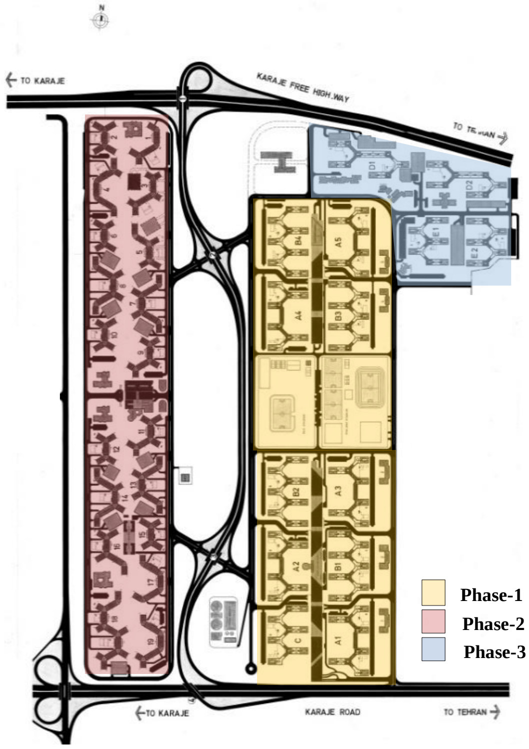


Figure 4.15.Three phases of Ekbatan (Author)

In Phase-1, Rahman Golzar Shabestari and Gruzen and Partners firm claimed to have been inspired by Le Corbusier's 1952 Unité d'Habitation in Marseilles to design 10 huge *Y-plan* blocks along a central commercial area that was designed to provide daily needs of this phase's inhabitants (Sedighi, 2018). Each one of these blocks has a set of green spaces and gardens embedded within it and sat upon a double row of V-shaped concrete columns to provide a continuous ground-level landscape (Sedighi, 2018). Phase-1, like the other two phases, was designed following a minimalistic approach. The simplicity of form, lack of ornamentation, continuous and linear windows, and rectangular compositions are the major architectural characteristics of Ekbatan MH (Moosavi, 2012).

Figure 4.16. (left) Unité d'Habitation, Le Corbusier's, 1952, source: (https://www.plataformaarquitectura.cl/cl/02-195195/), (right) Ekbatan, Jordan Gruzen and Rahman Golzar, 1975. Source: (Honar-e Memari Magazine, no.27, 2011).

The blocks of Phase-1 are oriented along the East-West axis. These 10 blocks totally contain 5611 apartment units with a residential area of 949,000 m^2. These blocks are divided by Shahid Dastgerdi and Rah-ahan Stadiums into two parts, 4 blocks in the north and 6 blocks in the south of the stadiums as shown in Figure 4.16.

Table 4.3. Architectural characteristics of Phase-1

years	Designer	Constructor	Area of residential building (m^2)	Number of blocks	Number of apartment units	Orientation
1975-1979	Rahman Golzar and Gruzen firm	Starrett firm	949,000	10	5611	along East-West axis

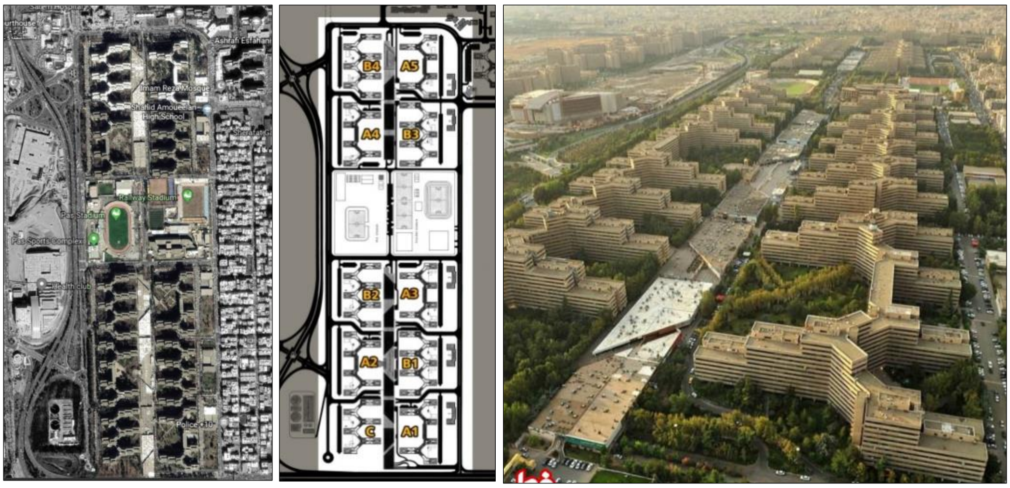


Figure 4.17. Phase-1 of Ekbatan

From the morphological aspect, each block of Phase-1 – and Phase-3 – contains 5, 9, and 12-story modular towers, with a triple-stepped profile (Figure 4.17). In this way, the designers provided a combination of different level towers to form a dynamic skyline for Phase-1 and Phase-3 (Sedighi, 2018).

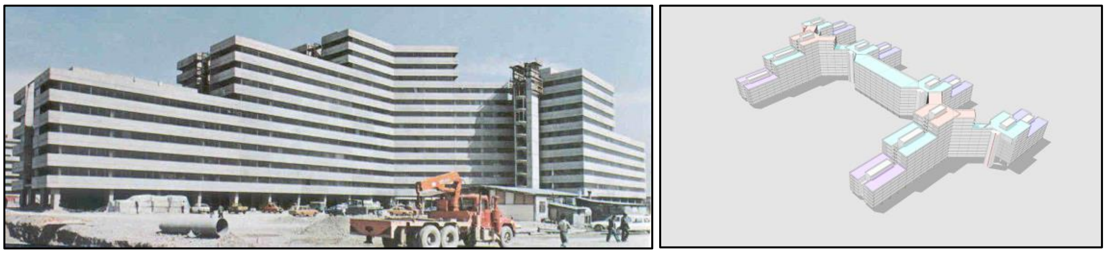


Figure 4.18. Morphology of Phase-1. Source (right): (Honar-e Memari Magazine, no.27, 2011), (left): Author.

The blocks of Phase-1 are categorized into three different types: *A*, *B*, and *C*. As indicated in Table 4.4, block types *A*, *B*, and *C* have 532, 613, and 514 residential units respectively. One of the differences between blocks *A* and two other types – *B* and *C* – is that blocks *A* have 2-bedroom apartment units, while blocks *B and C* do not have any type of these units but have studio apartments, 1-, and 3-bedroom dwellings. Figure 4.18 shows the different typologies of blocks and their characteristics in Phase-1 of Ekbatan MH.

Table 4.4. Typology of blocks and their characteristics in Phase-1

Type of Blocks	Numbers of blocks	Name of Blocks	Number of entries	Number of apartment units	Characteristics
Blocks *A*	5	A1(1)	14	517	With 2-bedroom apartments
		A2(4)	14	532	
		A3(5)	14	532	
		A4 (8)	14	532	
		A5 (9)	14	532	
Blocks *B*	4	B1 (3)	18	613	Without 2-bedroom apartments
		B2 (6)	18	613	
		B3 (7)	18	613	
		B4 (10)	18	613	
Block *C*	1	C (2)	15	514	Without 2-bedroom apartments
Total	**10**		**157**	**5611**	

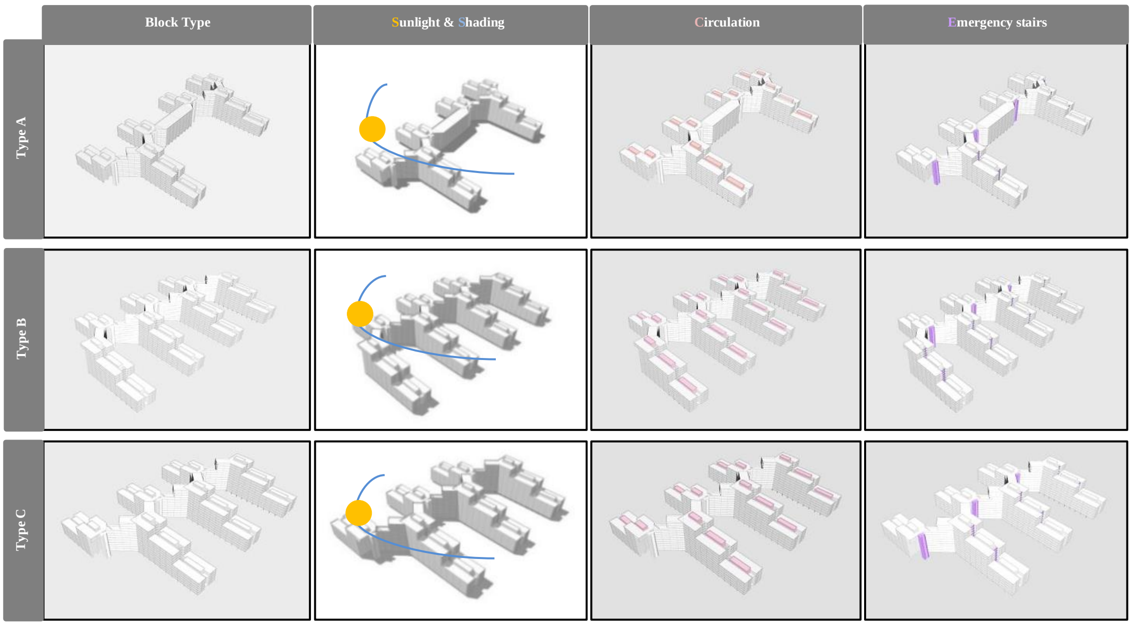


Figure 4.19. Typology of blocks and their characteristics in Phase-1. Source: Author

From building access arrangement and circulation aspects, Phase-1 has a central vertical corridor for each modular tower that 4 to 8 apartment units were built around this central corridor. In this phase, load-bearing walls divided interior spaces of apartment units, and therefore, there is not any **free plan** in this phase (Figure 4.19).

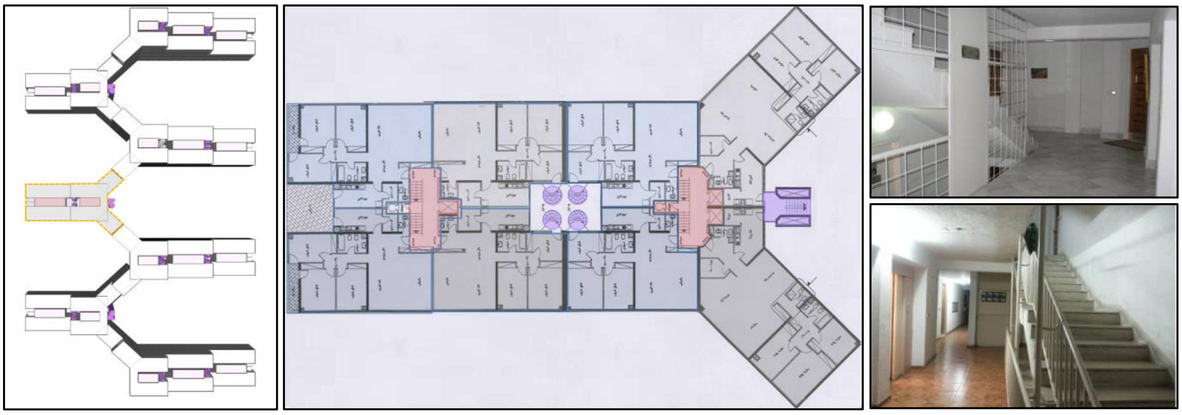


Figure 4.20.The architectural layout of Phase-1and its access and circulations.

In Phase-1, there are 13 different apartment unit types that were named based on the English alphabet as shown in Table 4.5.

Table 4.5.Typology of apartment units of Phase-1

Number of bedrooms	Type
Studio	I
One-bedroom apartment	E-H
Two-bedroom apartment	G, F(Just located on *A* block type)
Three-bedroom apartment	A, B, B1, C1, C2, C-r, D1, D2

Phase-2 consists of 19 blocks in pairs around a central green spine and it is oriented along the north-south axis (Figure 4.20). This phase has 7996 apartment units with a residential area of 1,482,000 m^2 as shown in Table 4.6.

Table 4.6. General characteristics of Phase-2

Years	Designer	Constructor	Area of residential building (m^2)	Number of blocks	Number of apartment units	Orientation
1976-1995	Kim Swoo Geun (Space group Company)	*Space group company* & *Development Organization of Ekbatan*	1,482,000	19	7996	Along the North-South axis

Figure 4.21. Phase-2 of Ekbatan. Source:(left) Author, (right): Safa Daneshvar (htpp://safa.daneshvar.ir).

In Phase-2, each one of these nineteen blocks was made of some semi-hexagonal cores as a vertical circulation that connected three 12-storey modular towers with an angle of 120 degrees to each other (Figure 4.21). For the modular towers, Geun designed an in-situ concrete frame with prefabricated concrete infill elements, similar to the Gruzen and Partners design for Phase-1 (Sedighi, 2018).

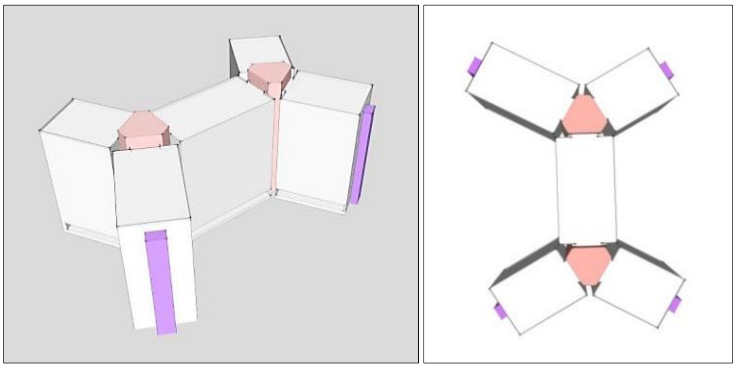


Figure 4.22. Morphology of blocks in Phase-2. Source: Author.

Table 4.7.Typology of blocks and their characteristics in Phase-2

Name of block	Number of apartment units	Number of entries
1	340	3
2	422	2
3	402	9
4	460	4
5	516	3
6	360	2
7	506	4
8	506	4
9	422	3
10	360	2
11	458	3
12	298	2
13	506	4
14	500	4
15	360	2
16	337	3
17	312	4
18	597	6
19	334	4
Total for these 19 blocks	**7996**	**68**

On the contrary to Phase-1 and -3, Phase-2 was designed based on a free plan through the separation of load-bearing elements from sub-dividing interior walls. In this regard, load-bearing concrete walls and floors had varied openings to create a playful combination of duplex dwellings and single-floor apartments to allow changeability and provide visual diversity (Sedighi, 2018).

In Phase-2, blocks can be categorized into three different categories. The first category consists of 13 blocks which are blocks number 1 to 15 except the blocks number 3 and 5. The second category includes blocks number 16 to 19 and the third one blocks number 3 and 5. The first and second categories were constructed between 1976 and 1979 and they have similar structures, shapes, and forms. However, they have different apartment unit types which are indicated in Table 4.8. Blocks 3 and 5 were constructed by *the Development Organization of Ekbatan* after the Islamic revolution – between 1994 and 1995. The third category has different shapes and apartment types compared to the two other categories.

Table 4.8. Different categories of Phase-2's blocks and their characteristics

Category of blocks	Shape and Form	Typology of apartment units	Number of blocks	Number of apartment units
Blocks number 1 to 15 (except 3 and 5)	Similar to blocks 16 to 19	Named by Persian alphabet	13	5,488
Blocks number 16 to 19	Similar to blocks 1 to 15 (except 3 and 5)	Named by English alphabet	4	1,580
Blocks 3 and 5	Not similar to other blocks	Named by English alphabet	2	918

(http://www.shahrakekbatan.ir/)

In the first category of Phase-2, there are 20 different apartment unit types that were named using the Persian Alphabet, while in the second and third categories, there are 17 different types named following the English alphabet (Table 4.9).

Table 4.9. Different types of apartment units in Phase-2

Number of bedrooms	Type
One-bedroom apartment	A,B,B1,B2 Aleph-1, Aleph-2, Aleph-3, Aleph-4 Be-1, Be-2, Be-3, Be-4, Be-5, Be-6
Two bedrooms apartment	A-B-C-D-D1-E-F- Gim-1, Gim-2, Gim-3, Gim-4
Three bedrooms apartment	A, B Dal-1, Dal-2, He-1, He-2,He-3,He-4
Four bedrooms apartment	A, B, C, C1

In 1985, the *Development Organization of Ekbatan* started to construct **Phase-3** of Ekbatan, and all of the 2086 apartment units of this phase were successfully built and completed in 1992 (http://www.shahrakekbatan.ir/; http://www.ekbatan.ir/; http://shahrak-ekbatan.ir/) (Table 4.10). This phase has 4 blocks that are oriented along the East-West axis.

Table 4.10. Architectural characteristics of Phase-3

years	Designer	Constructor	Area of residential building(m2)	Number of blocks	Number of apartment units	Orientation
1985-1992	Rahman Golzar and Jordan Gruzen	Sherkat-e Omran-e Ekbatan (Development Organization of Ekbatan)	354,100	4	2086	Along the East-West axis

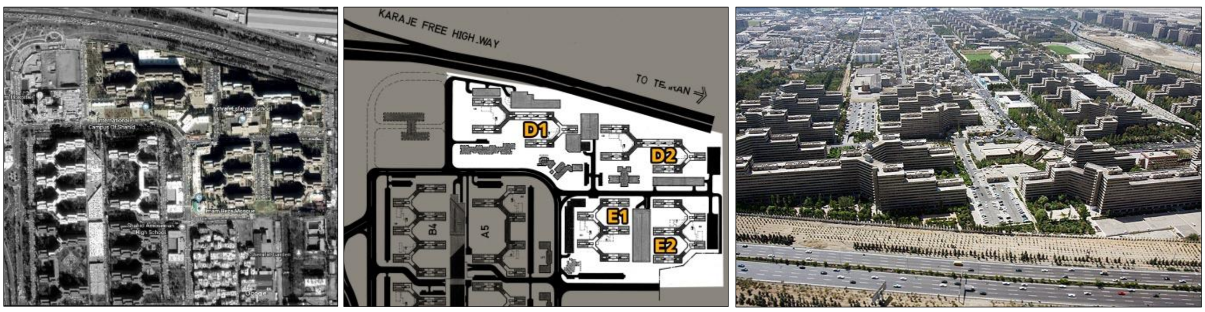


Figure 4.23. Phase-3 of Ekbatan

From the morphological aspect, Phase-3 is very similar to Phase-1 and each block of this phase consisted of 5, 9, and 12-story modular towers, with a triple-stepped profile.

Blocks from Phase-3 are categorized into two different types: *D* and *E*. Block types *D* and *E* have 598 and 445 residential units respectively. Neither blocks *D* nor *E* have 2-bedroom apartments but studio apartments, 1-, and 3-bedroom dwellings, as shown in Table 4.11. From the building access arrangement and circulation aspect, Phase-3, similar to Phase-1, has a central vertical corridor for each modular tower, around which from 4 to 8 apartment units were built (Figure 4.23). In Phase-3, load-bearing walls divide the interior spaces of apartment units and there are no free plans in this phase.

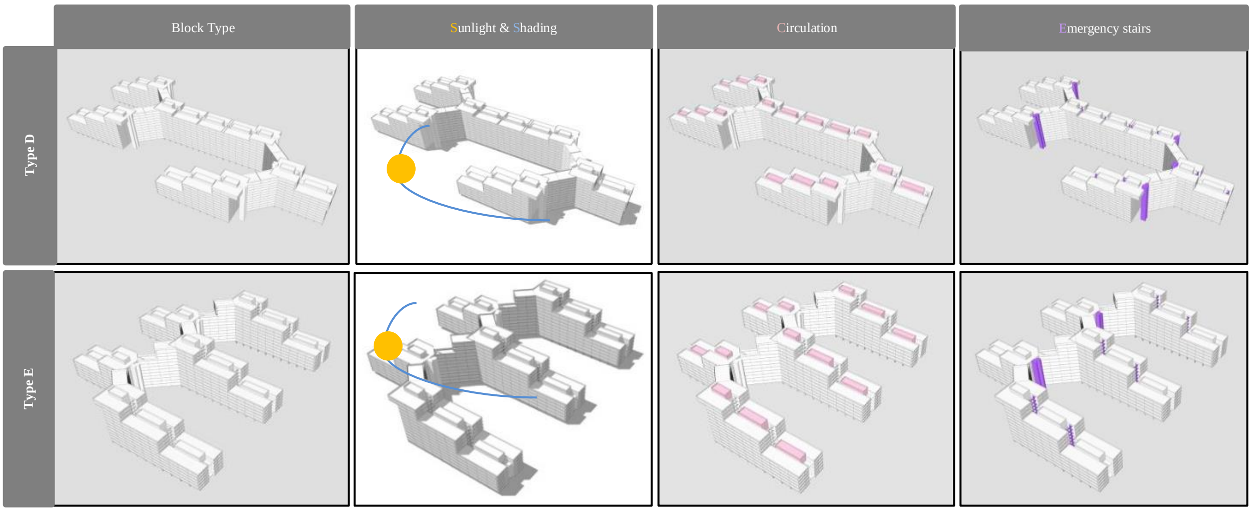


Figure 4.24. Different types of blocks and their characteristics in Phase-3

Table 4.11.Typology of blocks and their characteristics in Phase-3

Types of Blocks	Name of block	Numbers of blocks	Number of entries	Number of apartment units	Characteristics
Type D	Block D1	1	16	598	Without 2-bedroom apartments
	Block D2	1	16	598	Without 2-bedroom apartments
Type E	Block E1	1	13	445	Without 2-bedroom apartments
	Block E2	1	13	445	Without 2-bedroom apartments
Total		4	58	2086	

In this phase, there are 11 different apartment unit types and, as shown in Table 4.11, there is not any 2-bedroom apartment in this phase studio apartments, 1-, and 3-bedroom dwellings. These apartment types were named based on the English alphabet as indicated in Table 4.12.

Table 4.12.Typology of apartment units of Phase-3

Number of bedrooms	Type
Studio flat	K
One-bedroom	H
Three-bedroom	A, B, B1,C1,C2,C_r,D,D1,D2

4.2. The selection of the phase and sample of this thesis case study

In this section, based on the comprehensive study of Ekbatan’s general and technical information – see section 4.1 –, the author has selected and justified the most representative phase and the apartment unit type that is the sample of this thesis. In consequence, sections 4.2.1 and 4.2.2 explain this phase and sample respectively.

4.2.1. Phase selection and justification

Based on the defined boundaries and limitations of the present doctoral dissertation – see section 1.5 –, the author has limited the study to the post-war MHs built in Iran in the 1970s. Therefore, **Phase-3** and **2 blocks of Phase-2** are **out of this thesis’s scope**. Based on a comprehensive analysis of the main characteristics of Ekbatan's three phases – see section 4.1 –, **blocks 1 to 15** – except 3 and 5 – **of Phase-2** as illustrated in Table 4.13 were selected **as the area of the study** because of the following reasons:

1) Based on the total number of blocks in Ekbatan, the selected area has 13 blocks of the total of 33 blocks in this MH. This means that more than 39% of the total blocks are in this selected area.

2) Based on the area of residential building (m^2), this area has 1.019.014 m^2 of total 2,784,000 m^2 residential area in Ekbatan. In other words, more than 37% of the total residential area is in this selected area.

3) According to the total number of apartment units in Ekbatan that is 15,693, the selected area has 5,498 dwellings that means more than 35% of the total apartment units of this MH.

4) Based on the typology of apartment units, all blocks in the selected area have 1-, 2-, 3-bedroom apartments while some blocks in phase-1 and all blocks in phase-3 do not have any 2-bedroom apartments. This means that the selected area has more variety of apartment types for people with different needs and demands.

5) On the contrary of Phase-1 and -3, the selected area of Phase-2 was designed based on a free architectural plan through the separation of load-bearing elements from sub-dividing interior walls. In this regard, the load-bearing concrete walls and floors had varied openings to create a playful combination of duplex and single-floor apartments to allow changeability and provide visual diversity. Moreover, this characteristic enables architects to have freedom to rehabilitate interior spaces with less complexity.

Table 4.13. Category of blocks and their characteristics in Ekbatan MH

Phase	Typology of blocks	Years	Area of residential building (m^2)	Number of blocks	Number of apartment units	Typology of apartment units	Interior layout of the apartments	Orientation
Phase-1	Blocks type A	1975-1979	447,354	5	2,645	Studio, 1,2 and 3 bedrooms	Not free plan	Along East-West axis
	Blocks type B	1975-1979	414.712	4	2,452	Studio, 1 and 3 bedrooms	Not free plan	Along East-West axis
	Blocks type C	1975-1979	86,934	1	514	Studio, 1 and 3 bedrooms	Not free plan	Along East-West axis
Phase-2	Blocks number 1 to 15 (except 3 and 5)	1976-1979	1,019,015	13	5,498	1,2 and 3 bedrooms	Free plan	Along North-South axis
	Blocks number 16 to 19	1976-1990	292,841	4	1,580	1,2,3 and 4 bedrooms	Free plan	Along North-South axis
	Blocks 3 and 5	1985-1992	170,144	2	918	1,2,3 and 4 bedrooms	Free plan	Along North-South axis
Phase-3	Blocks type D	1994-1995	203,361	2	1,198	Studio, 1 and 3 bedrooms	Not free plan	Along East-West axis
	Blocks type E	1994-1995	150,739	2	890	Studio, 1 and 3 bedrooms	Not free plan	Along East-West axis

4.2.2. Selection and justification of the sample of the study

After selecting the most representative phase of Ekbatan and area of the study – see section 4.2.1 –, this section selects and justifies the **most repetitive and representative apartment** type as **a sample of the study**. In this regard, in Appendix 4.A, the author has studied the different apartment types in the selected area, their characteristics – architectural plans, number of bedrooms, and states (single floor or duplex) – the total number of each type, and the total area of each type.

It is worthy to note that in the selected area – the first 15 blocks (except blocks 3 and 5) of Phase-2 –, there are 20 different apartment unit types which were named by Persian alphabet. Moreover, these 20 types are categorized into 5 main groups: Aleph, Be, Gim, Dal, and He. Consequently, after a comprehensive analysis of the mentioned apartment types – see Appendix 4.A –, *Aleph-1* has been selected as the sample of the study because of the following reasons:

1) Not only **Aleph-1** is the **most repetitive apartment type** – with a number of 1144 dwellings – in the selected area **but also is the most frequent** one among **all apartment types in Ekbatan**.

2) The architectural plan and space distribution of Aleph-1 is similar to other one-bedroom apartment types in Ekbatan such as Aleph-2, Aleph-3, Aleph-4, Be-1, Be-2, Be-3, and Be-4. Therefore, **the existing and feasible rehabilitation activities of Aleph-1** could be **easily modified and applied in other abovementioned types** with small changes.

4.3. Conclusion of chapter 4

This chapter has studied the selected case study which is Ekbatan MH – both in the neighborhood and dwelling scale – in sections 4.1. and 4.2. The derived conclusions from each section have been drawn in the following paragraphs separately.

In section 4.1, the author has contributed to collect, organize, classify, and digitalize the general and technical information of the selected case study. The conclusions derived from this section are as follows:

1) Ekbatan MH was constructed with the latest construction technologies of the 1970s. Therefore, based on several studies the lifespan of this MH has been estimated over 300 years and it is not facing serious structural issues. Consequently, as explained in the boundaries and limitations of the present thesis – see section 1.5 –, analyzing this MH from the structural aspect is out of the scope of this study.

2) Regarding the obtained data from the climate section, this data has been employed to calculate the values of indicators I_{10} and I_{11} – Operational Energy (OE) and Operational Carbon (OC) respectively – see section 6.2.4. Moreover, the attained data from interior rehabilitation regulations in Ekbatan – sections 4.1.2.c and 2.2.4 – has been used to calculate the values of economic and environmental indicators – see sections 6.1, 6.2, and 7.3.

3) According to the collected demographic information of Ekbatan, it is revealed that, during 1996 to 2016, the number of households – from 12,978 to 14,832 – and occupancy rate – from 83.37% to 93.36% – have increased, which shows the growing habitancy demand in this MH. On the other hand, during the abovementioned period, the household size shrunk significantly – from 4.95 to 3.04 –, which caused space distribution changes by some owners based on their current needs. Based on the age pyramid of Ekbatan from 2006 to 2016, it can be concluded that Ekbatan population got older over the mentioned time. Furthermore, the average number of adults per household remained constant or even has slightly increased in that period. This information can be useful to have a better comprehension regarding Ekbatan’s inhabitants' social issues and calculate the defined social indicators more precisely – see section 6.3.

4) The conducted comprehensive study of the general and technical information of Ekbatan helped the author to increase his knowledge regarding the topic of study, facilitate the selection process of the sample of the study, calculate the values of the defined indicators, and consequently assess the sustainability index of the selected scenarios of the defined sample of study (see sections 6.1 to 6.4).

5) Moreover, the conducted study in section 4.1 provided a comprehensive database of Ekbatan MH for the first time that could be utilizable for the local government, decision-makers, stakeholders, and relative future studies. In this regard, **the third defined objective of the present thesis** – see section 1.3 – **has been satisfactorily fulfilled.**

In section 4.2, based on the collected data from section 4.1, the most representative phase – as an area of the study – and apartment type – as a sample of study – were selected. The conclusions derived from this section are as follows:

1) The first 15 blocks of Phase-2 – except 3 and 5 – were selected as the area of the study. This selected area contains more than 39% of the total blocks, 37% of the total residential area, and 35% of the total apartment units of Ekbatan. Moreover, the selected area has 1-, 2-, 3-bedroom apartments that have more variety of apartment types for people with different needs and demands in comparison with other phases. The free architectural plan of the selected area enables architects to have more freedom to rehabilitate interior spaces with less complexity.

2) To select the most repetitive and representative apartment type as a sample of the study, the author has studied different apartment types in the selected area. Consequently, *Aleph-1* apartment

type was selected as the sample of the study because this type is the most repetitive apartment type – more than 20% of the total apartment units – among all apartment types in Ekbatan, and its architectural plan and space distribution is similar to other one-bedroom apartments of this MH. Therefore, the existing and feasible rehabilitation activities of *Aleph-1* can be modified and applied in other Ekbatan's one-bedroom apartments with small changes.

CHAPTER 5

Definition of the studied alternatives: Scenarios 1–3 of Aleph-1

Chapter 5: Definition of the studied alternatives: Scenarios 1-3 of Aleph-1

Introduction

One of the main steps of the established MIVES-Delphi model – see section 3.2 – is **defining** and **determining the alternatives** that will be assessed among a wide range of feasible ones. In the present doctoral dissertation, the assessed alternatives are different rehabilitation scenarios of the sample of the study – Aleph-1 – which has been already defined in chapter 4, section 4.2. To do so, for defining proper scenarios, this chapter consists of the following sections:

1) Section 5.1 studies **the initial state of Aleph-1** to identify **general** and **particular characteristics** of this state and **facilitate a more precise comparison** between this state and other Aleph-1 rehabilitated apartments. This study considers this initial state as that in which this apartment has remained as same as its original design and construction condition without applying any changes, rehabilitation activities, or interventions.

2) Section 5.2 analyzes 71 Aleph-1 apartment units using on-site surveying, consultations with experts, studies on Iran's construction market, and the thesis author's contribution, **three different real rehabilitation projects** have been selected as being representative of three main groups. In this thesis, these three groups are **named as scenarios 1 to 3**, which are those with the **most frequent** and **common rehabilitation activities in Ekbatan** and **Iran**. Moreover, to identify general and specific characteristics of the defined scenarios, this section studies these scenarios' architectural, structural, technical, mechanical, and electrical characteristics.

3) Finally, section 5.3 concludes on previous sections 5.1 and 5.2. Figure 5.1 illustrates the structure of chapter 5.

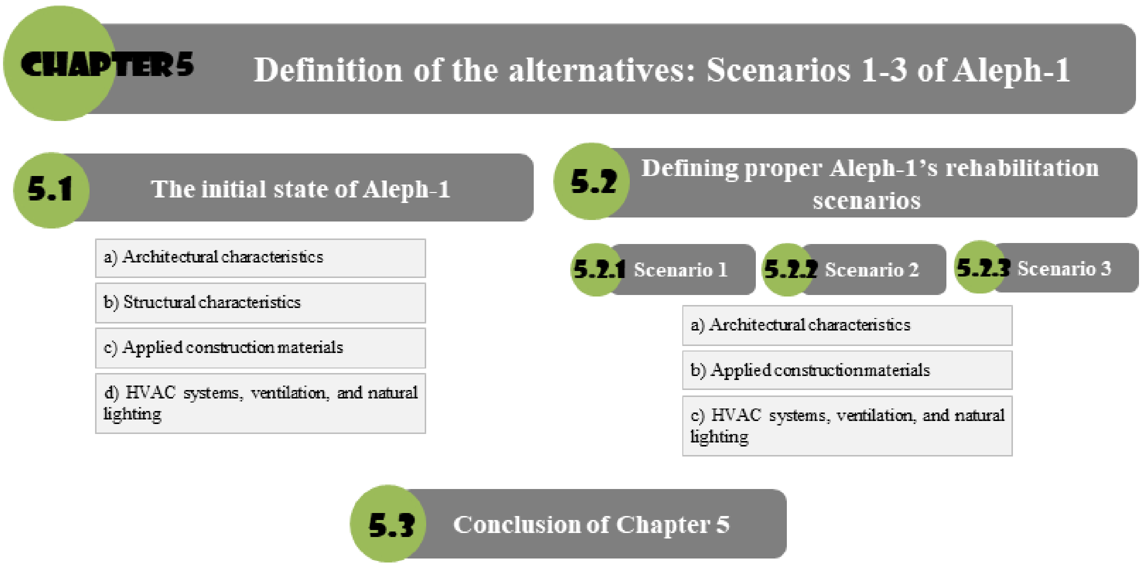


Figure 5.1. Structure of chapter 5

5.1. Initial state of Aleph-1

As previously explained, the initial state of Aleph-1 refers to a state in which this apartment has remained as same as its original design and construction condition without applying any changes, rehabilitation activities, or interventions. In this section, the author studies and analyzes the abovementioned state to (1) identify general and particular characteristics of this state besides its requirements, problems, lacks, and limitations through sustainability parameters, and (2) facilitate a more precise comparison between this initial state of Aleph-1 and other defined Aleph-1's rehabilitation projects. To do so, the following paragraphs describe this Aleph-1 initial state's (a) architectural characteristics, (b) structural features, (c) applied construction materials, and (d) HVAC systems, mechanical, electrical, and natural lighting.

a) Architectural characteristics

The initial state of Aleph-1 is a one-bedroom apartment with a super built-up area of 63.32 m^2, a built-up area of 59.33 m^2, and a useable or carpet area of 54.13 m^2 (Madanipour, 1998; Honar-e Memari Magazine, no.27, 2011). This apartment type has a rectangular plan that: (1) is 7.17 m wide and 9.25 m long; (2) contains a kitchen, a bedroom, a bathroom, a WC, and a living room that includes a dining space; and (3) its ceiling height is 2.6 m (Table 5.1).

Table 5.1. Areas, proportions, and ceiling height of Aleph-1

Super built-up area (m^2)	Built-up area (m^2)	Carpet area (m^2)	Proportions (m)	Ceiling height (m)
63.32	59.33	54.13	7.17*9.25	2.60

It is worthy to note that in its first design, apartment units in Ekbatan were supposed to be delivered furnished but later on, this decision changed, and they were submitted unfurnished to their inhabitants. In some cases, customers could choose the color or type of ceramics and cabinets for their apartment units. Figures 5.2 to 5.5 illustrate this initial state of Aleph-1, its architectural layouts, functional layouts, and space distributions.

Figure 5.2. Aleph-1 initial state

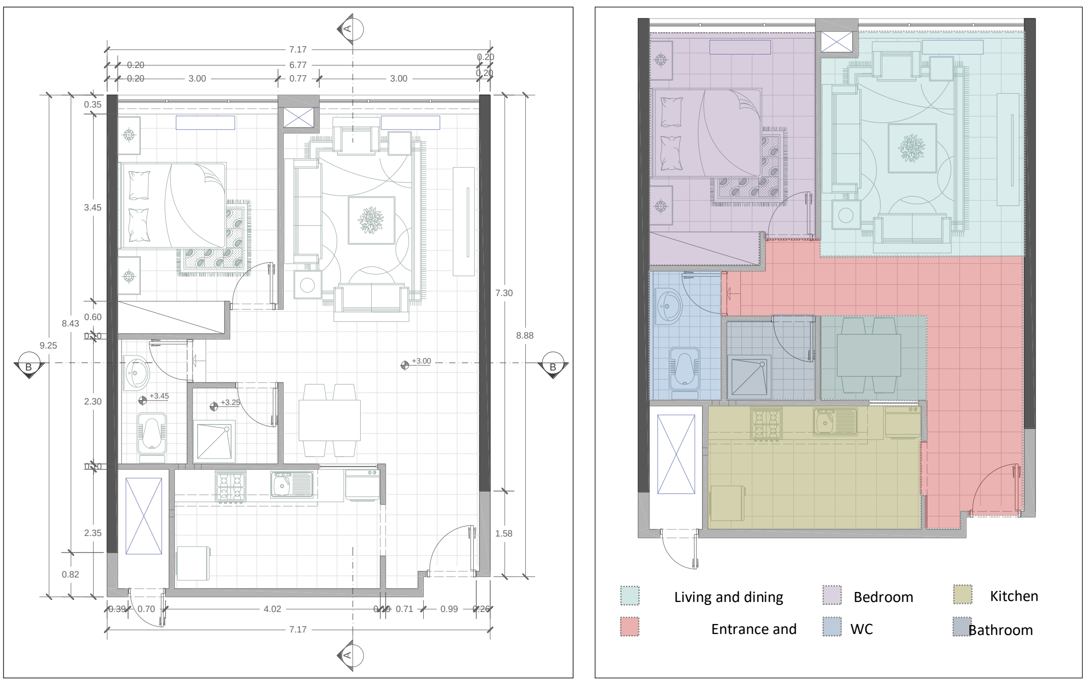


Figure 5.3. Architectural plan (left); Functional layouts and space distribution (right)

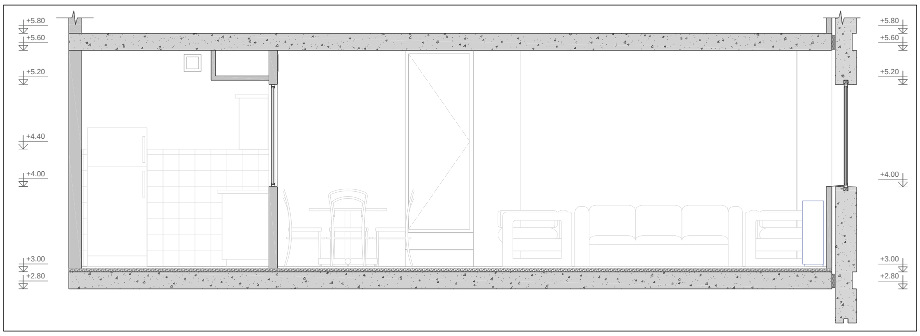


Figure 5.4. Section A-A

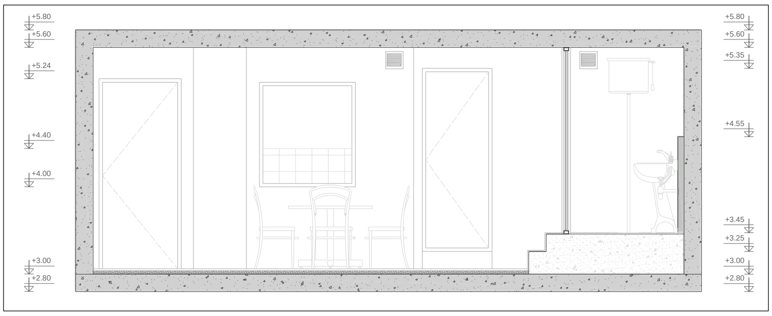


Figure 5.5. Section B-B

Table 5.2 shows the size and proportions, useful area of each space beside their relative storage spaces.

Table 5.2. Size and proportions, useful area, and storage spaces of Aleph-1 initial state

	Kitchen	Living room	Dining room	Bedroom	Bathroom	WC	Entrance	circulation	Total
Size (m)	2.20*3.85	3.67*4.00	1.75*2.00	3.00*3.50	1.40*1.60	1.30*2.30	1.76*1.98	-	-
Useful area (m^2)	8.47	14.45	3.50	11.55	2.24	2.99	3.68	7.25	**54.13**
Storage or cabinet space (m^3)	1.74	0	0	3	0	0	0	0	**4.74**

b) Structural characteristics

As mentioned in section 4.1.2, the structure of Aleph-1 apartment is a semi-tunnel system with U-shape molds and poured on-site concrete reinforced with steel meshes and bars. The space between each U-shape mold was 20 cm in order to place reinforced concrete walls. Therefore, Aleph-1 was constructed between two reinforced concrete walls with a distance of center to center around 7 m (Figure 5.6). These reinforced concrete walls were covered with a gypsum plaster coat with an average thickness of 6 mm (Figure 5.8).

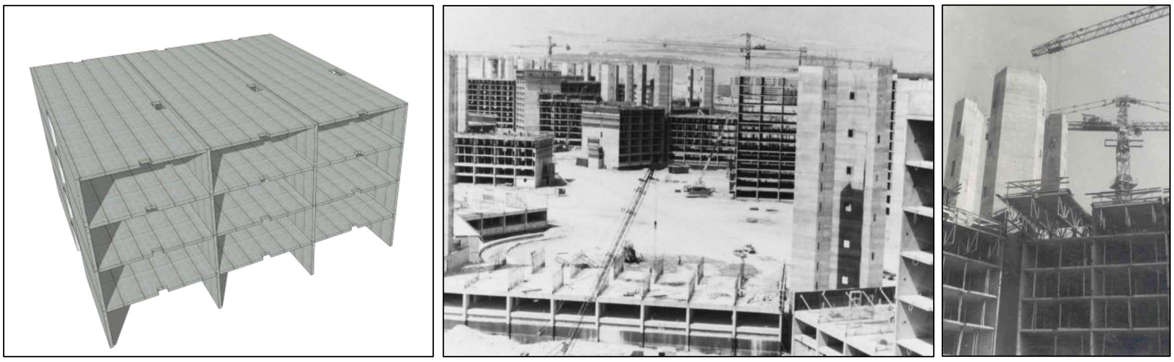


Figure 5.6. Loadbearing elements of Aleph-1 initial state

c) Applied construction materials

In the initial state of Aleph-1, **interior walls** were made of gypsum blocks except the walls of wet spaces like WC and bathroom. These walls for WC and bathroom were constructed with cement blocks with a size of 400*200*100 mm and covered with 200*200*6 mm tiles. Also, kitchen walls were covered by patterned 20*20 cm tiles until a height of 1.40 m. Figures 5.7 and 5.8 and Table 5.3 illustrate the applied construction material in Aleph-1 initial state.

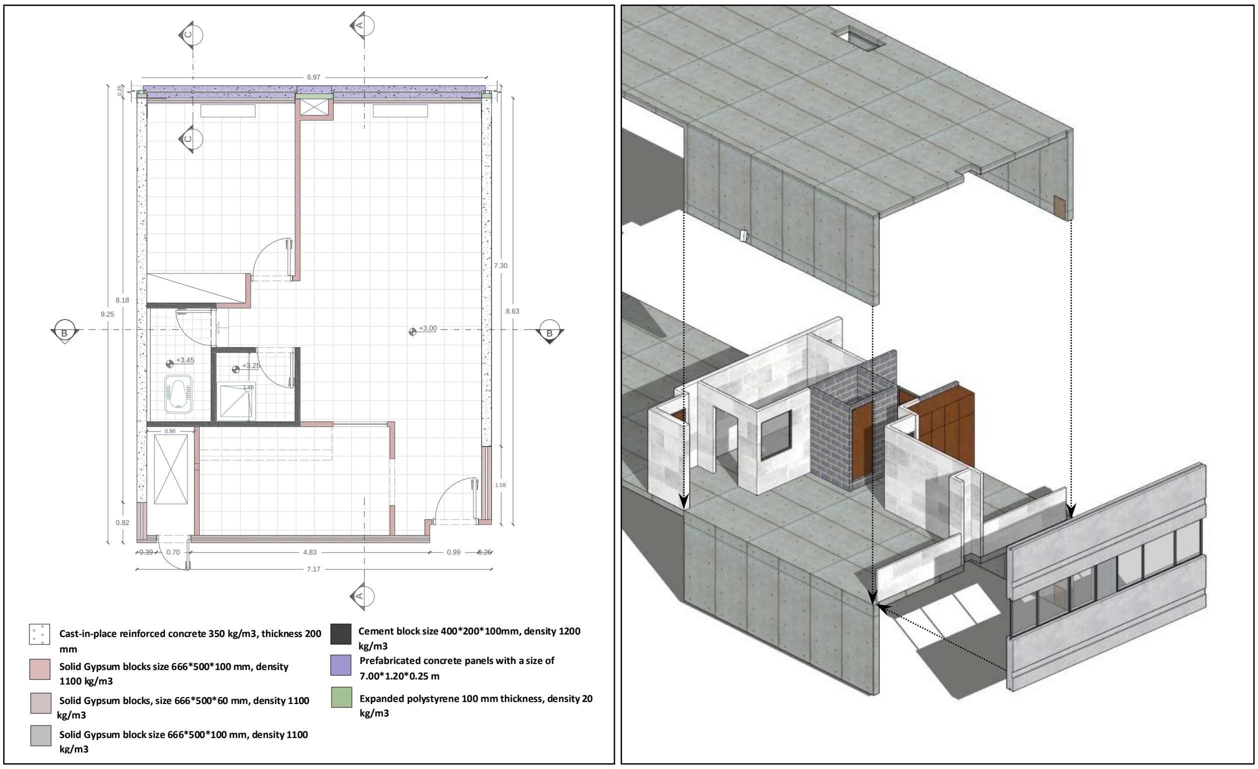


Figure 5.7. Applied construction materials in Aleph-1 initial state (left); Isometric (right). Source: Author

Figure 5.8. Interior and exterior walls of the initial state

Table 5.3. The applied construction materials of Aleph-1 initial state

Applied construction materials in Aleph-1 initial state		
Wall	Interior walls	Wet spaces: Cement blocks, size 400*200*100mm, density 1200 kg/m^3; bituminous, thickness 4mm; cement mortar 350 kg/m^3, thickness 10 mm; and ceramic tiles 20*20 cm.
		Dry spaces: Solid gypsum blocks, size 666*500*100 mm, density 1100 kg/m^3; plaster, 10 mm thickness; and water-based paint.
	Exterior walls	Façade: Prefabricated concrete panels, size 7.00*1.20*0.25 m, 6 cm for air gap; solid gypsum blocks, size 666*500*60 mm; and water-based paint.
		Corridor walls: Solid gypsum blocks, size 666*500*100 and 666*500*60 mm, density 1100 kg/m^3; plaster, 10 mm thickness; water-based paint.
Floor	Living room, bedroom, and kitchen	Cement mortar 350 kg/m^3, thickness 20 mm; and ceramic tiles 35*35 cm.
	Bathroom and WC	Filler, cement mortar 150 kg/m^3 thickness: 180 mm in bathroom and 380 mm in WC; bituminous, thickness 4mm; cement mortar 350 kg/m^3, thickness 10 mm; and ceramic tiles 35*35 cm.
Ceiling	Living room, bedroom, and kitchen	Structural slab, reinforced concrete, thickness 20 cm; gypsum plaster coat with an average thickness of 10 mm; and water-based paint.
	Bathroom and WC	Structural slab, reinforced concrete, thickness 20 cm; white cement coat with an average thickness of 10 mm; and oil-based paint.
Window	Window frame	Galvanized steel frame.
	Window glass	Double glazing – clear glass 6 mm and 13 mm air.

As indicated in Figure 5.9 and Table 5.3, **exterior walls** of Aleph-1's initial state – except its façade – were constructed with gypsum blocks that had different thicknesses. Moreover, the main part of this apartment façade is composed of prefabricated concrete panels – measuring 7.00*1.20*0.25 m – that was connected to the main building structure with two L-shape steel plates – with a size of 500*400*8 mm (Figures 5.9 and 5.10). In the façade of this apartment type, there are two windows with double-glazing glasses and galvanized steel frames – measuring 3.00*1.2*0.04 m. The space between these two windows – that was designed as fan coils' duct – was filled by a steel frame, expanded polystyrene sheets, and air seal mastics (Figure 5.9). Also, under each window, there is a gypsum block wall – with a size of 3.00*1.00*0.06 m – where fan coil pipes pass behind it.

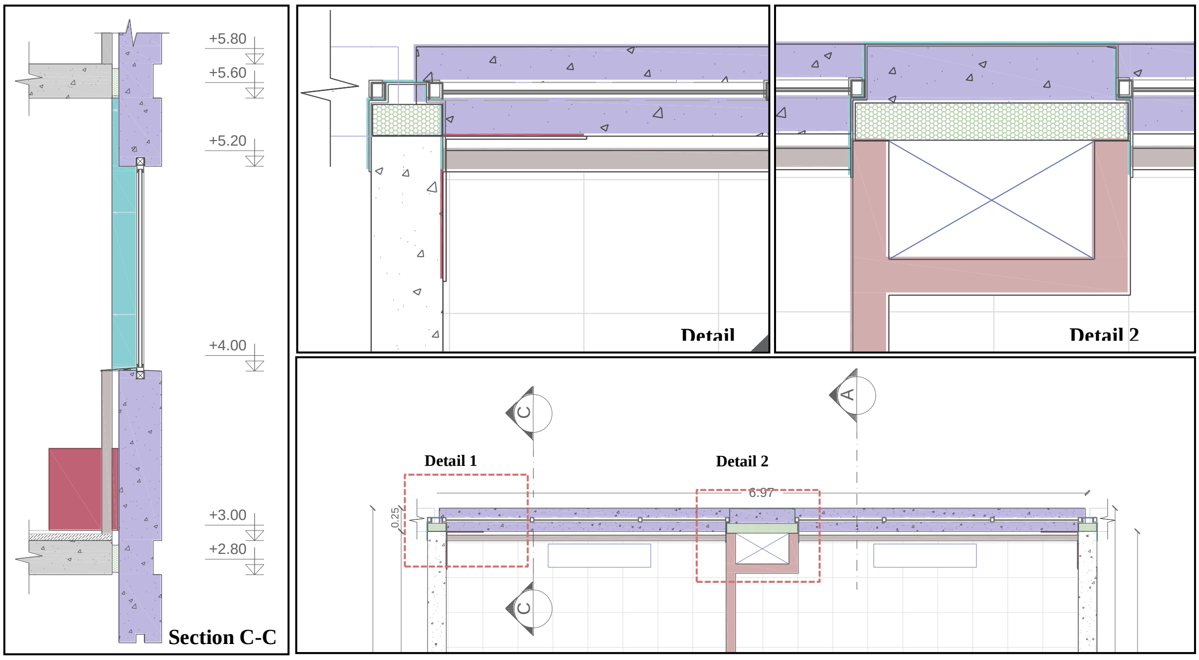


Figure 5.9. Façade of Aleph-1 initial state

Figure 5.10. Envelope of Aleph-1 initial state

d) HVAC systems, mechanical and natural ventilation, and natural lighting

HVAC systems: Two fan coils were designed for cooling and heating of Aleph-1 apartment. One of them is located in its living-dining room and the other one in its bedroom as depicted in Figure 5.11. While there is not any heating or cooling system designed for other spaces such as kitchen, bathroom, and toilet. The cooling system of this apartment is supplied by chilled water (5°C) and steam 10 kg/cm^2 from chillers in the building's mechanical room. On the other hand, heating system is supplied by hot water (80°C) and steam 10 kg/cm^2 from the gas-fired steam boilers in the building's central mechanical room.

Figure 5.11. HVAC systems of the initial state of Aleph-1

Mechanical ventilation: The mechanical ventilation system of the initial state of Aleph-1 consists of a simple flux mechanical ventilation system for each wet room – kitchen, bathroom, and WC. The mentioned ventilation system provides adequate fresh air for kitchen, bathroom, and WC which are 250, 100, and 100 m^3/h respectively. Moreover, its kitchen was equipped with a hood exhaust fan, discharging air into the vertical air ducts which are connected to a roof-mounted central fan (Figure 5.12). Also, this central fan is operated at cooking time, from 11 to 14 and from 18 to 20.

Figure 5.12. Mechanical ventilation of the initial state of Aleph-1

Natural ventilation: Also, for natural ventilation, two windows with a size of 1.20*3.00 m located in its bedroom and living room provide fresh air. These windows consist of three parts and only the middle part which is a vertical pivot window with a size of 1.10*1.20 m can be opened (Figure 5.13). One of the problems of this type of window is that window screens cannot be installed to prevent the entrance of insects, bugs, birds, and air-borne debris. For this reason, occupants installed a cylindrical window screen on the main façades (Figure 5.13).

Figure 5.13. Natural ventilation of the initial state of Aleph-1

Natural lighting: Aleph-1 has two windows with a size of 1.20*3.00 in its bedroom and living room that provide direct natural light during the day. Kitchen has no direct natural light and the indirect natural light of this space is provided by a window measuring 1.10*1.10 m toward the living room. Moreover, WC and bathroom have no natural light (Figure 5.14).

Figure 5.14. Natural lightening conditions

Table 5.4. HVAC, insulations, ventilation, and natural lighting of Aleph-1 initial state

HVAC, insulation, ventilation, and natural lighting of Aleph-1 initial state		
HVAC	Cooling	Fan coil unit (cooling = comp. chiller, hot water (5°C))
	Heating	Fan coil unit (heating = boiler, hot water (80°C))
Insulation	Thermal insulation	Without insulation
	Acoustic insulation	Without insulation
	Moisture insulation	Bituminous, thickness 4mm
Window frame		Galvanized steel frame
Window glass		Double glazing, 6mm clear glass, and 13 mm air
Mechanical ventilation	Kitchen	Hood = A roof-mounted central fan, 350 m^3/h
	Bathroom and WC	Exhaust fan = Simple flux mechanical ventilation system, 100 m^3/h
Natural ventilation	Living room and bedroom	Two vertical pivot windows with a size of 1.10 *120
Natural lighting	Living room and bedroom	Two windows – 1.20*3.00 m – provide direct natural lighting
	Kitchen	A window – 1.10*1.10m – provides indirect natural lighting

5.2. Defining proper Aleph-1's rehabilitation scenarios

As previously mentioned in section 2.2.2, there is a wide range of techniques and building processes for interior rehabilitation of MHs due to the variety of: the growing number of construction techniques and technologies, materials, designs and market trends, and stakeholders' opinions. Moreover, based on **analyzing the existing interior rehabilitation projects in Iran** through **Iran's construction market**, **on-site surveying** of the rehabilitated apartment units in the defined case study, and **consulting with experts** – architects, designers, engineers, and construction practitioners –, it was revealed that these projects were rehabilitated **partially** or **integrally**. For instance, some owners simply have done partial rehabilitation such as applying wallpapers, painting walls, changing ceramics or toilet tiles, while others have applied more significant changes in spaces and rehabilitated their apartment integrally by demolishing one or several walls, changing architectural plan – e.g., proportion, size, shape, and space distribution –, changing the functional layouts, improving heating or cooling systems and so on.

In this regard, the author surveyed – through conducting on-site surveying of different real interior rehabilitation projects of Aleph-1 and questionnaires from their inhabitants – 71 rehabilitated Aleph-1 apartment units in the defined case study – Ekbatan – to: (1) figure out different implemented rehabilitation techniques and activities of Aleph-1, (2) find out the main rehabilitation reasons of these apartments besides their problems, requirements, lacks and limitations, advantages, and disadvantages regarding the implemented rehabilitation techniques, and (3) identify and select the most representative and common rehabilitation activities and techniques in this apartment type. Consequently, based on the abovementioned surveys, consulting with experts, and overviewing Iran's construction market, **three different real rehabilitation projects were chosen as representative from three main groups** – named as scenario 1, scenario 2, and scenario 3 in this thesis –, which have been selected due to the following reasons:

1) Although each one of the 71 surveyed Aleph-1 apartments has its own general and specific characteristics, due to some similarities – e.g., architectural plan, space distribution, applied construction materials, and HVAC systems – that these apartments have with the defined scenarios, mostly they can be categorized into these three groups. Among these surveyed apartments, 19 of them were similar to scenario 1 – 26% –, 13 of them were similar to scenario 2 – 18% –, and 11 of them were similar to scenario 3 – 15% – and the rest of them – 41% – could not be categorized into any group. Therefore, these three selected scenarios not only are the **most frequent rehabilitation techniques for Aleph-1** – more than 59% of surveyed apartments – but also are the **most common** and **representative rehabilitation techniques in Iran**.

2) These selected scenarios and the chosen three respective real projects are **different from each other** from (a) being rehabilitated partially – scenario 1 – to integrally – scenario 3 –, and (b) their applied rehabilitation techniques, construction materials, design, and space distributions point of view and consequently they **cover a wide range of MH's interior rehabilitation activities in Iran**. Therefore, selecting the abovementioned scenarios provides an opportunity to have a more holistic perspective for the sustainability assessment of different existing rehabilitation techniques applied for MHs in Iran.

In the following parts, the defined scenarios besides their (a) architectural characteristics, (b) applied construction materials, and (c) HVAC systems, mechanical and natural ventilation, and natural lighting have been described.

5.2.1. Scenario 1

Scenario 1 is a rehabilitated Aleph-1 apartment in which partial rehabilitation activities have been implemented. Therefore, this scenario has some similarities with the initial state of Aleph-1. In the studied representative rehabilitation project – that lasted 26 days – the following minor interventions were implemented:

1. Bathroom and WC were rehabilitated – e.g., ceramics and furniture were completely replaced.
2. Apartment floor pavement was replaced with new ceramics with a size of 50*50*1 cm.

3. Kitchen cabinets were replaced by new ones without any changes in their distribution.
4. Wallpapers applied to the living room's walls.
5. Apartment fan coils were repaired to improve their functionality. Moreover, to change the fan coils' pipes, two walls that were located under the windows were reconstructed.
6. Bedroom's walls and apartment ceiling were painted with water-based paint.

Therefore, this scenario was rehabilitated without any changes in its space distribution. Figures 5.15 illustrates the applied changes in this scenario.

Figure 5.15. The applied interventions on Scenario 1

a) Architectural characteristics of scenario 1

According to the abovementioned explanations, as the space distribution had remained without any changes, proportion, size, area, and ceiling height of scenario 1 are the same as the initial state of Aleph-1 (Table 5.5).

Table 5.5. Areas, proportions, and ceiling height of scenario 1

Super built-up area (m^2)	Built-up area (m^2)	Carpet area (m^2)	Proportions (m)	Ceiling height (m)
63.32	59.33	54.13	7.17*9.25	2.60

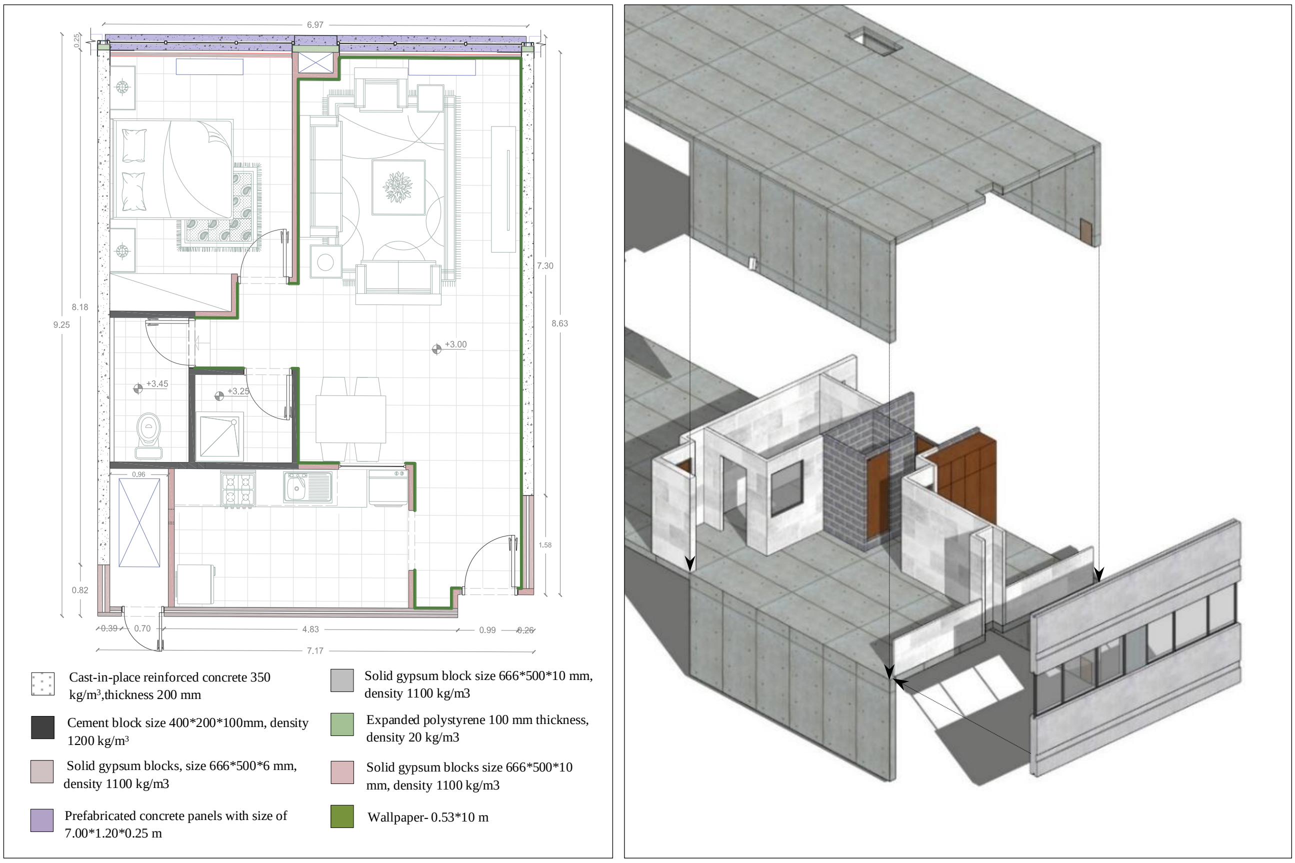


Figure 5.16. Architectural plan of scenario 1 (left); Isometric of scenario 1 (right). Source: Author

b) Applied construction materials of scenario 1

Due to the similarity between scenario 1 and the initial state of Aleph-1, there were not applied many significant different construction materials in this scenario. Table 5.6 illustrates the applied construction materials in scenario 1.

Table 5.6. The applied construction materials of scenario 1

Applied construction materials of scenario 1		
Wall	Interior walls	Wet spaces: Cement blocks, size 400*200*100mm, density 1200 kg/m^3; bituminous, thickness 4mm; cement mortar 350 kg/m^3, thickness 10 mm; and **ceramic tiles 40*35 cm**.
		Dry spaces: Solid gypsum blocks, size 666*500*100 mm, density 1100 kg/m^3; plaster, 10 mm thickness; and **wallpaper**.
	Exterior walls	Façade: Prefabricated concrete panels with a size of 7.00*1.20*0.25 m, 6 cm of the air gap, and solid gypsum blocks with a size of 666*500*60 mm; and **wallpaper**.
		Corridor walls: Solid gypsum blocks, size 666*500*100 and 666*500*60 mm, density 1100 kg/m^3; plaster, 10 mm thickness; and **wallpaper**.
Floor	Living room, bedroom, and kitchen	Cement mortar 350 kg/m^3, thickness 20 mm; and **ceramic tiles 50*50*1 cm**.
	Bathroom and WC	Filler, cement mortar 150 kg/m^3 thickness: 180 mm in bathroom and 380 mm in WC; bituminous, thickness 4mm; cement mortar 350 kg/m^3, thickness 10 mm; and **ceramic tiles 35*35 cm**.
Ceiling	Living room, bedroom, and kitchen	Structural slab, reinforced concrete, thickness 20 cm; gypsum plaster coat with an average thickness of 10 mm; and water-based paint.
	Bathroom and WC	Structural slab, reinforced concrete, thickness 20 cm; white cement coat with an average thickness of 10 mm; and oil-based paint.
Window	Window frame	Galvanized steel frame
	Window glass	Double glazing – clear glass 6mm and 13mm air

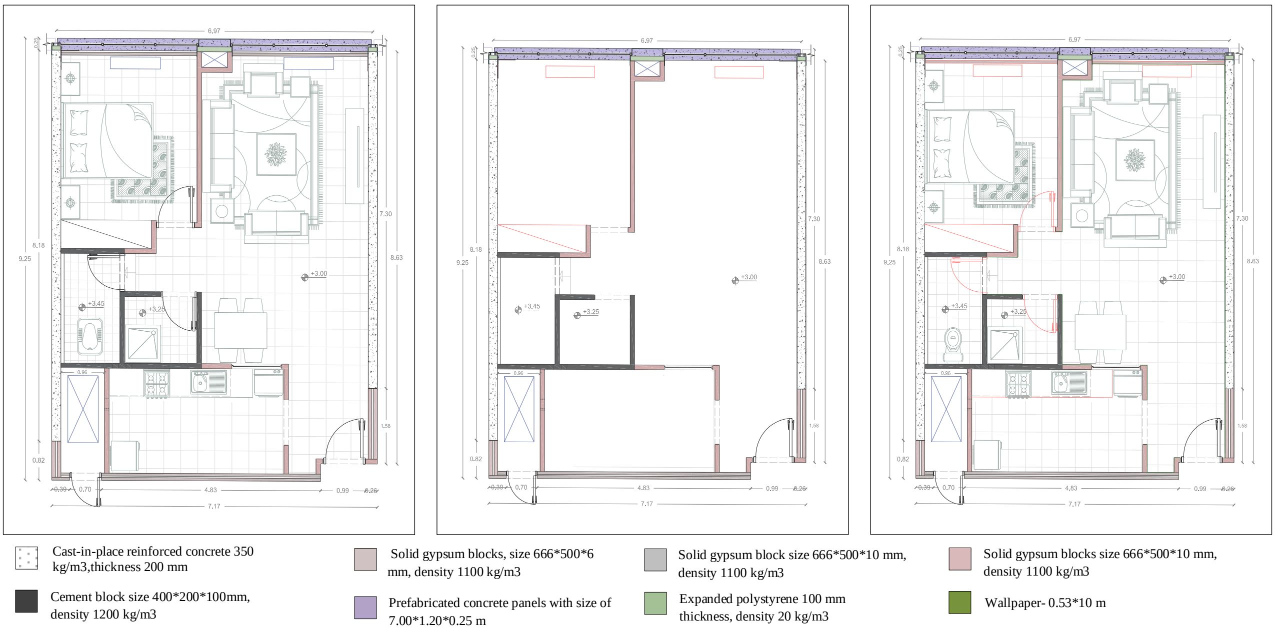


Figure 5.17. Rehabilitation process of scenario 1; Source: Author. Left: Initial state of Aleph-1, middle: demolition process, right: Scenario 1.

c) HVAC systems, mechanical and natural ventilation, and natural lighting of scenario 1

Table 5.7 presents the HVAC systems, insulations, ventilation, and natural lighting of scenario 1.

Table 5.7. HVAC, insulations, ventilation, and natural lighting of scenario 1

HVAC, insulation, ventilation, and natural lighting of scenario 1		
HVAC	Cooling	Fan coil unit (cooling = comp. Chiller, hot water (5°C))
	Heating	Fan coil unit (heating = boiler, hot water (80°C))
Insulation	Thermal insulation	Without insulation
	Acoustic insulation	Without insulation
	Moisture insulation	Bituminous, thickness 4mm
Window frame		Galvanized steel frame
Window glass		Double glazing, 6mm clear glass, and 13mm air
Mechanical ventilation	Kitchen	Hood = **Bimax B1002U**, **size 90cm, 480 m^3/h**
	Bathroom and WC	Exhaust fan = Simple flux mechanical ventilation system, **Sabalan**, **95 m^3/h**
Natural ventilation	Living room and bedroom	Two vertical pivot windows with a size of 1.10 *1.20 m
Natural lighting	Living room and bedroom	Two windows – 1.20*3.00 m – provide direct natural lighting
	Kitchen	A window – 1.10*1.10m – provides indirect natural lighting

5.2.2. Scenario 2

Scenario 2 is a rehabilitated Aleph-1 apartment that was changed more integrally compared to scenario 1. In the representative project to this scenario group, the rehabilitation process of which lasted 38 days, the following interventions were implemented (Figure 5.20):

1. Wall located between living room and kitchen was demolished and replaced with a counter bar to provide an open kitchen.
2. Wall between kitchen and entrance was demolished to increase kitchen area and provide some storage space in the apartment entrance.
3. Two walls between living room and bathroom were reconstructed – using hollow brick – to change the location of this door. This intervention provided more privacy and blind the visibility of the bathroom door from living room.
4. Wall between living room and bedroom was reconstructed – using hollow brick – to align it with the new bathroom wall and define a more spacious living room area.
5. Bathroom and WC were integrally rehabilitated – e.g., ceramics and furniture completely replaced.
6. Apartment pavement was replaced with parquet with a size of 1220*118*10 mm. Also, kitchen floor was replaced with new ceramic tiles measuring 50*50*0.6 cm.
7. Kitchen cabinets and furniture replaced by new ones with new distribution.
8. Some false ceilings were designed for this project to better define its spaces.
9. Interior walls and ceilings were painted with water-based paint.
10. Apartment fan coils were replaced with new ones – Saravel-TE02 and TE04. Moreover, to change the fan coils' pipes and add the thermal insulation – 3 cm of mineral wool batt –, two walls located under the windows were reconstructed.

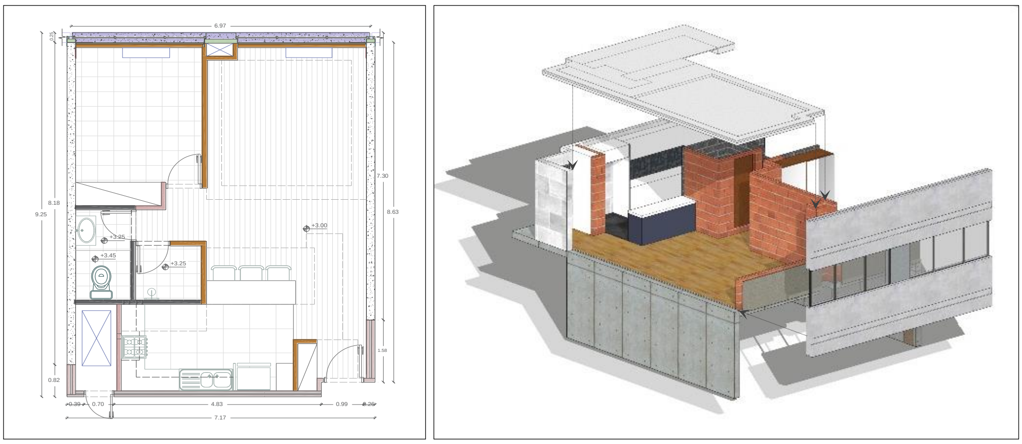
Figure 5.18. Interventions on scenario 2

a) The architectural characteristics of scenario 2

Table 5.8 and Figure 5.21 illustrate the proportion, areas, ceiling height, and the architectural plan of scenario 2 respectively.

Table 5.8. Areas, proportions, and ceiling height of scenario 2

Super built-up area (m^2)	Built-up area (m^2)	Carpet area (m^2)	Proportions (m)	Ceiling height (m)
63.32	59.33	53.97	7.17*9.25	2.51



Cast-in-place reinforced concrete 350 kg/m3, thickness 200 mm
Cement block size 400*200*100mm, density 1200 kg/m3
Solid gypsum blocks size 666*500*10 mm, density 1100 kg/m3
Prefabricated concrete panels with size of 7.00*1.20*0.25 m
Solid gypsum blocks, size 666*500*6 mm, density 1100 kg/m3
Solid gypsum block size 666*500*10 mm, density 1100
Expanded polystyrene 100 mm thickness, density 20 kg/m3
Hollow brick size 190*180*80 mm, density 1300 kg/m3

Figure 5.19. The architectural plan of scenario 2 (left); Isometric of scenario 2 (right). Source: Author

Table 5.9 shows the size, proportions, and useful area of each space beside their relative storage spaces of scenario 2 and the initial state of Aleph-1.

Table 5.9. Size and proportions, useful area, and storage spaces of Aleph-1 initial state and scenario 2

		Kitchen	Living room	Dining room	Bedroom	Bathroom	WC	Entrance	circulation	Total
Size (m)	**Initial state**	2.20*3.85	3.67*4.00	1.75*2.00	3.00*3.50	1.40*1.60	1.30*2.30	1.76*1.98	-	-
	Scenario 2	2.20*3.99	3.72*3.96	1.60*2.07	2.95*3.47	1.38*1.53	1.30*2.30	1.70*1.87	-	-
Useful area (m^2)	**Initial state**	8.47	14.45	3.50	11.55	2.24	2.99	3.68	7.25	**54.13**
	Scenario 2	8.78	14.50	3.31	11.43	2.11	2.99	3.16	7.69	**53.97**
Storage spaces (m^3)	**Initial state**	1.74	0	0	3	0	0	0	0	**4.74**
	Scenario 2	3.58	0	0	3	0	0.19	1.35	0	**8.12**

b) Applied construction materials of scenario 2

Table 5.10 depicts the construction materials in scenario 2.

Table 5.10. The applied construction materials of scenario 2

Applied construction materials of scenario 2		
Wall	Interior walls	Wet spaces: **Hollow brick, size 190*180*80 mm, density 1300 kg/m^3**; bituminous, thickness 4mm; cement mortar 350 kg/m^3, thickness 10 mm; and **ceramic tiles 40*60 cm**. Dry spaces: **Hollow brick, size 190*180*80 mm, density 1300 kg/m^3**; **clay plaster, 15 mm thickness plaster**; **10 mm thickness**; and water-based paint.
	Exterior walls	Façade: Prefabricated concrete panels with a size of 7.00*1.20*0.25 m; 6 cm of the air gap; **hollow brick, size 190*180*80 mm**; **clay plaster, 15 mm thickness**; **plaster; 10 mm thickness**; and water-based paint. Corridor walls: Solid gypsum blocks, size 666*500*100 and 666*500*60 mm, density 1100 kg/m^3; plaster, 10 mm thickness; and water-based paint.
Floor	Living room and bedroom	Cement mortar 150 kg/m^3 thickness 50mm; cement mortar 350 kg/m^3, thickness 20 mm; and **parquet Direct Pressure Laminate (DPL)**, **10mm thickness**.
	Kitchen, bathroom, and WC	Filler, cement mortar 150 kg/m^3 thickness: 50mm in kitchen, 180 mm in bathroom, and 380 mm in WC; bituminous, thickness 4mm; cement mortar 350 kg/m^3, thickness 10 mm; and **ceramic tiles 50*50*0.6 cm**.
Ceiling	Living room, bedroom, and kitchen	Structural slab, reinforced concrete, thickness 20 cm; gypsum plaster coat with an average thickness of 10 mm; **false ceilings**; and water-based paint.
	Bathroom and WC	Structural slab, reinforced concrete, thickness 20 cm; white cement coat with an average thickness of 10 mm; and oil-based paint.
Window	Window frame	Galvanized steel frame
	Window glass	Double glazing – clear glass 6mm and 13 mm air

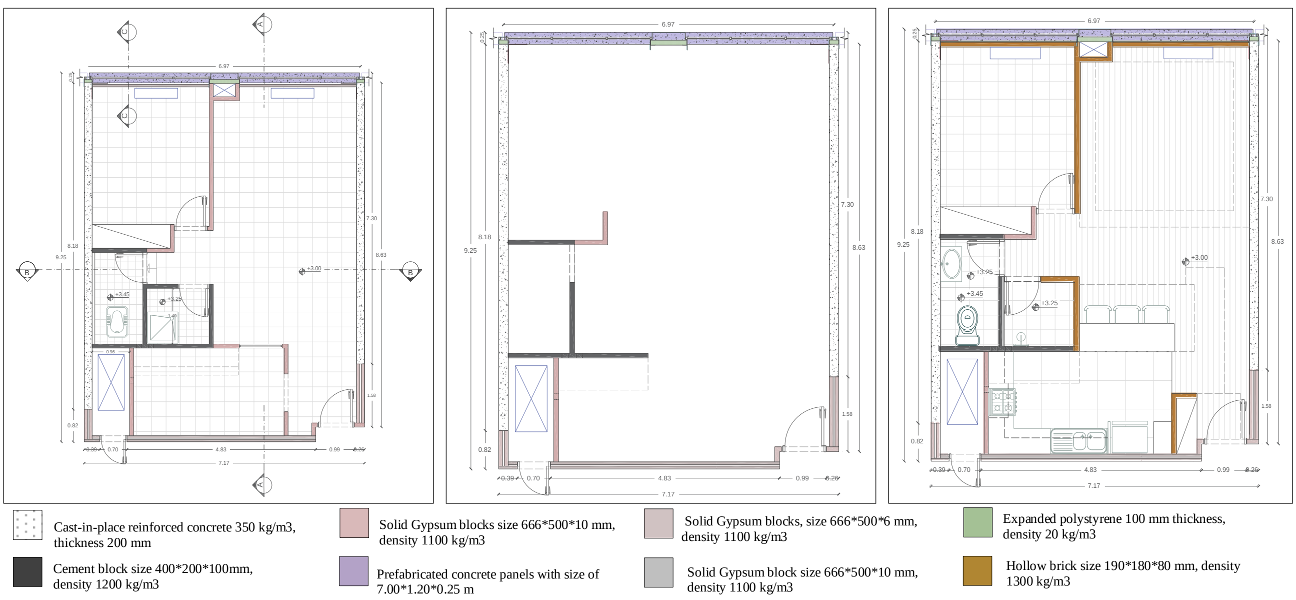


Figure 5.20. Rehabilitation process of scenario 2. Left: Initial state of Aleph-1, middle: demolition process, right: Scenario 2



Figure 5.21. Rehabilitation process of scenario 2.

c) HVAC systems, mechanical and natural ventilation, and natural lighting of scenario 2

Table 5.11 explains the HVAC, insulations, ventilation, and natural lighting of scenario 2.

Table 5.11. HVAC, insulations, ventilation, and natural lighting of scenario 2

HVAC, insulation, ventilation, and natural lighting of scenario 2		
HVAC	Cooling	Fan coil unit (cooling = comp. Chiller, hot water (5°C))
	Heating	Fan coil unit (heating = boiler, hot water (80°C))
Insulation	Thermal insulation	**3 cm of mineral wool batt**, u-value = 0.42 W/m^{2}K
	Acoustic insulation	Without insulation
	Moisture insulation	Bituminous, thickness 4mm
Window frame		Galvanized steel frame
Window glass		Double glazing, 6mm clear glass, and 13mm air
Mechanical ventilation	Kitchen	Hood = **Dorsa Mahdis Hood, size 90cm-540 m^3/h**
	Bathroom and WC	Exhaust fan = Simple flux mechanical ventilation system, **Damandeh, VBX-20S2S, 150 m^3/h**
Natural ventilation	Living room and bedroom	Two vertical pivot windows with a size of 1.10 *1.20 m
Natural lighting	Living room and bedroom	Two windows – 1.20*3.00 m – provide direct natural lighting

5.2.3. Scenario 3

Scenario 3 is an improved Aleph-1 apartment that was rehabilitated more integrally in comparison with the two previous scenarios. In the representative project of this scenario that was studied in-depth in this section – which lasted 40 days – the following interventions were implemented (Figures 5.24):

1. Wall located between living room and kitchen was demolished and replaced with a counter bar and a dining table to provide an open kitchen.
2. Wall between kitchen and entrance was demolished to increase kitchen area and provide some storage space in the entrance.
3. Two walls between living room and bathroom were reconstructed – using hollow brick – to change the location of this door and provide more privacy and blinding the visibility of the bathroom door from the living room.
4. Wall between living room and bedroom was reconstructed – using drywall – to align it with the new bathroom wall and enlarge the living room space.
5. Bathroom and WC were integrally rehabilitated – e.g., ceramics and furniture completely replaced.
6. Apartment pavement was replaced with new tiles measuring 60*60*1 cm.
7. Kitchen cabinets and furniture were replaced by new ones with new distribution.
8. Some false ceilings were designed for this project to better define its spaces.
9. Interior walls and ceilings were painted with water-based paint.
10. Apartment fan coils were replaced with radiators and split air conditioners for heating and cooling respectively. Moreover, to change the fan coils' pipes and add thermal insulation – 3 cm of glass wool –, two walls that were located under the windows were reconstructed.
11. The apartment windows were changed with UPVC frame windows and double glazing – clear glass 6 mm and 13 mm argon gas.

Figure 5.22. Interventions on Scenario 3

a) The architectural characteristics of scenario 3

Table 5.12 and Figure 5.25 illustrate the proportion, areas, and ceiling height and the architectural plan of scenario 3 respectively.

Table 5.12. Areas, proportions, and ceiling height of scenario 3

Super built-up area (m^2)	Built-up area (m^2)	Carpet area (m^2)	Proportions (m)	Ceiling height (m)
63.32	59.33	54.81	7.17*9.25	2.48

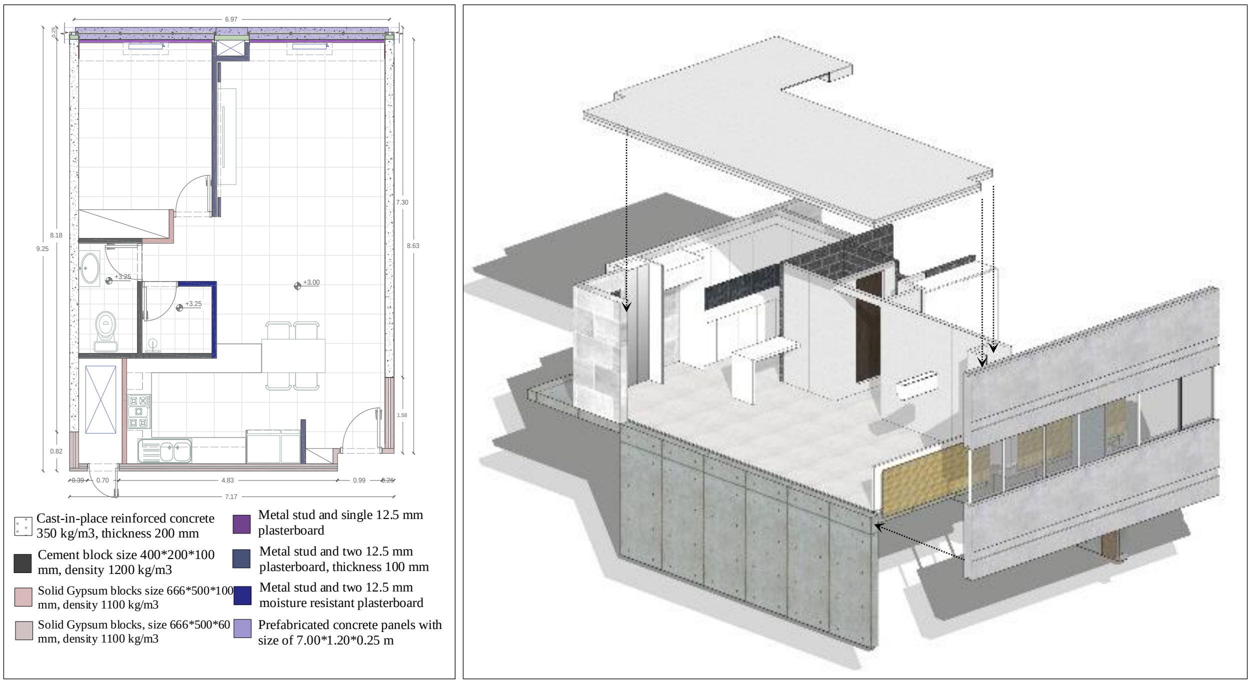


Figure 5.23. Architectural plan of scenario 3 (left); Isometric of scenario 3 (right). Source: Author

Table 5.13 compares the size and proportions, useful area of each space beside their relative storage spaces between scenario 3 and the initial state of Aleph-1.

Table 5.13. Size and proportions, useful area, and storage spaces of Aleph-1 initial state and scenario 3

		Kitchen	Living room	Dining room	Bedroom	Bathroom	WC	Entrance	circulation	Total
Size (m)	**The initial state**	2.20*3.85	3.67*4.00	1.75*2.00	3.00*3.50	1.40*1.60	1.30*2.30	1.76*1.98	-	-
	Scenario 3	2.20*3.85	3.72*4.20	1.84*2.10	2.95*3.53	1.40*1.55	1.30*2.30	1.58*1.58	-	-
Useful area (m^2)	**The initial state**	8.47	14.45	3.50	11.55	2.24	2.99	3.68	7.25	**54.13**
	Scenario 3	8.47	15.06	4.16	11.61	2.14	2.99	2.69	7.69	**54.81**
Storage spaces (m^3)	**The initial state**	1.74	0	0	3	0	0	0	0	**4.74**
	Scenario 3	3.93	0	0	3	0	0.20	0.49	0	**7.62**

b) Applied construction materials of scenario 3

Table 5.14 illustrates the construction materials in scenario 3.

Table 5.14. Construction materials of scenario 3

Applied construction materials of scenario 3		
Wall	Interior walls	Wet spaces: **Metal stud and two 12.5 mm moisture resistant plasterboards**; **cement mortar 350 kg/m^3, thickness 10 mm**; and **ceramic tiles 40*60 cm**.
		Dry spaces: **Metal stud and two 12.5 mm plasterboards, thickness 100 mm**; and water-based paint.
	Exterior walls	Façade: Prefabricated concrete panels with a size of 7.00*1.20*0.25 m; 6 cm of the air gap; **3 cm of the glass wool**; **metal stud and one-layer plasterboard with a thickness of 12.5 mm**; and water-based paint.
		Corridor walls: Solid gypsum blocks, size 666*500*100 and 666*500*60 mm, density 1100 kg/m^3; plaster, 10 mm thickness; and water-based paint.
Floor	Living room, bedroom, and kitchen	Cement mortar 350 kg/m^3, thickness 20 mm; and **ceramic tiles 60*60 cm**.
	Bathroom and WC	**Filler**, cement mortar 150 kg/m^3 thickness: **180 mm**; Bituminous, thickness 4mm; Cement mortar 350 kg/m^3, thickness 10 mm; and **ceramic tiles 50*50 cm**.
Ceiling	Living room, bedroom, and kitchen	Structural slab, reinforced concrete, thickness 20 cm; **false ceiling, metal stud and plasterboard**; and water-based paint.
	Bathroom and WC	Structural slab, reinforced concrete, thickness 20 cm; white cement coat with an average thickness of 10 mm; and oil-based paint.
Window	Window frame	**UPVC frame**
	Window glass	Double glazing, **clear glass 6mm and 13mm argon gas**

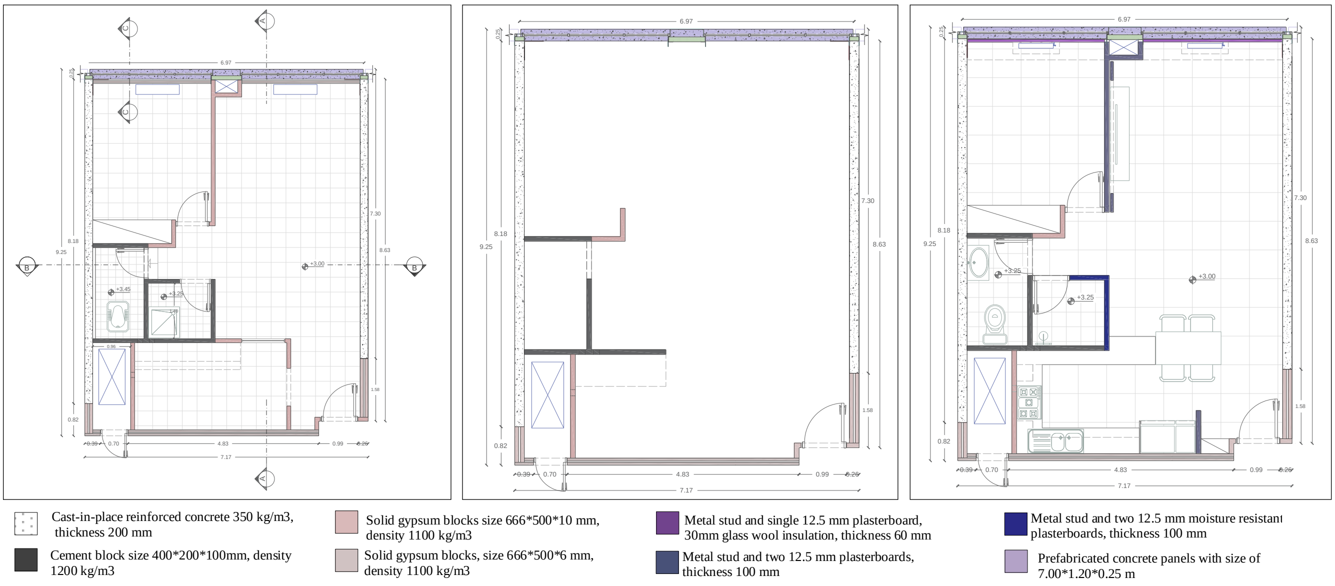


Figure 5.24. Rehabilitation process of scenario 3, Source: Author. Left: Initial state of Aleph-1, middle: demolition process, right: Scenario 3

c) HVAC systems, mechanical and natural ventilation, and natural lighting of scenario 3

Table 5.15 explains the HVAC, insulations, ventilation, and natural lighting of scenario 3.

Table 5.15. HVAC, insulations, ventilation, and natural lighting of scenario 3

HVAC, insulation, ventilation, and natural lighting of scenario 3		
HVAC	Cooling	**General split** (General GNR-24WN)
	Heating	**Radiator** (Thermal capacity 126kcal/h per panel) & **general package** (Thermal capacity 20636 kcal/h)
Insulation	Thermal insulation	**3 cm of glass wool**, u-value = 0.38 W/m^{2}K
	Acoustic insulation	Without insulation
	Moisture insulation	Bituminous, thickness 4mm
Window frame		**UPVC frame**
Window glass		Double glazing – clear glass 6mm and **13mm argon gas**
Mechanical ventilation	Kitchen	Hood = **Dorsa Roya Diagonal Hood**, **size 90cm-680m^3/h**
	Bathroom and WC	Exhaust fan = Simple flux mechanical ventilation system, Ilka, **VIK-40L4S, 150 m^3 /h**
Natural ventilation	Living room and bedroom	Four tilt and turn windows with a size of 1.10 *1.20 m
Natural lighting	Living room and bedroom	Two windows – 1.20*3.00 m – provide direct natural lighting

5.3. Conclusion of chapter 5

This chapter has defined the alternatives that will be assessed from the sustainability point of view – chapter 6 – among a wide range of feasible ones. These alternatives are different rehabilitation scenarios of the selected sample of study which is Aleph-1 apartment. The derived conclusions from sections 5.1 and 5.2 have been drawn in the following paragraphs.

In section 5.1, the author has contributed to survey, collect, organize, classify, catalog, and digitalize general and technical information of the initial state of Aleph-1 to identify general and particularities of this state and facilitate a more precise comparison between this state and other Aleph-1 rehabilitated apartments.

In section 5.2, based on the conducted on-site surveying of 71 Aleph-1 apartments, three rehabilitated projects – named as scenarios 1 to 3 – were selected (Figures 5.27 and 5.28). These three selected scenarios not only were the most frequent rehabilitation techniques of Aleph-1 – more than 59% of surveyed apartments – but also were the most common and representative rehabilitation techniques in Iran. Moreover, the author intended to select the rehabilitated Aleph-1 apartments those were had differences from each other to provide a more holistic perspective for the sustainability assessment of different existing rehabilitation techniques applied for MHs in Iran. The main differences between these selected scenarios and the initial state of Aleph-1 – from architectural, space distribution, applied material, mechanical, electrical, and natural lighting point of view – have been illustrated in Tables 5.16 to 5.19 as the conclusion of this chapter.

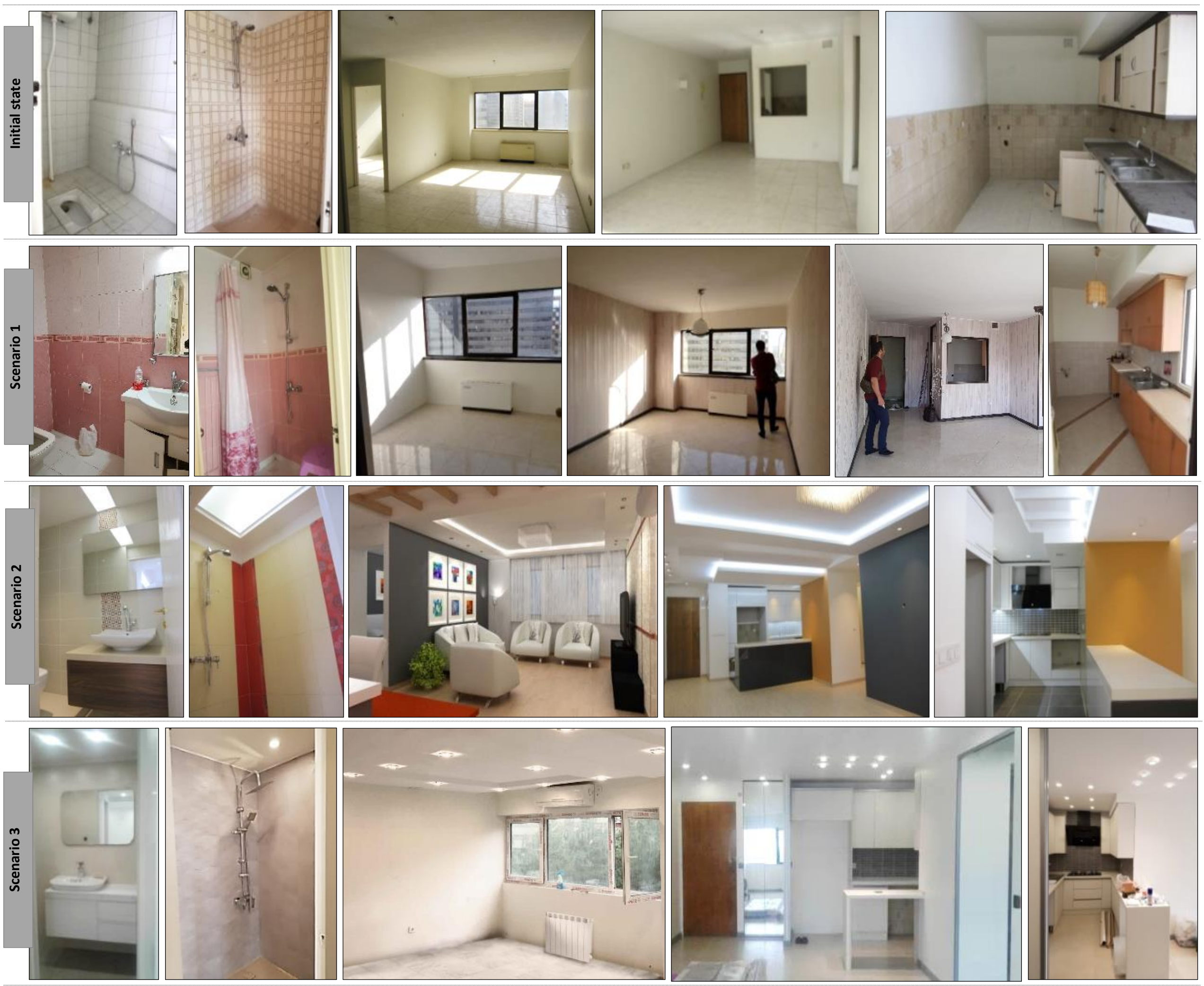


Figure 5.25. Initial state and defined scenarios of Aleph-1

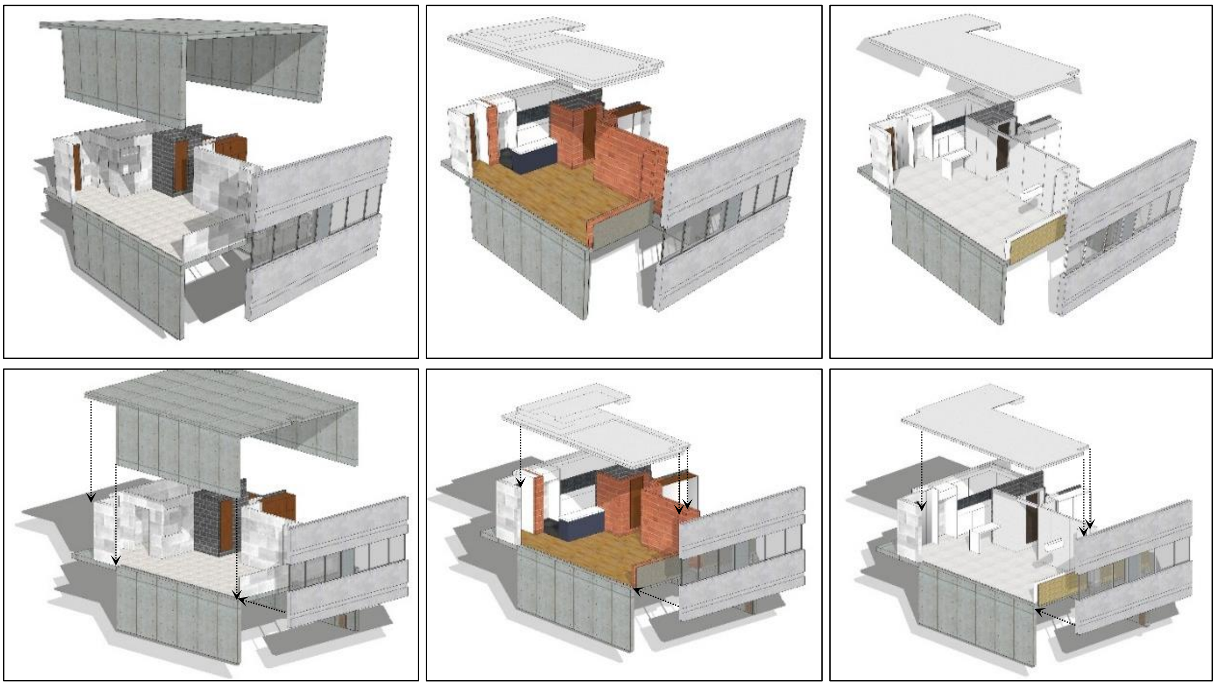


Figure 5.26. Defined scenarios of Aleph-1. Scenario 1 (left), Scenario 2 (middle), Scenario 3 (right).

Table 5.16. Interventions of the defined scenarios compared to the initial state of Aleph-1.

		Scenario 1	**Scenario 2**	**Scenario 3**
Spatial layout	Kitchen	✗	✓	✓
	Livingroom	✗	✓	✓
	Bedroom	✗	✓	✓
	Bathroom and WC	✗	✓	✓
Spatial Unity		✗	✓	✓
Interior partitions	Wall	✗	✓	✓
	Ceiling	✗	✓	✓
	Floor	✓	✓	✓
Windows	Window frame	✗	✗	✓
	Window glass	✗	✗	✓
Interior Doors		✗	✓	✓
Insulations	Thermal insulation	✗	✓	✓
	Acoustic insulation	✗	✗	✓
	Moisture insulation	✓	✓	✓
Mechanical equipment	Plumping	✗	✓	✓
	Shower	✓	✓	✓
	Lavatories	✓	✓	✓
	Sink	✓	✓	✓
	Taps	✓	✓	✓
	HVAC	✗	✗	✓
Electrical equipment	Wire and cable	✗	✗	✓
	Switches and sockets	✗	✓	✓
	Main switchboard	✗	✗	✓
Furnishing	Cabinets	✓	✓	✓
	Wardrobes and closets	✓	✓	✓

(✓) Changed, (✗) Not changed.

Table 5.17. Construction materials of Aleph-1 initial state and defined scenarios

		Initial state	Scenario 1	Scenario 2	Scenario 3
Wall	Interior walls	Wet spaces: Cement blocks, size 400*200*100mm, density 1200 kg/m3; bituminous, thickness 4mm; cement mortar 350 kg/m3, thickness 10 mm; and ceramic tiles 20*20 cm.	Wet spaces: Cement blocks, size 400*200*100mm, density 1200 kg/m3; bituminous, thickness 4mm; cement mortar 350 kg/m3, thickness 10 mm; and ceramic tiles 40*35 cm.	Wet spaces: Hollow brick, size 190*180*80 mm, density 1300 kg/m3; bituminous, thickness 4mm; cement mortar 350 kg/m3, thickness 10 mm; and ceramic tiles 40*60 cm.	Wet spaces: Metal stud and two 12.5 mm moisture resistant plasterboards; cement mortar 350 kg/m3, thickness 10 mm; and ceramic tiles 40*60 cm.
		Dry spaces: Solid gypsum blocks, size 666*500*100 mm, density 1100 kg/m3; plaster, 10 mm thickness; and water-based paint.	Dry spaces: Solid gypsum blocks, size 666*500*100 mm, density 1100 kg/m3; plaster, 10 mm thickness; and wallpaper.	Dry spaces: Hollow brick, size 190*180*80 mm, density 1300 kg/m3; clay plaster, 15 mm thickness plaster; 10 mm thickness; and water-based paint.	Dry spaces: Metal stud and two 12.5 mm plasterboards, thickness 100 mm; and water-based paint.
	Exterior walls	Façade: Prefabricated concrete panels, size 7.00*1.20*0.25 m, 6 cm for air gap; solid gypsum blocks, size 666*500*60 mm; and water-based paint.	Façade: Prefabricated concrete panels with a size of 7.00*1.20*0.25 m, 6 cm of the air gap, and solid gypsum blocks with a size of 666*500*60 mm; and wallpaper.	Façade: Prefabricated concrete panels with a size of 7.00*1.20*0.25 m; 6 cm of the air gap; hollow brick, size 190*180*80 mm; clay plaster, 15 mm thickness; plaster; 10 mm thickness; and water-based paint.	Façade: Prefabricated concrete panels with a size of 7.00*1.20*0.25 m; 6 cm of the air gap; 3 cm of the glass wool; metal stud and one-layer plasterboard with a thickness of 12.5 mm; and water-based paint.
		Corridor walls: Solid gypsum blocks, size 666*500*100 and 666*500*60 mm, density 1100 kg/m3; plaster, 10 mm thickness; water-based paint.	Corridor walls: Solid gypsum blocks, size 666*500*100 and 666*500*60 mm, density 1100 kg/m3; plaster, 10 mm thickness; and wallpaper.	Corridor walls: Solid gypsum blocks, size 666*500*100 and 666*500*60 mm, density 1100 kg/m3; plaster, 10 mm thickness; and water-based paint.	Corridor walls: Solid gypsum blocks, size 666*500*100 and 666*500*60 mm, density 1100 kg/m3; plaster, 10 mm thickness; and water-based paint.
Floor	Living room, bedroom, and kitchen	Cement mortar 350 kg/m^3, thickness 20 mm; and ceramic tiles 35*35 cm.	Cement mortar 350 kg/m^3, thickness 20 mm; and ceramic tiles 50*50*1 cm.	Cement mortar 150 kg/m^3, thickness 50mm; cement mortar 350 kg/m3, thickness 20 mm; and parquet Direct Pressure Laminate (DPL), 10mm thickness.	Cement mortar 350 kg/m3, thickness 20 mm; and ceramic tiles 60*60 cm.
	Bathroom and WC	Filler, cement mortar 150 kg/m3 thickness: 180 mm in bathroom and 380 mm in WC; bituminous, thickness 4mm; cement mortar 350 kg/m3, thickness 10 mm; and ceramic tiles 35*35 cm.	Filler, cement mortar 150 kg/m3 thickness: 180 mm in bathroom and 380 mm in WC; bituminous, thickness 4mm; cement mortar 350 kg/m3, thickness 10 mm; and ceramic tiles 35*35 cm.	Filler, cement mortar 150 kg/m3 thickness: 50mm in kitchen, 180 mm in bathroom, and 380 mm in WC; bituminous, thickness 4mm; cement mortar 350 kg/m3, thickness 10 mm; and ceramic tiles 50*50*0.6 cm.	Filler, cement mortar 150 kg/m3 thickness: 180 mm; Bituminous, thickness 4mm; Cement mortar 350 kg/m3, thickness 10 mm; and ceramic tiles 50*50 cm.
Ceiling	Living room, bedroom, and kitchen	Structural slab, reinforced concrete, thickness 20 cm; gypsum plaster coat with an average thickness of 10 mm; and water-based paint.	Structural slab, reinforced concrete, thickness 20 cm; gypsum plaster coat with an average thickness of 10 mm; and water-based paint.	Structural slab, reinforced concrete, thickness 20 cm; gypsum plaster coat with an average thickness of 10 mm; false ceilings; and water-based paint.	Structural slab, reinforced concrete, thickness 20 cm; false ceiling, metal stud and plasterboard; and water-based paint.
	Bathroom and WC	Structural slab, reinforced concrete, thickness 20 cm; white cement coat with an average thickness of 10 mm; and oil-based paint.	Structural slab, reinforced concrete, thickness 20 cm; white cement coat with an average thickness of 10 mm; and oil-based paint.	Structural slab, reinforced concrete, thickness 20 cm; white cement coat with an average thickness of 10 mm; and oil-based paint.	Structural slab, reinforced concrete, thickness 20 cm; white cement coat with an average thickness of 10 mm; and oil-based paint.
Window	Window frame	Galvanized steel frame	Galvanized steel frame	Galvanized steel frame	UPVC frame
	Window glass	Double glazing – clear glass 6mm and 13mm air	Double glazing – clear glass 6mm and 13mm air	Double glazing – clear glass 6mm and 13mm air	Double glazing – clear glass 6mm and 13mm argon gas

Table 5.18. HVAC, insulations, ventilation, and natural lighting of Aleph-1 initial state and defined scenarios

		Initial state	Scenario 1	Scenario 2	Scenario 3
HVAC	Cooling	Fan coil unit (cooling = comp. chiller, hot water (5°C))	Fan coil unit (cooling = comp. Chiller, hot water (5°C))	Fan coil unit (cooling = comp. Chiller, hot water (5°C))	General split (General GNR-24WN)
	Heating	Fan coil unit (heating = boiler, hot water (80°C))	Fan coil unit (heating = boiler, hot water (80°C))	Fan coil unit (heating = boiler, hot water (80°C))	Radiator (Thermal capacity 126kcal/h per panel) & general package (Thermal capacity 20636 kcal/h)
Insulation	Thermal insulation	Without insulation	Without insulation	3cm of mineral wool batt, u-value = 0.42 W/m^2K	3 cm of glass wool, u-value = 0.38 W/m^2K
	Acoustic insulation	Without insulation	Without insulation	Without insulation	Without insulation
	Moisture insulation	Bituminous, thickness 4mm	Bituminous, thickness 4mm	Bituminous, thickness 4mm	Bituminous, thickness 4mm
Window	Window frame	Galvanized steel frame	Galvanized steel frame	Galvanized steel frame	UPVC frame
	Window glass	Double glazing, 6mm clear glass, and 13mm air	Double glazing, 6mm clear glass, and 13mm air	Double glazing, 6mm clear glass, and 13mm air	Double glazing, clear glass 6mm and 13mm argon gas
Mechanical ventilation	Kitchen	Hood = A roof-mounted central fan, 350 m^3/h	Hood = Bimax B1002U, size 90cm, 480 m^3/h	Hood = Dorsa Mahdis Hood, size 90cm,540 m^3/h	Hood = Dorsa Roya Diagonal Hood, size 90cm-680m3/h
	Bathroom and WC	Exhaust fan = Simple flux mechanical ventilation system, 100 m^3/h	Exhaust fan = Simple flux mechanical ventilation system, Sabalan, 95 m^3 /h	Exhaust fan = Simple flux mechanical ventilation system, Damandeh, VBX-20S2S, 150 m^3 /h	Exhaust fan = Simple flux mechanical ventilation system, Ilka, VIK-40L4S, 150 m^3 /h
Natural ventilation	Living room and bedroom	Two vertical pivot windows with a size of 1.10 *1.20 m	Two vertical pivot windows with a size of 1.10 *1.20 m	Two vertical pivot windows with a size of 1.10 *1.20 m	Four tilt and turn windows with a size of 1.10 *1.20 m
Natural lighting	Living room and bedroom	Two windows –- 1.20*3.00 m – provide direct natural lighting	Two windows – 1.20*3.00 m – provide direct natural lighting	Two windows – 1.20*3.00 m – provide direct natural lighting	Two windows – 1.20*3.00 m – provide direct natural lighting
	Kitchen	A window – 1.10*1.10m – provides indirect natural lighting	A window – 1.10*1.10m – provides indirect natural lighting	-	-

CHAPTER 6

Application of the proposed MIVES-Delphi model on the defined existing rehabilitation scenarios: scenarios 1 to 3

Chapter 6: Application of the proposed MIVES-Delphi model on the defined existing rehabilitation scenarios: scenarios 1 to 3

Introduction

This chapter aims to conduct the **6th stage** of the **proposed MIVES-Delphi model** – see chapter 3, section 3.2 – which is **the application of this model** on the **defined existing real rehabilitated scenarios** (scenarios 1 to 3) of Aleph-1 in Ekbatan – see chapters 4 and 5 – to (1) prove the applicability and suitability of this proposed model, (2) identify the challenges when facing its application, and (3) demonstrate how it enables decision-makers to identify the strengths and weaknesses of interior rehabilitation of MHs from economic, environmental, and social points of view and select the most sustainable ones. To do so, this chapter consists of the following sections:

1) **Sections 6.1** to **6.3 calculate the values of** the defined economic, environmental, and social **indicators** respectively for the defined scenarios – scenarios 1 to 3. To do so, the definition, justification, scope and boundaries, method/s and effective parameters for assessment, and value calculation of each defined indicator have been studied rigorously.

2) **Section 6.4** calculates the **Global Sustainability index (GSi)** of each defined scenario. In this section, by the application of the defined value functions – see Appendix 3.B –, the obtained indicators' values – from sections 6.1 to 6.3 – convert to indicators non-dimensional values. Consequently, by considering the previously defined decision-making tree – section 3.2, Figure 3.3 –, its components' weights – section 3.2, Figure 3.4 –, and the obtained indicators non-dimensional values, the GSi of each defined scenario has been calculated through Equations 3.5 to 3.7.

3) **Section 6.5 analyzes**, **interprets**, and **discusses the obtained results** from previous sections – sections 6.1 to 6.4 – to (a) prove the applicability of the proposed model, (b) identify the strengths and weaknesses of the defined scenarios from economic, environmental, and social points of view, and (c) find the most sustainable rehabilitation scenario by comparing their GSis values.

4) Section 6.6 concludes previous sections 6.1 to 6.5. Figure 6.1 illustrates the structure of chapter 6.

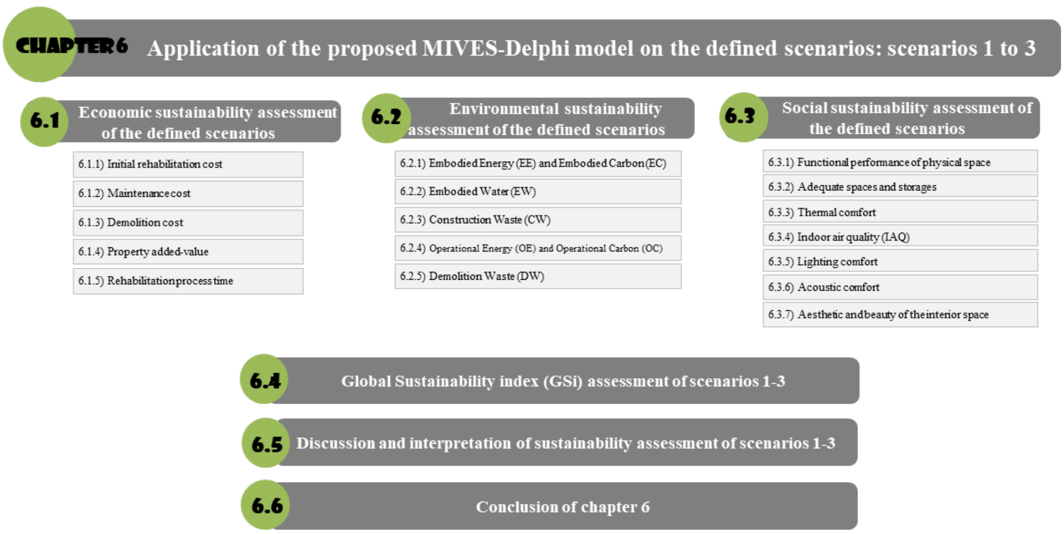


Figure 6.1. Structure of chapter 6

6.1. Economic sustainability assessment of the defined scenarios: scenarios 1-3

The building industry accounts for a major share of the world's economy, up to 45% (Rhodes, 2015). In this regard, several studies (Zabihi, Habib and Mirsaeedie, 2012; Cetiner and Edis, 2014; Chardon *et al.*, 2016; Ahmad and Thaheem, 2018; Kamali, Hewage and Milani, 2018) proved that the economic requirement of buildings has a substantial contribution regarding their sustainability performance. In other words, the economic requirement that measures the economic impact of a building and implies the affordability to support the building costs – both direct and indirect – during its entire life cycle (Kamali, Hewage and Milani, 2018; Maleki *et al.*, 2019), aims to minimize the economic impacts and consequently improves its sustainability performance.

In several studies regarding the economic sustainability in the building sector (Chen, Okudan and Riley, 2010; Zabihi, Habib and Mirsaeedie, 2012; Banirazi, Pons and Hosseini, 2021), the economic sustainability performance of a building has been assessed through its two main criteria: (1) **cost**, and (2) **time**. It is worth noting that according to several studies, although the quality is one of the main parameters of the economic requirement, it has been discarded in the present thesis because quality overlaps with other economic and social indicators – see initial rehabilitation cost, maintenance cost (life expectancy of materials), and aesthetic parameters (details quality). Traditionally, building cost and time were used to be calculated with manual measurements of various building elements and processes which were mostly time-taking, inaccurate, and unreliable (Bečvarovská and Matějka, 2014; Ma and Liu, 2014; Olsen and Taylor, 2017). However, in recent years, the construction industry has seen a shift toward the **Building Information Modeling (BIM)** method **for measuring buildings' construction cost and time** (Ma and Liu, 2014; Wang *et al.*, 2014; Olsen and Taylor, 2017). The Building Information Modeling (BIM) is a methodology for design and information management built upon a virtual model of the building that can digitize a great amount of building information – e.g., construction cost, maintenance cost, rehabilitation cost, demolition cost, and construction time – (C. Eastman, P. Teicholz, R. Sacks, 2011; Hu and Zhang, 2011; Monteiro and Poças Martins, 2013; Wang *et al.*, 2014; Olsen and Taylor, 2017; A. Borrmann, M. König, C. Koch, 2018) that can not only provide the abovementioned building information simpler, more detailed and accurate but also reduce consuming time and expenses (Bečvarovská and Matějka, 2014; Olsen and Taylor, 2017). ArchiCAD (http://www.graphisoft.com/) and Autodesk Revit Architecture (http://usa.autodesk.com/revit/2020) are the two most common BIM tools for architectural design. Both include routines to automatically extract quantities – **Quantity Take-Off (QTO)** – (Bečvarovská and Matějka, 2014; Ma and Liu, 2014; Olsen and Taylor, 2017), and **construction process** from the model (Farah and Guillermo F. Salazar, 2005).

To assess the **economic sustainability performance** of interior rehabilitation of MHs in Iran, the present doctoral dissertation takes into account the abovementioned criteria – **the cost criterion** including initial rehabilitation cost, maintenance cost, demolition cost, and property added-value and **time criterion** including rehabilitation process time (see section 3.2) – as presented in Figure 6.2.

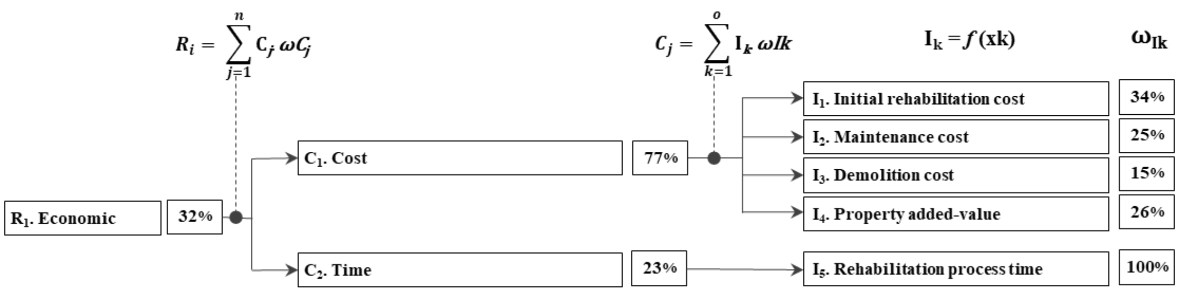


Figure 6.2. Economic requirement and its defined criteria and indicators

In this regard, the author has employed the BIM method by taking the following steps: (a) collect the required data – such as applied materials, their relevant parameters (e.g., length, width, height, area, and volume), and construction process time – for each defined scenario through on-site surveying and physical measurements, (b) insert the collected data in a BIM tool, which is Autodesk Revit 2020 software, for developing the BIM model, and (c) export the calculated material quantities and their construction process time for each scenario to ".txt" files using the data-exporting function of Revit and import to Microsoft Excel Worksheet (.xlsx format). Figure 6.3 presents the quantities of applied materials for scenario 3.

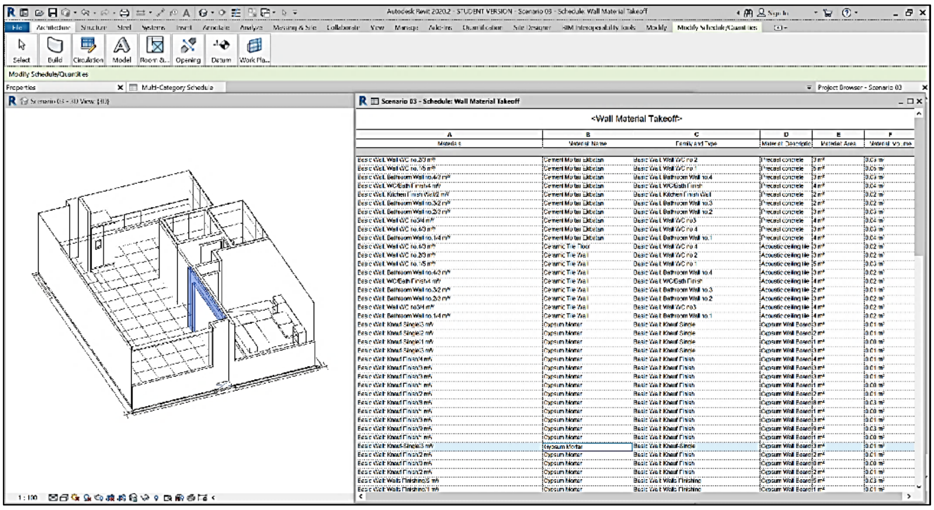


Figure 6.3. Screenshot of quantity data of scenario 3 stored in the BIM model

It is worthy to mention that, in the present thesis, all of the costs have been calculated in euro currency by considering the constant exchange rate from euro to Toman – Toman is the official unit of Iran currency – which is equal to 15000 – 1 euro =15000 Toman.

Moreover, some of the apartment characteristics such as block, floor, orientation, and household size have been considered equal for all selected scenarios in order to be able to compare the obtained results – indicators' values – more accurately. For instance, scenario 1 is located on the 9^{th} floor of block 4, and scenarios 2 and 3 are located on the 7^{th} floor of blocks 13 and 4 respectively. Although these three scenarios are located in different blocks and floors, in this dissertation, they have been assumed on the 7^{th} floor of block 4 as shown in Table 6.1.

Table 6.1. Assumed characteristics for value calculation of all defined scenarios

	Block	Floor	Orientation	Household size
Assumed characteristics for all defined scenarios	4	7	North-West	2

In the following sections – sections 6.1.1 to 6.1.5 –, the definition, justification, effective parameters for assessment, and value calculation of each defined economic indicator have been explained particularly more in detail in its corresponding section.

6.1.1. Initial rehabilitation cost (I_1)

Initial rehabilitation of apartment in the present thesis refers to implemented rehabilitation activities and applied interventions for converting – one time – the initial state of Aleph-1 apartment to its current state. In this regard, the initial rehabilitation cost is the total cost of initial rehabilitation activities which is one of the most important economic indicators (Kamali, Hewage and Milani, 2018) which has a direct effect on the decision of stakeholders to whether or not to rehabilitate their apartments (Ahmad and Thaheem, 2018).

For calculating the value of indicator 1 – initial rehabilitation cost – for each defined scenario of Aleph-1 apartment, the following costs have been considered: (a) **apartment evacuation** and occupant movement **cost** – transportation cost and labor cost –, (b) **demolition cost** – labor cost for demolition, the labor cost of waste disposal, transportation cost of waste disposal –, (c) **designing cost** – the detailed executive architectural, mechanical, and electrical layouts –, (d) **construction cost** – used material included transportation cost, labor and constructor company cost –, and (e) **apartment repatriation** (reoccupation) **cost** – transportation and labor cost.

a) Apartment evacuation cost:

For assessing and calculating the **apartment evacuation cost** for each scenario, **the truck**, **labor**, and **packing costs** have been considered. Equation 6.1 calculates the apartment evacuation cost:

Evacuation cost = Truck cost+ labor cost + packing cost Equation 6.1

As consulted with several transportation agencies in Iran, a truck with a load capacity of 4 tons is needed for evacuating and moving a one-bedroom apartment like Aleph-1. With the elaboration of two laborers, this process takes almost 3 hours. It is worthy to mention that based on Ekbatan buildings regulations – see section 4.1.2.c –, as transportation of construction materials and furniture is prohibited with the building's elevators, the specific cargo elevators must be used.

According to the Iran Road Maintenance and Transportation Organization (IRMTO) (http://rmto.ir/) and the rate of National Freight and Transportation Association of Iran (NFTAI) (http://ehkt.ir/), the price of a truck with a load capacity of 4 tons for 3 hours is 12.33 €. This price is for a distance up to 30 km between the loading and discharging of the cargo points. The labor wage for 3 hours is 2.66 € per person. Also, for each additional hour, 3.67 € will be charged for a truck and 1 € for each laborer. On the other hand, for each additional floor, labor wage increases 0.66 € (Table 6.1).

Table 6.2. Apartment evacuation cost

	Load Capacity (Tons)	Loading Space (m^3)	Price (€)	Additional Hour for the truck (€)
Truck for 3hours up to 30 km distance	2	2.40*2.50*1.6=9.60	8.33	2.33
	4	2.40*4*2=19.20	12.33	3.67
	6	3*4.70*2.20=31.02	15	4.33
	10	3*5.80*2.30=40.02	19.67	5.67
Labor/mover (3hour)	**Price (€)**	**Additional floor (€)**	**Additional Hour for laborers (€)**	
	2.67	0.67	1	
Total packing cost	28.67			

(http://rmto.ir/, http://ehkt.ir/, http://barast.com/)

As previously mentioned in Table 6.1, for calculating labor cost, it has been considered that all of the defined scenarios are located on the 7th floor. In this regard, the total evacuation cost of each scenario calculates according to Equation 6.1 is:

*Evacuation cost = 12.33 + 2 (2.66+ 7*0.66) + 28.67= 55.56 €*

For all three selected scenarios, the apartment evacuation costs have been considered the same amount which is equal to 55.56 €.

b) Initial demolition cost

For assessing and calculating the **initial demolition cost** of each scenario – which refers to the cost of required demolishing activities to convert the initial state of Aleph-1 to its current state –, the **labor cost for demolition**, the **labor cost of waste disposal**, and **the transportation cost of waste disposal** have been considered.

According to the Iran Construction Material Price List (ICMPL) of 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019) published by the Plan and Budget Organization of the Islamic Republic of Iran (https://www.mporg.ir/en), after the calculation of the QTOs – extracted from the BIM model – of required products – construction materials and building components in the present thesis – that should be demolished, the labor cost for initial demolition of scenario 1, 2, and 3 are 233.45 €, 328.10 €, and 361.03 € respectively. Appendix 6.A explains the labor cost more in detail.

Also, based on the rate of the Waste Management Organization of Tehran Municipality (http://pasmand.tehran.ir/), the disposing price of the construction waste for each ton is 4.57 €. This price is for a distance up to 75 km between the loading and discharging the cargo points and includes the labor and transportation cost of construction waste disposal. Accordingly, the construction waste disposal amount for scenarios 1, 2, and 3 are 9.497 tons, 15.862 tons, and 16.163 tons, and the construction waste disposal costs are 43.40, 72.49, and 73.86 € respectively. Consequently, the total initial demolition cost for scenarios 1, 2, and 3 are 276.86, 400.59, and 434.90 €.

c) Designing cost

Based on Iran Construction Engineering Organization (IRCEO) (http://www.irceo.net/), the prices for designing the interior layout of residential buildings with the detailed executive architectural, mechanical, and electrical layouts are presented in Table 6.3.

Table 6.3. Designing cost

Types of engineering consulting company	Designing the interior layout of residential building (€/m2)
First-grade licensed (> 12 years' experience)	7.66
Second-grade licensed (12> years' experience >3)	6.12
Third-grade licensed (< 3 years' experience)	4.34

(http://www.irceo.net/)

Scenario 1 has been designed by the third-grade licensed consulting engineering company and scenarios 2 and 3 have been both designed by the second-grade licensed ones. Therefore, as Aleph-1 has an area of 54 m^2, the designing cost for scenario 1 is 234.36 €, and scenarios 2 and 3 are 330.48 €.

d) Construction cost

Construction cost includes **the applied products' costs** besides their supplying and **transportation costs**, **laborers' costs**, and **constructor company costs** – including costs for obtaining required permits, building licenses grant, approvals, and inspections (see sections 2.2.4 and 4.1.2.c). In the present thesis, construction cost has been generally calculated based on the Iran Construction Material Price List (ICMPL) of 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019), and for those materials that had not been mentioned in the ICMPL, other common building material price databases have been considered (https://kargosha.com/,https://engineerplus.ir/,https://salamsakhteman.com/,https://sanjagh.pro/tehran/,https://www.digikala.com/). The construction cost of an item is its used quantity – extracted from the BIM model – multiplying by its associated price which is indicated in the ICMPL. Therefore, the total construction cost is the sum of the costs of the associated items. Therefore, the total construction cost for scenarios 1, 2, and 3 are 3723.06 €, 4496.07 €, and 6132.90 € respectively (Appendix 6.A).

e) Apartment repatriation cost:

As the repatriation (reoccupation) cost is almost equal to the evacuation cost, it has been considered 55.56 € per apartment unit.

The value of indicator 1 for each defined scenario:

Based on all the above-mentioned costs, Table 6.4 presents the value of the initial rehabilitation cost for each defined scenario of Aleph-1 apartment.

Table 6.4. The value of initial rehabilitation costs for scenarios 1 to 3

Initial rehabilitation costs	Scenario 1 (€)	Scenario 2 (€)	Scenario 3 (€)
a) Apartment evacuation cost	55.56	55.56	55.56
b) Initial demolition Cost	276.86	400.59	434.90
c) Designing cost	234.36	330.48	330.48
d) Construction cost	3723.06	4496.07	6132.90
e) Apartment repatriation cost	55.56	55.56	55.56
Total initial rehabilitation cost	**4345.40**	**5338.26**	**7009.40**

As Aleph-1 apartment has an area of 54 m^2, the values of I_1 for scenarios 1, 2, and 3 – with the functional unit of €/m^2 – are 80.47, 98.86, and 129.80 €/m^2 respectively (Table 6.4).

Table 6.5. The value of initial rehabilitation costs (€/m^2) for scenarios 1 to 3

Initial rehabilitation costs	Scenario 1 (€/m^2)	Scenario 2 (€/m^2)	Scenario 3 (€/m^2)
The total value of I_1	**80.47**	**98.86**	**129.80**

6.1.2. Maintenance cost (I_2)

Maintenance cost as one of the most important economic indicators (Kamali, Hewage and Milani, 2018) refers to the required total cost for future rehabilitating – excluding the initial rehabilitation – and maintaining a building in an adequate and good shape during its lifetime – based on the expected lifespans of applied products – (Cetiner and Edis, 2014).

To calculate the value of indicator 2 – maintenance cost – for the defined scenarios over a study period of 50 years, the following **parameters** have been considered: (a) **durability and life expectancies** of applied products – construction materials and building components in this thesis – to figure out **the numbers of their required rehabilitation** or **replacement** during the study period, (b) **Quantity Take-Offs (QTOs)** – a quantity takeoff in construction estimates quantities from drawings and construction plans including materials' area, volume, density, construction costs, and construction time and recording them in the *Bill of Quantities* (Farah and Guillermo F. Salazar, 2005; Simon Tolson, 2012; Monteiro and Poças Martins, 2013; Olsen and Taylor, 2017) – of applied products, (c) **demolition or repairing cost** – the labor cost for demolition or repairing, the labor cost for waste disposal, transportation cost for waste disposal –, and (d) **implementation cost** – the implementation cost of applied products besides their transportation, laborers, and constructor company cost. It is noteworthy to mention that a **study period** of **50 years** has been assumed for this thesis due to: (1) recommended by Eurocode 1990 as a building service life, and (2) Grant and Ries suggest a period of 50 years as the baseline year of study for building operations, maintenance and service lifetime (Grant and Ries, 2013).

a) Numbers of required rehabilitation

To calculate **the numbers of rehabilitation** during the defined study period, durability and **life expectancies of the applied products** in each scenario should be investigated. However the life services of products vary and depend on the function of the building, the quality of applied products, installation, the level of maintenance, the weather and climate conditions, and the intensity of use (National Association of Home Builders, 2017), there are several well-known databases to estimate the lifespan of building products. For instance, a Spanish database "Institut de Tecnologia de la Construcció de Catalunya (ITeC)" (Institut de Tecnologia de la Construcció de Catalunya: ITeC, 1991), a UK database "Housing Association Property Mutual Ltd (HAPM)" (Housing Association Property Mutual, 1999), and three North American databases National Association of Home Builders (NAHB) (National Association of Home Builders, 2017), "The Whitestone Facility Maintenance and Repair Cost Reference 2009-2010" (Douglas Abate *et al.*, 2009), and "UNIFORMAT II" (American Standard of Testing Materials: ASTM E1557–09, 2009) are some of the most commonly used databases that contain information about maintenance activities and life expectancies of building products (Brito and Raposo, 2011; Freitas, Costa, and Delgado, 2013).

In the present thesis, NAHB has been selected as the main reference due to (1) it is the most recent and updated English language database, and (2) it provides a wide range of building products' life expectancies. Table 6.6 presents the life expectancies of some building products extracted from the selected database.

Table 6.6. Life expectancies of building components extracted from NAHB database

Products (Material/Component)	Life expectancy (year)
Gypsum block (interior wall)	60
Concrete block (interior wall)	+75
Brick (interior wall)	+70
Ceramic tile (wall)	50-70
Ceramic tile (flooring)	50-75
Laminate parquet (flooring)	15-25
Oriented Strand Board (OSB)	25-30
MDF	15-30
kitchen cabinets	25-30
Closet	+50
Induction and fan-coil units	10-15
Package water heaters, tankless	+20
Aluminum thermal break window	70
Wall paint (interior)	10-15
Door (hollow-core interior)	20-30

(National Association of Home Builders, 2017)

To estimate more precisely the life service of the applied building products, besides using the mentioned database, life expectancy guidelines and catalogs of products published by their manufacturer have been overviewed for two main reasons: (1) some of the applied products were not mentioned in these databases, and (2) some products were mentioned with a wide range of service life – mostly depending on their quality. For instance, the longevity of ceramic tile is estimated between 50 to 70 years; while there are several types of ceramic tiles that have different qualities and thus have different lifespans.

After defining the study period and life expectancies of applied products, the numbers of required rehabilitation – excluding the initial rehabilitation – have been calculated by Equation 6.2:

$NMR_p = (SP/ EL_p) - 1$ Equation 6.2

where NMR_p is the numbers of required rehabilitation and replacement – excluding the initial rehabilitation – of the product for building maintenance; SP is the defined study period which is equal to 50 with the functional unit of year; EL_p is the expected lifetime of the product with the functional unit of year.

It is worthy to mention that for products that their numbers of required maintenance rehabilitation (NMR_p) are equal or smaller than 0 – in other words, their estimated lifetimes (EL_p) are equal or more/greater than 50 years –, no maintenance cost over the defined study period has been calculated. For instance, as the estimated lifetime of cement block is 75 years, no maintenance cost during the 50 years of study period has been calculated for this product.

b) Quantity Take-Offs (QTOs) of applied building products

The QTOs of the building products have been extracted from the BIM model to obtain the quantities of required products to be repaired, demolished or/and reconstructed.

c) Demolition or repairing cost

For assessing and calculating the demolition cost for each scenario, the labor cost for demolition or repairing, the labor cost for waste disposal, and the transportation cost for waste disposal have been considered. The obtained QTO of each product has been multiplied by its corresponding demolition cost per unit for obtaining the demolition or repairing cost of that product as shown in Equation 6.3.

$DC_p = QTO_p \times DCU_p$ Equation 6.3

where DC_p is the demolition cost of the product with the functional unit of €; QTO_p is the quantity take-off of the product with the functional unit of m^2, m^3, or unit; DCU_p is the demolition cost of the product per unit with the functional unit of €/ m^2, m^3, or unit.

d) Implementation cost

The implementation cost includes the applied building products' cost besides their supplying and transportation, laborers, and constructor company costs. The implementation cost has been generally calculated based on the ICMPL of 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019), and for those products that had not been mentioned in the list, other common products price databases have been considered (https://kargosha.com/,https://engineerplus.ir/,https://salamsakhteman.com/,https://sanjagh.pro/tehran/,https://www.digikala.com/). The implementation cost of each product has been calculated by Equation 6.4:

$IC_p = QTO_p \times ICU_p$ Equation 6.4

where IC_p is the implementation cost of the product with the functional unit of €; QTO_p is the quantity take-off of the product with the functional unit of m^2, m^3, or unit; ICU_p is the implementation cost of the product per unit with the functional unit of €/ m^2, m^3, or unit.

The value of indicator 2 (maintenance cost) for each defined scenario:

In this regard, the total maintenance cost for a study period of 50 years is calculated according to Equation 6.5:

$I2.\mathrm{TMC} = \sum_{p=1}^{n} \mathrm{NRM_p} \times (\mathrm{DC_p} + \mathrm{IC_p})$ Equation 6.5

where TMC is the total maintenance cost for each scenario; NRM_p is the numbers of required rehabilitation and replacement of the product for building maintenance; DC_p is the demolition cost of the product with the functional unit of €; IC_p is the implementation cost of the product with the functional unit of €.

Consequently, the total maintenance cost for a study period of 50 of the defined scenarios 1, 2, and 3 are 9882.38, 7309.10, and 6500.07 €/50yrs. **Appendix 6.B** presents the maintenance cost for each scenario more in detail.

Table 6.7. The value of maintenance cost (€) for each defined scenario

Costs	**Scenario 1 (€/50yrs)**	**Scenario 2 (€/50yrs)**	**Scenario 3 (€/50yrs)**
Maintenance cost	9882.38	7309.10	6500.07

As Aleph-1 apartment has an area of 54 m^2, the values of I_2 for scenarios 1, 2, and 3 – with the functional unit of €/m^2 – are 183.01, 135.35, and 120.37 €/m^2 respectively.

Table 6.8. The value of maintenance cost (€/m^2.50yrs) for scenarios 1 to 3

Maintenance cost (€/m^2)	Scenario 1 (€/m^2.50yrs)	Scenario 2 (€/m^2.50yrs)	Scenario 3 (€/m^2.50yrs)
The total value of I_2	**183.01**	**135.35**	**120.37**

6.1.3. Demolition cost (I_3)

In the present thesis, indicator 3 which is the demolition cost of an apartment refers to the total required costs for demolition, destruction, removal, and clearance of all building interior components and products – including interior walls and partitions, false ceilings, pavement floors, windows, and furniture – to convert the apartment to its framework stage (Figure 6.4).

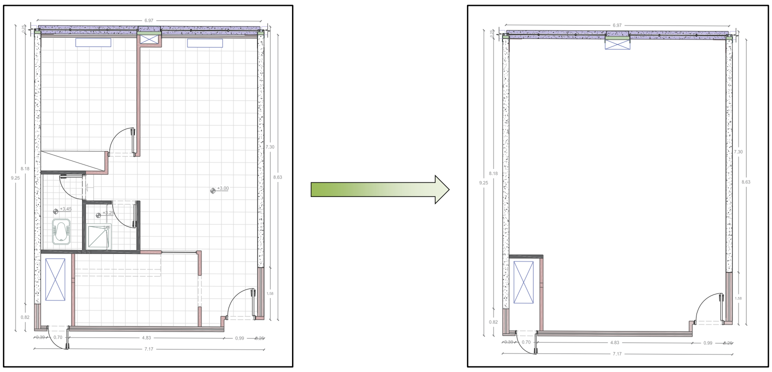


Figure 6.4. left: scenario 1, right: the state of scenario 1 after demolition

For assessing and calculating the total demolition cost for each scenario, two parameters have been considered: (a) the **labor cost for demolition**, and (b) **waste disposal cost** – the labor cost for waste disposal, and the transportation cost.

a) To calculate the total labor cost for demolition of each scenario, the QTOs of demolished products in each scenario have been multiplied by their corresponding labor cost – based on the ICMPL – shown in Equation 6.6.

$$\text{TLC} = \sum_{p=1}^{n} \text{QTOp} \times \text{LCUp} \qquad \text{Equation 6.6}$$

where TLC is the labor cost for demolition of each scenario with the functional unit of €; QTO_p is the quantity take-off of the demolished product with the functional unit of m^2, m^3, or unit; LCU_p is the labor cost for demolition of the product per unit with the functional unit of €/ m^2, m^3, or unit.

Therefore, the labor cost for scenarios 1, 2, and 3 are 503.47 €, 531.75 €, and 493.59 € respectively.

b) To calculate the total waste disposal cost for each scenario, based on the rate of the Waste Management Organization of Tehran Municipality (http://pasmand.tehran.ir/), the disposing price of the construction waste for each ton is 4.57 €. This price is for a distance up to 75 km between the loading and discharging the cargo points and includes the labor and transportation cost of construction waste disposal. Equation 6.7 calculates the waste disposal cost for each scenario:

$$TWDC = TMW \times WDC \quad \text{Equation 6.7}$$

where TWDC is the total waste disposal cost of each scenario with the functional unit of €; TMW is the total mass of generated waste of each scenario with the functional unit of ton; WDC is the waste disposal cost with the functional unit of €/ton.

Accordingly, the total mass of generated waste for scenarios 1, 2, and 3 are 21.645 tons, 23.202 tons, and 16.486 tons, and total waste disposal costs are 98.35 €, 105.42 €, and 74.9 € respectively.

Therefore, the value of I_3 has been calculated by Equation 6.8:

$$I_3.TDC = TLC + TWDC \quad \text{Equation 6.8}$$

where TDC is the total demolition cost of each scenario with the functional unit of €; TLC is the labor cost for demolition of each scenario with the functional unit of €; TWDC is the waste disposal cost for demolition of each scenario with the functional unit of €.

Consequently, the total demolition cost for scenarios 1, 2, and 3 are 599.59 €, 641.28 €, and 585.27 € as shown in Table 6.9.

Table 6.9. The value of demolition cost(€) for scenarios 1 to 3

Costs	**Scenario 1 (€)**	**Scenario 2 (€)**	**Scenario 3 (€)**
Labor cost	503.47	531.75	493.59
Waste disposal cost	96.12	109.53	91.68
Demolition cost	599.59	641.28	585.27

As Aleph-1 apartment has an area of 54 m^2, the values of I_3 for scenarios 1, 2, and 3 – with the functional unit of €/m^2 – are 11.10, 11.88, and 10.84 €/m^2 respectively (Table 6.10).

Table 6.10. The value of demolition cost (€/m^2) for scenarios 1 to 3

Demolition cost (€/m^2)	Scenario 1 (€/m^2)	Scenario 2 (€/m^2)	Scenario 3 (€/m^2)
The total value of I_3	**11.10**	**11.88**	**10.84**

6.1.4. Property added value (I_4)

Property added value is a term given to describe the increment of the property's value in comparison with its previous one due to some interventions, factors, or parameters (https://www.mashvisor.com/ value-add-real-estate-guide/). According to several recent surveys conducted by Tehran municipality (https://www.tehran.ir/), **renovation and rehabilitation of a property** has been reported as one of the most **common ways to add value to that property in Iran**. In this regard, based on the Tehran Municipality Statistic Year Book 2019-2020 published by the Information and Communication Technology Organization of Tehran Municipality (http://tmicto.tehran.ir/), the number of issued building rehabilitation licensees in Tehran has significantly increased: from 66,078 in 2014 to 175,656 in 2019 (Table 6.11) (The Information and Communication Technology Organization of Tehran Municipality, 2019).

Table 6.11. The number of issued building rehabilitation licensees in Tehran

	2014	**2015**	**2016**	**2017**	**2018**	**2019**
The number of issued building rehabilitation licensees	66,078	59,431	70,885	121,938	148,212	175,657

(The Information and Communication Technology Organization of Tehran Municipality, 2019)

To calculate the value of this indicator for the defined scenarios, it is essential to figure out the property's price of each scenario besides its initial state property's price. In this regard, the thesis author has followed the following steps:

1) Through https://ekbataneman.com/ webpage, nine real estate experts/agencies in Ekbatan have been selected to be consulted regarding properties prices of the defined scenarios,

2) The apartment characteristics that affect the pricing of an apartment – see Table 6.1 – such as block, floor, orientation, and view have been considered equal.

3) The scenarios' photos have been sent to each expert and they were asked to price each scenario by considering them with the same abovementioned characteristics,

4) Through four real estate websites in Iran (https://ihome.ir/, https://kilid.com/, https://shabesh.com/, https://divar.ir/s/tehran/buy-apartment/), similar apartments to each scenario have been identified,

5) After obtaining all the prices from experts and relative websites, the average property price of each scenario has been calculated as shown in Table 6.12, and

6) The average property price of each scenario has been subtracted from its initial state price to obtain the property added-value of each scenario as presented in Table 6.13.

Table 6.12. The property price of the defined scenarios and the initial state of Aleph-1

	Agency1 (Didar)	Agency 2 (Ariya)	Agency 3 (Khatereh)	Agency 4 (Ayandeh)	Agency 5 (Shahriar)	Agency 6 (Golha)	Agency 7 (Novin)	Agency 8 (Hamid)	Agency 9 (Almas)	ihome.ir	Shabesh.com	Divar.ir	Kelid.com	Average price (€)
Initial state	91,667	93,333	92,000	94,667	91,333	91,667	90,667	93,333	91,667	-	-	-	-	92,259
Scenario 1	92,000	93,333	93,333	94,667	93,333	91,667	90,667	96,667	93,333	-	-	92,667	-	93,167
Scenario 2	101,667	100,000	103,333	101,333	103,333	100,000	98,333	106,667	106,667	-	96,667	-	99,667	101,606
Scenario 3	108,333	105,000	110,000	104,667	106,667	103,333	104,000	116,667	110,000	110,000	-		-	107,867

The property price of the initial state of Aleph-1 apartment unit averagely is 92,259 €. Also, the average property price of scenarios 1, 2, and 3 are 93,167 €, 101,606 €, and 107,867 € respectively. Therefore, the property added value for scenarios 1, 2, and 3 are 908 €, 9347 €, and 15608 €.

Table 6.13. The value of indicator 4 (property added-value) for each scenario

Costs	Scenario 1 (€)	Scenario 2 (€)	Scenario 3 (€)
Property added-value	908	9,347	15,608

6.1.5. Rehabilitation process time (I_5)

To figure out a construction project duration, its scheduling has paramount importance for construction management (Yoon, 2019). Over the years, numerous techniques for planning, scheduling, and controlling projects have been developed to coordinate activities, resources, and budgets based on a timeline (Andersson and Christensen, 2007). For instance, "Gantt charts", "Time Space Scheduling Method", "Critical Path Method", "Line of Balance", and "Location-Based Scheduling" are the most well-known methods for planning and scheduling construction projects (Chitkara, 1998; Kenley, 2006; Andersson and Christensen, 2007; Uher and S. Zantis, 2012). In recent years, several construction scheduling software tools such as Microsoft Project Professional (https://www.projectmanager.com/), Procore (https://www.procore.com/), Smartsheet (https://www.smartsheet.com/), and Buildertrend (https://buildertrend.com/) have been developed to facilitate the scheduling process.

In the present doctoral dissertation, **rehabilitation process time refers** to the **period between** the **apartment evacuation stage** and the **reoccupation** of that apartment – the final reception of the apartment – excluding the time dedicated for designing and obtaining required permits, building licenses grant, approvals, and inspections. To obtain the value of indicator 5 for the defined scenarios, the constructors of each scenario have been consulted to report the duration of the rehabilitation process. It is worthy to mention that the reported rehabilitation processes were considered 8 hours of work per day – from 8 am to 13 and from 16 to 19 according to specific buildings rehabilitation regulations in Ekbatan (see section 4.1.2.c) – continuously and without any unforeseen work stoppages, which is applicable to Iran's present context. The reported schedules were inserted into the BIM model and they have been developed by using Microsoft Project Professional due to its simplicity and accuracy as shown in Appendix 6. D. Therefore, the value of I_5 for scenarios 1, 2, and 3 are 26, 38, and 40 working days respectively.

6.2. Environmental sustainability assessment of the selected scenarios: scenarios 1-3

Environmental sustainability has received ever-growing attention since its concept was defined, for the first time, in 1995 by Goodland (Goodland, 1995). In this regard, during the last decades, several policies and treaties, such as the Clean Air Act (Martineau and Novello, 2004), Kyoto Protocol (United Nations Framework Convention on Climate Change, 1998), European Union policies (European Commission, 2014), policies in China (China.org.cn, 2014), and many other policies around the world have been established (Klemeš, 2015). Also, many different methods and tools have been developed for assessing, measuring, and monitoring environmental sustainability (De Bennedetto and Klemes, 2008). One of these methods and tools which is well-recognized and wildly accepted is **Life-Cycle Assessment/Analysis (LCA)** (Erlandsson and Borg, 2003; Khasreen, Banfill and Menzies, 2009). LCA is a set of tools and ideas for compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system – products, processes, or services – throughout its life cycle https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en, (von Blottnitz and Curran, 2007; Khasreen, Banfill and Menzies, 2009; Klemeš, 2015; Souto-Martinez, Arehart and Srubar, 2018). Until present, several LCA methods have been developed that among them, the complete LCA and simplified LCA are the most employed ones. As **a complete LCA** is complex and time and cost consuming (Pons and Wadel, 2011), in the building sector, **a simplified LCA** has been developed (Zabalza Bribián, Aranda Usón, and Scarpellini, 2009). The simplified LCA methodology is an application of environmental assessment in the building sector, providing a list of existing tools, goals and scopes, potential users, and purposes of LCA studies in this sector (Zabalza Bribián, Aranda Usón, and Scarpellini, 2009). This method – which is based on the most recognized LCA guidelines and standards published by the International Standards Organization (ISO), ISO 14040 (International Organization for Standardization, 2006a), and ISO 14044 (International Organization for Standardization, 2006b) – is useful to determine environmental impact tendencies (Pons and Wadel, 2011). According to ISO 14040/14044 (International Organization for Standardization, 2006a, 2006b), CEN TC 350 (CEN/TC 350, 2011), and EN 15804 (EN 15804, 2012) Standards, **the life cycle phases** of a building are: (1) production phase, (2) construction phase, (3) use phase – also called occupancy or operation phase –, and (4) the end-of-life phase. The present doctoral dissertation has been considered the following LCA phases and their relevant indicators – which are previously defined in section 2.3.3 –:

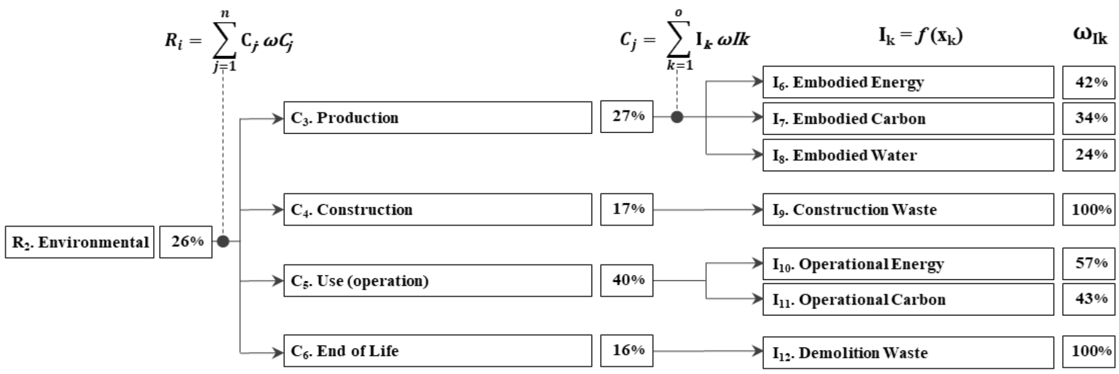


Figure 6.5. The defined criteria (LCA phases) and their corresponding environmental indicators

1) The **production phase** including embodied energy – indicator 6 –, embodied carbon – indicator 7 –, and embodied water – indicator 8 – of applied building products – construction materials and components in this thesis – from **cradle to gate** that is from resource extraction – cradle – to factory and building materials manufacturers – gate –;

2) The **construction phase** considering the construction waste – indicator 9 – of applied products;

3) The **use phase** consisting **the operational energy – indicator 10 – and operational carbon** – indicator 11 – for heating and cooling the building; and

4) The **end-of-life phase** considering demolition waste – indicator 12.

The abovementioned indicators – I_6 to I_{12} – and LCA phases have been explained and justified in their corresponding sections – 6.2.1 to 6.2.5.

Moreover, according to ISO 14040 and 14044, the simplified LCA method consists of **four distinct analytical steps**: (1) **goal** and **scope** definition; (2) **Life Cycle Inventory** (LCI); (3) **Life Cycle Impact Assessment** (LCIA); and (4) **interpretation** (https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en). In this regard, in the following paragraphs, the mentioned analytical steps that are considered generally in the present dissertation have been described:

1) For the first analytical step, **the general goal of LCA** in this thesis is to calculate the life cycle environmental sustainability performance of the selected scenarios of Aleph-1 throughout the defined indicators. For defining the general scope of LCA:

- A **study period (SP) of 50 years** has been assumed as a building lifetime because: (a) it is recommended by Eurocode 1990 as a useful building lifespan, and (b) in many other similar LCA studies (Adalberth, Almgren and Petersen, 2001; Khasreen, Banfill and Menzies, 2009; Ortiz, Castells and Sonnemann, 2009; Zabalza Bribián, Aranda Usón, and Scarpellini, 2009; Cuéllar-Franca and Azapagic, 2012; Grant and Ries, 2013), a study period of 50 years was considered.
- **The building characteristics** – see Table 6.1 – such as orientation, block, and floor have been **considered equal** for all defined scenarios.
- **The users' profile** – e.g., the number of users, their schedule, and planned temperatures – has been considered **equal** as well.

It is worthy to mention that **the particular goal and scope** of each environmental indicator have been explained more in detail in its corresponding section – 6.2.1 to 6.2.5.

2) In the second aforementioned analytical step, **the data collection portion** of LCA and its **relative database**/s have been determined for each indicator in the corresponding sections – 6.2.1 to 6.2.5.

3) The **LCIA** that is the third analytical step of LCA, **calculates the value of each indicator**.

4) Finally, the fourth step, which is **interpretation**, compares the obtained environmental indicators' values of each scenario with other scenarios to interpret and draw some conclusions in section 6.5.

6.2.1. Embodied Energy (EE) and Embodied Carbon (EC) – I_6 and I_7

In Iran, the residential building sector accounts for 40% of consumed energy and 33% of CO_2 emissions (Iran construction engineering organization, http://www.irceo.net/fullstory.aspx? id=5278, 2014.). These total consumed energy and CO_2 emissions have resulted from different amounts for each life cycle phase of a building (Kamali and Hewage, 2016). Depending on the design and type of building, energy consumption and CO_2 emissions account: in **the use phase from 70% to 98%**, in **the production phase from 2% to 26%**, and in **the construction and end-of-life phases less than 1%** of the total energy consumption and CO_2 emissions during the whole life cycle (Scheuer, Keoleian and Reppe, 2003; SETAC-Europe *et al.*, 2003; Ortiz, Castells and Sonnemann, 2009; Monahan and Powell, 2011; Klemeš, 2015; Mangan and Oral, 2015; Kamali and Hewage, 2016). Therefore, in this dissertation, **the system boundaries** for energy consumption and CO_2 emissions have been limited to the **production phase** – I_6. Embodied Energy (EE) and I_7. Embodied Carbon (EC) – and the **use phase** – I_{10}.Operational Energy (OE) and I_{11}.Operational Carbon (OC).

As long as the concepts of Embodied Energy (EE) and Embodied Carbon (EC) refer to the sum of all energy and carbon respectively involved in the acquisition of raw materials, processing and manufacture of the building materials and components, and their transportation (Sahagun and Moncaster, 2012; Klemeš, 2015), the following analytical steps have been taken to quantify the value of I_6 and I_7 for each selected scenario:

1) The **goal and scope** are evaluating the value of EE and EC of required products – materials and components in this thesis – for rehabilitation activities – including the initial rehabilitation and subsequent activities to keep each defined scenario in suitable shape – over the defined study period.

2) To define **the LCI** of EE and EC, the **Inventory of Carbon and Energy (ICE)** of each product has been extracted from the international ICE databases. Due to the lack of a precise written ICE database in Iran, the author has selected the University of Bath's Inventory of Carbon and Energy (ICE) database, Version 3.0 (Geoff and Craig, 2019); because of (a) being international, (b) being free and open-access database, and (c) providing a wide range of construction materials. Also, this database provides a list of embodied carbon and embodied energy coefficients in MJ/kg and $kgCO_2/kg$ respectively over the life cycle of a building within the boundaries of **cradle-to-gate** (Sahagun and Moncaster, 2012). In instances where EE and EC coefficients were not available in the mentioned database, primary data was obtained by using the Environmental Product Declarations (EPDs) and published literature (Zabalza Bribián, Aranda Usón and Scarpellini, 2009; Moncaster and Symons, 2013; *Environmental Product Declaration (EPD)*, 2015; Dincer and Rosen, 2015; Souto-Martinez, Arehart and Srubar, 2018).

3) To calculate the value of indicators 6 and 7 **through LCIA**, it is necessary to obtain: (a) **EE** and **EC coefficients**, (b) **the mass of each product** for the initial rehabilitation, (c) **the numbers of required rehabilitation** activities during the defined study period, and (d) **the total mass of required products** during the mentioned period.

a) The obtained EE and EC coefficients from the previous analytical step for each product have been determined.

b) To obtain the mass of products, the mass of some products has been acquired from their relative's data and information such as catalog, manufacturer website, and so on. For those products that their masses were not determined, the obtained volume of each product that was extracted from the BIM model has been multiplied by its density (Equation 6.9).

$$M_p = V_p \times D_p \qquad \text{Equation 6.9}$$

where M_p is the mass of product with the functional unit of kg; V_p is the volume of product with the functional unit of m^3; D_p is the density of product with the functional unit of kg/m^3.

c) To calculate the numbers of required rehabilitation and replacement of each product within 50 years, the aforementioned study period has been divided into the product's expected lifetime (Equation 6.10). The expected lifetime of each product was derived from the extensive database 'NAHB'(National Association of Home Builders, 2017) which is based on real data from product failures in buildings.

$$NR_p = SP / EL_p \qquad \text{Equation 6.10}$$

where NR_p is the numbers of required rehabilitation and replacement of the product; SP is the defined study period which is equal to 50 with the functional unit of year; EL_p is the expected lifetime of the product with the functional unit of year.

d) The total mass of each required product to keep each scenario in an adequate and good shape during the lifetime of 50 years has been calculated as indicated in Equation 6.11.

$$TM_p = M_p \times NR_p \qquad \text{Equation 6.11}$$

Therefore, to calculate the total amount of EE and EC, the total mass of required products for a study period of 50 years (Equation 6.11) has been multiplied by the EE and EC coefficients of each associated product as indicated in Equations 6.12 and 6.13.

$$I6.TEE = \sum_{p=1}^{n} \mathrm{TM_p} \times \mathrm{EEC_p} \qquad \text{Equation 6.12}$$

$$I7.TEC = \sum_{p=1}^{n} \mathrm{TM_p} \times \mathrm{ECC_p} \qquad \text{Equation 6.13}$$

where TEE is the total embodied energy with the functional unit of MJ; TEC is the total embodied carbon with the functional unit of $kgCO_2$; TM_p is the total mass of each required product to keep each scenario in good shape during the lifetime of 50 years with the functional unit of kg; EEC_p is the embodied energy coefficient with the functional unit of MJ/kg; ECC_p is the embodied carbon coefficient with the functional unit of $kgCO_2$/kg.

Therefore, the value of EE for scenarios 1, 2, and 3 are 204255, 167662, and 156863 MJ and for EC are 12126, 7640, and 7824 $kgCO_2$ respectively. Moreover, as Aleph-1 apartment has an area of 54 m^2, the values of I_6 for scenarios 1, 2, and 3 – with the functional unit of MJ/m^2 – are 3783, 3105, and 2905 MJ/m^2 and the values of I_7 – with the functional unit of $kgCO_2/m^2$ – are 225, 141, and 145 $kgCO_2/m^2$ respectively. **Appendix 6.E** presents the value calculations of I_6 and I_7 more in detail.

6.2.2. Embodied Water (EW) – I_8

The growing global water crisis highlights the importance of water conservation, especially in those sectors that consume a lot (Han *et al.*, 2016). According to the Worldwatch Institute report, **the construction industry** is in charge of **16% of the global water consumption** in the world (Worldwatch Institute, 2014). So, identification and evaluation of water consumption in the construction industry enable the countries to better manage their water resources (Guggemos and Horvath, 2005; Stephan and Stephan, 2017), especially for those countries that encounter water scarcity like Iran (Heravi and Abdolvand, 2019b). Iran has the highest water demand for the future, and the third-largest water shortage among 22 similar countries in the Middle East and North Africa (Droogers *et al.*, 2012). To evaluate the water consumption in the construction industry, previous relevant studies such as Crawford and Pullen, 2011; Zabalza Bribián, Valero Capilla and Aranda Usón, 2011; Abd El-Hameed, Mansour and Faggal, 2017; Stephan and Stephan, 2017; Abd El-Hameed, 2018; and Heravi and Abdolvand, 2019 have employed the **simplified LCA method** through its four distinct analytical steps. The present doctoral dissertation also took into account these analytical steps of the mentioned LCA. The first three steps are described in the following paragraphs and the fourth one has been explained in section 6.5.

1) **The goal and scope** are evaluating the **cradle-to-gate embodied water** of required products for the rehabilitation activities of selected scenarios over the defined 50 years of building lifetime.

As long as Embodied Water (EW) – also named as virtual water – refers to the overall needed water to create and deliver a product, including both direct and indirect consumed water throughout the **production phase** of LCA (McCormack *et al.*, 2007; A. Abd El-Hameed, Mansour and Faggal, 2017; Stephan and Stephan, 2017; Heravi and Abdolvand, 2019b), this phase has been selected as the system boundary. Also, the consumed water in the **operational phase has not been considered** in this dissertation because: (a) it directly depends on the inhabitants' consumption habits and/or patterns which are often impossible to determine (Chmielewska, Szulgowska-Zgrzywa and Danielewicz, 2017), and (b) by comparing the collected water bills of the defined scenarios, no significant logical correlation between the defined scenarios and their water consumption can be obtained. Moreover, as the water consumed directly in **the construction and end-of-life phases** is less than 1% of the whole life cycle (Treloar and Crawford, 2004; McCormack *et al.*, 2007), these phases **have been put aside** in this thesis.

2) **To define the water LCI**, due to the lack of precise written database in Iran, the database proposed by Zabalza et al. (Zabalza Bribián, Valero Capilla and Aranda Usón, 2011) has been selected because: (a) the applied **scope** of the mentioned database relies on **cradle-to-gate** as same as the defined scope in the present thesis – see section 6.2 –, and (b) the applied LCIs for the previous environmental indicators in the mentioned database and the present dissertation are the same and caused the integrity and consistency of defined environmental indicators. This database provides a list of Embodied Water Coefficients (EWCs) with the functional unit of l/kg. In instances where EWCs were not available in the mentioned database, primary data was obtained by using the Environmental Product Declarations (EPDs) and published literature (BERGE, 2009; Bardhan, 2011; Crawford and Pullen, 2011; *Environmental Product Declaration (EPD)*, 2015; Ferriz-papi, 2015; Bardhan and Choudhuri, 2016; A. K. Abd El-Hameed, Mansour and

Faggal, 2017; Abd El-Hameed, 2018; Heravi and Abdolvand, 2019b). Table 6.14 presents the EWCs of applied products in the selected scenarios from different databases.

Table 6.14. The EWCs of applied products in the selected scenarios from different databases

Product (Material/Component)	(Zabalza Bribián, Valero Capilla and Aranda Usón, 2011) (l/kg)	(A. K. Abd El-Hameed, Mansour and Faggal, 2017) (kl/unit)	(Crawford and Pullen, 2011) (kl/unit)	(Heravi and Abdolvand, 2019b) (l/kg)	(Bardhan and Choudhuri, 2016) (l/unit)	(*Environmental Product Declaration (EPD),* 2015) (l/kg)
Cement mortar	2.768-3.329					
Concrete block	3.937					
Porcelain		0.2939 m3/m2				
Ceramic tile	14.153					
Brick	1.890					
Clay plaster						0.76
Gypsum mortar						0.46
Gypsum block						0.84
Plasterboard						0.84
Bituminous						11
Mineral wool	32.384					
EPS foam slab	192.729					
Plastic						44.2
UPVC	51.99					
Laminate parquet	8.366					
Oriented Strand Board	24.761					
MDF	8.788					
Glass	16.537					
Galvanized steel			98.64 l/kg			
Copper	77.794					
Aluminum					88 l/kg	
Water-based paint				4.58		

3) To calculate the value of indicator 8 through **LCIA**, it is necessary to obtain: (a) **EW coefficients** and its associated **functional unit**, (b) **the quantities of each product** for the initial rehabilitation, (c) **the numbers of required rehabilitation** during the 50 years study period, and (d) **the total quantities of required products** during the mentioned period.

a) The obtained EWC from the previous analytical step for each product and its associated functional unit has been determined as indicated in Table 6.14.

b) According to each product's functional unit – usually in ton, kg, m^2, or m^3 –, the quantity of each product has been obtained – see **Appendix 6. F**. The quantity of some products has been acquired from their relative data and information such as catalog, manufacturer website, and so on. For those products that their quantities were not determined, their quantities have been obtained based on QTO that was extracted from the BIM model.

c) The numbers of required rehabilitation for each product (NR_p) during the defined study period have been obtained from Equation 6.10 of this chapter.

d) The total quantity of each required product to keep each scenario in good shape during the lifetime of 50 years has been calculated as indicated in Equation 6.14.

$$TQ_p = Q_p \times NR_p \qquad \text{Equation 6.14}$$

where TQ_p is the total quantity of product over the defined study period with the functional unit of kg, m^2, or m^3; Q_p is the quantity of product with the functional unit of kg, m^2, or m^3; NR_p is the numbers of required rehabilitation and/or replacement of product.

Therefore, the value of indicator I_8 has been calculated by Equation 6.15:

$$I_8.\ TEW = \sum_{p=1}^{n} \mathrm{EWC_p} \times \mathrm{TQ_p} \qquad \text{Equation 6.15}$$

where TEW is the total embodied water within the 50 years of building lifetime with the functional unit of l; EWC_p is the embodied water coefficient of products with the functional unit of l/unit (ton, kg, m^2, or m^3); TQ_p is the total quantity of product over the mentioned study period with the functional unit of kg, m^2, or m^3.

Consequently, the value of EW for scenarios 1, 2, and, 3 are 245779, 250434, and 188619 l respectively. Therefore, as Aleph-1 apartment has an area of 54 m^2, the values of I_8 for scenarios 1, 2, and 3 – with the functional unit of l/m^2 – are 4551, 4638, and 3493 l/m^2 respectively. Appendix 6. F presents the value calculations of I_8 more in detail.

6.2.3. Construction Waste (CW) – I_9

The construction industry waste has recently received significant attention due to its negative environmental impacts (Khoshand and Khanlari, 2020). This unavoidable waste as a direct consequence of rapid urbanization has more importance in most developing countries, such as Iran (Asgari *et al.*, 2017; Kabirifar *et al.*, 2020; Khoshand and Khanlari, 2020). In Iran, according to the Tehran Waste Management Organization (TWMO) (http://pasmand.tehran.ir/) report of 2019-2020, the construction industry produces over 60 Mt of waste annually. This waste is categorized into Construction Waste (CW) and Demolition Waste (DW) (El-Haggar, 2007; Asgari *et al.*, 2017). The CW refers to any produced solid waste within construction or rehabilitation activities (Yuan and Shen, 2011; Pacheco-Torgal and Labrincha, 2013; Asgari *et al.*, 2017; Kabirifar *et al.*, 2020), often caused by material's damage, loss, over-ordering, cut-offs or packaging (European Commission, 2016; Araee and Boushehri, 2019). Therefore, the evaluation and quantification of CW play an important role to minimize the economic and environmental impacts (European Commission, 2016). Among the different approaches for evaluating the CW, LCA has been employed in several relative studies such as Cuéllar-Franca and Azapagic, 2012; Simion, Bonoli, and Gavrilescu, 2013; Yeheyis *et al.*, 2013; Bovea and Powell, 2016; Peixoto *et al.*, 2019. In this regard, to evaluate indicator 9. CW, the present doctoral dissertation took into account the four simplified LCA's analytical steps. The first three steps are described in the following paragraphs and the fourth one has been explained in section 6.5.

1) **The goal and scope** for I_9 include evaluating **the CW quantities of required products** for **rehabilitation** activities of selected scenarios over the 50 years of building lifetime.

2) To define **the LCI of CW**, according to the Tehran Waste Management Organization (TWMO) (http://pasmand.tehran.ir/) and ICMPL 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019), in general, the Average Construction Waste Rate (ACWR) of a building has been considered as the 5 percent of the total used products. Moreover, in chapter 28th of ICMPL, the ACWR of each product ($ACWR_p$) has been defined individually. In this regard, for evaluating CW more precisely, this study has employed the defined $ACWR_p$s in chapter 28th of the ICMPL. In instances where the $ACWR_p$s were not available in this chapter 28th, primary data was obtained by using other related technical literature (Coelho and De Brito, 2011; Mercader-Moyano P, 2013; Sáez *et al.*, 2014; Asgari *et al.*, 2017; Araee and Boushehri, 2019). Table 6.15 presents the $ACWR_p$s of applied products in the selected scenarios.

Table 6.15. The $ACWR_p$s of applied products in the defined scenarios

Product (Material/Component)	ACWR of products	References
Cement mortar	6%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Concrete block	10%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Ceramic tile	10.5%	(Mercader-Moyano P, 2013; Asgari *et al.*, 2017)
Brick	12%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019), http://www.shakhesomran.ir/
Clay plaster	6%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Gypsum mortar	6%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Gypsum block	10%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Plasterboard	6.4%	(Coelho and De Brito, 2011; Sáez *et al.*, 2014)
Bituminous	5%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Mineral wool	5%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
EPS foam slab	5%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
PVC and UPVC	4%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Laminate parquet	6%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
MDF	9%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Glass	1%	(Asgari *et al.*, 2017)
Galvanized steel	2.5%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Bars and pipes	7.16%	(Araee and Boushehri, 2019)
Aluminum	2.5%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Water-based paint	0.2%	ICMPL(Plan and Budget Organization of the Islamic Republic of Iran, 2019)
Wallpaper	1%	(Asgari *et al.*, 2017)

3) To calculate the value of indicator 9 through **LCIA**, it is necessary to obtain: (a) **the ACWR of each product**, (b) **the mass of each product** for the initial rehabilitation, (c) **the numbers of required rehabilitation** activities during the 50 years study period, and (d) **the total mass of required products** during the mentioned period.

a) The ACWR of each product has been determined from the previous analytical step as indicated in Table 6.15.

b) The mass of each product for the initial rehabilitation has been obtained from Equation 6.9 of this chapter. Also, it is worthy to mention that the mass of some products has been acquired from their relative's data and information such as catalog, manufacturer website, and so on. For those products that their masses were not determined, the obtained volume of each product that was extracted from the BIM model has been multiplied by its density as shown in Equation 6.9 of the present chapter.

c) The numbers of required rehabilitation and replacement for each product (NR_p) during the 50 years study period has been obtained from Equation 6.10 of this chapter.

d) The total mass of each required product to keep each scenario in good shape during the lifetime of 50 years has been obtained from Equation 6.11 of the present chapter.

Therefore, the value of indicator I_9 has been calculated by the following equation:

$$I_9.\ TCW = \sum_{p=1}^{n} \mathrm{ACWR_p} \times \mathrm{TM_p} \qquad \text{Equation 6.16}$$

where TCW is the total construction waste within the 50 years of building lifetime with the functional unit of kg; $ACWR_p$ is the average construction waste rate of product with the functional unit of percent; TM_p is the total mass of each required product to keep each scenario in good shape during the lifetime of 50 years with the functional unit of kg.

Therefore, the total construction waste for scenarios 1, 2, and 3 are 2364, 2646, and 1315 kg respectively. Also, as Aleph-1 apartment has an area of 54 m^2, the values of I_9 for scenarios 1, 2, and 3 – with the functional unit of kg/m^2 – are 44, 49, and 24 kg/m^2 respectively. Appendix 6.G presents the value calculations of I_9 more in detail.

6.2.4. I_{10} and I_{11}. Operational Energy (OE) and Operational Carbon (OC)

The existing residential building sector accounts for a large share of worldwide energy consumption and CO_2 emissions (Carratt, Kokogiannakis, and Daly, 2020). For instance, in Iran, according to Iran Construction Engineering Organization (ICEO) report, this sector accounts for **40%** and **33%** of the total **consumed energy** and **carbon emissions** respectively (Iran construction engineering organization, http://www.irceo.net/fullstory.aspx? id=5278, 2014.). Based on several studies (Scheuer, Keoleian and Reppe, 2003; SETAC-Europe *et al.*, 2003; Sartori and Hestnes, 2007; Cárdenas, Muñoz and Fuentes, 2011; Quale *et al.*, 2012; Beccali *et al.*, 2013; Kamali and Hewage, 2016; Su and Zhang, 2016; Su *et al.*, 2020), among the life cycle phases of conventional residential buildings, **the operational phase has a substantial contribution** to environmental impacts, in particular on the energy consumption and carbon emissions. Therefore, the evaluation of Operational Energy (OE) and Operational Carbon (OC) has significant effects on terms of sustainability (Liang *et al.*, 2018; Carratt, Kokogiannakis, and Daly, 2020). These effects include economic impact reduction – e.g., cost reduction and investment returns –, environmental impact reduction – e.g., reduced carbon emissions and energy demand –, and social performance improvement – e.g., improved living conditions, health and well-being for occupants, and Indoor Environmental Quality (IEQ) within buildings (Cárdenas, Muñoz and Fuentes, 2011; Krarti *et al.*, 2017; Monteiroa *et al.*, 2017; Carratt, Kokogiannakis and Daly, 2020). **To evaluate OE and OC**, previous relevant studies such as Cárdenas, Muñoz and Fuentes, 2011; Beccali *et al.*, 2013; Azzouz *et al.*, 2017; Macias *et al.*, 2017; Koezjakov *et al.*, 2018; Pombo, Rivela and Neila, 2019; and, Shadram and Mukkavaara, 2019; Su *et al.*, 2020, **have employed the simplified LCA method** through its four distinct analytical steps. The present doctoral dissertation also took into account the mentioned analytical steps of LCA as explained in section

6.2. The first three steps are described in the following paragraphs and the fourth one has been explained in section 6.5.

1) **The goals** of I_{10} and I_{11} are the calculation of the OE and OC values of the selected scenarios over the 50 years of the building lifetime.

OE and OC refer to all consumed energy and produced carbon – for heating, cooling, domestic hot water, lighting, and auxiliary energy – in the operational phase of a building within its lifetime (Mangan and Oral, 2015). Although in the present thesis, for calculating the values of OE and OC, domestic hot water and auxiliary energy have been put aside because they directly depend on the inhabitants' consumption habits and patterns which are often impossible to determine (Chmielewska, Szulgowska-Zgrzywa and Danielewicz, 2017; Mitra *et al.*, 2020). To define **the scope** of I_{10} and I_{11}, the mentioned general scope indicated in section 6.2 and Table 6.1 has been considered beside the following considerations and assumptions:

a) A set-point temperature for winter months – October to March – of 21 °C, 24 h a day (see section 4.1.1.c).
b) A set-point temperature for summer months – April to September – of 24 °C, 24 h a day (see section 4.1.1.c).
c) An airtightness rate – infiltration and ventilation rate – of 1 ac/h.
d) The number of occupants living in the Aleph-1 apartment unit was set to 2.
e) The apartment orientation was set to the North-West.
f) The floor was set to the 7th floor (14 m of height from the street level).
g) As all blocks in Ekbatan have 12 floors and Aleph-1 apartments are located on the odd floors and in the middle of corridors (see chapter 4, Figure 4.A.1), all the adjoining surfaces – walls, ceiling, and floors excluding the main façade – are adiabatic meaning that there is no heat flow with the outer edges. Moreover, the applied materials for the main facades of the defined scenarios have been modeled according to Table 6.16.

Moreover, each one of the selected scenarios has its own particular intervention and rehabilitation characteristics as indicated in Table 6.16.

Table 6.16. The rehabilitation characteristics of the defined scenarios

		Scenario 1	Scenario 2	Scenario 3
Facade		Prefabricated concrete panels with a size of 7.00*1.20*0.25 m, 6 cm of the air gap, and solid gypsum blocks with a size of 666*500*60 mm; and wallpaper.	Prefabricated concrete panels with a size of 7.00*1.20*0.25 m; 6 cm of the air gap; hollow brick, size 190*180*80 mm; clay plaster, 15 mm thickness; plaster; 10 mm thickness; and water-based paint.	Prefabricated concrete panels with a size of 7.00*1.20*0.25 m; 6 cm of the air gap; 3 cm of the glass wool; metal stud and one-layer plasterboard with a thickness of 12.5 mm; and water-based paint.
HVAC	Cooling	Fan coil unit (cooling = comp. Chiller, hot water (5°C))	Fan coil unit (cooling = comp. Chiller, hot water (5°C))	General split (General GNR-24WN)
	Heating	Fan coil unit (heating = boiler, hot water (80°C))	Fan coil unit (heating = boiler, hot water (80°C))	Radiator (Thermal capacity 126kcal/h per panel) & general package (Thermal capacity 20636 kcal/h)
Used fuel	For heating system	Natural gas	Natural gas	Natural gas
	For cooling system	Electrical energy (electricity)	Electrical energy (electricity)	Electrical energy (electricity)
Insulation	Thermal insulation	Without insulation	3cm of mineral wool batt, u-value = 0.42 W/m^{2}K	3 cm of glass wool, u-value = 0.38 W/m^{2}K
	Acoustic insulation	Without insulation	Without insulation	Without insulation
	Moisture insulation	Bituminous, thickness 4mm	Bituminous, thickness 4mm	Bituminous, thickness 4mm
Window	Window frame	Galvanized steel frame	Galvanized steel frame	UPVC frame
	Window glass	Double glazing, 6mm clear glass, and 13mm air	Double glazing, 6mm clear glass, and 13mm air	Double glazing, 6mm clear glass, and 13mm argon gas
Mechanical ventilation	Kitchen	Hood = Bimax B1002U, size 90cm-480m^3/h	Hood = Dorsa Mahdis Hood Size 90cm-540 m^3/h	Hood = Dorsa Roya Diagonal Hood Size 90cm-680m^3/h
	Bathroom and WC	Exhaust fan = Simple flux mechanical ventilation system, Sabalan, 95 m^3 /h	Exhaust fan = Simple flux mechanical ventilation system, Damandeh, VBX-20S2S, 150 m^3 /h	Exhaust fan = Simple flux mechanical ventilation system, Ilka, VIK-40L4S, 150 m^3 /h
Natural ventilation	Living room and bedroom	Two vertical pivot windows with a size of 1.10 *120	Two vertical pivot windows with a size of 1.10 *120	Four tilt and turn windows with a size of 1.10 *120

2) **To define the LCI of I_{10} and I_{11}**, the following standards, sources, and databases have been selected:

a) Chapter 19th of the National Regulations for Buildings of Iran published by the Ministry of Roads and Urban Development of Iran (https://www.mrud.ir/en/en-us/), entitled "Energy conservation", for energy efficiency in buildings besides the standard ISIRI 14253 published by the Institute of Standards and Industrial Research of Iran (ISIRI) (http://standard.isiri.gov.ir/SearchEn.aspx), entitled "Residential building criteria for energy consumption and energy labeling instruction" have been selected as the main OE databases and standards.

b) According to the report published by the Power and Energy Planning & Macroeconomic Department of Iran Ministry of Energy (Power & Energy Planning & Macroeconomic Department, 2019), the associated carbon emissions caused to produce 1 kWh energy from natural gas and electricity were reported as 0.221 and 0.564 $kgCO_2$ respectively.

c) Hourly climate data in the last thirty years – from 1988 to 2018 – obtained from Weather Station of Tehran-Mehrabad (http://www.tehranmet.ir/) has been used for the calculations and modeling, including air temperature, relative humidity, solar radiation, wind direction, and wind speed – see chapter 4, section 4.1.1.

3) To calculate the values of OE and OC through **LCIA**, the building energy simulation software **DesignBuilder** version 6.1.6 and the calculation engine **EnergyPlus** have been employed. The characteristics of each scenario as indicated in Table 6.16, the assumptions as explained in the goal and scope of these indicators besides their defined inventories as explained in LCI section were inserted to model each scenario in the DesignBuilder software. Figure 6.6 illustrates the calculation of OE value of scenario 2.

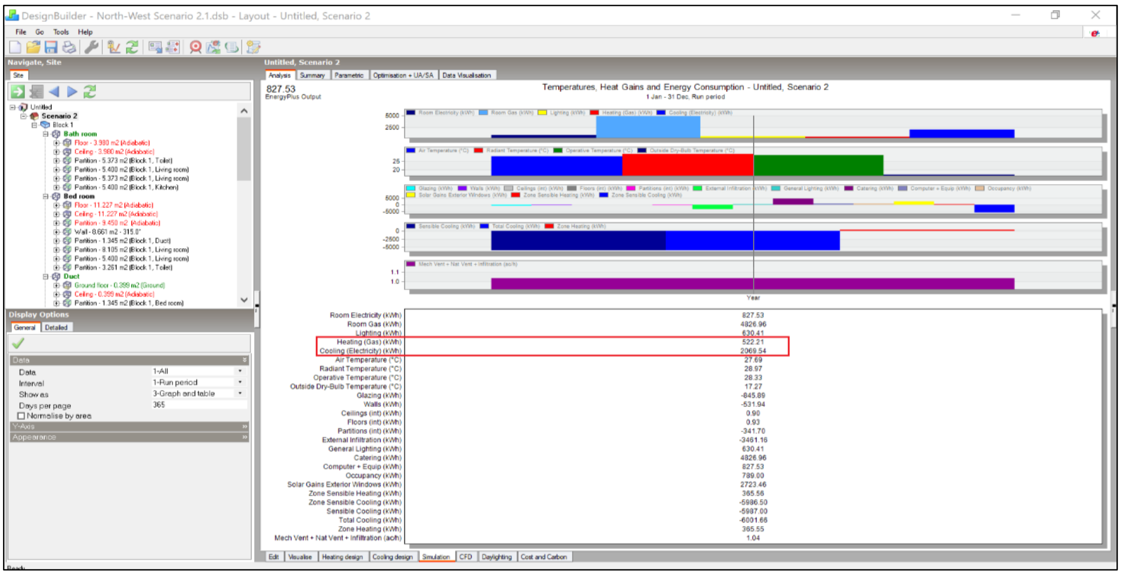


Figure 6.6. Screenshot of OE value calculation by DesignBuilder software, scenario 2

Therefore, the value of OE for scenarios 1, 2, and 3 are 135851, 129587.5, and 92757.5 kWh/50 years and for OC are 65897.44, 64131.45, and 48981.44 kgCO2/50 years respectively. Moreover, as Aleph-1 apartment has an area of 54 m^2, the values of I_{10} for scenarios 1, 2, and 3 – with the functional unit of kWh/m2/year – are 50.32, 48, and 34.35 kWh/m2/year, and the values of I_{11} – with the functional unit of kgCO2/m2/year – are 24.41, 23.75, and 18.14 kgCO2/m2/year respectively. Table 6.17 presents the value calculations of I_{10} and I_{11} more in detail.

Table 6.17. The value calculations of I_{10} and I_{11}

	I_{10}.Operational Energy (OE)					**I_{11}.Operational Carbon (OC)**				
	OE for Heating (kWh/year)-Natural gas	OE for Cooling (kWh/year)-Electricity	Total OE (kWh/year)	Total OE for the study period (kWh/50 years)	**I_{10}.Total OE ($kWh/m^2/year$)**	OC for heating from natural gas ($kgCO_2$/year)	OC for cooling from electricity ($kgCO_2$/year)	Total OC ($kgCO_2$/year)	Total OC for the study period ($kgCO_2$/50 years)	**I_{11}.Total OC ($kgCO_2/m^2/year$)**
Scenario 1	625.22	2091.8	2717.02	135851	**50.32**	138.17	1179.78	1317.95	65897.44	**24.41**
Scenario 2	522.21	2069.54	2591.75	129587.5	**48.00**	115.41	1167.22	1282.63	64131.45	**23.75**
Scenario 3	194.39	1660.76	1855.15	92757.5	**34.35**	42.96	936.67	979.63	48981.44	**18.14**

6.2.5. Demolition Waste (DW) – I_{12}

As mentioned before – section 6.2.3 –, the construction industry waste is categorized into Construction Waste (CW) and Demolition Waste (DW) (El-Haggar, 2007; Asgari *et al.*, 2017). DW refers to any generated waste from complete or selective demolishing of applied materials and/or components within the demolition or rehabilitation activities during a project lifetime (European Commission, 2016). According to literature (Kartam *et al*., 2004; Zheng *et al*., 2017; Araee and Boushehri, 2019), the **contribution of DW** in comparing with **CW** is **highly significant** in the construction industry waste. For instance, Zheng et al. reported that the DW rate with the contribution of 97% – with the mean value of 1,360.2 kg/m^2 – is much higher than the CW rate with the contribution of 3% – with the mean value of 34.2 kg/m^2 – of the total construction industry waste in China (Zheng *et al.*, 2017). Also, Araee and Boushehri revealed that DW rate is 10 to 20 times more than CW rate in Iran (Araee and Boushehri, 2019). Among the different approaches for evaluating the DW, LCA has been employed in several relevant studies such as Cuéllar-Franca and Azapagic, 2012; Simion, Bonoli, and Gavrilescu, 2013; Yeheyis *et al*., 2013; Bovea and Powell, 2016; Peixoto *et al.*, 2019. In this regard, to evaluate indicator 12. DW, the present doctoral dissertation took into account the four simplified LCA's analytical steps. The first three steps are described in the following paragraphs and the fourth one has been explained in section 6.5.

1) **The goal and scope** are calculating the generated DW amount/value from the complete or selective demolishing of applied products in the selected scenarios over the defined 50 years of building lifetime. The DW that was produced before the initial rehabilitation of each scenario has been put aside in this thesis.

2) In the second aforementioned analytical step, the data collection portion of LCA has been obtained from the **BIM model**.

3) Based on the Material flow analysis (MFA) approach, the input and output of total construction products that come into service are equal (Zheng *et al.*, 2017; Guo and Huang, 2019). In this regard, to calculate the value of DW (output), the total mass of applied products for the construction (input) during the defined study period should be calculated. To do so, it is necessary to obtain: (a) **the mass of each product** that has been used for the construction – including rehabilitation – of each scenario, and (b) **the numbers of required rehabilitation and replacement** of product during the mentioned study period.

a) To obtain the mass of products, the masses of some products have been acquired from their relative data and information such as catalog, manufacturer website, and so on. For those products that their masses were not determined, the obtained volume of each product that was extracted from the BIM model has been multiplied by its density as indicated in Equation 6.9 of this chapter.

b) The numbers of required rehabilitation and replacements for each product (NR_p) during the study period have been obtained from Equation 6.10 of the present chapter.

Therefore, the value of indicator I_{12} has been calculated by Equation 6.17:

$$I_{12}.\ TDW = \sum_{p=1}^{n} \mathrm{M_p} \times \mathrm{NR_p} \qquad \text{Equation 6.17}$$

where TDW is the total demolition waste within the 50 years of building lifetime with the functional unit of kg; M_p is the mass of each product that has been used for the construction – including rehabilitation – of each scenario with the functional unit of kg; NR_p is the numbers of required rehabilitation and replacement of product during the lifetime of 50 years.

Therefore, the total demolition waste for scenarios 1, 2, and 3 are 34823, 32546, and 20611 kg respectively. Also, as Aleph-1 apartment has an area of 54 m^2, the values of I_{12} for scenarios 1, 2, and 3 – with the functional unit of kg/m^2 – are 645, 603, and 382 kg/m^2 respectively. Appendix 6.H presents the value calculations of I_{12} more in detail.

6.3. Social sustainability assessment of the selected scenarios: scenarios 1-3

Several studies have shown that **the main driver behind the rehabilitation activities** of residential buildings and MHs is increasing occupants' **comfort levels and social sustainability** (van der Flier and Thomsen, 2006; Meijer, Itard and Sunikka-Blank, 2009; Thuvander *et al.*, 2012; Mustafa, 2016; Karji *et al.*, 2019a). These rehabilitation activities take place mostly for better responding to occupant's needs, providing more flexible and multi-functional spaces, maintenance, repair, replacement, or modernization aimed at extending component service life, improving aesthetic aspect, and increasing occupants' comfort such as thermal, lighting, indoor air and acoustic comfort (Mustafa, 2016; Sanni-Anibire, Hassanain, and Al-Hammad, 2016; Kamari, Corrao and Kirkegaard, 2017; Saldaña-Márquez *et al.*, 2018; Abdulelah, Al and Kamaran, 2019; Karji *et al.*, 2019; Carratt, Kokogiannakis and Daly, 2020).

Based on academic literature, **despite social sustainability** is the **most crucial aspect of the sustainability** performance of residential buildings and MHs (van der Flier and Thomsen, 2006; Meijer, Itard and Sunikka-Blank, 2009; Thuvander *et al.*, 2012; Ahmad and Thaheem, 2017a), there has often been a focus on environmental and economic aspects and the social one **is the most ignored** as it has been rarely investigated (Davoodi, Fallah and Aliabadi, 2014; Gould, Missimer and Mesquita, 2017; Karji, Woldesenbet, and Khanzadi, 2017; Xiahou *et al.*, 2018; Karji *et al.*, 2019; Liu and Qian, 2019; Olakitan Atanda, 2019; Shirazi and Keivani, 2019; Zarghami, Fatourehchi and Karamloo, 2019; Olawumi *et al.*, 2020). However, in recent years, some studies, policies, and practices such as commissioned by the Berkeley Group, the European Investment Bank, the World Bank, the United Nations Environment Programme, the European Investment Bank, and the European Bank for Reconstruction and Development had investigated on the social sustainability aspect (Dixon and Woodcraft, 2013), most of these investigations are **focused on the rehabilitation of MHs in the urban scale** (Pedro, Silva, and Duarte, 2018; Karji *et al.*, 2019) such as the neighborhood, community interaction, urban regeneration, and urban management (Colantonio and Dixon, 2009; Karji, Woldesenbet, and Khanzadi, 2017; Karji *et al.*, 2019; Joon, 2020). Therefore, the social sustainability assessment of **interior rehabilitation of MHs**, which is one of the defined boundaries of the present doctoral dissertation – see chapter 1, section 1.5 –, has **rarely been investigated and needs to receive more attention** to fill the mentioned gap.

To evaluate social sustainability performance, several methods and tools have been developed (Karji *et al.*, 2019a). The **main challenges** for this evaluation are: (1) **the difficulty in quantitatively measuring social sustainability** in comparing with the economic or environmental sustainability (McKenzie, 2004; Littig and Griessler, 2005; Karji *et al.*, 2019a), (2) **the difficulty to define its scopes**, relative indicators and data collection methods (Karji *et al.*, 2019a; Liu and Qian, 2019), and (3) as each construction project is unique and has its own characteristics, **the social sustainability performance can vary from case to case** (Ivani and Rostami, 2014; Karji *et al.*, 2019a; Liu and Qian, 2019). Several studies have employed the **questionnaire survey** as a key component of social evaluation to overcome the abovementioned challenges (David Jiboye, 2012; Nooraei, Littlewood and Evans, 2013; Offia, Opoko, and Adeboye, 2013; Sanni-Anibire, Hassanain, and Al-Hammad, 2016; Silva *et al.*, 2017; Janjua, Sarker and Biswas, 2020; Joon, 2020; Nair and Nayar, 2020; Olawumi *et al.*, 2020). This method is not only well-recognized and widely accepted (Nooraei, Littlewood, and Evans, 2013), but also is a scientific approach for converting qualitative data to quantitative one that enables and facilitates statistical analysis of collected data (Becker, 1990).
Based on Becker, 1990, for conducting a questionnaire survey, there are two different approaches: (1) user-based approach and (2) expert-based approach (Becker, 1990). In the user-based approach, the focus is on recording the users' opinions or their satisfactions (Becker, 1990). As reported in several studies (Bordass and Leaman, 2005; Jiun, 2005; David Jiboye, 2012; Sanni-Anibire, Hassanain and Al-Hammad, 2016; Mustafa, 2017), **the satisfaction level of users** regarding building performance is one of **the most important parts of the social sustainability evaluation** process due to **their direct exposure and real experience** with their living space. On the other hand, the expert-based approach is a method to assess building performance that relies on the experts' judgments (Becker, 1990).

In the present doctoral dissertation, the **user-based questionnaire** has been conducted for value calculation of **all defined social indicators** (Figure 6.7) for **scenarios 1 to 3** – I_{13} to I_{18} – **except I_{19}** which is the aesthetic and beauty of the interior space. For I_{19}, the **expert-based questionnaire** has been carried out because this indicator is highly subjective and the user's opinions vary from person to person (Lindenthal, 2020). Also, **in the absence of users' experience** regarding **the proposed scenario which is not built** – see chapter 7 –, **experts' judgment can be a solution for the evaluation of social sustainability performance** (Jiun, 2005; Nair and Nayar, 2020).

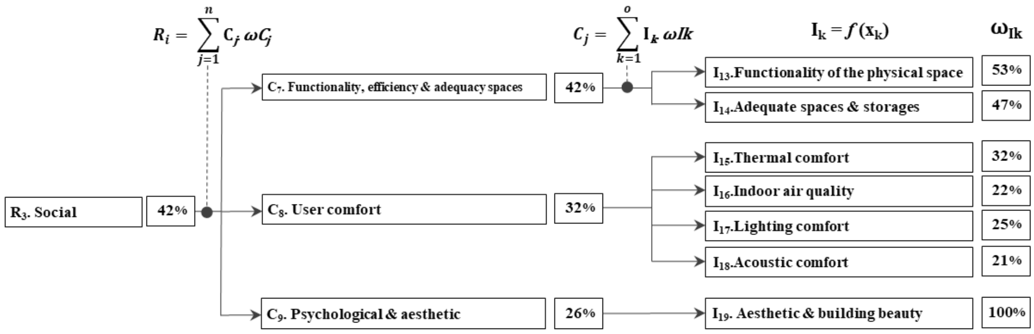


Figure 6.7. Social requirement and its defined criteria and indicators

In this regard, two questionnaires have been conducted through three main steps which are: (1) **designing**, (2) **carrying out**, and (3) **analyzing** the questionnaire. In the following paragraphs, each step of the user-based questionnaire has been elaborated in more detail and the expert-based one has been explained in the corresponding section of indicator 19 – section 6.3.7.

1) To **design** a proper framework for questionnaires, it is essential to identify the required data for measuring each indicator (Nair and Nayar, 2020) as defined previously in chapter 3, section 3.2. To do so, a comprehensive literature review and consulting with the experts in this domain have been conducted. Subsequently, short and simple questions in a meaningful order were designed to easily be comprehensible for the respondents. Moreover, the questionnaire was designed by using a five-point Likert scale, where 5 represents strongly satisfied (SS), 4 represents satisfied (S), 3 represents moderately satisfied (MS), 2 represents dissatisfied (D), and 1 represents strongly dissatisfied (SD). It is worthy to mention that a Likert scale is a psychometric scale commonly involved in research based on survey questionnaires that the respondents specify their level of agreement or disagreement on a symmetric agree-disagree scale for a series of questions or statements (Likert, 1932; Susan Jamieson, 2004; James Carifio and Rocco J. Perla, 2007). The range of the Likert scale captures the intensity of respondents' satisfaction for a given question or item (Likert, 1932; James Carifio and Rocco J. Perla, 2007). The designed user-based questionnaire contained items such as apartment characteristics, general information of residents, and rehabilitation status as well as inhabitant's opinions and their satisfaction levels regarding the defined social indicators for each spatial layout – kitchen, living room, dining room, and bedroom.

2) To **carry out** the questionnaire, it is essential to determine a sample size – the minimum number of respondents to consider the study statistically valid. To do so, the Sloven's formula (Kanire, 2013) was used as indicated in Equation 6.18.

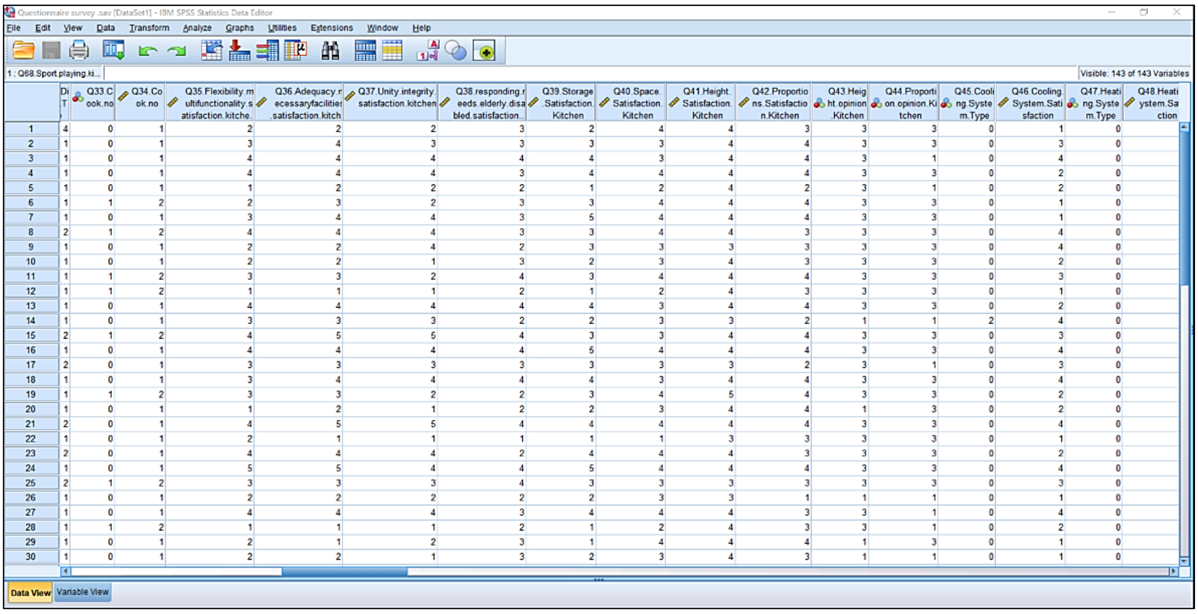
$$n = \frac{\text{N}}{1+\text{Ne}^2} \qquad \text{Equation 6.18}$$

where n is the sample size, N is the effective population size, and e is the sample error.

In the present thesis, the effective population size (N) was the total 1,144 apartment units of Aleph-1 in Ekbatan. The sample error (e) was considered 0.15, indicating an 85% confidence that the sample size accurately represents the population. This process resulted in a sample size (n) of 42 Aleph-1 apartment units.

It is worth noting that in the present thesis, the author surveyed 71 Aleph-1 apartments and conducted 49 questionnaires from/among the mentioned surveyed apartments. Consequently, a total of 43 valid questionnaires were collected from apartments that had similar characteristics – based on Tables 5.16 to 5.18 – with the defined scenarios; those 19 of them had similarities with scenario 1, 13 with scenario 2, and 11 with scenario 3. This number – 43 valid questionnaires – **was considered adequate** for the subsequent analysis since **the minimum sample size** was defined as **42 questionnaires**. Surveys were answered either in the presence of the principal investigator or his absence depending on the availability of respondents and their approval. The author does not expect any demand effect as the questions did not address any socially or personally desirable issue.

3) To **analyze** the collected data from questionnaires, the obtained data have been inserted into IBM SPSS Statistics V. 22 software (Figure 6.8). Subsequently, to obtain the value of each social indicator, a mean score of the collected data for each scenario besides their standard deviation has been calculated. Finally, to analyze and interpret the value of each indicator, descriptive and inferential statistics have been explained in section 6.5.


Questionnaire survey .sav [DataSet1] - IBM SPSS Statistics Data Editor

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	DiT	Q33.Cook.no	Q34.Cook.no	Q35.Flexibility.multifunctionality.satisfaction.kitche.	Q36.Adequacy.necessaryfacilities.satisfaction.kitch	Q37.Unity.integrity.satisfaction.kitchen	Q38.responding.needs.elderly.disabled.satisfaction..	Q39.Storage.Satisfaction.Kitchen	Q40.Space.Satisfaction.Kitchen	Q41.Height.Satisfaction.Kitchen	Q42.Proportions.Satisfaction.Kitchen	Q43.Height.opinion.Kitchen	Q44.Proportion.opinion.Kitchen	Q45.Cooling.System.Type	Q46.Cooling.System.Satisfaction	Q47.Heating.System.Type	Q48.Heating.System.Satisfaction
1	4	0	1	2	2	2	3	2	4	4	3	3	3	0	1	0	
2	1	0	1	3	4	3	3	3	3	4	4	3	3	0	3	0	
3	1	0	1	4	4	4	4	4	3	4	4	3	1	0	4	0	
4	1	0	1	4	4	4	3	4	4	4	4	3	3	0	2	0	
5	1	0	1	1	2	2	2	1	2	4	2	3	1	0	2	0	
6	1	1	2	2	3	2	3	3	4	4	4	3	3	0	1	0	
7	1	0	1	3	4	4	3	5	4	4	4	3	3	0	1	0	
8	2	1	2	4	4	4	3	3	4	4	3	3	3	0	4	0	
9	1	0	1	2	2	4	2	3	3	3	3	3	3	0	4	0	
10	1	0	1	2	2	1	3	2	3	4	3	3	3	0	2	0	
11	1	1	2	3	3	2	4	3	4	4	4	3	3	0	3	0	
12	1	1	2	1	1	1	2	1	2	4	3	3	3	0	1	0	
13	1	0	1	4	4	4	4	4	3	4	4	3	3	0	2	0	
14	1	0	1	3	3	3	2	2	3	3	2	1	1	2	4	0	
15	2	1	2	4	5	5	4	3	3	4	4	3	3	0	3	0	
16	1	0	1	4	4	4	4	5	4	4	4	3	3	0	4	0	
17	2	0	1	3	3	3	3	3	3	3	2	3	1	0	3	0	
18	1	0	1	3	4	4	4	4	3	4	4	3	3	0	4	0	
19	1	1	2	3	3	2	2	3	4	5	4	3	3	0	2	0	
20	1	0	1	1	2	1	2	2	3	4	4	1	3	0	2	0	
21	2	0	1	4	5	5	4	4	4	4	4	3	3	0	4	0	
22	1	0	1	2	1	1	1	1	1	3	3	3	3	0	1	0	
23	2	0	1	4	4	4	2	4	4	4	3	3	3	0	2	0	
24	1	0	1	5	5	4	4	5	4	4	4	3	3	0	4	0	
25	2	1	2	3	3	3	4	3	3	3	3	3	3	0	3	0	
26	1	0	1	2	2	2	2	2	3	3	1	1	1	0	1	0	
27	1	0	1	4	4	4	3	4	4	4	3	3	1	0	4	0	
28	1	1	2	1	1	1	2	1	2	4	3	3	1	0	2	0	
29	1	0	1	2	1	2	3	1	4	4	4	1	3	0	1	0	
30	1	0	1	2	2	1	3	2	3	4	3	1	1	0	1	0	

Data View Variable View

Figure 6.8. Screenshot of the collected data from questionnaires inserted in SPSS software

The definition, justification, effective parameters for assessment, and value calculation of each defined social indicator have been explained particularly more in detail in its corresponding section – sections 6.3.1 to 6.3.7.

6.3.1. Functional performance of physical space (I_{13})

According to several investigations (Meijer, Itard and Sunikka-Blank, 2009; Mustafa, 2016, 2017; Sanni-Anibire, Hassanain and Al-Hammad, 2016; Abdulelah, Al and Kamaran, 2019), the functional performance of physical space is one of the main reasons for interior rehabilitation of residential buildings. This indicator refers to the functionality and efficiency level of each space and its elements for responding to the occupant activities and needs (Mustafa, 2016; Sanni-Anibire, Hassanain, and Al-Hammad, 2016). In this regard, several studies (Szigeti *et al.*, 2002; Jiun, 2005; van der Flier and Thomsen, 2006; Allameh *et al.*, 2011; Mustafa, 2016, 2017; Gopikrishnan and Topkar, 2017; Kamali and Hewage, 2017; Kamali, Hewage and Milani, 2018; Abdulelah, Al and Kamaran, 2019; Davoodi and Da˘glı, 2019; de Wilde, 2019) reported the effective parameters those are crucial to be considered for the evaluation of this indicator. **The most important parameters** are (1) **flexibility and multifunctionality** capacity – capacity of satisfying multiple occupants' needs –, (2) **adequacy of necessary facilities and amenities**, (3) **unity and integrity** of space, and (4) **responding to** specific **needs of elderly or disabled people** – e.g., free access for elderly or the disabled people – (Szigeti *et al.*, 2002; Jiun, 2005; van der Flier and Thomsen, 2006; Allameh *et al.*, 2011; Mustafa, 2016, 2017; Gopikrishnan and Topkar, 2017; Kamali and Hewage, 2017; Kamali, Hewage and Milani, 2018; Abdulelah, Al and Kamaran, 2019; Davoodi and Da˘glı, 2019; de Wilde, 2019). Each one of the abovementioned parameters was explained and asked in the questionnaire content to the respondents not only to clarify more in detail the different aspects of this indicator but also for obtaining more precise data and results. Subsequently, to obtain the value of indicator 13, a mean score of the collected data for each scenario besides their standard deviation has been calculated by SPSS. Table 6.18 presents the value of each parameter and the total value of indicator 13. Therefore, the values of I_{13} for scenarios 1, 2, and 3 are 2.59, 3.38, and 3.47 respectively.

Table 6.18. Functional performance of physical space of defined scenarios

Satisfaction regarding:		**Scenario 1**				**Scenario 2**				**Scenario 3**			
		Kitchen	Livingroom	Bedroom	**Total**	Kitchen	Livingroom	Bedroom	**Total**	Kitchen	Livingroom	Bedroom	**Total**
1. Flexibility and multifunctionality of space	**Mean**	**1.95**	**2.78**	**2.84**	**2.52**	**3.38**	**3.23**	**3.07**	**3.22**	**3.55**	**3.45**	**3.09**	**3.36**
	Std. Deviation	.705	.787	.764	.752	.650	.599	.759	.669	.820	.820	.831	.824
2. Adequacy of necessary facilities and amenities	**Mean**	**1.84**	**2.84**	**2.63**	**2.38**	**3.85**	**3.38**	**3.07**	**3.43**	**3.82**	**3.45**	**3.27**	**3.51**
	Std. Deviation	.765	.834	.895	.831	.689	.960	.759	.803	.874	.687	.646	.736
3. Unity and integrity of space	**Mean**	**1.53**	**2.63**	**3.10**	**2.42**	**3.77**	**3.76**	**3.23**	**3.58**	**3.82**	**3.81**	**3.27**	**3.63**
	Std. Deviation	.513	.955	.809	.759	.599	.599	.599	.599	.603	.603	.782	.663
4. Responding to specific **needs of elderly or the disabled people**	**Mean**	**2.32**	**3.42**	**3.47**	**3.07**	**3.15**	**3.38**	**3.30**	**3.27**	**3.36**	**3.36**	**3.45**	**3.39**
	Std. Deviation	.749	.606	.611	.655	.689	.650	.630	.656	.806	.674	.687	.722
The total value of I_{13}	**Mean**				**2.59**				**3.38**				**3.47**
	Std. Deviation				.749				.682				.736

6.3.2. Adequate spaces and storages (I_{14})

Adequate spaces and storages is another reason for interior rehabilitation that refers to provide adequate living and storing spaces for occupants (Meijer, Itard and Sunikka-Blank, 2009; Mustafa, 2016; Sanni-Anibire, Hassanain and Al-Hammad, 2016; Berezin *et al.*, 2017; Abdulelah, Al and Kamaran, 2019). To evaluate this indicator, the occupants' satisfaction for each spatial layout regarding **two parameters** (a) **size and useful area**, and (b) **storage space** – e.g., closets and cabinets – were obtained. Afterward, a mean score of the obtained data for each scenario besides their standard deviation has been calculated by SPSS. Table 6.19 presents the value of each parameter and the total value of indicator 14. Therefore, the values of I_{14} for scenarios 1, 2, and 3 are 2.69, 3.35, and 3.60 respectively.

Table 6.19. Adequate spaces and storages of the defined scenarios

Satisfaction regarding:		**Scenario 1**				**Scenario 2**				**Scenario 3**			
		Kitchen	Livingroom	Bedroom	**Total**	Kitchen	Livingroom	Bedroom	**Total**	Kitchen	Livingroom	Bedroom	**Total**
a) Size of space	**Mean**	**3.05**	**3.47**	**3.42**	**3.31**	**3.54**	**3.54**	**3.46**	**3.51**	**3.55**	**3.73**	**3.55**	**3.61**
	Std. Deviation	.911	.697	.692	.767	.660	.776	.660	.699	.522	.647	.522	.564
b) Storage space	**Mean**	**1.84**	**2.10**	**2.32**	**2.08**	**3.38**	**3.00**	**3.23**	**3.20**	**4.00**	**3.27**	**3.55**	**3.60**
	Std. Deviation	.898	.994	.885	.926	.870	.912	.725	.836	.755	.904	.820	.826
The total value of I_{14}	**Mean**				**2.69**				**3.35**				**3.60**
	Std. Deviation				.846				.767				.695

6.3.3. Thermal comfort (I_{15})

Thermal comfort as one of the main reasons for interior rehabilitation (Sanni-Anibire, Hassanain and Al-Hammad, 2016; Mustafa, 2017) effects on human health, well-being, and performance (Silva *et al.*, 2017; Carratt, Kokogiannakis and Daly, 2020). ASHRAE 55 (ASHRAE, 2014) defined thermal comfort as "the state of mind that expresses satisfaction with the surrounding thermal environment." (ASHRAE, 2014). Also, thermal comfort is achieved when there is a balance of body heat and mass transfer with the environment, and when skin temperature and sweat rate are within comfort range (Fanger, 1972; Höppe, 2002). This concept is quite subjective and difficult to calculate and it depends on several parameters (Giancola *et al.*, 2014). These parameters can be categorized into (1) **physical parameters in the built environment** such as temperature, relative humidity, and air velocity (Dall'O', 2013; Sanni-Anibire, Hassanain and Al-Hammad, 2016; Mustafa, 2017), and (2) **individual parameters** like clothing, physical activity, gender, and so on (Dall'O', 2013; Giancola *et al.*, 2014; Sanni-Anibire, Hassanain and Al-

Hammad, 2016; Mustafa, 2017; Carratt, Kokogiannakis and Daly, 2020). **Both of these mentioned parameters** affect **the holistic thermal satisfaction** of inhabitants. In this regard, in the present doctoral dissertation, the **holistic thermal satisfaction** of occupants was asked to evaluate their satisfaction regarding the **cooling** and **heating** status. Table 6.20 presents the values of cooling and heating satisfaction and the total value of indicator 15. Therefore, the values of I_{15} for scenarios 1, 2, and 3 are 3.01, 3.20, and 3.93 respectively.

Table 6.20. Thermal comfort of the defined scenarios

Satisfaction regarding:		Scenario 1				Scenario 2				Scenario 3			
		Kitchen	Livingroom	Bedroom	**Total**	Kitchen	Livingroom	Bedroom	**Total**	Kitchen	Livingroom	Bedroom	**Total**
a) Cooling	**Mean**	**1.63**	**3.21**	**3.32**	**2.72**	**2.77**	**3.15**	**3.31**	**3.07**	**3.64**	**3.73**	**4.00**	**3.79**
	Std. Deviation	.684	.787	.582	.684	.927	.689	.480	.699	.674	.905	.775	.785
b) Heating	**Mean**	**3.11**	**3.32**	**3.47**	**3.30**	**3.08**	**3.38**	**3.54**	**3.33**	**3.91**	**4.00**	**4.27**	**4.06**
	Std. Deviation	.875	.671	.697	.748	.760	.650	.776	.729	.539	.632	.647	.606
The total value of I_{15}	**Mean**				**3.01**				**3.20**				**3.93**
	Std. Deviation				.716				.714				.695

6.3.4. Indoor air quality (IAQ) – I_{16}

In modern lifestyles, since people spend more than 87% of their lifespan indoors (Delgado-saborit *et al.*, 2011; Zhao and Liu, 2020), Indoor Air Quality (IAQ) is a crucial factor (Kozielska *et al.*, 2020; Zhao and Liu, 2020) that effects on human health and well-being (Földváry *et al.*, 2017). Anderson et al. (2014) defined IAQ as the comfortable range of the fresh air, ventilation, and chemical or biological contaminants of the buildings inside air. According to ASHRAE 62.1 (ASHRAE 2010b), acceptable IAQ is achieved by providing **fresh air** and **adequate ventilation** – including natural and mechanical ventilation – to remove or control contaminants to acceptable limits. In this regard, IAQ is provided through natural ventilation like openings – e.g., windows and doors – and mechanical ventilation systems (Dall'O', 2013; Silva *et al.*, 2017). In the present thesis, **the occupant's satisfaction** through **natural** and **mechanical ventilation** was asked. As in the defined scenarios, the mechanical ventilation system exists only in the kitchen, the inhabitant's satisfaction was asked only for this space. Meanwhile, for the natural ventilation, they were asked about all spatial layouts. Table 6.21 presents the values of natural and mechanical ventilation satisfaction and the total value of indicator 16. Therefore, the values of I_{16} for scenarios 1, 2, and 3 are 2.40, 3.42, and 3.51 respectively.

Table 6.21. IAQ of the defined scenarios

Satisfaction regarding:		Scenario 1				Scenario 2				Scenario 3			
		Kitchen	Livingroom	Bedroom	**Total**	Kitchen	Livingroom	Bedroom	**Total**	Kitchen	Livingroom	Bedroom	**Total**
a) Mechanical ventilation system	**Mean**	**1.89**	-	-	**1.89**	**3.31**	-	-	**3.31**	**3.45**	-	-	**3.45**
	Std. Deviation	.737			.737	.630			.630	.522			.522
b) Natural ventilation and Fresh air	**Mean**	**1.42**	**3.58**	**3.74**	**2.91**	**3.15**	**3.62**	**3.85**	**3.54**	**3.18**	**3.73**	**3.82**	**3.57**
	Std. Deviation	.507	.769	.806	.694	.689	.650	.555	.631	.603	.647	.751	.667
The total value of I_{16}	**Mean**				**2.40**				**3.42**				**3.51**
	Std. Deviation				.716				.631				.595

6.3.5. Lighting comfort (I_{17})

Several studies revealed that lighting can influence occupants' comfort, productivity, and health (Abdellatif and Al-shamma, 2015; Heydarian *et al.*, 2016; Leccese *et al.*, 2020; Nair and Nayar, 2020). The Illuminating Engineering Society of North America (IESNA, 2018) expressed that "sufficient light is an essential human need that can affect task performance, health and safety, and mood and atmosphere". The design of buildings and facilities creates a balance between **artificial** and **natural lighting**, whereby sufficient natural light is allowed to penetrate through transparent parts of the building envelope (Sanni-Anibire, Hassanain and Al-Hammad, 2016; Mustafa, 2017). As **artificial lighting** varies from apartment to apartment, the evaluation of this parameter has been **put aside in this thesis**. Therefore, the natural lighting of each scenario has been assessed through the conducted questionnaire to obtain the inhabitant's satisfaction regarding each spatial layout. Table 6.22 presents the total value of indicator 17 where this amount for scenarios 1, 2, and 3 are 3.15, 3.74, and 3.79 respectively.

Table 6.22. Lighting comfort of the defined scenarios

Satisfaction regarding:		Scenario 1				Scenario 2				Scenario 3			
		Kitchen	Livingroom	Bedroom	Total	Kitchen	Livingroom	Bedroom	Total	Kitchen	Livingroom	Bedroom	Total
a) Natural Light	**Mean**	**1.63**	**3.89**	**3.95**	**3.15**	**3.31**	**4.00**	**3.92**	**3.74**	**3.45**	**3.91**	**4.00**	**3.79**
	Std. Deviation	.496	.567	.524	.529	.855	.577	.760	.731	.688	.701	.632	.674
The total value of I_{17}	**Mean**				**3.15**				**3.74**				**3.79**
	Std. Deviation				.529				.731				.674

6.3.6. Acoustic comfort (I_{18})

Noise pollution has a negative impact on the occupant's health and well-being (Marques and Pitarma, 2020). Preiser et al. defined acoustic comfort as "the occupant's satisfaction regarding the ambient level of sound, the transmission of sound between areas and rooms, reverberation, and specific noises such as machine noise" (Preiser et al., 1988). It is worthy to mention that **indoor** and **outdoor** parameters have an effect on acoustical comfort (Sanni-Anibire, Hassanain, and Al-Hammad, 2016; Mustafa, 2017). In this regard, in the present dissertation, the occupant's satisfaction regarding both **indoor** and **outdoor** noises was asked to obtain the value of I_{18}. Table 6.23 presents the values of indoor and outdoor acoustic satisfaction and the total value of this indicator. Therefore, the values of I_{18} for scenarios 1, 2, and 3 are 3.86, 3.90, and 3.89 respectively.

Table 6.23. Acoustic comfort of the defined scenarios

Satisfaction regarding:		Scenario 1				Scenario 2				Scenario 3			
		Kitchen	Livingroom	Bedroom	Total	Kitchen	Livingroom	Bedroom	Total	Kitchen	Livingroom	Bedroom	Total
a) Outdoor noise	**Mean**	**3.63**	**3.89**	**3.79**	**3.77**	**3.77**	**3.92**	**3.85**	**3.85**	**3.73**	**4.00**	**3.91**	**3.88**
	Std. Deviation	.761	.737	.787	.0.762	.725	.862	.555	.714	.786	.632	.701	.706
b) Indoor noise	**Mean**	**3.89**	**3.95**	**4.05**	**3.96**	**3.85**	**3.92**	**4.08**	**3.92**	**3.82**	**3.82**	**4.09**	**3.91**
	Std. Deviation	.809	.705	.780	.765	.899	.641	.862	.785	.603	.603	.701	.636
The total value of I_{18}	**Mean**				**3.86**				**3.90**				**3.89**
	Std. Deviation				.763				.757				.671

6.3.7. Aesthetic and beauty of the interior space (I_{19})

According to several studies (Megahed and Gabr, 2010; Emmanuel Arenibafo, 2017; Sandak *et al.*, 2017; Ricci, 2018; Lindenthal, 2020), the **aesthetic and beauty of the interior space** is one of the **main reasons for interior rehabilitation**. This indicator has significant effects on the social aspects such as psychology, behavior, well-being, and productivity of inhabitants (Megahed and Gabr, 2010; Lindenthal, 2020). This issue is even more important in modern society because more than 87% of a person's lifespan is spent indoors based on the National Human Activity Pattern Survey (NHAPS) (Klepeis *et al.*, 2011). Especially, due to the recent Covid-19 Pandemic lockdowns, numerous people have spent entire months in their houses, and working from home has increased (Jones, Philippon and Venkateswaran, 2020; Kramer and Kramer, 2020). Also, the aesthetic and beauty of the interior space affects the economic aspects such as increasing rent or resale value and avoiding renovations and remodeling more frequently (Megahed and Gabr, 2010; Lindenthal, 2020). Until recently, **the evaluation of this indicator** has been facing **some challenges** due to (1) the difficulty in quantitatively measuring (McKenzie, 2004; Littig and Griessler, 2005; Karji *et al.*, 2019a), (2) the difficulty to define its scopes, effective parameters and data collection methods (Karji *et al.*, 2019a; Liu and Qian, 2019) and, (3) it is highly subjective and depends on the user's opinions and their expectations that can vary from person to person (Megahed and Gabr, 2010; Lindenthal, 2020).

To overcome the aforementioned challenges, several studies have employed **expert-based questionnaire surveys** (Megahed and Gabr, 2010; Chuang, Liu and Liu, 2019; Olakitan Atanda, 2019) based on some effective parameters that are crucial to be considered for the evaluation of this indicator. **The most important parameters** are: (a) **form**, **shape**, and **geometrical composition** – e.g., symmetry, repetition, equilibrium, disposition –, (b) **details quality** which refers to the **quality of the applied interior**

materials and elements, (c) **harmony** that is defined as the appropriate and **harmonious relationship from one part** to another or the whole as a good visual unity, and (d) **creativity and innovation** of design (Berlyne et al., 1968; 1971; 1974; Scha & Bod, 1993; Salingaros, 1995; Staudek, 1999; Alexander, 2003; Salingaros, 2007 Megahed and Gabr, 2010; da Luz Reis & Dias, 2010; Zinas & Jusan, 2012; Ghomeshi et al., 2012; Emmanuel Arenibafo, 2017; Sandak *et al.*, 2017; Nadoushani et al., 2018; Ricci, 2018; Olakitan Atanda, 2019; Lindenthal, 2020; Gilani, 2020). After defining the effective parameters for this indicator, an expert-based questionnaire was designed, carried out, and analyzed.

To **design** a proper framework for the expert-based questionnaire, each one of the mentioned parameters was explained and asked from the respondents not only to clarify more in detail the different aspects of this indicator but also for obtaining more precise data and results. Moreover, the architectural and technical characteristics of each defined scenario such as architectural layouts, applied materials, and construction details besides the pictures of each scenario were presented in the questionnaire. Also, the questionnaire was designed by using a five-point Likert scale, where 5 represents highly appropriate, 4 represents appropriate, 3 represents neutral, 2 represents inappropriate, and, 1 represents highly inappropriate. The designed expert-based questionnaire has been presented in Appendix 6.I more in detail. It is worthy to mention that by designing this expert-based questionnaire, the author attempted to reduce the subjectivity of indicator 19^{th} and proposed objective and reliable solutions for assessing the mentioned indicator.

To conduct the abovementioned questionnaire, 9 architects and interior designers who are experts in this domain were selected to be interviewed via email or by phone.

To **analyze** the collected data from questionnaires, this obtained data was **inserted into IBM SPSS Statistics V. 22 software** (Figure 6.8). Subsequently, to obtain the value of this indicator, a mean score of the collected data for each scenario besides their standard deviation has been calculated. Table 6.24 presents the value of each parameter and the total value of indicator 19. Therefore, the values of I_{19} for scenarios 1, 2, and 3 are 1.61, 3.37, and 3.62 respectively.

Table 6.24. The value of I19 for scenarios 1 to 3

Satisfaction regarding:		Scenario 1					Scenario 2					Scenario 3				
		Liv	Kit	Br	Bath	Total	Liv	Kit	Br	Bath	Total	Liv	Kit	Br	Bath	Total
a) **Form**, **shape**, and **geometrical composition**	**Mean**	**2.00**	**1.56**	**2.44**	**2.22**	**2.06**	**4.00**	**4.11**	**3.56**	**3.22**	**3.72**	**3.89**	**3.89**	**3.67**	**3.56**	**3.75**
	Std. Deviation	0.707	0.527	0.527	0.667	0.607	0.500	0.601	0.527	0.441	0.517	0.782	0.601	0.500	0.726	0.652
b) Quality	**Mean**	**1.44**	**1.22**	**1.44**	**1.56**	**1.42**	**3.78**	**3.56**	**3.11**	**2.89**	**3.33**	**4.00**	**3.67**	**3.78**	**3.44**	**3.72**
	Std. Deviation	0.527	0.441	0.726	0.527	0.555	0.667	0.527	0.601	0.601	0.599	0.500	0.707	0.667	0.527	0.600
c) Harmony	**Mean**	**1.78**	**1.33**	**2.00**	**1.89**	**1.75**	**3.44**	**3.44**	**3.33**	**2.56**	**3.19**	**3.67**	**3.67**	**3.56**	**3.78**	**3.67**
	Std. Deviation	0.441	0.500	0.500	0.601	0.511	0.527	0.527	0.500	0.527	0.520	0.500	0.500	0.527	0.441	0.492
d) Creativity and innovation of design	**Mean**	**1.11**	**1.11**	**1.33**	**1.33**	**1.22**	**3.78**	**3.56**	**3.11**	**2.67**	**3.28**	**3.44**	**3.56**	**3.11**	**3.33**	**3.36**
	Std. Deviation	0.333	0.333	0.500	0.500	0.417	0.667	0.527	0.782	0.707	0.671	0.527	0.527	0.782	0.500	0.584
The total value of I_{19}	**Mean**					**1.61**					**3.37**					**3.62**
	Std. Deviation					0.522					0.576					0.582

6.4. Global Sustainability index (GSi) assessment of scenarios 1-3

As previously mentioned in chapter 3, section 3.2, **the sixth stage (6.c) of the proposed MIVES-Delphi model** is **calculating the Global Sustainability index (GSi)** for each defined scenario by **considering the hierarchy-levels decision-making tree** (San-Jose Lombera and Garrucho Aprea, 2010; Fuente *et al.*, 2016; Hosseini, De la Fuente and Pons, 2016; Galant, 2020; Hosseini, Yazdani and De, 2020; Josa *et al.*, 2020; Ledesma, Nikolic and Pons, 2020) as indicated in Figure 3.6.

To calculate the GSi of each defined scenario, the obtained indicators' values – from sections 6.1 to 6.3 – were converted to indicators' non-dimensional values (Table 6.25) by application of the defined value functions – see Appendix 3.B. Consequently, by considering the previously defined decision-making tree – section 3.2, Figure 3.3 –, its components' weights – section 3.2, Figure 3.4 –, and the obtained indicators' non-dimensional values, the GSi of each defined scenario has been calculated through Equations 3.5 to 3.7.

Table.6.25. Value functions, indicators values, and Non-dimensional indicators' values for scenarios 1 to 3

#R		Unit	Shape	X_{max}	X_{min}	C_i	K_i	P_i	Indicator's value			Non-dimensional Indicator's value		
									Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Economic	I_1. Initial rehabilitation cost	€/m²	DCx	200	50	115	0.05	2.00	80.47	98.86	129.80	0.64	0.47	0.23
	I_2. Maintenance cost	€/m².50yrs	DCx	200	70	135	0.10	1.50	183.01	135.35	120.37	0.05	0.36	0.49
	I_3. Demolition cost	€/m²	DCv	12	8	10	0.15	0.70	11.10	11.88	10.84	0.41	0.11	0.49
	I_4. Property added-value	€/m².AU	ICx	26074	0	9017	0.10	1.50	908	9347	15608	0.01	0.26	0.52
	I_5. Rehabilitation process time	Day	DL	60	20	40	0.0	1.00	26	38	40	0.85	0.55	0.50
Environmental	I_6. Embodied Energy (EE)	MJ/m²	DCx	1300	7300	3250	0.10	0.80	3783	3105	2905	0.67	0.77	0.79
	I_7. Embodied Carbon (EC)	kgCO₂/m²	DCx	50	450	250	0.60	0.70	225	141	145	0.76	0.89	0.88
	I_8. Embodied Water (EW)	l/m²	DCx	2000	5000	3500	1.00	0.60	50.32	48	34.35	0.17	0.19	0.36
	I_9. Construction Waste (CW)	kg/m²	DCv	10	50	21.86	1.00	0.60	4551	4638	3493	0.42	0.38	0.76
	I_{10}. Operational Energy (OE)	kWh/m2/yr.	DCv	0	95	47.5	0.05	2.50	44	49	24	0.49	0.19	0.88
	I_{11}. Operational Carbon (OC)	kgCO₂/m²/yr.	DCx	0	75	37.5	0.05	2.50	24.41	23.75	18.14	0.41	0.42	054
	I_{12}. Demolition Waste (DW)	kg/m²	DCx	150	750	450	1.00	0.80	645	603	382	0.37	0.47	0.80
Social	I_{13}.Functionality of the physical space	Points	ICx	5	1	3	0.50	2.50	2.59	3.38	3.47	0.13	0.34	0.37
	I_{14}.Adequate spaces & storages	Points	ICx	5	1	3	0.40	2.00	2.69	3.35	3.60	0.22	0.41	0.49
	I_{15}.Thermal comfort	Points	ICx	5	1	3	0.50	2.00	3.01	3.20	3.93	0.34	0.40	0.64
	I_{16}.Indoor air quality	Points	ICx	5	1	3	0.50	1.50	2.40	3.42	3.51	0.27	0.57	0.59
	I_{17}.Lighting comfort	Points	ICx	5	1	3	0.50	1.50	3.15	3.74	3.79	0.49	0.66	0.67
	I_{18}.Acoustic comfort	Points	ICx	5	1	3	0.50	1.50	3.86	3.90	3.89	0.69	0.70	0.70
	I_{19}. Aesthetic & building beauty	Points	ICx	5	1	3	0.40	2.50	1.61	3.37	3.62	0.01	0.36	0.44

Legend: DCx: Decreasing Convex; DL: Decreasing Lineal; DCv: Decreasing Concave; ICx: Increasing convex; IL: Increasing Linear; ICv: Increasing concave; IS: Increasing S-shape; DS: Decreasing S-shape; AU: Apartment Unit.

As a result, the GSi for scenarios 1, 2, and 3 are 0.35, 0.42, and 0.53 respectively. The results from this evaluation are a Global Sustainability index (GS_i), 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 indicated in Table 6.26.

Table 6.26. The value of the Global sustainability index (GS_i) of scenarios 1-3

	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}	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	GS_i
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	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	0.64	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	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	0.47	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	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	0.23	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	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**

6.5. Discussion and interpretation of sustainability performance of scenarios 1-3

After measuring the GS_i of scenarios 1 to 3 with the proposed MIVES-Delphi model, in this section, the results have been analyzed and interpreted in order to (1) **prove the applicability**, **suitability**, and **validity** of the proposed approach for the thesis objectives, and (2) interpreting the obtained results **to provide valuable information** – the identification of strengths and weaknesses of the defined rehabilitation scenarios – **about crucial improvement points** of each rehabilitation scenario from requirements values (VR_i), criteria values (VC_j), and indicators values (VI_k) points of view. To this end, in the following paragraphs, the obtained results have been explained more in detail – see Figure 6.9 and Table 6.26.

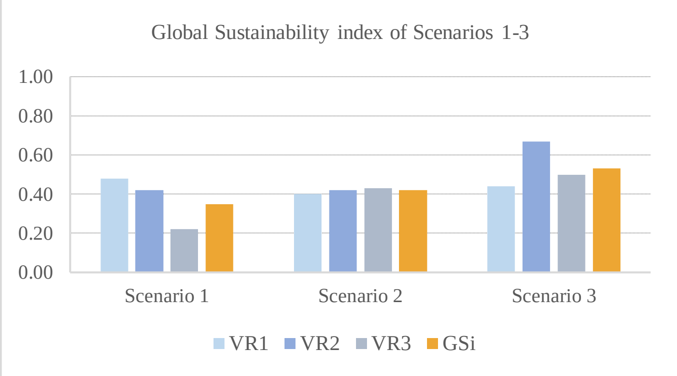


Figure 6.9. Global Sustainability index of scenarios 1-3

1) From **the economic requirement** (VR_1) point of view, this value for scenarios 1 to 3 are 0.48, 0.40, and 0.44 respectively. Although the results for all these three scenarios **mostly fell in the middle-value range**, the **highest value belongs to scenario 1** due to its lower initial rehabilitation cost (I_1) and rehabilitation process time (I_5), which the following paragraph explains more in detail. On the other hand, in scenarios 2 and 3, the maintenance cost (I_2) and the property added-value (I_4) have higher values in comparison with scenario 1 due to the application of construction materials with better quality and durability. The difference between obtained results occurred due to contrasting values in the defined indicators, e.g., scenario 1 needed lower initial rehabilitation cost (I_1) while it had the highest maintenance cost (I_2) during the building lifespan. It is worthy to mention that based on overviewing numerous relative literature such as (Gilani, 2020) and (Habibi, Pons, and Pena, 2020) as well as some well-known *SBRCSs* (Markelj, Kuzman and Zbašnik-Senegačnik, 2013), the author considered those scenarios which obtained values **less than 0.70** regarding a specific indicator do not meet **the standard minimum target value** of that indicator's sustainability and they need to be improved. Moreover, **the scenarios that obtained values less than 0.30** are considered to have serious sustainability issues in that indicator and they need urgent and critical improvements. Therefore, based on the above-mentioned points, **none of these three scenarios met the standard minimum target value of economic sustainability**.

Regarding **the rehabilitation cost (I_1)** and **the rehabilitation process time (I_5)**, **scenario 1** has the **greatest satisfaction values** – almost 0.41 and 0.35 more satisfaction than scenario 3 respectively – where **partial rehabilitation** was implemented. On the other hand, **scenario 3** obtained **the greatest satisfaction values in the maintenance cost (I_2) and property added-value (I_4)** – almost 0.44 and 0.49 more satisfaction than scenario 1 respectively – due to its higher quality and durability of the applied materials, improved construction techniques and design, and less need of repairing and maintenance during the building lifespan. In respect of **demolition costs (I_3)**, **scenario 2** attained **the lowest satisfaction value** due to the application of heavy construction materials and components in this scenario – e.g., the brick walls, cement mortars, and clay plaster – that caused higher waste disposal costs.

Table 6.27. Economic sustainability values of scenarios 1 to 3.

	VI_1	VI_2	VI_3	VI_4	VC_1	VI_5	VC_2	VR_1
Weight (ω)	0.34	0.25	0.15	0.26	0.77	1	0.23	**0.32**
Scenario 1	0.64	0.05	0.41	0.01	0.30	0.85	0.85	**0.48**
Scenario 2	0.47	0.36	0.11	0.26	0.33	0.55	0.55	**0.40**
Scenario 3	0.23	0.49	0.49	0.52	0.41	0.50	0.50	**0.44**

Legend: VR_i = Value of economic requirement, VC_j = Value of economic criteria, and VI_k = Value of economic indicators

2) In terms of **the environmental requirement** (VR_2), scenarios 1 to 3 obtained values 0.42, 0.42, and 0.67 respectively. **Scenario 3 attained a higher value** – almost 25 percent more than the two other scenarios –, while scenarios 1 and 2 have similar environmental performances. These results were obtained mostly due to the better performance of scenario 3 in the construction and demolition waste (I_9 and I_{12}), the operational energy (I_{10}), and operational carbon (I_{11}) as explained as follows. Moreover, **none of these three scenarios met the standard minimum target value of environmental sustainability**.

Regarding **the embodied energy (I_6)**, **embodied carbon (I_7)**, and **embodied water (I_8)**, although scenario 3 has better performance in comparing with two other scenarios, there is a contrast among the values of these indicators due to not considering these indicators in the design phase.

In the case of **the construction and demolition waste (I_9 and I_{12})**, **scenario 2 has the lowest satisfaction values** – almost 0.69 and 0.33 less than scenario 3 respectively – because of the heavy materials applied in scenario 2.

Regarding **the operational energy (I_{10})**, and **operational carbon (I_{11})**, **scenario 3** has **better performance** in comparison with the other two scenarios due to the improvements in its thermal insulations, applied HVAC systems, and applied windows.

Table 6.28. Environmental sustainability values of scenarios 1 to 3.

	VI_6	VI_7	VI_8	VC_3	VI_9	VC_4	VI_{10}	VI_{11}	VC_5	VI_{12}	VC_6	VR_2
Weight (ω)	0.42	0.34	0.24	0.27	1	0.17	0.57	0.43	0.4	1	0.16	**0.26**
Scenario 1	0.67	0.76	0.42	0.64	0.49	0.49	0.17	0.41	0.27	0.37	0.37	**0.42**
Scenario 2	0.77	0.89	0.38	0.71	0.19	0.19	0.19	0.42	0.29	0.47	0.47	**0.42**
Scenario 3	0.79	0.88	0.76	0.81	0.88	0.88	0.36	0.54	0.43	0.80	0.80	**0.67**

Legend: VR_i = Value of environmental requirement, VC_j = Value of environmental criteria, and VI_k = Value of environmental indicators

3) Regarding **the social requirement** (VR_3), scenarios 1, 2, and 3 obtained values 0.22, 0.43, and 0.50 respectively. According to the obtained results, **scenarios 2 and 3** significantly have **better social performance** in comparison with scenario 1. These tremendous differences are turned up due to the better performance of scenarios 2 and 3 in the functionality of spaces (I_{13}), the adequate spaces and storages (I_{14}), and the aesthetic and beauty of the interior spaces (I_{19}) as explained as follows.

Respecting **the functionality performance of interior spaces (I_{13})** and **adequate spaces and storage (I_{14})**, **scenarios 2 and 3** have significantly **better performance** – almost 0.21 and 0.24 more than scenario 1 respectively – due to their design that provides more living spaces with more **unity** and **integrity**, more **adequate facilities and amenities**, and more **living and storage spaces**. It is worthy to mention that scenarios 2 and 3 have almost similar performances regarding these two indicators because of **their similarity in the space distributions** and **architectural layouts**.

In the case of **the thermal comfort (I_{15})**, **scenario 3 obtained higher values** in comparison with scenarios 1 and 2 – 0.24 and 0.30 more satisfaction respectively – due to its applied HVAC systems – package and radiator for heating and air conditioner split for cooling –, its applied windows, and thermal insulation.

About **the indoor air quality (I_{16})** and **lighting comfort (I_{17})**, scenarios 2 and 3 attained almost the same values because of their similarity in the space distributions and architectural layouts. While scenario 1 had the lowest indoor air quality and lighting satisfaction due to its enclosed kitchen space.

Regarding **the acoustic comfort (I_{18})**, scenarios 1, 2, and 3 obtained the same satisfaction values of 0.70. **Since all of these three scenarios met the standard minimum target value of acoustic comfort**, it can be concluded that Aleph-1 apartments have almost no serious acoustic issues.

In the case of **the aesthetic and beauty of the interior spaces (I_{19})**, **scenarios 2 and 3 obtained the higher value** – almost 0.35 and 0.44 more than scenario 1 – compared to scenario 1 because of their better performances mostly in **form**, **shape**, and **geometrical composition**, **details quality**, and **harmony**.

Table 6.29. Social sustainability values of scenarios 1 to 3.

	VI_{13}	VI_{14}	VC_7	VI_{15}	VI_{16}	VI_{17}	VI_{18}	VC_8	VI_{19}	VC_9	VR_3
Weight (ω)	0.53	0.47	0.42	0.32	0.22	0.25	0.21	0.32	1	0.26	**0.42**
Scenario 1	0.13	0.22	0.17	0.34	0.27	0.49	0.69	0.44	0.01	0.01	**0.22**
Scenario 2	0.34	0.41	0.37	0.40	0.57	0.66	0.70	0.57	0.36	0.36	**0.43**
Scenario 3	0.37	0.49	0.42	0.64	0.59	0.67	0.70	0.65	0.44	0.44	**0.50**

Legend: VR_i = Value of social requirement, VC_j = Value of social criteria, and VI_k = Value of social indicators

6.6. Conclusion of chapter 6

This chapter, applies the proposed MIVES-Delphi model on the defined existing rehabilitation scenarios of Aleph-1, calculates the values of the selected economic, environmental, and social indicators for these scenarios and consequently, obtains their GSis. Then, section 6.5 discusses, analyzes, and interprets these obtained indicators' values and GSis of the defined scenarios. To identify the **main sustainability weak points** of each scenario, it is essential to **compare the obtained value of each indicator** besides determining which indicator has more **influence and contribution** – greater relative weight – on the GSi of that scenario. To do so, Tables 3.4 and 6.30 present the obtained indicators' values and the indicators' contribution weights ($C\omega_{Ik}$) on the GSi.

Table 6.30. The obtained indicators' values and the contribution weight ($C\omega_{Ik}$) of each indicator on the GS_i

Rank	Indicator	Indicator name	$C\omega_{Ik}$	Scenario 1	Scenario 2	Scenario 3
1	I_{19}	Aesthetic & building beauty	10.9%	0.01	0.36	0.44
2	I_{13}	Functionality of the physical space	9.3%	0.13	0.34	0.37
3	I_{1}	Initial rehabilitation cost	8.4%	0.64	0.47	0.23
4	I_{14}	Adequate spaces & storages	8.3%	0.22	0.41	0.49
5	I_{5}	Retrofitting process time	7.4%	0.85	0.55	0.50
6	I_{4}	Property added-value	6.4%	0.01	0.26	0.52
7	I_{2}	Maintenance cost	6.2%	0.05	0.36	0.49
8	I_{10}	Operational Energy (OE)	5.9%	0.17	0.19	0.36
9	I_{11}	Operational Carbon (OC)	4.5%	0.41	0.42	0.54
10	I_{9}	Construction Waste (CW)	4.4%	0.17	0.19	0.36
11	I_{15}	Thermal comfort	4.3%	0.34	0.40	0.64
12	I_{12}	Demolition Waste (DW)	4.2%	0.37	0.47	0.80
13	I_{3}	Demolition cost	3.7%	0.41	0.11	0.49
14	I_{17}	Lighting comfort	3.4%	0.49	0.67	0.66
15	I_{16}	Indoor air quality	3.0%	0.27	0.57	0.59
16	I_{6}	Embodied Energy (EE)	2.9%	0.67	0.77	0.79
17	I_{18}	Acoustic comfort	2.8%	0.69	0.70	0.70
18	I_{7}	Embodied Carbon (EC)	2.4%	0.76	0.89	0.88
19	I_{8}	Embodied Water (EW)	1.7%	0.42	0.38	0.76

Legend: $C\omega_{Ik}$ = Contribution weight of each indicator

As previously mentioned, the scenarios that obtained values less than **0.30** are considered to have serious sustainability issues in that indicator and they need urgent and critical improvements. Therefore, based on the above-mentioned points, the **main sustainability issues** of each scenario are as follows:

Regarding scenario 1, it can be remarked that this scenario has serious sustainability issues in I_{19}. aesthetic and building beauty, I_{13}. functionality of the physical space, I_{14}. adequate spaces & storages, I_4. property added-value, I_2. maintenance cost, I_{10}. Operational Energy (OE), I_9. Construction Waste (CW), and I_{16}. indoor air quality with obtained values of 0.01,0.13, 0.22, 0.01, 0.05, 0.17, 0.17, and 0.27 respectively.

Moreover, scenario 2 has serious sustainability issues regarding I_4. property added-value, I_{10}. Operational Energy (OE), I_9. Construction Waste (CW), and I_3. demolition cost with obtained values of 0.26, 0.19, 0.19, and 0.11 respectively.

In the case of scenario 3, the only indicator that obtained a value less than 0.30 is I_1. Initial rehabilitation cost.

All in all, the obtained **GSis of the defined scenarios** – as representatives and the most common rehabilitation activities in Iran – **did not meet the current and standard minimum target value of sustainability** – which is defined as 0.70. Therefore, significant **sustainability improvements – especially in their above-mentioned weak points – are needed**. To this end, **identifying new or improved rehabilitation activities and techniques can be a solution for the mentioned shortage,** which is studied in the next chapter.

CHAPTER 7

Application of the proposed MIVES-Delphi model on an improved rehabilitation scenario: scenario 4

Chapter 7: Application of the proposed MIVES-Delphi model on an improved rehabilitation scenario: scenario 4

Introduction

This chapter aims to apply the **proposed MIVES-Delphi model** – see chapter 3, section 3.2 – on **a rehabilitation project** designed to be constructed using **new or improved rehabilitation techniques** – named as scenario 4 in the present dissertation. To do so, this chapter consists of the following sections as indicated in Figure 7.1:

1) Section 7.1 aims to define a rehabilitation project designed to be constructed using new or improved rehabilitation techniques. To do so, based on the collected data of existing rehabilitation projects constructed with new or improved technologies all around the world – see chapter 2, section 2.2.3 –, **a specific rehabilitation project has been chosen**, **modified**, **and applied to *Aleph-1*** – named as scenario 4 in the present doctoral dissertation. It is worthy to mention that the present thesis has selected an existing real rehabilitation project instead of designing a new project from scratch for the sustainability assessment of the defined sample. The reasons are (a) according to the defined specific objective of the present doctoral thesis – section 1.4 –, designing a new rehabilitation project does not fit in the scope of this study, and (b) in case of selecting an existing improved rehabilitation project, a lot of reliable, precise, and rigorous information and data – such as rehabilitation costs, maintenance costs, rehabilitation process time, and so on – can be obtained from designers, constructors, and stakeholders thus facilitating the evaluation of the sustainability index for this scenario 4.

2) Section 7.2 overviews and determines **the main characteristics** of scenario 4 such as the applied construction systems, architectural, technical, mechanical, and electrical systems characteristics.

3) Section 7.3 calculates **the value of** the defined economic, environmental, and social **indicators** for scenario 4.

4) Section 7.4 calculates the **Global Sustainability index** (GSi) of scenario 4.

5) Section 7.5 is divided into two main parts. The first part – section 7.5.1 – **analyzes**, **interprets**, and **discusses** the obtained results **of all four scenarios** to (a) compare their sustainability performances, (b) identify the main sustainability issues of each scenario and consequently their needed crucial improvement points, and (c) find the most sustainable rehabilitation solution for decision-makers who are dealing with interior rehabilitation of MHs as well as testing validity of the assumed hypothesis – section 1.3. The second part – section 7.5.2 – conducts the 7th and the last stage of the proposed MIVES-Delphi model **to prove** its **suitability**, **validity**, **and robustness** by conducting a **sensitivity analysis** that considered different probabilistic weighting scenarios – named as states in this thesis.

6) Finally, section 7.6 concludes the previous sections of this chapter.

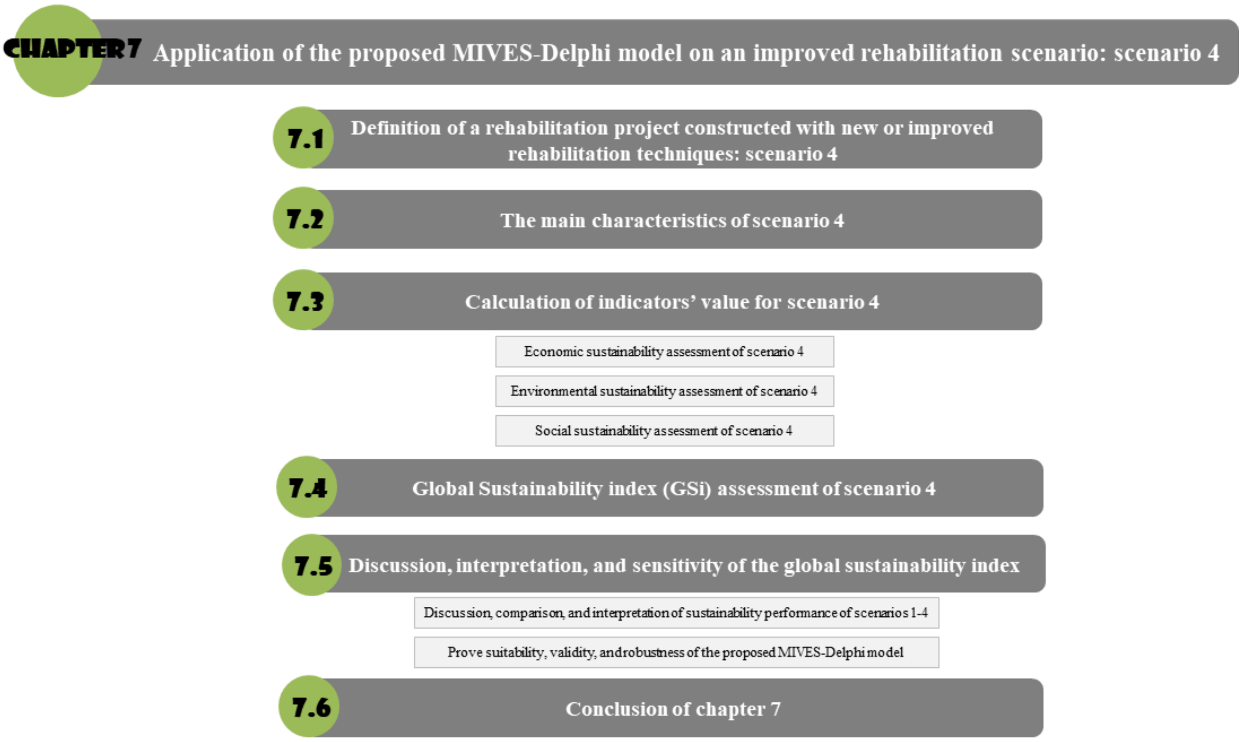


Figure 7.1. Structure of chapter 7

7.1. Definition of a rehabilitation project constructed with new or improved rehabilitation techniques: scenario 4

To define the 4th scenario for Aleph-1, after a comprehensive overview of several rehabilitation projects constructed with new or improved rehabilitation techniques around the world – see chapter 2, section 2.2.3 –, ***LifeEdited-1*** project has been selected due to the following reasons:

1) *LifeEdited* projects have been introduced for the first time by designing *LifeEdited-1* – also known as "6 rooms into 1" – in 2010. During the past decade, several LifeEdited projects have been designed and constructed such as LifeEdited-1, LifeEdited-2, Vero Tiny House from Covo and LifeEdited, VN Quata (São Paulo) LifeEdited, and River City (Toronto) LifeEdited (https://lifeedited.com/about/, https://www.dezeen.com/2018/08/09/lifeedited2-tiny-new-york-apartment-graham-hill-functions-like-one-twice-its-size/, https://www.businessinsider.com/graham-hill-lifeedited-apartment-2013-3#heres-the-bathroom-its-split-into-a-separate-shower-and-toilet-area-the-fixtures-are-from-fluid-and-caroma-designed-the-sink-and-toilet-12, https://faircompanies.com/videos/6-rooms-into-1-morphing-apartment-packs-1100-sq-ft-into-420/, https://lifeedited.com/very-brief-history-of-lifeedited/, https://www.jovoto.com/projects/lifeedited/ideas/10288?page=1&scope2=team_ideas&scope=rating, https://inhabitat.com/this-amazing-420-square-foot-transforming-apartment-can-be-yours-for-995000/lifeedited-graham-hill-apartment-lead/). These projects have been analyzed, modified, developed, and improved constantly. For instance, *LifeEdited-1* project which was designed for a 42 m^2 apartment, was redesigned and developed several times as shown in Figure 7.2. As this project **is known internationally as a successful rehabilitation project** (https://lifeedited.com/about/, https://www.dezeen.com/2018/08/09/lifeedited2-tiny-new-york-apartment-graham-hill-functions-like-one-twice-its-size/, https://www.businessinsider.com/graham-hill-lifeedited-apartment-2013-3#heres-the-bathroom-its-split-into-a-separate-shower-and-toilet-area-the-fixtures-are-from-fluid-and-caroma-designed-the-sink-and-toilet-12, https://faircompanies.com/videos/6-rooms-into-1-morphing-apartment-packs-1100-sq-ft-into-420/, https://lifeedited.com/very-brief-history-of-lifeedited/, https://www.jovoto.com/projects/lifeedited/ideas/10288?page=1&scope2=team_ideas&scope=rating, https://inhabitat.com/this-amazing-420-square-foot-transforming-apartment-can-be-yours-for-995000/lifeedited-graham-hill-apartment-lead/) and was **constantly developed**, it has been selected as scenario 4.

Figure 7.2. The different versions of LifeEdited-1; left: the initial version, middle and right: the improved versions

2) Based on consultations with the constructors, construction practitioners, and architects, the author concludes that the applied **construction technologies** on LifeEdited-1 are **available**, **applicable**, **and implementable** in Iran. Moreover, almost all of the used construction materials in LifeEdited-1 already exist in Iran's construction market or can be manufactured locally.

3) **As LifeEdited-1 has numerous similarities with the defined sample** – Aleph-1 apartment – such as their architectural layouts, space distribution, area, and proportion aspects, it can be **easily applied on Aleph-1 with only minor adaptations**. To do so, based on several meetings with experts – architects, engineers, construction practitioners, and interior designers – and considering the author's expertise, minimum changes have been considered. Then LifeEdited-1 has been applied as indicated in Figure 7.3. It is worthy to mention that the application of LifeEdited-1 on Aleph-1 **prioritized to apply as much as possible the same architectural layouts**, **space distributions**, **size**, **proportions**, **furniture**, **and appliance**.

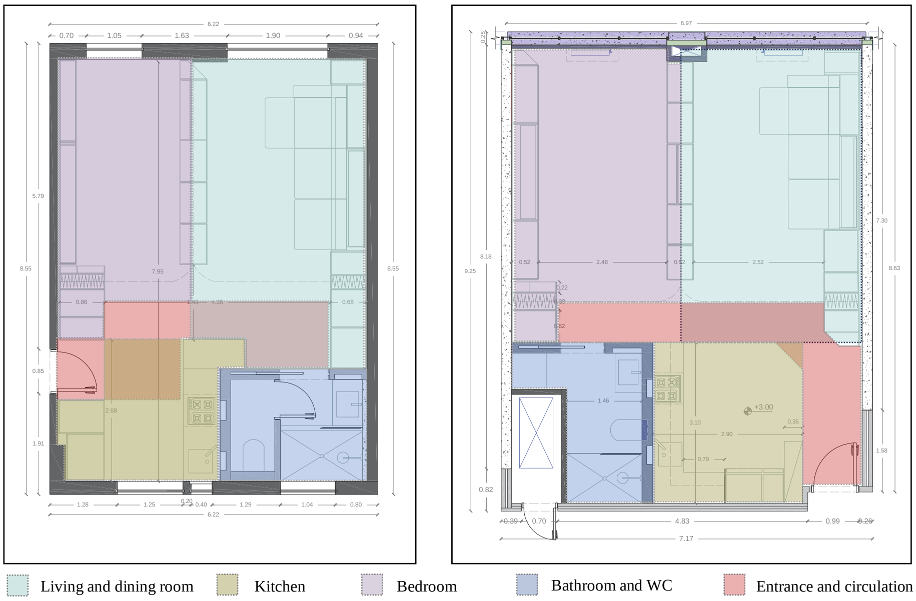


Figure 7.3. The LifeEdited-1 project (Left); The application of LifeEdited-1 on Aleph-1 (Right)

7.2. The main characteristics of scenario 4

As previously mentioned in chapter 2, section 2.2.3, LifeEdited-1 was designed to renovate a 50-year-old apartment by applying movable and transformable elements and furniture. Moreover, when designing this project, the designers made an effort to create more living and storage spaces that are more efficient and functional in order to better respond to its occupants' needs (https://lifeedited.com/about/, https://www.dezeen.com/2018/08/09/lifeedited2-tiny-new-york-apartment-graham-hill-functions-like-one-twice-its-size/, https://www.businessinsider.com/graham-hill-lifeedited-apartment-2013-3#heres-the-bathroom-its-split-into-a-separate-shower-and-toilet-area-the-fixtures-are-from-fluid-and-caroma-designed-the-sink-and-toilet-12, https://faircompanies.com/videos/6-rooms-into-1-morphing-apartment-packs-1100-sq-ft-into-420/, https://lifeedited.com/very-brief-history-of-lifeedited/, https://www.jovoto.com/projects/lifeedited/ideas/10288?page=1&scope2=team_ideas&scope=rating, https://inhabitat.com/this-amazing-420-square-foot-transforming-apartment-can-be-yours-for-995000/lifeedited-graham-hill-apartment-lead/). The movable wall (partition) which is located between the living room and bedroom not only separates these two spaces, but also includes some furniture such as TV, study desk, dining table, home office desk, home theater with a digital projector, and closets. By moving this wall, the living room and bedroom spaces can be expanded to provide an integrated area or shrunk when needed (Figure 7.4). Also, two murphy beds – one of them in the bedroom and the other one in the living room – have been designed to transform/convert this apartment into a two-bedroom apartment. Furthermore, to provide more visual and acoustic privacy for these two spaces, two magnetized curtains have been designed and applied. In general, the aforementioned features permit this space to be used, one at a time, as a living/lounge area for 8 people, a dining area for 6 people, and two bedrooms for 2 couples (https://lifeedited.com/about/).

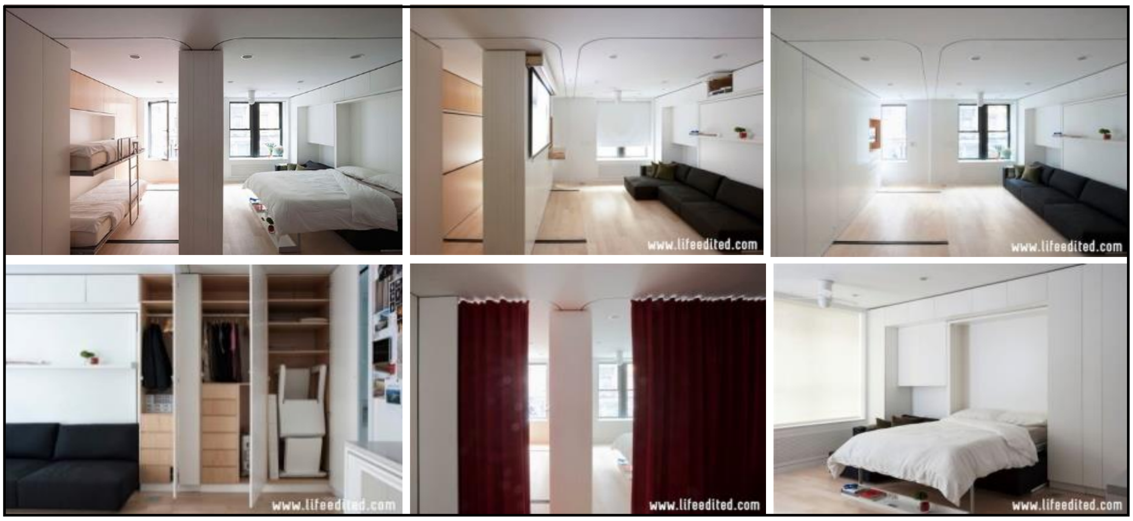
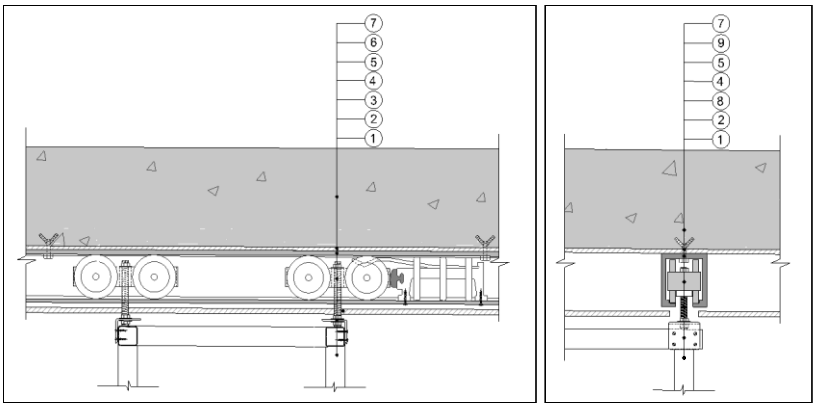


Figure 7.4. The LifeEdited-1 project

The construction systems were designed and applied for LifeEdited-1 elements such as movable walls and furniture, sliding doors, and curtains are track and trolley systems (Figure 7.5). In the improved version of LifeEdited-1, the mentioned system was applied from the ceiling due to the following reasons: (1) the ceiling connection versatility of the system and the straight-forward design allows the installation and maintenance to be much easier, convenient with a lower cost, and (2) the system is much smoother and less noisy since there is considerably less friction on the moving parts (https://www.jovoto.com/projects/lifeedited/ideas/10288?page=1&scope2=team_ideas&scope=rating,https://practicesports.com/playbook/track-trolley-kits-to-hang-netting/).



1. Standard rectangular structural hollow sections – HSS, Dimension 30*30*3 mm
2. Wall mounting bracket, Standard L- profile/ equal angles sections sizes 35mm
3. False ceiling, Knauf-KCF40A.L1C4, thickness 12 mm
4. four-wheeled trolleys, steel galvanized, Dimension 90*70*187 mm-hanger bolt M16
5. Predrilled running track, steel galvanized, U-shape steel 12*10 cm-Thickness 4mm
6. Ceiling finishing – 6 mm gypsum mortar with white water-based paint
7. Structural slab, reinforced concrete
8. Hanger bolt M16
9. Stainless steel butterfly screw GN 493

Figure 7.5. The construction system of scenario 4; track and trolly system

It is worthy to mention that the **technical**, **mechanical**, **and electrical system's characteristics** of scenario 4 are similar to the improved version of LifeEdited-1 as explained more in detail in the previous paragraphs and Table 7.1.

Table 7.1. The technical, mechanical, and electrical system's characteristics of scenario 4

		Scenario 4
Number of demolished walls		11 (All interior walls)
Applied materials	Wall	Drywall (stud, plasterboard, and water-based paint)
	Ceiling	False ceiling (false ceiling stud, plasterboard, and water-based paint)
	Floor	Parquet Direct Pressure Laminate (DPL), Size: 190*1200 mm, thickness: 10mm; and ceramic tile 50*50 cm for bathroom
Construction system	Movable elements	Track and trolley system (Figure 7.5)
HVAC	Cooling	Condensing Split (Inverter Split), LG ALL NEW GENCOOL(inverter) 24000BTU/hr
	Heating	Condensing Package (Iranradiator-ECO24C) and radiator (Iranradiator-termo 500, thermal capacity 126kcal/h per panel)
Insulation	Thermal insulation	5cm expanded polystyrene (EPS), thermal Conductivity = 0.042 W/mK, Wall U-Value = 0.704 W/m^{2}K
	Acoustic insulation	Vinyl layer, 4mm thickness
	Moisture insulation	Bituminous, 4mm thickness
Window	Window frame	Thermal Break Aluminum frame
	Window glass	Double Glazed Low-E Glass 6mm/13mm air
Mechanical ventilation	Kitchen	Dorsa Roya Diagonal Hood Size 90cm,680m^3/h
	Bathroom and WC	Exhaust fan = Simple flux mechanical ventilation system, FanIran, silent-100-CZ, 180 m^3 /h
Natural ventilation	Living room and bedroom	Four tilt and turn windows with a size of 1.10 *1.20 m
Natural lighting	Living room and bedroom	Two windows – 1.20*3.00 m – provide direct natural lighting

Also, **the architectural characteristics** of scenario 4 such as architectural plans and layouts, perspectives, and the size of the living and storage spaces have been presented in Figures 7.6 to 7.9 and Table 7.2. Moreover, the rehabilitation process of Aleph-1 with applying LifeEdited-1 has been presented in Figure 7.10.

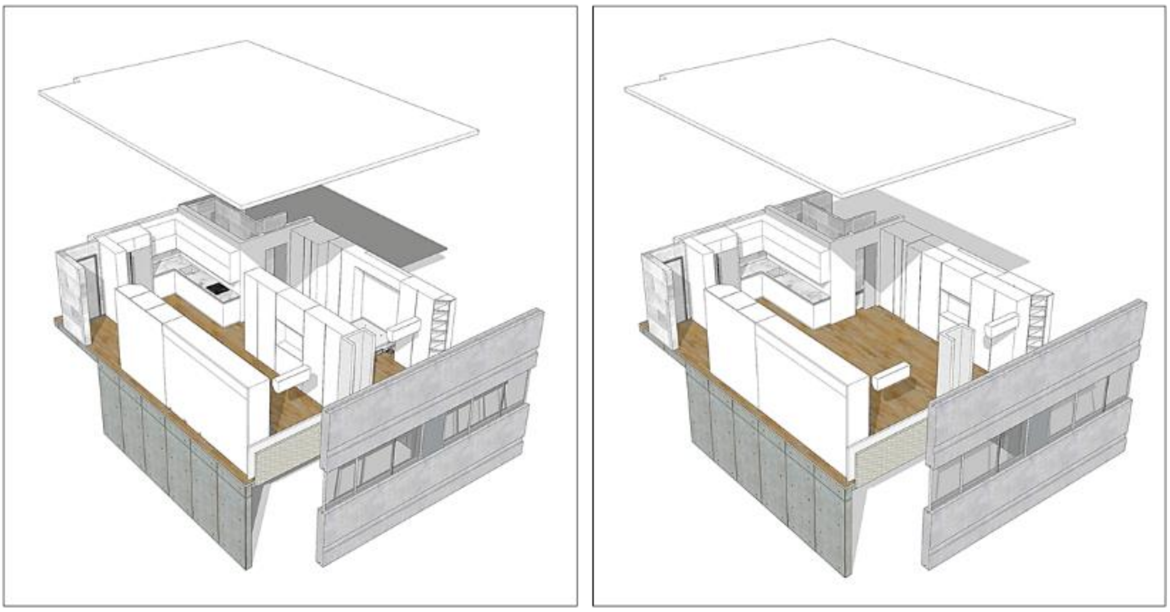
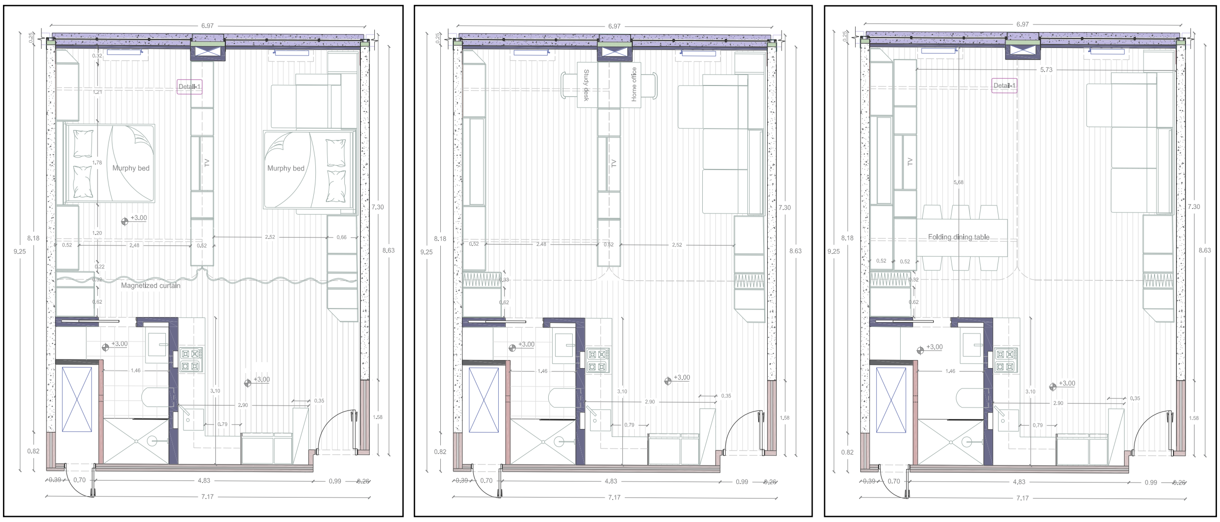


Figure 7.6. The different states of scenario 4



Cast-in-place reinforced concrete 350 kg/m3, thickness 200 mm

Metal stud and a 12.5 mm plasterboard, 50mm expanded polystyrene insulation

Prefabricated concrete panels with size of 7.00*1.20*0.25 m

Cement block size 400*200*100 mm, density 1200 kg/m3

Metal stud and two 12.5 mm moisture resistant plasterboard, thickness 200 mm

Solid Gypsum blocks size 666*500*100 mm, density 1100 kg/m3

Solid Gypsum blocks, size 666*500*60 mm, density 1100 kg/m3

Figure 7.7. Architectural plans – The different states of scenario 4

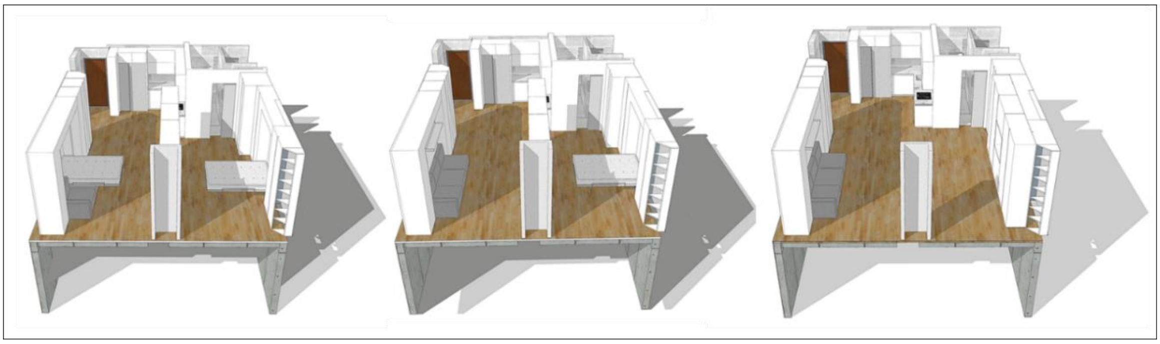
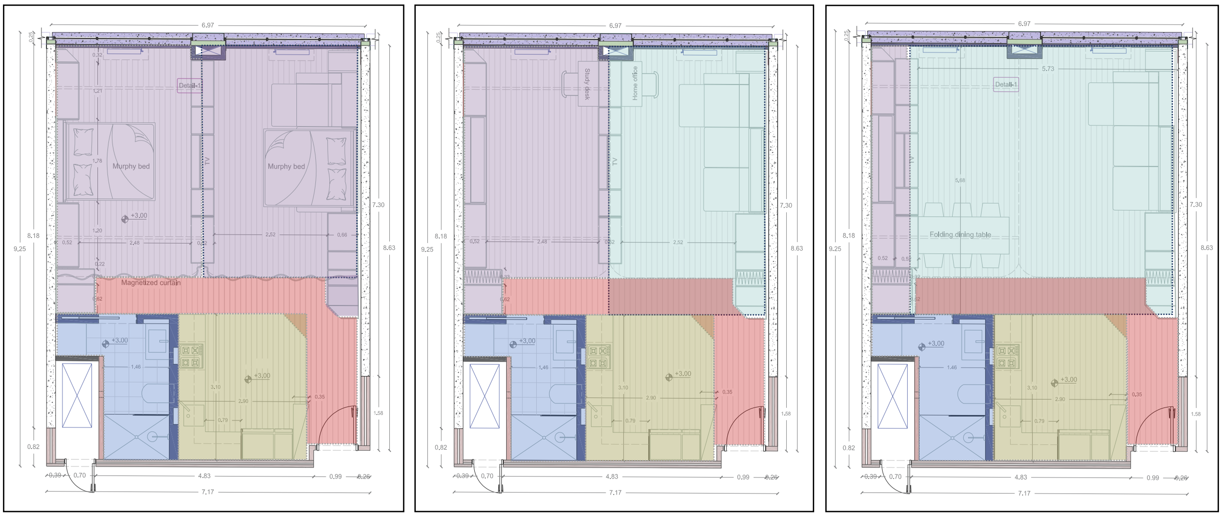


Figure 7.8. Perspectives, The different states of scenario 4



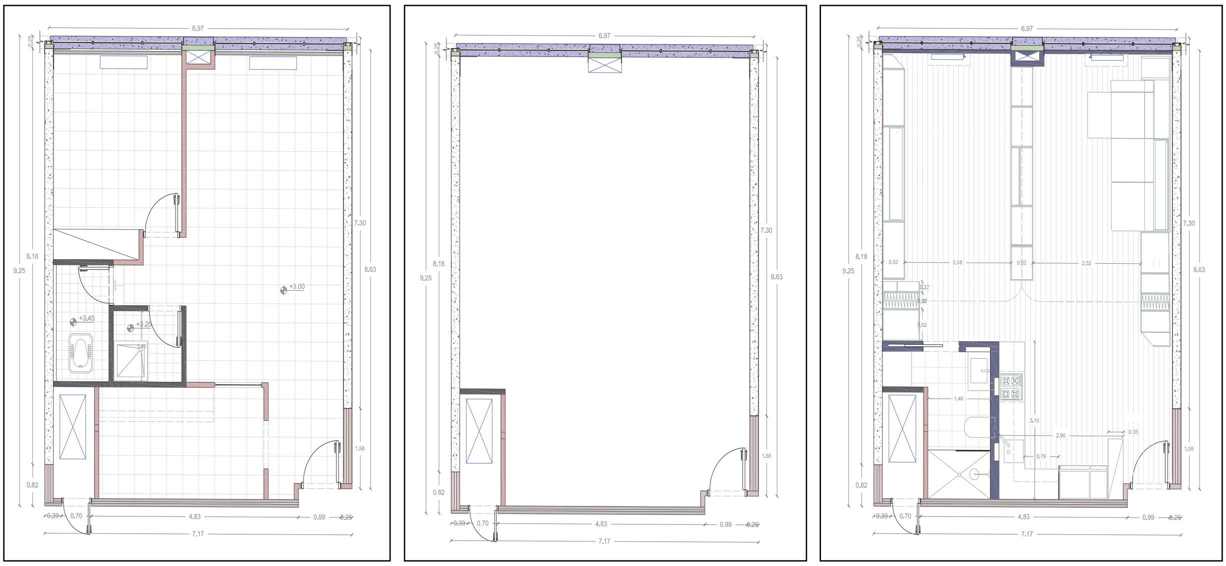
Living and dining room | Kitchen | Bedroom | Bathroom and WC | Entrance and circulation

Figure 7.9. Architectural layouts – The different states of scenario 4

As indicated in Table 7.2, by applying LifeEdited-1 to Aleph-1, **the useful area** and **storage spaces** of scenario 4 have increased from 54.13 m^2 and 4.74 m^3 up to 91.25 m^2 and 22.47 m^3 respectively.

Table 7.2. Architectural layouts and storage spaces

	Kitchen	Living space	Bedroom	Bathroom and WC	Entrance and circulation	Total
Useful area (m^2)	8.89	Up to 35.18	Up to 35.18	4.98	7.02	Up to 91.25
Storage spaces (m^3)	3.61	9.47	7.78	0.56	1.05	22.47



Cast-in-place reinforced concrete 350 kg/m3, thickness 200 mm

Metal stud and a 12.5 mm plasterboard, 50mm expanded polystyrene insulation

Prefabricated concrete panels with size of 7.00*1.20*0.25 m

Cement block size 400*200*100 mm, density 1200 kg/m3

Metal stud and two 12.5 mm moisture resistant plasterboard, thickness 200 mm

Solid Gypsum blocks size 666*500*100 mm, density 1100 kg/m3

Solid Gypsum blocks, size 666*500*60 mm, density 1100 kg/m3

Figure 7.10. The rehabilitation process of scenario 4. Left: The initial state of Aleph-1, middle: demolition process, right: scenario 4

7.3. Calculation of indicators' value for scenario 4

To calculate the values of the defined sustainability indicators for scenario 4, the employed methods besides their justifications have been explained in the following sub-sections.

7.3.1. The economic sustainability assessment of scenario 4

To evaluate the economic sustainability performance of scenario 4 through the defined indicators – indicators 1 to 5 –, the same methodology applied to scenarios 1 to 3 has been employed while the applied data collection method for this scenario has been explained in the following paragraphs:

1) To calculate **the values of the indicators 1**, **2**, **and 3** – initial rehabilitation cost, demolition cost, and maintenance cost respectively –, **the Quantity Take-Off (QTO)** of the applied products – construction materials and building components in the present thesis – has been calculated by employing **the Building Information Modeling (BIM)**. To do so, the general and specific data such as applied products and their relevant parameters (length, width, height, area, and volume), rehabilitation cost, and maintenance cost of LifeEdited-1 have been collected from the designers, constructors, and stakeholders of this project. Consequently, the collected data has been modified and inserted in a BIM tool, which is Autodesk Revit 2020 software, and exported by using the data-exporting function of Revit to obtain the QTOs – see Figure 7.11. Besides the BIM method, international guidelines – (National Association of Home Builders, 2017), (American Standard of Testing Materials: ASTM E1557–09, 2009) – National Building Rules and Regulations, scientific literature, and national databases – the ICMPL of 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019), (http://www.irceo.net/), (https://www.mporg.ir/en), (http://rmto.ir/) – have been employed to calculate the values of these indicators. Appendixes 7.A to 7.C and Table 7.3 present the values of I_1 to I_3 more in detail.

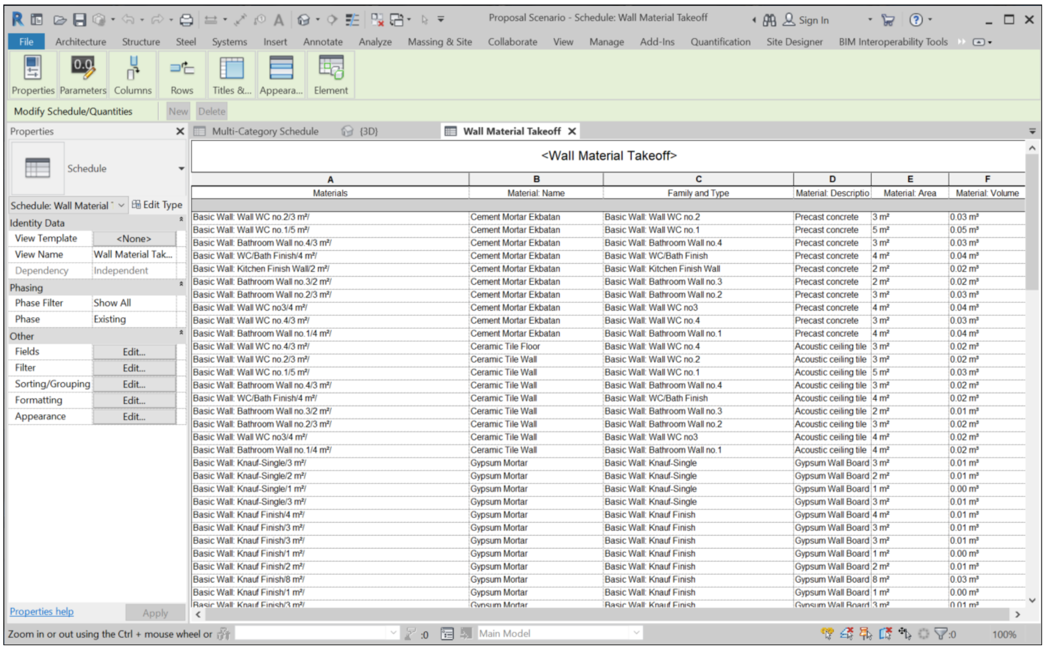


Figure 7.11. QTOs of scenario 4, developed in the BIM model

2) To calculate the value of **indicator 4**, which is the property added-value, nine real estate experts/agencies in Ekbatan were consulted. In this regard, the architectural layouts besides the 3D models of scenario 4 were sent to the selected experts and they were asked to price this project. Then the mean of the obtained prices was calculated and subtracted from the initial state price of Aleph-1 to obtain the value of I_4. Appendix 7.D and Table 7.3 present the value of I_4 more in detail.

3) To obtain the **rehabilitation process time (I_5)**, the author consulted the constructors of LifeEdited-1 project about the duration of this project's rehabilitation operations. Then, the obtained data was adapted to Aleph-1's particular context by considering constructors' and construction practitioners' opinions in Iran. The reported schedule has been developed by using **Microsoft Project Professional** software due to its simplicity and accuracy as shown in Appendix 7. E. Also, it is worthy to mention that to define the reported rehabilitation process time, the thesis author has considered 8 hours of work per day – from 8 am to 13 and from 16 to 19 according to specific buildings rehabilitation regulations in Ekbatan (see section 4.1.2.c) – and without any unforeseen work stoppages, which is applicable to Iran's present context. Table 7.3 presents the economic indicators' values for scenario 4.

Table 7.3. The economic indicators' values for scenario 4; AU: Apartment Unit

	Unit	Scenario 4	References and Methods
I_1. Initial rehabilitation cost	€/m^2	144.11	(BIM; ICMPL of 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019); https://www.cbi.ir/default_en.aspx; https://khedmatazma.com/subservice/building-repairs-and-reconstruction; https://seaart.ir/; https://sanjagh.pro; https://www.jadvalzarb.com/base/tools_119; https://www.arianparax.com/)
I_2. Maintenance cost	€/m^2.50yrs	88.10	(BIM; ICMPL of 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019); National Association of Home Builders, 2017; https://khedmatazma.com/subservice/building-repairs-and-reconstruction; https://seaart.ir/; https://sanjagh.pro, https://www.jadvalzarb.com/base/tools_119, https://www.arianparax.com/)
I_3. Demolition cost	€/m^2	8.35	(BIM; ICMPL of 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019); National Association of Home Builders, 2017; https://khedmatazma.com/subservice/building-repairs-and-reconstruction; https://seaart.ir/; https://sanjagh.pro; https://www.jadvalzarb.com/base/tools_119, https://www.arianparax.com/)
I_4. Property added-value	€/m^2.AU	19667	(Experts-based survey; https://ihome.ir/; https://kilid.com/; https://shabesh.com/; https://divar.ir/s/tehran/buy-apartment/)
I_5. Rehabilitation process time	Day	36	(BIM; Microsoft Project Professional; https://khedmatazma.com/subservice/building-repairs-and-reconstruction)

7.3.2. The environmental sustainability assessment of scenario 4

To evaluate the environmental sustainability performance of scenario 4 through its defined indicators – indicators 6 to 12 –, the same methodology applied to scenarios 1 to 3 has been employed (section 6.2). Appendixes 7.F to 7.J and Table 7.4 present the obtained values of environmental indicators.

Table 7.4. The environmental indicators' values for scenario 4

	Unit	Scenario 4	References
I_6. Embodied Energy (EE)	MJ/m^2	2723	(BIM; the University of Bath's Inventory of Carbon and Energy (ICE) database, Version 3.0 (Geoff and Craig, 2019); Environmental Product Declaration (EPD), 2015; Zabalza Bribián, Valero Capilla and Aranda Usón, 2011; Dilsiz, Felkner, Habert, & Nagy, 2019; Femando & Ekundayo, 2018; Hu, 2020; Klemeš, 2015; Monahan & Powell, 2011; Syngros, Balaras, & Koubogiannis, 2017)
I_7. Embodied Carbon (EC)	kgCO$_2$/m^2	70	(BIM; the University of Bath's Inventory of Carbon and Energy (ICE) database, Version 3.0 (Geoff and Craig, 2019); Environmental Product Declaration (EPD), 2015; Zabalza Bribián, Valero Capilla and Aranda Usón, 2011; Dilsiz, Felkner, Habert, & Nagy, 2019; Femando & Ekundayo, 2018; Hu, 2020; Klemeš, 2015; Monahan & Powell, 2011; Syngros, Balaras, & Koubogiannis, 2017)
I_8. Embodied Water (EW)	l/m^2	3361	(BIM; Environmental Product Declaration (EPD), 2015; Zabalza Bribián, Valero Capilla and Aranda Usón, 2011; ICMPL of 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019); National Association of Home Builders, 2017; McCormack *et al.*, 2007; Choudhuri and Roy, 2015; Bardhan and Choudhuri, 2016; Heravi and Abdolvand, 2019)
I_9. Construction Waste (CW)	kg/m^2	13	(BIM; ICMPL of 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019); Environmental Product Declaration (EPD), 2015; National Association of Home Builders, 2017; Llatas, 2010, 2013; Han et al., 2020; the Tehran Waste Management Organization (TWMO) (http://pasmand.tehran.ir/); Asgari et al., 2017)
I_{10}. Operational Energy (OE)	kWh/m^2/yr.	21.79	DesignBuilder version 6.1.6 and EnergyPlus; The National Regulations for Buildings of Iran (https://www.mrud.ir/en/en-us/), The standard ISIRI 14253(http://standard.isiri.gov.ir/SearchEn.aspx)
I_{11}. Operational Carbon (OC)	kgCO$_2$/m^2/yr.	11.57	DesignBuilder version 6.1.6 and EnergyPlus; The National Regulations for Buildings of Iran (https://www.mrud.ir/en/en-us/), The standard ISIRI 14253(http://standard.isiri.gov.ir/SearchEn.aspx)
I_{12}. Demolition Waste (DW)	kg/m^2	215	(BIM; ICMPL of 2019-2020 (Plan and Budget Organization of the Islamic Republic of Iran, 2019); Environmental Product Declaration (EPD), 2015; National Association of Home Builders, 2017; Llatas, 2010, 2013; Han et al., 2020; the Tehran Waste Management Organization (TWMO) (http://pasmand.tehran.ir/); Asgari et al., 2017)

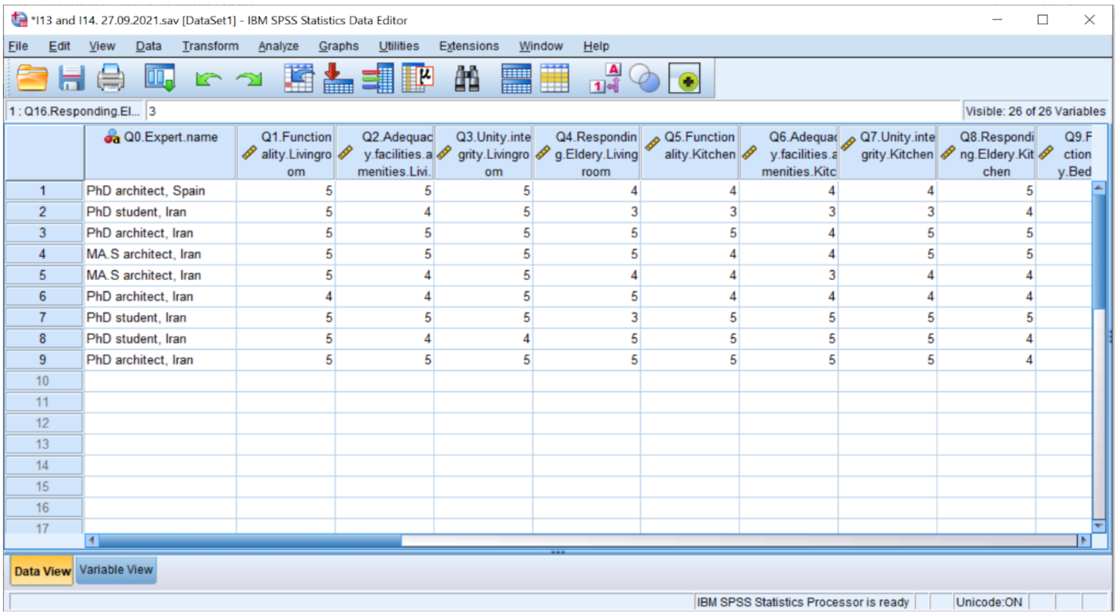
7.3.3. The social sustainability assessment of scenario 4

As previously mentioned in chapter 6, section 6.3, to evaluate the social sustainability aspect, which is the main driver behind the rehabilitation activities of residential buildings and MHs (van der Flier and Thomsen, 2006; Meijer, Itard and Sunikka-Blank, 2009; Thuvander *et al.*, 2012; Mustafa, 2016; Karji *et al.*, 2019a), several methods and tools have already been developed up to present (Karji *et al.*, 2019a). The main challenges for this evaluation are: (1) the difficulty in quantitatively measuring (McKenzie, 2004; Littig and Griessler, 2005; Karji *et al.*, 2019a), (2) the difficulty to define indicators' scopes, effective parameters, and data collection methods (Karji *et al.*, 2019a; Liu and Qian, 2019), and (3) the high subjectivity and dependency on user's opinions that can vary from person to person (Megahed and Gabr, 2010; Lindenthal, 2020).

To overcome the above-mentioned challenges, for the evaluation of social sustainability performance of scenarios 1 to 3, the user-based questionnaire survey was employed. Regarding **scenario 4** – which is **not a real built project**, there is **a lack of users' experience**, for the evaluation of all defined social indicators (I_{13} to I_{19}), the **expert-based questionnaire survey** has been employed. An expert-based questionnaire survey is a scientific approach widely accepted in the literature (Megahed and Gabr, 2010; Chuang, Liu and Liu, 2019; Olakitan Atanda, 2019). It is worthy to mention that in order to obtain more pierce and comparable results from both user- and expert-based questionnaires and facilitate the experts' judgment process, the following considerations have been taken into account: (a) for both questionnaires, the same scoring system – the Likert scale – has been employed, and (b) the obtained social indicators' values from the user-based questionnaires besides the main characteristics and photos of scenarios 1 to 3 have been presented in the expert-based questionnaires.

To design a proper framework for each expert-based questionnaire, the defined effective parameters of corresponding social indicators – see sections 6.3.1 to 6.3.5 – were explained and asked the respondents not only to clarify more in detail the different aspects of each indicator but also for obtaining more precise data and results. Moreover, the main characteristics of scenario 4 such as architectural layouts, applied materials, electrical and mechanical characteristics, and construction details besides its 3D models were presented in each questionnaire. Also, each questionnaire was designed by using a five-point Likert scale, where 5 represents highly appropriate, 4 represents appropriate, 3 represents neutral, 2 represents inappropriate, and, 1 represents highly inappropriate. Subsequently, three different expert-based questionnaires were designed for the evaluation of social indicators due to the diversity of their expert domains. Appendixes 7.K to 7.M present the mentioned questionnaires in more in detail. It is worthy to mention that by designing the aforementioned framework for the expert-based questionnaires, the author attempted to reduce the subjectivity of social indicators and proposed objective and reliable solutions for assessing the mentioned indicators.

To conduct the designed questionnaires, **five to nine experts** – which is the minimum required number of experts for conducting a scientific expert-based questionnaire (Ikart, 2019) – according to **their expertise domain regarding each social indicator** were selected to be interviewed via email or by phone. To analyze the collected data, this data was inserted into IBM SPSS Statistics V. 22 software (Figure 7.12). Subsequently, to obtain the value of social indicators, the mean of the collected data for each indicator besides its standard deviation has been calculated. Tables 7.5 to 7.11 present the values of social indicators.



	Q0.Expert.name	Q1.Functionality.Livingroom	Q2.Adequacy.facilities.amenities.Livi.	Q3.Unity.integrity.Livingroom	Q4.Responding.Eldery.Livingroom	Q5.Functionality.Kitchen	Q6.Adequacy.facilities.amenities.Kitc	Q7.Unity.integrity.Kitchen	Q8.Responding.Eldery.Kitchen	Q9.Function.y.Bed
1	PhD architect, Spain	5	5	5	4	4	4	4	5	
2	PhD student, Iran	5	4	5	3	3	3	3	4	
3	PhD architect, Iran	5	5	5	5	5	4	5	5	
4	MA.S architect, Iran	5	5	5	5	4	4	5	5	
5	MA.S architect, Iran	5	4	5	4	4	3	4	4	
6	PhD architect, Iran	4	4	5	5	4	4	4	4	
7	PhD student, Iran	5	5	5	3	5	5	5	5	
8	PhD student, Iran	5	4	4	5	5	5	5	4	
9	PhD architect, Iran	5	5	5	5	5	5	5	4	

Figure 7.12. The inserted data in SPSS for evaluation of I_{13} and I_{14}

Table 7.5. The value of I_{13} of scenario 4

Satisfaction regarding:		Scenario 4				
		Livingroom	Kitchen	Bedroom	Bathroom and WC	Total
1. **Flexibility** and **multifunctionality** of space	Mean	4.89	4.33	4.67	4.33	4.56
	Std. Deviation	.333	.707	.500	.707	.562
2. Adequacy of **necessary facilities** and amenities	Mean	4.56	4.11	4.78	4.22	4.42
	Std. Deviation	.527	.782	.441	.833	.646
3. Unity and **integrity** of space	Mean	4.89	4.44	4.56	4.44	4.58
	Std. Deviation	.333	.726	.726	.527	.575
4. Responding to specific needs of **elderly** or the **disabled people**	Mean	4.33	4.44	4.00	3.89	4.17
	Std. Deviation	.866	.527	.707	.782	.720
The total value of I_{13}	Mean					**4.43**
	Std. Deviation					.627

Table 7.6. The value of I_{14} of scenario 4

Satisfaction regarding:		Scenario 4				
		Livingroom	Kitchen	Bedroom	Bathroom and WC	Total
1. Size of space	Mean	4.89	4.44	4.67	4.44	4.61
	Std. Deviation	.333	.726	.500	.726	.572
2. Storage space	Mean	4.89	4.56	4.89	4.33	4.67
	Std. Deviation	.333	.527	.333	.707	.475
The total value of I_{14}	Mean					**4.64**
	Std. Deviation					.523

Table 7.7. The value of I_{15} of scenario 4

Satisfaction regarding:		Scenario 4				
		Livingroom	Kitchen	Bedroom	Bathroom and WC	Total
1. Cooling	Mean	4.14	3.86	4.43	2.86	3.82
	Std. Deviation	.690	.378	.535	.690	.573
2. Heating	Mean	4.43	4.43	4.71	3.71	4.32
	Std. Deviation	.535	.535	.488	.488	.511
The total value of I_{15}	Mean					**4.07**
	Std. Deviation					.542

Table 7.8. The value of I_{16} for scenario 4

Satisfaction regarding:		Scenario 4				
		Livingroom	Kitchen	Bedroom	Bathroom and WC	Total
1. Mechanical ventilation system	Mean	-	4.00	-	3.71	3.86
	Std. Deviation		.577		.488	.533
2. Natural ventilation and **Fresh air**	Mean	4.14	3.43	4.14	2.57	3.57
	Std. Deviation	.690	.535	.690	.787	.675
The total value of I_{16}	Mean					**3.67**
	Std. Deviation					.628

Table 7.9. The value of I_{17} for scenario 4

Satisfaction regarding:		Scenario 4				
		Livingroom	Kitchen	Bedroom	Bathroom and WC	Total
1. Natural light	Mean	4.00	3.60	4.00	-	3.87
	Std. Deviation	.000	.548	.000		.183
The total value of I_{17}	Mean					**3.87**
	Std. Deviation					.183

Table 7.10. The value of I_{18} for scenario 4

Satisfaction regarding:		Scenario 4				
		Livingroom	Kitchen	Bedroom	Bathroom and WC	Total
1. Outdoor noise	Mean	4.00	4.20	4.00	-	4.07
	Std. Deviation	.000	.447	.000		.149
2. Indoor noise	Mean	3.80	3.60	2.60	-	3.33
	Std. Deviation	.447	.548	1.140		.721
The total value of I_{18}	Mean					**3.70**
	Std. Deviation					.430

Table 7.11. The value of I_{19} for scenario 4

Satisfaction regarding:		Scenario 4				
		Livingroom	Kitchen	Bedroom	Bathroom and WC	Total
1. Form, **shape**, and **geometrical composition**	Mean	4.78	4.22	4.67	4.11	4.44
	Std. Deviation	.441	.667	.500	.782	.597
2. Details quality	Mean	4.78	4.22	4.78	4.11	4.47
	Std. Deviation	.441	.667	.441	.782	.583
3. Harmony	Mean	4.56	4.44	4.44	4.22	4.42
	Std. Deviation	.527	.527	.527	.667	.562
4. Creativity and innovation of design	Mean	4.78	4.11	4.67	3.78	4.33
	Std. Deviation	.441	.601	.500	.667	.552
The total value of I_{19}	Mean					**4.42**
	Std. Deviation					.574

7.4. Global Sustainability index (GS_i) assessment of scenario 4

The author has evaluated the Global Sustainability index (GS_i) of scenario 4 by conducting the sixth stage (6. c) of the proposed MIVES-Delphi model – section 3.2 –, as it was previously applied to the three studied existing scenarios (scenarios 1 to 3). In this regard, the obtained indicators' values of scenario 4 – from section 7.3 – were converted to indicators' non-dimensional values (Table 7.12) by application of the defined value functions – see Appendix 3.B. Consequently, by considering the previously defined decision-making tree – section 3.2, Figure 3.3 –, its components' weights – section 3.2, Figure 3.4 –, and the obtained indicators' non-dimensional values, the GSi of scenario 4 has been calculated through Equations 3.5 to 3.7.

Table.7.12. Value functions, indicators values, and Non-dimensional indicators' values for scenarios 1 to 3

#R		Unit	Shape	X_{max}	X_{min}	C_i	K_i	P_i	Indicator's value	Non-dimensional indicator's value
									Scenario 4	Scenario 4
Economic	I_1. Initial rehabilitation cost	€/m²	DCx	200	50	115	0.05	2.00	144.11	0.14
Economic	I_2. Maintenance cost	€/m².50yrs	DCx	200	70	135	0.10	1.50	88.10	0.81
Economic	I_3. Demolition cost	€/m²	DCv	12	8	10	0.15	0.70	8.35	0.95

	I_4. Property added-value	€/m².AU	ICx	26074	0	9017	0.10	1.50	19667	0.71
	I_5. Rehabilitation process time	Day	DL	60	20	40	0.0	1.00	36	0.60
Environmental	I_6. Embodied Energy (EE)	MJ/m²	DCx	1300	7300	3250	0.10	0.80	2723	0.82
	I_7. Embodied Carbon (EC)	$kgCO_2/m^2$	DCx	50	450	250	0.60	0.70	70	0.98
	I_8. Embodied Water (EW)	l/m²	DCx	2000	5000	3500	1.00	0.60	3361	0.79
	I_9. Construction Waste (CW)	kg/m²	DCv	10	50	21.86	1.00	0.60	13	0.98
	I_{10}. Operational Energy (OE)	kWh/m2/yr.	DCv	0	95	47.5	0.05	2.50	21.79	0.56
	I_{11}. Operational Carbon (OC)	$kgCO_2/m^2/yr.$	DCx	0	75	37.5	0.05	2.50	11.57	0.68
	I_{12}. Demolition Waste (DW)	kg/m²	DCx	150	750	450	1.00	0.80	215	0.95
Social	I_{13}.Functionality of the physical space	Points	ICx	5	1	3	0.50	2.50	4.43	0.74
	I_{14}.Adequate spaces & storages	Points	ICx	5	1	3	0.40	2.00	4.64	0.86
	I_{15}.Thermal comfort	Points	ICx	5	1	3	0.50	2.00	4.07	0.69
	I_{16}.Indoor air quality	Points	ICx	5	1	3	0.50	1.50	3.67	0.64
	I_{17}.Lighting comfort	Points	ICx	5	1	3	0.50	1.50	3.87	0.70
	I_{18}.Acoustic comfort	Points	ICx	5	1	3	0.50	1.50	3.70	0.65
	I_{19}. Aesthetic & building beauty	Points	ICx	5	1	3	0.40	2.50	4.42	0.76

Legend: DCx: Decreasing Convex; DL: Decreasing Lineal; DCv: Decreasing Concave; ICx: Increasing convex; IL: Increasing Linear; ICv: Increasing concave; IS: Increasing S-shape; DS: Decreasing S-shape; AU: Apartment Unit.

The resulting global sustainability index (GSi) for scenario 4 is 0.71. Table 7.13 depicts all the results from this evaluation, including this GS_i as well as requirements values (VR_i, i = 1 to 3), criteria values (VCj, j = 1 to 9), and indicators values (VI_k, k = 1 to 19) for this scenario.

Table 7.13. The value of the Global sustainability index (GS_i) of scenario 4

	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**
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
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

	VI_{10}	**VI_{11}**	**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**	**GS_i**
Weight (ω)	0.57	0.43	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 4	0.56	0.68	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**

7.5. Discussion, interpretation, and sensitivity of the global sustainability index

As previously explained in the introduction of this chapter, this section is divided into two sub-sections 7.5.1 and 7.5.2. Sub-section 7.5.1 analyzes, interprets, and discusses the obtained results of scenario 4 and compares it with the other three defined scenarios. Furthermore, sub-section 7.5.2 conducts the last stage of the proposed MIVES-Delphi model to prove its suitability, validity, and robustness by conducting a sensitivity analysis.

7.5.1. Discussion, comparison, and interpretation of sustainability performance of scenarios 1-4

This sub-section aims to: (a) compare the **obtained results from all four defined scenarios**, (b) provide valuable information regarding the **main sustainability issues of each scenario** and consequently **their needed crucial improvement points**, (c) find the **most sustainable rehabilitation scenario** for interior rehabilitation of Aleph-1 among the studied ones, and (d) **test validity of the assumed hypothesis** – see section 1.3.

a) Comparison of the obtained results from scenarios 1 to 4

This part discusses, compares, and interprets the obtained results from scenarios 1 to 3 – see sections 6.4 – and scenario 4 – see section 7.4 – with each other from GS_is, requirements values (VR_i), criteria values (VC_j), and indicators values (VI_k) points of view separately. Table 7.14 and Figure 7.13 present the obtained values of the sustainability requirements for all four defined scenarios.

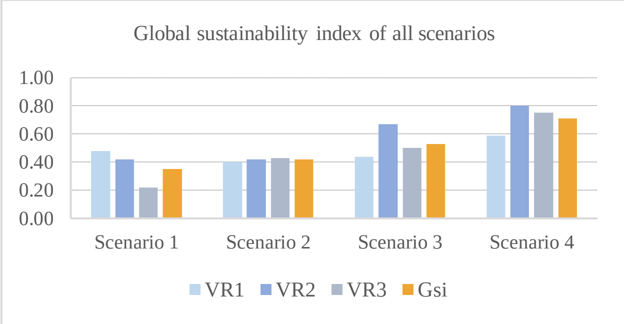


Figure 7.13. Global sustainability index of scenarios 1 to 4

Table 7.14. The value of the Global sustainability index (GS_i) 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}	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	GS_i
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	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	0.64	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	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	0.47	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	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	0.23	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	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	0.14	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	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**

i) 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 for all four scenarios **mostly fell in the middle-value range**, the **highest economic requirement value belongs to scenario 4** mainly due to its better performance in maintenance cost (I_2), demolition cost (I_3), and property added-value (I_4) which is explained more in detail in the following paragraphs. On the other hand, scenario 1 obtained the highest initial rehabilitation cost (I_1) and rehabilitation process time (I_5). The difference between the obtained 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 worthy to mention that **none of the analyzed scenarios met the standard minimum target value of economic sustainability**.

Table 7.15. Economic sustainability values of scenarios 1 to 4.

	VI_1	VI_2	VI_3	VI_4	VC_1	VI_5	VC_2	VR_1
Weight (ω)	0.34	0.25	0.15	0.26	0.77	1	0.23	**0.32**
Scenario 1	0.64	0.05	0.41	0.01	0.29	0.85	0.85	**0.48**
Scenario 2	0.47	0.36	0.11	0.26	0.33	0.55	0.55	**0.40**
Scenario 3	0.23	0.49	0.49	0.52	0.41	0.50	0.50	**0.44**
Scenario 4	0.14	0.81	0.95	0.71	0.58	0.60	0.60	**0.59**

Legend: VR_i = Value of economic requirement, VC_j = Value of economic criteria, and VI_k = Value of economic indicators

Regarding **the rehabilitation cost (I_1)** and **the rehabilitation process time (I_5)**, **scenario 1** has the **greatest satisfaction values** where **partial rehabilitation** was implemented that caused the least initial rehabilitation cost and rehabilitation process time concerning the other three scenarios. On the contrary, **scenario 4** obtained **the lowest I_1 satisfaction value** – almost 0.50 satisfaction value less than scenario 1 – where an **integral rehabilitation** was implemented. On the other hand, **scenario** 4 obtained **the greatest satisfaction values in the maintenance cost (I_2)**, **demolition cost (I_3)**, and **property added-value (I_4)** – almost 0.76, 0.54, and 0.70 more than scenario 1 respectively – due to its higher quality and durability of the applied materials, improved construction techniques and design, and less need of repairing and maintenance during the building lifespan.

ii) In terms of **the environmental requirement** (VR_2), scenarios 1 to 4 obtained values 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 of the environmental indicators**, this scenario has 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}) which have been explained in the following paragraphs. It is worth noting that **only scenario 4 met the standard minimum target value of environmental sustainability**.

Table 7.16. Environmental sustainability values of scenarios 1 to 4.

	VI_6	VI_7	VI_8	VC_3	VI_9	VC_4	VI_{10}	VI_{11}	VC_5	VI_{12}	VC_6	VR_2
Weight (ω)	0.42	0.34	0.24	0.27	1	0.17	0.57	0.43	0.4	1	0.16	**0.26**
Scenario 1	0.67	0.76	0.42	0.64	0.49	0.49	0.17	0.41	0.27	0.37	0.37	**0.42**
Scenario 2	0.77	0.89	0.38	0.71	0.19	0.19	0.19	0.42	0.29	0.47	0.47	**0.42**
Scenario 3	0.79	0.88	0.76	0.81	0.88	0.88	0.36	0.54	0.43	0.80	0.80	**0.67**
Scenario 4	0.82	0.98	0.79	0.86	0.98	0.98	0.56	0.68	0.61	0.95	0.95	**0.80**

Legend: VR_i = Value of environmental requirement, VC_j = Value of environmental criteria, and VI_k = Value of environmental indicators

Regarding **the embodied energy (I_6)**, **embodied carbon (I_7)**, and **embodied water (I_8)**, although scenario 4 had better performance compared to the other three scenarios, **there is a contrast among the values** of these indicators due to **not considering these indicators in the design phase**.

In the case of **the construction and demolition waste (I_9 and I_{12})**, scenario 4 has the highest satisfaction values – almost 0.79 and 0.48 more than scenario 2 respectively – because of the heavy materials used in scenario 2 – e.g., the brick walls, cement mortars, and clay plaster.

Regarding **operational energy (I_{10})**, and **operational carbon (I_{11})**, scenario 4 has a **significantly better performance** compared to the other scenarios due to the improvements in its thermal insulations, applied HVAC systems, and applied windows.

iii) In the case of **the social requirement** (VR_3), scenarios 1 to 4 obtained values 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 except the acoustic comfort (I_{18})** as explained more in detail in the following paragraphs. It is remarkable that **only scenario 4 met the standard minimum target value of social sustainability**.

Table 7.17. Social sustainability values of scenarios 1 to 4.

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

Legend: VR_i = Value of social requirement, VC_j = Value of social criteria, and VI_k = Value of environmental indicators

Regarding **the functionality performance of interior spaces (I_{13})** and **adequate spaces and storage (I_{14})**, **scenario 4 has significantly better performance** – almost 0.61 and 0.64 more than scenario 1 respectively – due to its design that provides more **flexible and multifunctional** spaces with more **unity** and **integrity**, more **adequate facilities and amenities**, and more **living and storage spaces**. It is worthy to mention that scenarios 2 and 3 had almost similar performances regarding these two indicators – scenario 2 = 0.34 and scenario 3 = 0.37 for I_{13} and scenario 2 = 0.41 and scenario 3 = 0.49 for I_{14} – because of the similarity of these scenarios 2 and 3 space distributions and architectural layouts.

In the case of **thermal comfort (I_{15})**, **scenarios 3 and 4** obtained almost the **same values** – 0.64 and 0.69 respectively – due to their similar applied HVAC systems – package and radiators for heating and air conditioner splits for cooling –, which caused higher thermal satisfaction compared to scenarios 1 and 2 – fan coils as their HVAC system.

Regarding **indoor air quality (I_{16})** and **lighting comfort (I_{17})**, **scenarios 2**, **3**, **and 4 attained almost the same values** because of their similarity in the space distribution, while scenario 1 has the lowest indoor air quality and lighting satisfaction due to its enclosed kitchen space.

Regarding **acoustic comfort (I_{18})**, while **scenario 4** has **slightly better** performance in **outdoor acoustic comfort** due to the application of acoustic insulations in its skin – vinyl layer, 4 mm thickness –, it has **significantly lower** performance in **indoor acoustic comfort** – where a movable wall and magnetized curtains have been applied for separating the living and bedroom spaces – in comparison with the other three scenarios. Consequently, the **total acoustic performance of scenario 4** attained **the lowest value**.

In the case of **the aesthetic and beauty of the interior spaces (I_{19})**, **scenario 4 obtained the highest satisfaction value** – almost 0.75 more than scenario 1 – in comparison with the other scenarios because of its better performance in **form**, **shape**, and **geometrical composition**, **details quality**, **harmony**, and **creativity and innovation of design**.

b) Identification of main sustainability issues of each scenario and their needed crucial improvement points

To identify the **main sustainability issues** of each scenario, it is essential to **compare the obtained value of each indicator** besides determining which indicator has more **influence and contribution** – greater relative weight – on the GSi of that scenario. To do so, Tables 3.4 and 7.18 present **the obtained indicators' values** and the **indicators' contribution weights** ($C\omega_{Ik}$) on the GSi.

Table 7.18. The obtained indicators' values and the contribution weight ($C\omega_{Ik}$) of each indicator on the GS_i

Rank	Indicator	Indicator name	$C\omega_{Ik}$	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	I_{19}	Aesthetic & building beauty	10.9%	0.01	0.36	0.44	0.76
2	I_{13}	Functionality of the physical space	9.3%	0.13	0.34	0.37	0.74
3	I_1	Initial rehabilitation cost	8.4%	0.64	0.47	0.23	0.14
4	I_{14}	Adequate spaces & storages	8.3%	0.22	0.41	0.49	0.86
5	I_5	Retrofitting process time	7.4%	0.85	0.55	0.50	0.60
6	I_4	Property added-value	6.4%	0.01	0.26	0.52	0.71
7	I_2	Maintenance cost	6.2%	0.05	0.36	0.49	0.81
8	I_{10}	Operational Energy (OE)	5.9%	0.17	0.19	0.36	0.56
9	I_{11}	Operational Carbon (OC)	4.5%	0.41	0.42	0.54	0.68
10	I_9	Construction Waste (CW)	4.4%	0.17	0.19	0.36	0.98
11	I_{15}	Thermal comfort	4.3%	0.34	0.40	0.64	0.69
12	I_{12}	Demolition Waste (DW)	4.2%	0.37	0.47	0.80	0.95
13	I_3	Demolition cost	3.7%	0.41	0.11	0.49	0.95
14	I_{17}	Lighting comfort	3.4%	0.49	0.67	0.66	0.70
15	I_{16}	Indoor air quality	3.0%	0.27	0.57	0.59	0.64
16	I_6	Embodied Energy (EE)	2.9%	0.67	0.77	0.79	0.82
17	I_{18}	Acoustic comfort	2.8%	0.69	0.70	0.70	0.65
18	I_7	Embodied Carbon (EC)	2.4%	0.76	0.89	0.88	0.98
19	I_8	Embodied Water (EW)	1.7%	0.42	0.38	0.76	0.79

Legend: $C\omega_{Ik}$ = Contribution weight of each indicator

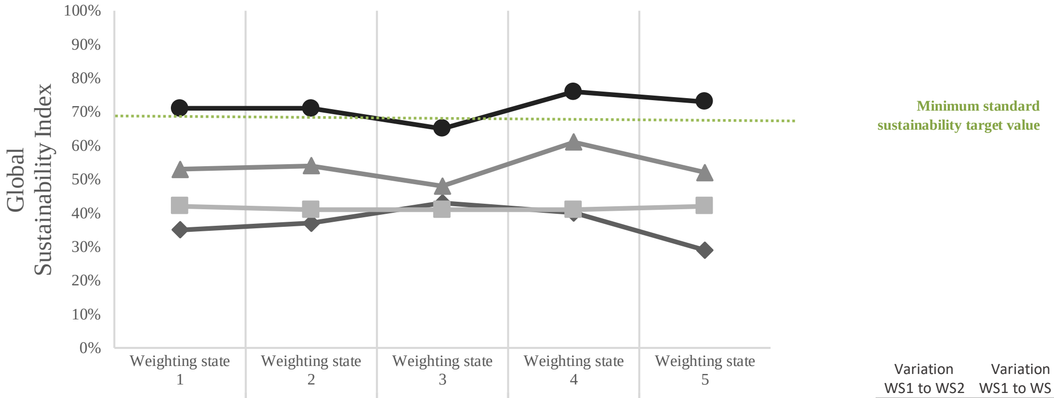
In the conclusion of chapter 6, the main sustainability issues of each first three scenarios were explained. Moreover, the **main sustainability issue** of scenario 4 is I_1. initial rehabilitation cost that obtained a value of less than 0.30.

c) Find the most sustainable rehabilitation scenario for interior rehabilitation of Aleph-1

The resulting **global sustainability index (GSi)** 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 GSis of scenarios 1 to 3 respectively.

7.5.2. Prove suitability, validity, and robustness of the proposed MIVES-Delphi model

This section conducts the 7th and the last stage of the proposed MIVES-Delphi based model **to prove** its **suitability**, **validity**, **and robustness** by conducting a **sensitivity analysis**. In this regard, as the global sustainability index (GSi) quantification depends directly on the weighting of the requirements tree components (Gilani, 2020; Habibi, Pons and Pena, 2020; Hosseini, Yazdani and De, 2020; Ledesma, Nikolic and Pons, 2020), its consistency in different weighing states – based on different situations and conditions – proves the relative objectivity and validity of the proposed model. Although the employment of the Delphi and BIAS reduction techniques could further improve the proposed model (Ledesma, Nikolic and Pons, 2020), **applying sensitivity analyses** by consideration of different and diverse probabilistic weighting states **enhance the proposed model's robustness**. In this regard, the GSis of all four defined scenarios were recalculated and assessed by changing the assigned weights for their requirements (ωR_i) in five different probabilistic weighting states as shown in Figure 7.14. These five weighting states are: Weighting state 1 represents the assigned weights – Ec=32%, En=26%, Sc=42% – by experts in section 3.2, Weighting state 2 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 Weighting state 3 the greater weight placed on the economic requirement – Ec=70%, En=15%, Sc=15% –, in Weighting state 4 the environmental requirement has the greatest value – Ec=15%, En=70%, Sc=15% –, and Weighting state 5 consists the greatest social requirement – Ec=15%, En=15%, Sc=70%.



	Weighting state 1	Weighting state 2	Weighting state 3	Weighting state 4	Weighting state 5
Scenario 1	35%	37%	43%	40%	29%
Scenario 2	42%	41%	41%	41%	42%
Scenario 3	53%	54%	48%	61%	52%
Scenario 4	71%	71%	65%	76%	73%

Variation WS1 to WS2	Variation WS1 to WS 3	Variation WS1 to WS4	Variation WS1 to WS5
2%	8%	5%	-6%
-1%	-1%	-1%	0%
1%	-5%	8%	-1%
0%	-6%	5%	2%

Figure 7.14. Sensitivity analysis and variations of each weighting state for the defined scenarios Weighting state 1 (Ec=32%, En=26%, Sc=42%), Weighting state 2 (Ec=33.33%, En=33.33%, Sc=33.34%), Weighting state 3 (Ec=70%, En=15%, Sc=15%), Weighting state 4 (Ec=15%, En=70%, Sc=15%), Weighting state 5 (Ec=15%, En=15%, Sc=70%).

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 0.08 as shown in Figure 7.14. Therefore, as the GS_i variations are less than ±10% (Gilani, 2020; Habibi, Pons and Pena, 2020; Hosseini, Yazdani and De, 2020; Ledesma, Nikolic and Pons, 2020), **the robustness of the proposed MIVES-Delphi model has been achieved**. It is worthy to mention that in most weighting states (1, 2, 4 and 5), only scenario 4 attained the standard minimum target value of GS_i – 70%. 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 minimum target value. Also, in all weighing states, the trends of GSis for all scenarios were monotonic, except in weighting state 3 that scenario 2 attained the lowest value.

7.6. Conclusion of chapter 7

This section concludes the previous results obtained from the 6th and 7th stages of the proposed MIVES-Delphi model.

The **6th stage** was successfully applied to the defined scenarios that three of them (scenarios 1 to 3) were existing real rehabilitation projects in the selected case study as representatives and the most common rehabilitation activities in Iran and the fourth one was a rehabilitation project constructed with new or improved rehabilitation techniques (scenario 4). The conclusions derived from the 6th stage of the proposed model are as follows:

a) **scenario 1** – where **the partial rehabilitation** was implemented –, obtained **the lowest value in GSi** in comparison with the other three scenarios. Also, it was revealed that this scenario has serious sustainability issues in several defined sustainability indicators such as $I_{19.}$ aesthetic and building beauty, I_{13}. functionality of the physical space, I_{14}. adequate spaces and storages, I_4. property added-value, I_2. maintenance cost, I_{10}. Operational Energy (OE), I_9. Construction Waste (CW), and I_{16}. indoor air quality. Therefore, **partial rehabilitation could not serve as a solution for sustainable interior rehabilitation**.

b) **scenarios 2 and 3**, **which are the** most common existing rehabilitation activities and techniques in Iran, attained **the middle range of GSi values**. It is worth noting that although these two scenarios have some similarities in their space distribution and architectural plans, they obtained different GSi values – $GSi_{\text{scenario 2}} = 0.42$ and $GSi_{\text{scenario 3}} = 0.53$ – mainly due to the better performance of scenario 3 regarding environmental indicators. Moreover, considering the fact that these common rehabilitation techniques in Iran had better sustainability performance in comparison with partial rehabilitations, but they still **could neither meet the minimum sustainability target value nor serve as proper solutions for interior rehabilitation**.

c) scenario 4 which is an applied interior rehabilitation project constructed with new or improved techniques on Aleph-1, obtained significantly greater GSi value than three other scenarios – 0.36, 0.29, and 0.18 in comparing with scenarios 1 to 3 respectively. Moreover, only this scenario could meet the standard minimum target value of GSi. Therefore, **the assumed hypothesis of the present thesis has been satisfactorily validated.** In this regard, it can be concluded that **the new and improved rehabilitation activities are more sustainable alternatives than other common existing interior rehabilitation techniques in Iran** and they could have positive effects on increasing the social and economic performance as well as decreasing the negative environmental impacts of buildings during their whole lifecycle.

d) Although **scenario 4** attained the mentioned minimum target value for social and environmental requirements, it **could not achieve** the mentioned target value **in economic requirement**. Therefore, there is still an important room for improving the/its economic requirement, particularly regarding I_1.initial rehabilitation cost that this indicator should be considered in the design phase.

Moreover, the **7th** and the last stage of the proposed MIVES-Delphi model was successfully carried out by conducting a sensitivity analysis that considered five different probabilistic weighting states. As the obtained GSi variations under these different weighting states were less than ±10%, this conducted sensitivity analysis proved the relative objectivity, validity, and robustness of the proposed model. The conclusions derived from this 7th stage are as follows:

a) 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**.

b) In **all weighting states**, **only scenario 4** attained **the standard minimum target value of** GS_i **except in the third weighting state** – where the economic requirement was considered with the highest weight. Therefore, it can be concluded that this scenario still needs improvements in its defined economic requirement.

c) Also, in **all weighing states**, the trends of GSis for all scenarios were **monotonic**, **except in weighting state 3** that scenario 2 attained the lowest value. These monotonic trends confirmed the higher obtained requirement values of scenarios 3 and 4 compared to scenarios 1 and 2.

CHAPTER 8

Conclusions

Chapter 8: Conclusions

Introduction

This final chapter aims to present and discuss the conclusions of the present doctoral dissertation as explained in the following sections:

1) Section 8.1 investigates the **fulfillment** of the **defined hypothesis and objectives** of this dissertation – see sections 1.3 and 1.4 – as the **main conclusions**.

2) Section 8.2 draws some conclusions from both **descriptive** and **operational** points of view in the present thesis – see section 1.6 – as the **specific conclusions**.

3) Section 8.3 proposes several uncovered topics as **future research lines** and perspectives.

8.1. Main conclusions

This main conclusion section evaluates the fulfillment of the defined hypothesis and objectives of the present thesis in two following parts:

In the first part, to achieve the main defined thesis objective – see section 1.4 – which is **contributing to moving forward more sustainable rehabilitation activities and techniques for interior rehabilitation of MHs in Iran**, the following four specific objectives were defined and satisfactorily fulfilled:

1) A **novel Multi-Criteria Decision Making (MCDM) model** based on the **MIVES** and **Delphi** methods for **holistic sustainability assessment of interior rehabilitation of MHs in Iran** was **successfully developed and validated** through its defined seven stages. This MIVES-Delphi model relied on a comprehensive literature review – including relevant scientific literature, international guidelines, and national building rules and regulations –, seminars composed by experts, on-site surveying, BIM, simplified LCA, user- and expert-based questionnaires, bias reduction, and sensitivity analysis. The whole procedure was designed to guarantee the transparency, objectivity, and robustness of the results. The following conclusions regarding the developed model were drawn:

a) Since the developed model is a combination of MIVES and Delphi methods, it can be considered **more complete and rigorous** than existing MIVES tools but it is **not so agile** and requires more time to be fully employed. Moreover, this model takes an advantage of combination of quantitative and qualitative analysis and methods that use data from different sources and make the established model more hybrid, robust and reliable.

b) This new model assessed the sustainability for four defined scenarios in which **three of them** (scenarios 1 to 3) were **real rehabilitated projects** in the selected case study and the **fourth one** was a designed rehabilitation project **to be constructed** to determine the most suitable solution. Therefore, this developed model can be applied in different building phases including design, construction, and rehabilitation.

c) Since this model was **developed for the first time in Iran**, it can be served as **a framework** for the local government, decision-makers, and stakeholders who are dealing with interior rehabilitation of MHs in Iran to facilitate the assessment and selection process. Moreover, the use of the proposed model allows **maximizing the stakeholders' satisfaction**.

d) The proposed model is **flexible**, **adaptable**, and **applicable** for **any type of interior rehabilitation of MHs in Iran**. Furthermore, **it could be applied to other locations and countries** after configuring it to particularities in each context, since local conditions can be objectively considered by using MIVES. Moreover, as explained in section 8.3 – future perspectives – the developed model could be combined with other methods, simulation tools, and building standards and certifications.

2) The **second specific objective** of the present thesis was an **application of the developed MCDM model to one of Tehran's MHs**. In this regard, the established model was successfully applied on the largest MH in Iran which is Ekbatan MH. The conclusions derived from the second specific objective are as follows:

a) Most of the MHs constructed **from 1960 to 1980** in Iran, including the selected case study, have several **interior performance issues** and **do not respond to** the current **needs of their occupants**.

b) According to the technical literature, most of the investigations regarding the sustainability assessment on MHs focused mostly on one aspect of sustainability **instead of having a holistic** approach. Moreover, among those reviewed studies that investigated all three sustainability aspects, most of them focused on the rehabilitation of MH at the urban scale – e.g., neighborhood, community interaction, urban regeneration, and urban management – instead of the dwelling scale – e.g., interior rehabilitation. Therefore, **considering a holistic sustainability approach** in the **design**, **assessment**, **and selection procedure** for MHs' interior rehabilitation is a crucial issue that **should receive more attention**, especially in developing countries where sustainability issues are mostly ignored.

3) To fulfill the **third thesis's specific objective**, the author contributed to collect, organize, classify, and digitalize the general and technical information of the selected case study and provide an **integrated database**. This database provided valuable and reliable information for decision-makers, stakeholders, relative future studies, and even the local government. Moreover, this database already assisted this thesis author to increase his knowledge regarding the topic of study, facilitate the sample selection process, calculate the values of the defined indicators, and consequently assess the sustainability index for the selected scenarios. The conclusions derived from this third specific objective are as follows:

a) Since **Ekbatan MH** was constructed with the latest construction technologies of the 1970s, this MH is **not facing serious structural issues**.

b) Over the past decades, the number of Ekbatan's households and its occupancy rate increased which shows **the growing habitancy demand in this MH**.

c) On the other hand, bypassing time, the **household size shrunk significantly**, which **caused space distribution changes** by some owners based on their current needs. This information was useful to have a better comprehension regarding Ekbatan's inhabitants' social issues and calculate the defined social indicators more precisely (see section 6.3).

d) A comprehensive analysis of the general and technical information of the selected case study helped the thesis author to select the most representative apartment type as a sample of the study. In this regard, ***Aleph-1*** **apartment type was selected as the representative sample of the study** because this type was the most repetitive apartment type – with more than 20% of the total apartment units – among all apartment types in Ekbatan, and its architectural plan and space distribution were similar to other one-bedroom apartments in this MH. Therefore, the existing and feasible rehabilitation activities of *Aleph-1* could be modified and applied in other Ekbatan's one-bedroom apartments with small changes.

4) The **fourth defined specific objective** of this thesis is divided into two parts. The first part overviewed and identified the most common existing interior rehabilitation activities and techniques in Iran besides studying some significant examples of interior rehabilitation projects constructed with new or improved techniques in the world. Consequently, three real rehabilitated projects implemented in Aleph-1 those were representatives of interior rehabilitation activities in

Iran (scenarios 1 to 3), and one designed interior rehabilitation project to be implemented in Aleph-1 with new or improved techniques (scenario 4) were selected. The second part assessed and compared these four defined rehabilitation scenarios through the developed MCDM model from the economic, environmental, and social points of view and identified the most sustainable one. The derived conclusions from this specific objective are as follows:

a) **Scenario 1** with a frequency of more than 26% of the total surveyed Aleph-1 apartments is a project which implemented partial interior rehabilitation. Although this scenario had low initial rehabilitation cost and rehabilitation process time, during the assumed 50 years building lifetime, this scenario could not meet the minimum standard sustainability target value – $GSi_{scenario\ 1} = 0.35$ – and thus faced several sustainability issues, does not respond to its occupants' needs, and does not fulfill the contemporary building norms and standards. Therefore, **partial rehabilitation**, which is the most frequent interior rehabilitation activity in the selected case study, **could not serve as a solution for sustainable rehabilitation**.

b) **Scenarios 2 and 3**, with frequencies of 18% and 15% of the total surveyed Aleph-1 apartments, are common existing rehabilitation activities and techniques in Iran. Although these two scenarios had better sustainability performance in comparison with partial rehabilitation, their obtained GSi values fell in the middle range – $GSi_{scenario\ 2} = 0.42$ and $GSi_{scenario\ 3} = 0.53$ – due to not considering sustainability indicators in their design phase, construction phase, and manufacturing of their applied materials. Since these common rehabilitation techniques could still not meet the minimum sustainability target value, they **do not serve as proper solutions for interior rehabilitation** and sustainability improvements – especially in the above-mentioned weak point – are needed.

c) Regarding scenario 4 in which new or improved rehabilitation techniques were designed to be applied on Aleph-1, its obtained GSi value – $GSi_{scenario\ 4} = 0.71$ – was significantly greater than three other scenarios – 0.36, 0.29, and 0.18 in comparing with scenarios 1 to 3 respectively. Considering the fact that only this scenario could meet the standard minimum target value, this thesis concludes that **the new and improved rehabilitation activities could have positive effects on increasing the sustainability performance** of buildings.

In the **second part**, the thesis's hypothesis – see section 1.3 – has been satisfactorily validated by fulfillment of the defined thesis's objectives. **As a result, it can be concluded that the new and improved rehabilitation activities are more sustainable alternatives than other common existing interior rehabilitation techniques and they could have positive effects on increasing the social and economic performance as well as decreasing the negative environmental impacts of buildings during their whole lifecycle**.

8.2. Specific conclusions

This doctoral thesis employed descriptive and operational approaches – see section 1.6, Figure 1.5. The descriptive approach enables the author to identify problems, deficiencies, and gaps in knowledge and set a research foundation, while the operational approach presents a new model for assessing the sustainability of interior rehabilitation of MHs. Regarding the **descriptive approach**, the specific conclusions derived from this approach are as follows:

a) Through a deep review of existing building intervention terminologies – see section 2.2.1 –, "rehabilitation" was selected as the most proper term regarding this thesis topic because it refers to a wider range of intervention activities and is aligned with the sustainability concept.

b) A holistic and comprehensive literature review regarding the sustainability performance of residential buildings and MHs – see section 2.3 – revealed that more than 60% of the existing investigations focused on the environmental aspect, while only 10% of the available literature incorporated all the three sustainability aspects – economic, environmental and social.

c) Despite the fact that the social aspect is the most crucial one for residential buildings' sustainability since it is the main reason for interior rehabilitation, it was the most ignored aspect. The social aspect was rarely investigated and, therefore, this aspect needs to receive more attention to fill in the mentioned gap.

d) Through a deep review and analysis of the existing Building Sustainability Assessment (BSA) methods and tools – see section 2.3.2 –, it was figured out that most of these tools neglected the evaluation of stakeholders' satisfaction. Moreover, among BSA tools, most of the existing *Sustainable Building Rating and Certification Systems (SBRCSs)* have several shortfalls that lead numerous researchers to develop *Individual Sustainability Assessment Models (ISAMs)* – that are mostly based on Multi-Criteria Decision Making (MCDM) methods – to fulfill their projects' objectives.

e) Through an extensive and comprehensive analysis of different scientific and well-known MCDM methods, the MIVES method was selected due to (i) being a well-known scientific MCDM method that was already satisfactorily employed in a wide range of investigations, (ii) assessing holistic sustainability as well as evaluating the stakeholder's satisfaction regarding each specific sustainability component, (iii) its adaptability to be combined with other methods; for weighting – e.g., AHP and Delphi – and validating and robustness analyses – e.g., sensitivity analysis –, and (iv) being flexible to be applied in different geographic locations with diverse conditions.

f) Moreover, the Delphi method was selected as an appropriate weighting method regarding this thesis because of (i) being precise, widely accepted, and user-friendly weighting method, (ii) qualifying the expert panel members based on their expertise level regarding a specific topic, and (iii) controlling and minimizing possible biases.

Besides, within the **operational approach** of this research, the following conclusions have been drawn:

a) Scenario 4, which obtained the highest GSi ($GSi_{scenario\ 4}$ = 0.71), is the most sustainable rehabilitation scenario among the ones studied. Although this fourth scenario met the minimum sustainability target value for environmental and social aspects – 0.82 and 0.75 respectively –, it did not meet this target value for the economic aspect. This underperformance of the economic aspect is due to: (i) the contrast among the obtained values of economic indicators, and (ii) the fact that these indicators were not considered in the design phase of *LifeEdited-1* that is a rehabilitation project constructed with new or improved rehabilitation techniques to be adapted to define scenario 4 – see 7.1. Therefore, there is still important room to improve its economic requirement, particularly regarding I_1.initial rehabilitation cost. Two following conclusions might be a solution for the above-mentioned shortage.

b) To propose a proper solution for sustainable interior rehabilitation of MHs, by considering the defined sustainability indicators in the building design and construction phases as well as attending/considering general and specific characteristics and conditions of the case study, to minimize the contrast among the defined indicators values and improve the building sustainability performance can be expected.

c) There is a fact that rehabilitation activities that occur in the MHs of Iran are mostly carried out by owners independently and individually based on their budget and expectations – see section 2.2.2. In this regard, due to the existence of similar repetitive apartments in MHs – e.g., 1144 Aleph-1 units in Ekbatan –, establishing proper, organized, and holistic **rehabilitation programs and policies** for these MHs can **encourage owners** to take advantage and participate in these programs. For instance, regarding the economic issues that all defined scenarios face, proper economic legislations and policies – e.g., rehabilitation loan's allocation with a low rate of interest and long pay-back period available – can reduce the rehabilitation time and costs, and encourage owners to rehabilitate their property in a more sustainable way.

By the fulfillment of all **four thesis specific objectives** – see section 8.1 – and specific conclusions derived from both **descriptive** and **operational** approaches – see section 8.2 –, the thesis main objective which is to contribute moving forward to more sustainable rehabilitation techniques for interior rehabilitation in MHs as well as moving towards more sustainable architecture and construction was successfully achieved. Furthermore, the assumed **hypothesis** was satisfactorily tested as well.

8.3. Future perspectives

In this doctoral thesis, a comprehensive investigation was conducted to assess the sustainability of interior rehabilitation of MHs in Iran from both technological and decision-making research fields in an objective manner. However, there are still several uncovered issues regarding this topic that should be investigated in future studies as mentioned in the following paragraphs.

a) This research proposed a model for sustainability assessment of interior rehabilitation of the **defined sample** – **Aleph-1** –, while another next step of this doctoral dissertation is expected to be the application of the developed model for the assessment of **other apartment types** in Ekbatan as well (see Appendix 4. A). This model also could be particularized for sustainability assessment of public and common spaces of this MH.

b) Moreover, the proposed model assessed the sustainability of the interior rehabilitation of the defined cases study – Ekbatan that is the largest MH in Iran. Future works could be the implementation of this model in MHs located in **other cities and countries**. To do so, this model should be adapted by considering problems and boundaries, geographic contexts, sustainability requirement tree components and their assigned weights, and stakeholders' preferences in each specifically selected MH. The development and test of the established model in different MHs, not only will enable making more interesting comparisons but also consolidate and reinforce the proposed model.

c) In this present doctoral dissertation, only one significant example of interior rehabilitation constructed with new or improved rehabilitation techniques was selected, assessed, and compared to the other defined scenarios. For future studies, **other possible advanced or improved rehabilitation activities and techniques** should be assessed by the proposed model to identify the most sustainable ones for interior rehabilitation of MHs.

d) As the GSi quantification depends directly on the weighting of the requirements tree, the employment of other weighting techniques – e.g., AHP and BOD, see Table 2.4 – and comparing them with the employed ones in this thesis – the Delphi and BIAS reduction techniques – can provide more precise weights and results. Moreover, the developed model can be **combined with Fuzzy logic** to overcome its possible weaknesses and reach a superior methodology

e) As previously mentioned in section 6.3, the assessment of the social aspect is inherently subjective while it is the most crucial sustainability requirement for interior rehabilitation. However, this thesis intended to quantify social indicators by conducting both user- and expert-based questionnaires in a scientific and objective manner. Future studies could incorporate a **combination** of the **Optimization Algorithm (OA)** and/or **Artificial Intelligence (AI)** techniques as well as **different simulation tools** for quantifying social indicators – e.g., Dialux for lighting comfort and SONarchitect for acoustic comfort – with both employed **questionnaires** to **reduce human errors**, **obtain more precise results**, and **facilitate the evaluation process**. Furthermore, by **increasing the sample size** in both **user**- and **expert-based questionnaires**, **the accuracy of results** will be improved. Moreover, to move forward on social issues and further include users' opinions and the gender perspective future versions of the established model could include the experience of householders - especially women - in the design process of interior rehabilitations.

While this present doctoral thesis has been completed at this stage, it has opened up opportunities for further research to accomplish the ultimate goal to promote and improve sustainable practices in architecture and the construction sector.

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