SEPTEMBER 2019 M.Sc. in Civil Engineering JUMANA ALRAHAL

REPUBLIC OF TURKEY

GAZIANTEP UNIVERSITY

GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

CONCEPTUAL DESIGN METHODOLOGY FOR FOLDABLE SHELTERS

M.Sc. THESIS

IN

CIVIL ENGINEERING

BY

JUMANA ALRAHAL

SEPTEMBER 2019

CONCEPTUAL DESIGN METHODOLOGY FOR FOLDABLE SHELTERS

M.Sc. Thesis

in

Civil Engineering

Gaziantep University

Supervisor

Prof. Dr. Mustafa ÖZAKÇA

by

Jumana ALRAHAL

September 2019

REPUBLIC OF TURKEY
GAZİANTEP UNIVERSITY
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES
CIVIL ENGINEERING

Name of the thesis : Conceptual Design Methodology For Foldable Shelters

Name of the student : Jumana ALRAHAL

Exam date : 09.09.2019

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. Ahmet Necmeddin YAZICI
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master Science.

Prof. Dr. Hanifi ÇANAKCI
Head of Department

This is to certify that we have read this thesis and that in our consensus opinion, it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Prof. Dr. Mustafa ÖZAKÇA
Supervisor

Examining Committee Members:	Signature
Prof. Dr. Mustafa ÖZAKÇA	…………………..
Prof. Dr. Ali Hamza TANRIKULU	…………………..
Assoc. Prof. Dr. Nildem TAYŞİ	…………………..

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Jumana ALRAHAL

ABSTRACT

CONCEPTUAL DESIGN METHODOLOGY FOR FOLDABLE SHELTERS

ALRAHAL, Jumana
M.Sc. in Civil Engineering
Supervisor: Prof. Dr. Mustafa ÖZAKÇA
September 2019
72 pages

With the rapid changing in global climate and the resulting disasters, prefabricated and quick-to-install shelters can provide victims of disasters with the opportunity to survive harsh natural and man-made disasters. Seeking to cater for this need and to reflect the topic of the mobile sheltering system, this thesis focuses on the case study development of a prefabricated, modular mobile shelter, from emergency scenarios to the permanent phase. The purpose of this paper is to propose a lightweight foldable and modular shelter that can be considered for the post-disaster shelter response and can be replaced, upgraded in size and geometrical configuration, and stored in a very short period of time. Using the folding technique, the specific mobile shelter structure investigated in this study has the ability to transform from a compact closed-form to a large living space open form. The suggested structure of these shelters is incrementally expandable by adding more modular units to its ends and sides. Furthermore, this thesis examines the practicability of the proposed concept and structure systems through a literature review, design-based research and digital model development.

Key Words: Incremental Architecture, Foldable Structure, Shelter Design.

ÖZET

BARINAKLAR İÇİN KAVRAMSAL TASARIM METODOLOJİSİ

ALRAHAL, Jumana
Yüksek Lisans Tezi, İnşaat Mühendisliği
Danışman: Prof. Dr. Mustafa ÖZAKÇA
Eylül 2019
72 sayfa

Küresel iklimdeki hızlı değişim ve bunun sonucunda ortaya çıkan felaketlerle birlikte, prefabrik ve kolay kurulumlu sığınaklar, afet mağdurlarına sert doğal ve insan kaynaklı felaketlerden kurtulma imkânı sağlayabilir. Bu ihtiyacı karşılamak ve mobil barınma sistemi konusunu yansıtmak isteyen bu tez, acil durum senaryolarından kalıcı aşamaya kadar prefabrik, modüler bir mobil barınağın vaka çalışması geliştirilmesine odaklanmaktadır. Bu tezin amacı, felaket sonrası barınak tepkisi için düşünülebilecek, değiştirilebilecek, boyut ve geometrik olarak yükseltilebilecek ve çok kısa bir süre içinde saklanabilecek hafif katlanabilir ve modüler barınak önermektir. Bu çalışmada incelenen mobil barınak yapısı, katlama tekniğini kullanarak, kompakt kapalı formdan geniş bir yaşam alanı açık forma dönüşüm yeteneğine sahiptir. Bu sığınakların önerilen yapısı uçlarına ve yanlarına daha fazla modüler ünite eklenmesiyle aşamalı olarak genişletilebilir. Ayrıca, bu tez önerilen kavram ve yapı sistemlerinin uygulanabilirliğini literatür taraması, tasarım temelli araştırma ve dijital model geliştirme yoluyla incelemektedir..

Anahtar Kelimeler: Artımlı Mimari, Katlanabilir Yapı, Barınak Tasarımı.

Grateful for all the mercies and blessings of God and all the appreciation to my parents, their unconditional love and patience, and for their infinite support and encouragement.

ACKNOWLEDGEMENTS

Praise be to Allah blessed, by His good graces.

I would like to extend a warm thank you to my supervisor Prof.Dr Mustafa ÖZAKÇA for his time, advice and insights throughout my M.Sc.

Finally, my special thanks are reserved for my parents, all my family. They have given me an endless enthusiasm and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF SYMBOLS

AS	Accordion Shelter
CS	Compact Shelter
WS	Winged Shelter

LIST OF ABBREVIATIONS

GSC	Global Shelter Cluster
IASC	Inter-Agency Standing Committee
IFRC	International Federation of the Red Cross
NGOs	Non-Governmental Organizations
UNHCR	United Nations High Commissioner for Refugees

CHAPTER 1

INTRODUCTION

1.1 General

Global trends report of the United Nations High Commissioner for Refugees (UNHCR) stated that 44,400 people are displaced around the world every day. At the end of 2017, 68.5 million people, including children, men and women, were forced to displacement, escaping violence, conflict and persecution and searching for safety and easier life. 25.4 million Refugees and 3.1 million asylum seekers had to leave their countries behind, and an additional 40 million were internally displaced persons who are displaced inside their own country. Figure 1.1 shows this evolution over the last decades. The conflicts in Syria, Afghanistan, South Sudan, Myanmar and Somalia have led to huge increase in displacement levels observed nowadays (UNHR, 2017).

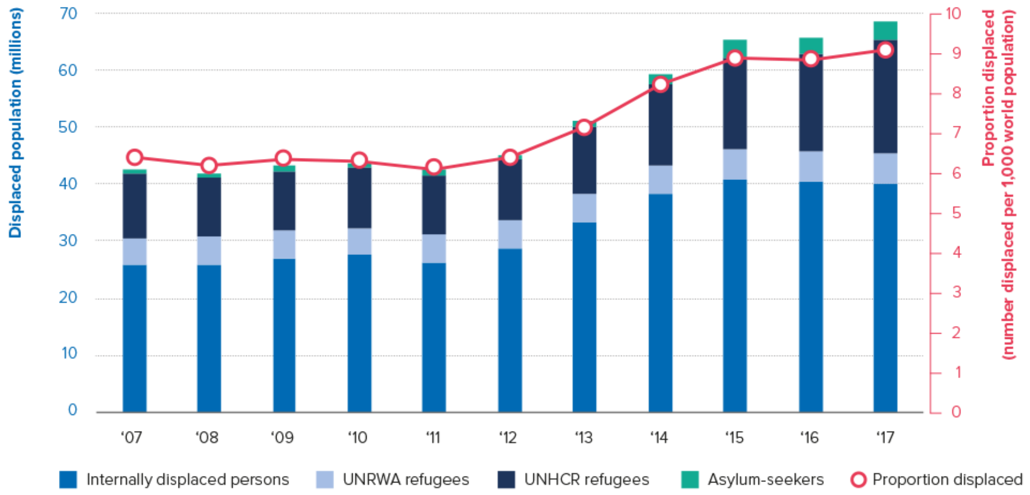


Figure 1.1 Trend of global displacement and proportion of displaced 2007-2017 (UNHCR, 2017)

Apart from this, natural disasters, such as earthquakes, tsunamis, hurricanes, floods, etc., are also considered to be a main cause of significant damage to buildings and infrastructure. Numerous homes are damaged and become unusable, causing many people to become homeless. For example, in August 2005, hurricane Katrina caused a disastrous increase in water levels near New Orleans, USA, bursting embankments and resulting in 80% of the city to be flooded. Despite the evacuation, 100,000 people were left, either people who did not want to leave or people who could not leave the disaster area. 1500 people lost their lives and the damage to the infrastructure was devastating (Kronenburg, 2009).

These natural/manmade disasters have caused considerable damage to buildings. Consequently, many homes have been damaged and rendered uninhabitable, creating an elevated number of refugees. Housing reconstruction programs take a significant part in disaster recovery, and short-term shelters are an essential supplier and a critical part of this disaster recovery. The shelter provides homeless victims with privacy, safety and comfort to restart their daily activities and return to normal life as soon as possible after a disaster (Félix et al, 2013).

After the Second World War, the governments were trying to develop urgent solutions to the drastic housing problem. With the support of the industries, architects and engineers developed alternative solutions such as prefabricated buildings, mobile architecture and modular, transformable structures. These alternative solutions expanded with the need for affordable, rapidly-constructed housing (Werner, 2013). The need for shelter and housing reconstruction program was not limited to the post-war period; however, it became the main issue after every disaster. To coordinate activities associated with the right to have a proper shelter, Global Shelter Cluster (GSC) was established in 2005 by the Inter-Agency Standing Committee (IASC) and GSC is co-instructed worldwide by UNHCR and International Federation of the Red Cross (IFRC), the leading agency for shelter in conflict situations and IFRC societies in natural disaster situations. GSC is responsible for emergency urgent requirements (such as plastic, sheeting, tents, cash, etc) and long-term requirements (such as mobile shelters, building or reconstruction of houses and related matters). Moreover, A shelter cluster is responsible for site planning and settlement design working in close cooperation with other cluster (UNHCR, 2015), given that the reconstruction, or resettlement, generally takes between 2 to 15 years (do Nascimento, 2015).

1.1.1 The Objective of The Thesis

The main objective of this research is to assess current or existing examples of the use of sheltering systems with geometric rules and architectural and structural perspective in order to evaluate the feasibility and performance of what is typically being in shelter objects. Therefore, the aim of this thesis is to analyze the characteristics and properties of a mobile shelter project, suggest a new design, and adopt a better-quality design.

1.1.2 Methodology

The method of research is to evaluate various solutions already used during previous human or natural disasters. Therefore, it is based mainly on the main data collection method. The research is supported with data from credible sources such as books, journal articles, magazines, reports, conferences and so on. The subsequent concern of this research is to adopt a solution to the problem in the new proposed design of shelters which must:

- be transported as easily as necessary,
- be assembled quickly and easily without the need for high skills and sturdy tools,
- reduce the costs and become an economic solution for government and human organizations,
- have the durability for long-term use,
- be upgradable in area, size and geometrical configuration,
- provide the standard, acceptable levels of normal living conditions,
- be easily reassembled for restoration, relocation or reselling for other purposes,
- and provide the advantage of a small compact living package that expands to provide living space units, which can be combined with other units for different applications

1.2 Categories of Shelter/Housing

Figure 1.2 shows multiple kinds of shelters used after a disaster in Indonesia, Pakistan, Peru, Haiti and Vietnam. In the view of different shelters, shelters can be classified into four major categories in all recovery stages depending on the period required for recovery and the limitation of that shelter.

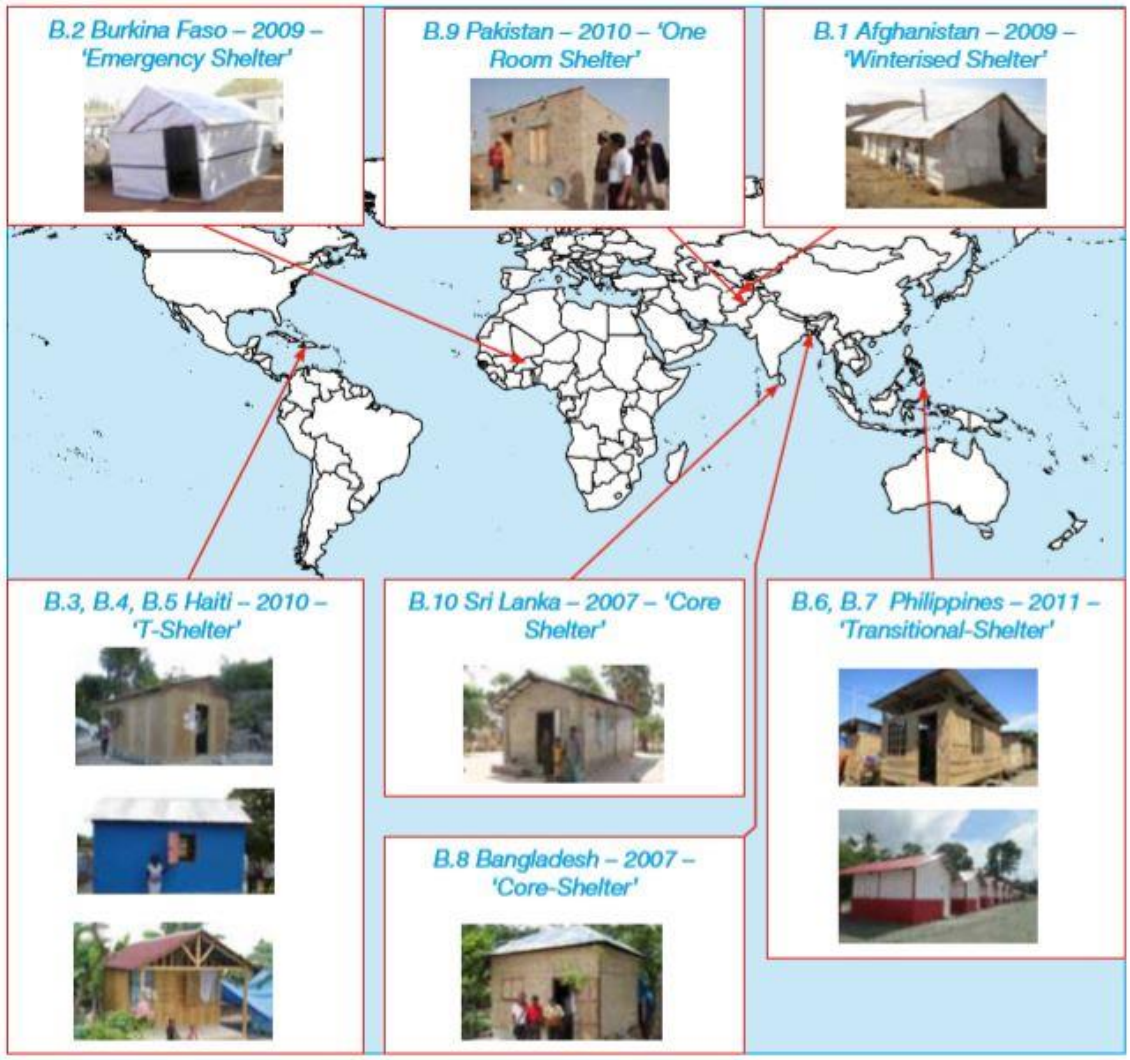


Figure 1.2 Examples of multiple shelters. An image is taken from (IFRC/RCS,2013)

Shelters can be categorized as:

- Emergency shelters,
- Temporary shelters/housing,
- Transitional/Progressive sheltering
- Permanent housing.

However, IFRC/RCS (2013) has attached extra categories to these, like progressive shelters, and core shelters/one-room shelters. Figure 1.3 shows the overlapping phases of types of sheltering system (Bashawri et al, 2014).

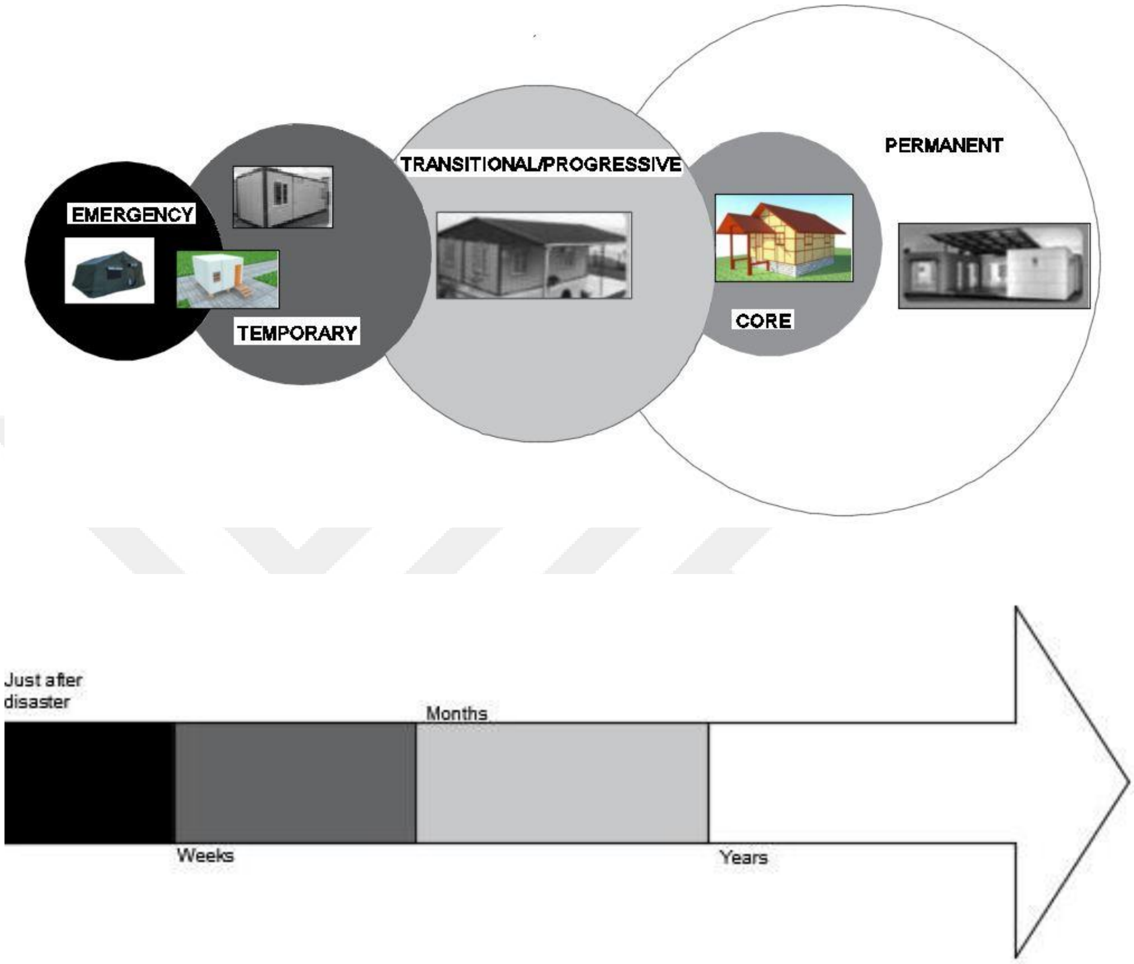


Figure 1.3 Illustration of the main categories of sheltering systems

Determining which term to use is a mixture of contextual factors. These factors range from the level of persistence expected of shelters and the materials they are made of to where they are built and to the scope of local politics–in some places, governments may stand against certain terms.

- Emergency shelters are usually provided in the aftermath of disasters.
- T shelters, temporary shelters, or transitional shelters are usually designed to be relocated and reused.
- Progressive shelters and core shelters are built in permanent locations with the aim of becoming part of a permanent solution (IFRC/RCS, 2013).

1.2.1 Emergency Shelters

This kind of shelters is utilized to provide life-saving support for a short period of time, and this kind is a basic type of sheltering system which can be available immediately after the disaster (IFRC/RCS, 2013). Emergency shelters can last for a single night to a few weeks during an emergency. Generally, this type of shelters does not support long-term preparation of food and long-term medical services (Bashawri et al, 2014).

1.2.2 Temporary Shelters/ Housing

According to the IFRC/RCS (2013), post-disaster household shelters are designed as a rapid shelter solution. Temporary shelters are built to quickly meet the basic needs of survivors with optimal convenience. Moreover, these shelters/houses are a habitable covered living space that provides a safe and healthy living environment with privacy and dignity. During the rebuilding of the permanent housing, the victim can live in a safe place and go back to normal life. This type of sheltering has been widely utilized after a lot of disasters. By prioritizing speed and limiting costs of the construction, this kind of shelter is distributed for short-term periods. It can take the form of prefabricated housing, such as containers. (Bashawri, 2014; Félix et al, 2013).

1.2.3 Transitional/Progressive Shelters

The transitional shelter can support victims from the time of emergency until the time when long-term housing is reconstructed. It is a part of the ongoing shelter development process (IFRC/RCS, 2011). The transitional shelter can be used in the reconstruction program through its five characteristics:

1. Upgraded to part of permanent housing.
2. Reused for other purposes.
3. Relocated from a temporary location to a permanent one.
4. Resold to produce revenue to help in recovery.
5. Recycled for rebuilding (IOM, 2012).

Such transitional shelters are expected to serve for several months or years (Bashawri et al, 2014). In some countries, the terminology “transitional shelter” may become unacceptable, especially where reconstruction on a permanent site is possible. These shelters can be called “progressive shelters” (IFRC/RCS, 2013).

1.2.4 Core Shelters / One-Room Shelters

Core shelters are planned and designed to be part of future permanent residences; they enable and promote future expansion processes by households according to their budget and resources (IFRC/RCS, 2013). In addition, certain complementary structures, such as foundations or toilets, can also be constructed. Although core shelters will eventually be “expanded” into permanent homes, this approach does not allow reusing them for another purpose, relocating them to another location, or recycling their components for permanent rebuilding. Furthermore, certain parts of the core house are unlikely to be resold (IOM, 2012).

1.2.5 Permanent Housing

Permanent housing means to return to the reconstructed house or resettle in a new one to live permanently (Félix et al, 2013). Permanent housing may develop from a core shelter, transitional shelter, or even a new dwelling, which means that permanent housing is the sustainable solution among other kinds of shelters. Thus, such houses have to be resistant and flexible for future risk and disasters (Bashawri et al, 2014).

1.3 The Layout of the Thesis

The contents of this thesis are divided into five chapters including an introduction which presents categories of shelter/housing and also explains the objective of this research. The second chapter explains the literature review for mobile shelters and presents a comparison between the rigid form of shelter and the flexible one with some examples of current and futuristic shelters. The third chapter discusses the design methodology used in the proposed concepts with structural techniques. It also explains the standards of design and the expansion of the proposed design unit using the incremental architecture. The fourth chapter presents three suggested designs of modular shelter units using incremental architecture in the sheltering system by functionally and structurally upgrading each module and employ these ideas to work according to the required purposes, duration and performance. The fifth chapter briefly explains the problems of the objectives and the suggested solutions in the proposed design and provides a general conclusion.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

The shelter is a refuge used for short term accommodation, but the house is a human habitation used for long term dwelling. However, with the possibility to be expanded and developed, shelters can play a more important role beyond providing an immediate and short-term refuge. They can be a vital part of the rehabilitation process of victims of disasters and finally become their permanent home.

Since the number of homeless population all over the world represents a large humanitarian crisis that urges humanitarian assistance, it is important to ensure basic human rights such as food, drinking water, appropriate shelter, education, health, etc. The number of affected people, their geographical distribution, and the need for support across multiple disciplines require complex interdisciplinary responses and strong coordination between all involved sectors and stakeholders (do Nascimento, 2015).

From the early emergency relief phase until the reconstruction or return phase, the need for an appropriate shelter can play an important role in preventing further distress, illness and death if it is made available instantly; therefore, emergency shelter must be available for refugees within the first few days of the post-disaster stage (Kronenburg, 2009).

Architects and engineers with experience have devoted time to create initial and innovative models for post-emergency relief. However, these activities did not alleviate human suffering. For example, after the earthquake of San Francisco in 1906, the majority of the large town was demolished by the subsequent fire The first affected people made a rough shelter from whatever materials were available or were trying to find shelter in a better situation with the help of friends and relatives By the time the authorities responded, first of all, a basic shelter was offered with the help of the army (which can act quickly with an efficient hierarchical organization). Later, some tents could have been replaced by better shelters. When people came back to their houses, many of the residents took their short-term residences, put them on the wheels and pulled them to the location of their permanent home where some still remain today (Kronenburg, 2009).

After the Second World War, the governments were trying to develop urgent solutions to the drastic housing problem. With the support of the industries, architects and engineers developed alternative solutions such as prefabricated buildings, mobile architecture and modular, transformable structures. These alternative solutions expanded with the need for affordable, rapidly-constructed housing (Werner, 2013).

2.2 Rigid Form Versus Flexible Form Shelters

Generally, there are two basic kinds of shelters in terms of materials, utilization and construction technology as shown in Figure 2.1. The first type is the shelter with non-convertible elements (use of rigid materials) which represent the rigid form. The properties of the rigid form shelters are:

- Less flexibility
- Large volume
- Difficult transportation
- Heavy
- Easy to assemble but time consuming
- Easy to manufacture and secure

The second type is the shelter with convertible elements (use both solid and flexible materials) which represent the flexible form (Asefi and Sirus, 2012). The basic properties of these shelters are:

- Flexibility of form
- Foldability and expandability
- Ease of transportation
- Light weight

- Using recyclable materials
- User’s aesthetic preferences

(a)

(b)

Figure 2.1 Shelters (a) rigid form (b) flexible form

2.3 Foldable Transitional Shelter

The researcher starts to investigate sustainable solutions. One possible shelter solution is supplying affected families with the means to start reconstruction directly after the disaster through the foldable transitional shelter approach as shown in Figure 2.2. In fact, the foldable transitional shelter can be considered as incremental process, not a final product. It supports the post-disaster affected families as they seek to sustain alternative options for recovering the damage, starting just after the disaster, and achieving a durable permanent house in a progressive manner within a limited period of time (IOM, 2012).

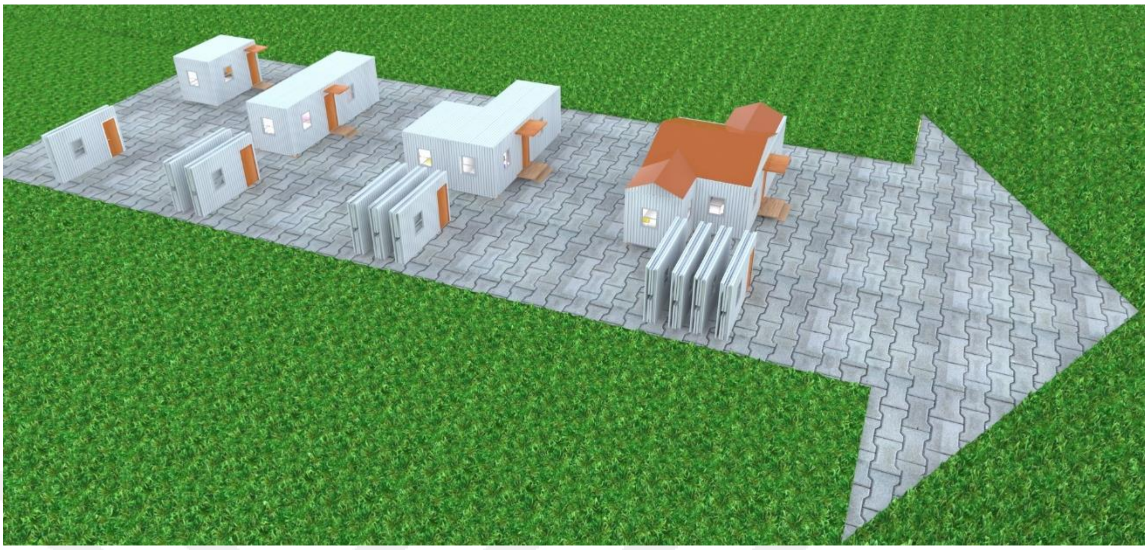


Figure 2.2 Incremental process of foldable transitional shelter

The transitional shelter can begin just after the disaster by distributing a foldable shelter package. Further support, such as cash or further material distribution, enables incremental building and upgrading of shelter towards the permanent house as presented in Figure 2.2. This period depends mainly on the economic situation.

Additionally, the transitional shelter is grounded on five characteristics which are defined by IOM (2012). These shelters are upgradable, reusable, relocatable, resalable and recyclable. Consequently, the mobile transitional shelter is expected to be a continuous process for months and even years. The mobile transitional shelter offers the opportunity to link relief and future development perspectives towards a sustainable solution (IOM, 2012).

As a response for the increasing need for decent, more sustainable sheltering system, this research aims to suggest a design of a mobile shelter following a modular methodology and innovate an easy foldable unit that can fold in a short time. The suggested shelter will be well equipped for quick deployment immediately after the disaster. The suggested design is controlled to be light, so that it can be compactly folded in the package to make transportation easier. Moreover, it has the capability to be expanded as needed. The suggested mobile shelter design has objectives (such as security, size, lifespan, relief, and privacy) and limitation (such as cost, quantity, timeliness, materials availability, cultural appropriateness, and construction skills).

2.4 Examples of Previous Shelter Solutions

2.4.1 Core Shelter of Bangladesh

Cyclone Sidr struck the Southwest Coast of Bangladesh in November 2007, and destroyed more than 450,000 homes across 30 areas due to wind damage, floods and storm surge. More than 50% of all households in the six worst affected areas have been damaged or destroyed.

Both national and international organizations participated in shelter response. Programs provided by these organizations included basic shelter item distribution, shelter construction, and training in safer construction. The shelter construction program provided support for families to upgrade their shelters as shown in Figure 2.3. Many families were able to improve and expand from the core shelter to multiple developed structures.

Built on a mud platform, the core shelter with15m^2) floor area consists of strengthened concrete pillars and steel truss roof installed according to cyclone resistance techniques. Because of the height of the core shelter, families could extend the shelter in all directions. The walls were made from woven bamboo mats (UN-HABITAT and IFRC/RCS, 2010).

Figure 2.3 Core shelter of Bangladesh and its upgrading (UN-HABITAT and IFRC, 2010)

2.4.2 T-Shelter in Haiti

An Mw 7.0 earthquake in Haiti on 12 January 2010 resulted in an approximately 300,000 deaths, caused more than 1 million people to be evacuated and damaged nearly half of all the buildings in the epicenter (DesRoches et all, 2011).

In the 2010 Haiti response, The T-Shelter was designed as a rectangular timber-framed structure with a gable roof and a covered floor area of approximately 21 square meters. The walls are made of wood studs with plywood exteriors, and the roof is made of metal roofs of wooden purlins and trusses. The truss is supported by wooden pillars in the surrounding wall. Wooden trusses can be prefabricated and shipped to construction sites. The foundation consists of masonry walls between the concrete jetty at the four corners and the jetty. The floor is a cast-in-place concrete slab. As designed, the shelter has one door and one window as shown in Figure 2.4. This T-shelter is built within 2-3 days by a team of 9 people (IFRC/RCS, 2013).

Figure 2.4 T-shelter in Haiti (IFRC/RCS, 2013)

2.4.3 Caravan Shelter for Syrian Refugees

Since the beginning of the war in Syria in March 2011, estimated 2,697,808 refugees had to flee to neighbouring countries. Jordan hosts 589,792 refugees. Al Za'atari camp, opened on July 2012, is the biggest camp in Jordan and is run by UNHCR in cooperation with the Jordanian government, with a several of Non-Governmental Organizations (NGOs) and UN agencies.

When Al Za'atari first opened, UNHCR supplied tents to refugees. However, tents are not convenient in winter and cannot resist floods. As a result, UNHCR introduced a housing strategy to move from relief to the temporary shelter as shown in Figure 2.5. Caravans were the basic shelter solution; the tent, however, was distributed for families to have additional space if needed.

Many households have more than one shelter: 52.3% have only 1 caravan, while 31.8% have 2 caravans, and 11.3% have 3 caravans (UNHCR, 2014).

Figure 2.5 Caravan shelter in Al Za'atari camp (Household with multiple parts of caravans joined together) (UNHCR, 2014)

2.4.4 Shelter of Philippines

In late 2011, more than 39,000 homes were damaged and more than 400,000 people were evacuated by wind, floods and landslides after a tropical cyclone Washi (also known as Sendong). In the first phase of the response, a collective centre was established and items other than food were distributed. After the emergency response stage, the transition site has been established, rebuilding 18m^2 floor area transitional shelters (with bamboo weave walls) with frames made of bamboo and other types of wood (see Figure 2.6) (do Nascimento, 2015, IFRC/RCS, UN-HABITAT and UNHCR, 2013).

Figure 2.6 Shelter example from Philippines (do Nascimento, 2015)

2.4.5 One Room Shelter of Pakistan

The 2010 flood in Pakistan directly affected an estimated 14 to 20 million people and caused more than 1,700 death. About 1.1 million homes were damaged or destroyed, and at least 436 medical facilities were destroyed (Kirsch et al, 2012).

For the first few months, the government of Pakistan along with many organizations distributed sheets, tents and other non-food items in the disaster areas. After the emergency response, a "one-room shelter" approach was adopted, through which organizations supported affected families to construct a permanent shelter, which families could expand later (IFRC/RCS, UN-HABITAT, and UNHCR, 2012).

This 4.8m x 3.9m shelter is built with locally procured materials, unreinforced brick exterior walls, tile roof supported on steel framing as shown in Figure 2.7 (IFRC/RCS, 2013).

Figure 2.7 One room shelter of Pakistan and upgrading (IFRC/RCS, UN-HABITAT, and UNHCR, 2012, IFRC/RCS, 2013)

2.4.6 Core Shelter of Sri Lanka

The district of Karukamunai, in north-east Sri Lanka, was at the forefront of the battle between the Sri Lankan government and the Tamil Elam liberation tiger. During the height of hostility in 2006, an estimated 520,000 families were displaced by the end of 2006; families in this area were evacuated to a camp near the large port town Batticaloa. In July 2007, many displaced people returned to their villages to find numerous of their homes destroyed or smashed into pieces.

After research and discussions in the communities, the local authorities and NGOs came to the conclusion that a smaller 18.6m^2 floor area core shelter would be acceptable to the communities (Ashmore, 2008).

This core shelter is built as a rectangular shape with a saddleback roof and a walled floor area of nearly 3.5 × 2.8 m with an extra covered balcony of nearly 3.5 × 2.8 m, and locally purchased items: unreinforced masonry exterior walls and metal roofing on wood trusses as shown in Figure 2.8.

This 3.5 × 2.8m shelter is constructed in 5 days (after fabricating blocks) by a team of 2-3 people, having an expected lifespan of more than 10 years (IFRC/RCS, 2013).

Figure 2.8 Complete core shelter in Sri Lanka and its durable upgrade (Ashmore, 2008)

2.5 Proposed Shelter Solutions

2.5.1. Hex House

Architects for Society, based in Minnesota, has developed a rapidly deployable residential prototype that can shelter sufferers of devastating disasters.

A 40 square meters unit, the Hex House is primarily made of steel-and-foam structural insulated panels. It can also be easily assembled using very simple tools and requires no construction skills.

The Hex House shown in Figure 2.9 is a decent home that can easily serve as both a transitional and permanent shelter. All the components are designed to be packed and shipped flat so it can be rapidly deployed. It has a toilet, a shower, a kitchen, two bedrooms and a living space.

Hex House is rapidly evolving, not only built by non-builders but also designed as a scalable solution with typical household amenities. The house is designed as emergency shelters for displaced people including refugees and victims of natural and man-made disasters. With its passive low-tech features and durability of the exterior shell and base, it can withstand long-term habitation of 15 to 20 years.

Figure 2.9 Hex House (de Zeen, 2016)

The unit can be disassembled, relocated, scalable and reused elsewhere. It is designed to benefit Camps and Hosts (de Zeen, 2016). Hex House is an easy construction method that helps residents assemble their homes using simple tools and little training. All parts are designed to be packed flat with conventional transportation trailers. The average capacity of one trailer can easily accommodate 3 units (Isawsomethingnice, 2016).

2.5.2. M2 Model Shelter

Maddel International proposes an unfolded flat-packed module M2 Model made of polypropylene core-flute board that unskilled labour less than 30 minutes to construct. It can be combined with other modular units to form a cluster of 4 to 6 assembled units. The total package is 78kg in a volume of 0,37m³ and can be packed vertically on a 120x80cm euro pallet to facilitate transportation. Moreover, this material is repairable and reusable and can be folded, relocated and reconstructed many times without losing its structural integrity (do Nascimento, 2015). Figure 2.10 shows this transitional shelter proposal.

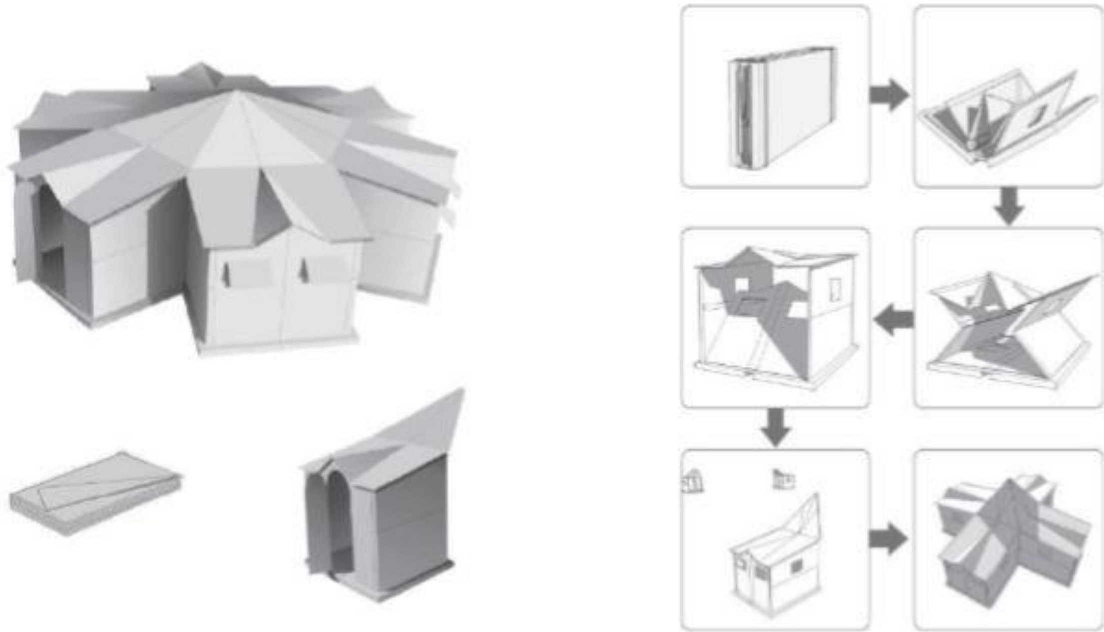


Figure 2.10 M2 Model transitional shelter prototype (DFID, 2009)

2.5.3. Lowell Norman's Collapsible Portable Structure

This structure is a portable structure that can be quickly converted between a fully upright formation and a fully collapsed formation by one person, without disassembling or separating any basic parts. In its extended configuration, the structure is stable instantly when it is installed.

The basic portable structure does not involve separation and reassembly of its components at any point before, during, or after the conversion from the folded or extended configuration as shown in Figure 2.11 (Norman, 1989).

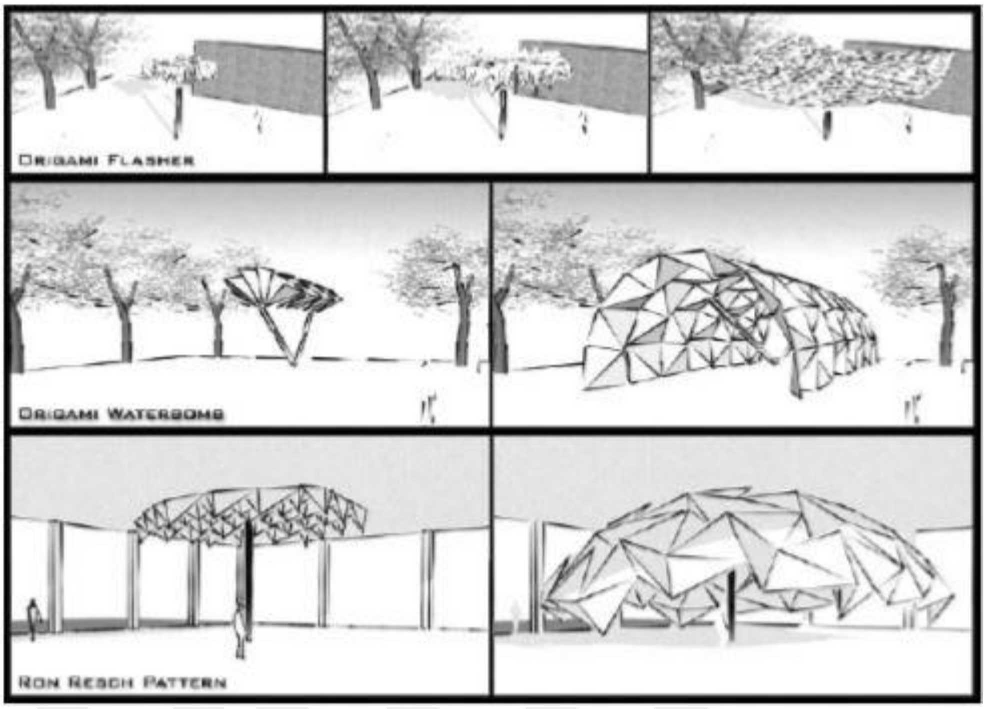


Figure 2.11 Collapsible portable structure of Norman Lowel (Werner, 2013)

2.5.4. Folding Bamboo House

Ming Tang's wonderful origami folding bamboo house was designed to be utilized as a temporary shelter after the 7.9 earthquakes hit China's central part.

To relocate the people who lost their homes, the Chinese government decided to build 1.5 million temporary houses. For this purpose, Ming Tang proposed a cheap, environmentally friendly shelter that could be easily manufactured using bamboo (see Figure 2.12). This concept uses a system of bamboo pillars assembled in advance into a strong geometric shape (Inhabitat, 2008). The geometry of these forms supplies the completeness of each structure and enables to quickly assemble various lightweight module structures at the factory and transport them to the destination. Once constructed, the shelter is covered with recycled paper.

The structure can be folded in various shapes, and various structures can be created. Its elegant design and re-configurability make this shelter suitable for temporary use and can be used especially as exhibition space (Asefi and Sirus, 2012).

Figure 2.12 Folding bamboo house (Asefi and Sirus, 2012)

2.5.5. Accordion Recover Shelter

The Accordion recover shelter was designed as a first response shelter by Matthew Malone, Amanda Goldberg, Jennifer Metcalf and Grant Meacham (Inhabitat, 2008). The structure of an oversized origami can be folded completely into two different shapes which are horseshoe or flat shape, not just one, depending on which one is easy to transport. Multiple units can be piled on a trailer or shipped quickly to a disaster location.

The structure as presented in Figure 2.13 can be erected by one person in just a few minutes, and it can accommodate a family of 4 people for up to a month. The whole structure is 100% polypropylene, and after use, it is 100% recyclable (Inhabitat, 2008).

It provides a quick roof over the victim's head. Aside from the emergency use of evacuation centres, it can be utilized as a short-term shelter for exhibitions (Asefi and Sirus, 2012).

Figure 2.13 Accordion recover shelter (Inhabitat, 2008)

2.5.6. Cube Foldable Transitional Shelter

The main module of this proposal is designed as a cube with 2600 mm length. The area of this shelter is enough to serve at least two people for emergency life needs. The main module cube is created with interconnection and foldable system angular rotation with multiples of 90° of six various panels. Each panel element is connected by a hinge. The rotation and folding procedures are performed by the hinges. Housing unit cubes are folded and transformed into a rectangular prism during transport. Housing facilities can be expanded by connecting different modules (see Figure 2.14). Housing units can be extended by placing modules side by side or putting modules on top of each other (Bakbak et al, 2016).

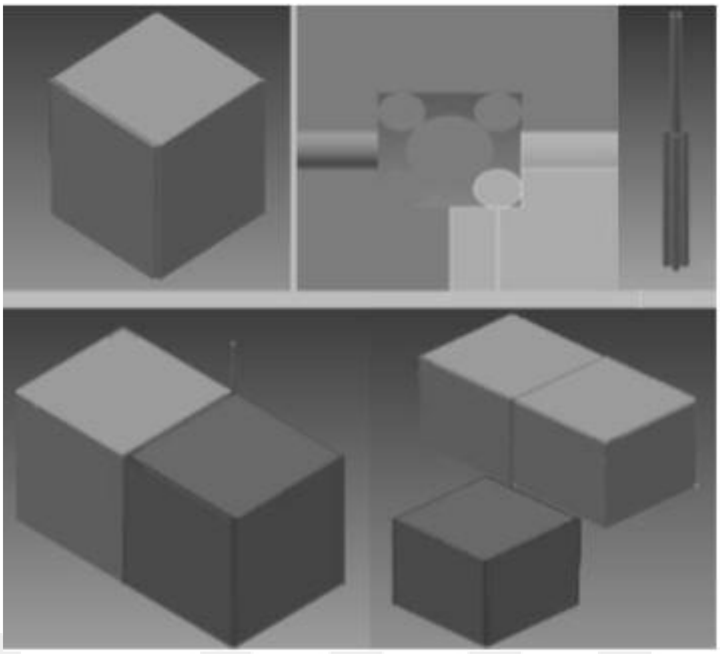


Figure 2.14 Cubic base unit and extension modules (Bakbak et al, 2016)

2.6. Observations about the Previous/Proposed Shelters

Upon considering the examples of the previous shelters, it can be noted that most of the shelters are constructed using local materials, some of which were heavy such as unreinforced masonry or brick while others were light such as wood or bamboo. Furthermore, the size of these shelters range between 15 m^2 and 25 m^2, and most of them are upgradable and expandable to become a permanent home.

Benefited from the experiences and history of shelters, architects and construction engineers have sought suggestions for lightweight shelters that could be converted into the small, upgradeable structure of permanent homes.

2.7. Background of Foldable Structure

The need for a deployable/foldable construction has existed for several decades. This has ever appeared since people came to the need to move from one place to another to find a more suitable environment to live in. Lightweight, little and compact structures seemed a more satisfactory solution. Thus, it can be seen that the concept of a foldable structure is not new (Babaei and Sanaei, 2010).

In the latest years, due to the urgent need for multifunctional buildings and the need to protect the environment, the demand for deformable and foldable structures has increased quickly (Werner, 2013). The foldable plat structure began to appear at the beginning of the 20th century as it was seeking an efficient and lightweight structure (Samuelsson and Vestlund, 2015).

The development of prefabricated buildings leads to improvements of foldable structures so that the folding structure can be built by assembling prefabricated components and elements. Based on research and analysis of existing examples of folding structural systems, the folding structure method was based on shape and geometry.

The term folding structure refers to a foldable structure including structures made with planes and structures made with frames that create folded bodies by their interrelationship in space (Šekularac, et al, 2012). The term 'foldable structure' can be used to describe a structure that can undergo large displacements between a compact 'folded' form and a larger 'expanded' form (Farrugia, 2008). Since folding is a relatively simple and rapid process to acquire three-dimensional shape, it inspired numerous architects to design from extended roofs to exceptional building structures. In addition, with the combination of parametric graphics tools, folding technology significantly accelerates the design cycle. More specifically, the existing application of folding technology in architectural design is basically focused on structural design and surface design (Shen and Nagai, 2017).

Folding structures have two different applications both in terrestrial and outer space contexts. Some important applications are as follows: emergency shelters; bridges, hospitals and other public buildings; buildings and shelters in remote locations; short-term protective covers covering sports facilities; lightweight camping and recreational structures; temporary exhibition structures; antennas and towers; greenhouses and other agricultural applications; grand terraces, theatres and concerts; packaging industry; toy industry; agricultural, military, social, cultural, entertainment, industrial and other space applications. (Babaei and Sanaei, 2010).

These types of structures have many advantages. Foldable structures are easy to install, quickly constructed and prefabricated, easy to transport and store, and reusable. Additionally, these structures are of reasonable cost, easy to connect, and packed in a lightweight deployable configuration (Babaei and Sanaei, 2010).

2.8. Structural Development

Folding technology started with origami (see Figure 2.15) which is an ancient traditional art used in Japan. It involves the technique of folding a piece of paper into shape without gluing, stretching or cutting. Folding origami techniques are often mentioned when talking about more complicated folding structures. In the structure, it is not usually practical to fold the structure from one sheet, as in origami. Instead, they are made up of several plates that are often assembled into one structure which is applied to many fields such as robot structure, electrical equipment, architectural design (Samuelsson and Vestlund, 2015).

Figure 2.15 An example of rigid folding (Shen and Nagai, 2017)

Folding technology is popular mainly in architectural design for the two following reasons:

1. It has a creative architectural structure with an advantageous bearing capacity
2. Generation of aesthetic and adaptable construction form

Shen and Nagai (2017) provide an overview of folding techniques in architecture design which classifies folding techniques as:

- Computation geometry folding techniques that are researching folding techniques with an emphasis on algorithmic aspects.
- Manual folding techniques

The manual folding are divided into

1. Rigid folding is when all the deformation is concentrated in the hinges and the surface between the folds remain flat (see Figure 2.15)
2. Curved folding is when the fold line is curved, which is more complex than rigid folding (see Figure 2.16) In fact, it is difficult to geometrically explain the processes involved in the curved folding due to the change in the curvature of both the fold line and faces between the folds (Shen and Nagai, 2017)

Figure 2.16 An example of curved folding (Shen and Nagai, 2017)

The initial need for folded structure techniques in civil engineering is to:

- achieve more structural height,
- increase rigidity,
- decrease the net weight of the constructional element and
- minimize the body size of the structure.

The strength and rigidity of the folded structure are obtained primarily by the suitable design of the structure and, to a lesser extent, the thickness and dimensions of the elements forming it. This solution was reached through the development of structural systems and the use of reinforced concrete. (Šekularac, et al, 2012).

Common door hinges, which are one way to deal with problems related to rigid origami thickness, can be used as an example of a rigid foldable thick origami application with a single fold line. Samuelsson and Vestlund (2015) describe the structure of these hinges which can be fully developed (the door is closed) and can be folded flat (the door is open and parallel to the wall). This is possible because the position of the rotation axis is shifted from the ideal plane of the fold (centre of the door) to the valley side of the fold line. This method is called the *axis shift* and is suitable for doors and other simple folding applications as shown in Figure 2.17.

Folded-plate structures are thin and hard structured surfaces that are effective for the action of beams or plates and can span amazing lengths for efficient use of materials. Furthermore, they are very compact and can be stored in a narrow space when folded flat. Architectural design based on the concept of foldable structure can be both architecturally expressive and material efficient. Folding can also be a suitable solution for deployable structures (Samuelsson and Vestlund, 2015).

The bearing capacity of full-flat panels depends entirely on the thickness and quality of the material of the panels. Large range of the whole plate becomes thick and very heavy, and thus not economical. If we form the folded structure of slanted slabs, vertical projection becomes the height of the folded construction, thus enabling the smallest thickness of the structural element. By using folded structures much larger ranges can be overcome than by applying of a full flat plate.

Different spatial forms can be created by using a folded structure. The straight elements forming the folded structure may be in various shapes: rectangular, trapezoidal or triangular. Through combining these elements, different forms will be resulting in a variety of shapes and amazing architectural expressions.

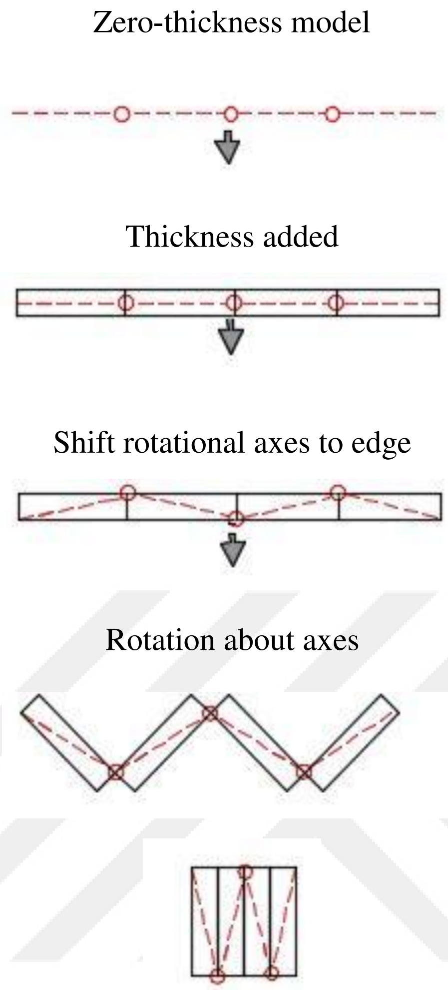


Figure 2.17 Simple fold thick-origami with hinges shifted to the corresponding valley sides of the mechanism. This structure can be folded from 0 to π

The folding structures have been applied in both architectural and engineering buildings. Based on the location of the building structure, this kind of structure can be divided into folded structures of roof, floor and walls. For architectural structures, bridges, retaining walls and different structural elements can be constructed based on the principle of foldable structure. The principle of greater rigidity of individual components, by introducing the folded model, has been applied into many consumer products (Šekularac, et al, 2012).

CHAPTER 3

FOLDABLE STRUCTURE METHODOLOGY AND MODEL DESIGN

3.1. Introduction

The modular architecture is often related to the Utopian ideal of the 1960s in which the architects created temporary and mobile proposals and used new materials and new erection and disassembly techniques. In the present day, the modular structure is adopted not only for Utopian ideals but also for standard construction, to shorten the project period, minimize cost and improve quality. In the spectrum of the degree to which prefabrication is completed, modular is the greatest, offering the possibility of constituting upward of 95 per cent complete before setting of the structure onsite (Smith, 2010).

Modular design construction can be defined as: A module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units. Obviously, there are degrees of connection, so there are gradations of modularity (Baldwin and Clark, 2000).

Permanent stage or semi-permanent house construction can take years for affected families according to the diverse variables and potential challenges and difficulties that confuse every affected family such as land, deficiency of land or lack of accessible materials. Consequently, a small base modular shelter can be the only available place for affected communities to live during the reconstruction process. Later, they will modify their shelters to meet their needs, and these changes are defined by their resources, capabilities, status and security. These changes can upgrade the quality of housing in the transition period, but can also reconstruct vulnerabilities due to deficiency of supervision or technical knowledge (IFRS/RCS, 2013).

3.2. Methodology of the Foldable Design

The need for a deployable /foldable construction has existed for several years. This has ever appeared. Since people came to the need to move from site to another to find a more suitable environment to live in. Lightweight, little and compact structures for example tents and yurts constantly seemed more satisfactory to them. So, it can be seen the concept of collapsible structure is not new (Babaei, and Sanaei, 2010).

Transformable and deformable architecture is a strategy appropriate for buildings and building structures that need to be reconfigured by folding in a compact form to facilitate construction and transportation, or to be able to respond to changes in functional and aesthetic requirements, geometric shape and form (Asefi and Sirus, 2012).

The terminology 'foldable structure' can be used to describe a structure that can undergo large displacements between a compact 'folded' form and a larger 'expanded' form (Farrugia, 2008). Folding technology is common in architectural design because of the ability to create an aesthetic and deployable architectural form having an artistic architectural structure with an advantageous bearing capacity (Shen and Nagai, 2017).

Folding technique is generally used in the pre-hinged structure system. In foldable structures, in order to enable the folding to occur, static plate elements are connected by movable joints, which converts them into kinetic components. Taking this into consideration, it is understood that movable joints are not only a connection between two plates, but also it must transfer loads permitting relative motion in some directions while constraining motion in others (Werner, 2013).

Every building is designed in accordance with specific parameter sets such as use, size, material etc. Traditionally, this set of parameters is fixed earlier at the design process. However, the modular design features the changeability of parameters into the current design process. Use of folding and interlocking techniques will improve the system to be more flexible for easy assembling, transportation, restorability and extendibility. This leads to a more dynamic and flexible design where "late change" such as adding a kitchen unit to a base mobile shelter does not result in the difficult laborious manual integration of a new element into an existing design (Bakbak et al, 2016).

The modular design grid described by Smith (2010) and adopted in this current study is a geometric configuration system that enables building components and module elements to have standard dimensions. These configuration systems are generally based on square and rectangular structure, thus creating linear, component-like, flat-panel and box-like modules, although not necessarily. Structural systems are often placed on an axial grid, and panels and modules are deployed on a modular grid. Although this is effective from a design standpoint, there are problems in adjusting how other materials and elements are combined with the main module. If each column, beam, or structural element is in a different dimension, the 2D and 3D grid loses the ability to have a standardized panel or filling element associated with the frame with a standardized connection. Every time you connect a major structural system to another enclosure or interior system on the axis grid, you need to make special connections. A review of current challenges regarding folds and structures is presented and the different mechanical modelling of folded structures are investigated by Lebée (2015). Rigid folding, in which all the deformation is concentrated in the hinges while the faces between the folds remain flat, is adopted in this study.

3.3. Design Consideration

The challenge for shelters center advisors and programmers is to clarify exactly what habitability constitutes and convert it to a design overview or, more properly, performance specifications.

It may be proposed that there are 12 qualities that contribute to habitability; w1eather resistance, temperature, ventilation, light, privacy, space, cooking, water and sanitation management, vector control, safety, security, structural integrity. Ensuring that all types of features are adequately provided will result in a habitable housing that supports, environment protection, health and well-being, safety, security and dignity and facilitates household activities and livelihoods.

Durability relates to the long-term sheltering experience and whether shelters can stand during the period necessary for reconstruction or resettlement. Durability qualities are structural integrity, material selection, repair and maintenance, adaptability (Da Silva, 2007).

If the shelter design is appropriate, it reflects the needs, local culture, vulnerability and ability, and available resources of affected communities. Since every status is different, the shelter design must adapt to each location, response, and project. Once the decision to start a shelter construction project is taken, the first step is to develop the design brief. A design brief is a document that determines shelter performance. In the design brief, shelter design can be verified against important criteria such as

- *Safety*: The shelter design should not increase the resident's vulnerability to natural hazards such as earthquakes, storms or diseases.
- *Cost:* Reduce the cost of each unit.
- *Durability*: Multi-purpose space for long-term use and expandable for future upgrade.

A shelter design brief has to balance the perfect building from a structural perspective with obstacles such as

- Limited time
- Limited budget and
- Will depend on the overall shelter strategy adopted (IFRS/RCS, 2013).

In addition to the important criteria and the constraints of the shelter design, there are geometric dependencies that should be adopted in the shelter design such as

- The dimensions of the base unit and the expansion unit must be the same.
- In order to minimize the transportation cost and fast delivery of the unit, the maximum number of the unit should be carried in one transportation container, flatbed trailer, overseas container, or helicoptered to a remote camp site. The dimension of the folded unit must fit with the transportation container (the maximum height of the package should be less than 2.69 m), depending on the standard container internal dimensions such as high cube-containers (12.03 length, 2.35m width, 2.69m height) (Council, 2017).

3.4. The Expansion of Housing Unite

Extension by the assembly of several modules needs to handle the connection between modules. However, *incremental architecture* involves addition, subtraction and substitution in order to meet the ranges of configurations of components or interaction with other modules (Werner, 2013).

The incremental housing is a step-by-step process and is designed to be one part of the sustainable response. It starts with a starter core shelter which can be a bedroom unit or a naked lot with the possibility of a utility connection. It is not quick, immediate or complete but the owner manages housing expansion based on his needs and resources. The implementation of the incremental strategy is not as simple as ready-set-go. Possible policies must tackle three related issues (Goethert, 2010):

- To establish a frame for structuring land development (minimally, a main grid of streets and a basic infrastructure network).
- To provide a starter house core (an immediate way to provide many families with shelter and offer expansion flexibility).
- To set and implement support policies and programs that provide a simple, feasible expansion process, reinforce both individuality and community, provide safe, fine quality installing procedures, and promote maintenance of basic services.

3.5. Design Procedure and Prelimenary Model Design

This section describes the different attempts done to design the foldable shelter, which is the housing unit aimed to be designed. Each structure should be designed according to some general parameters. In this case, some of the parameters are technical while others are dependent on the needs of the user. Table 3.1 shows the technical parameters to consider during the design process.

The design begins by trials on models with "zero-thickness" materials which are hereby called *Model A*. The prileminary ideas presented in next sections are based on Model A. The rest of this chapter deals with a model trials, while Chapter 4 deals with models made of materials with thickness, called *Model B*.

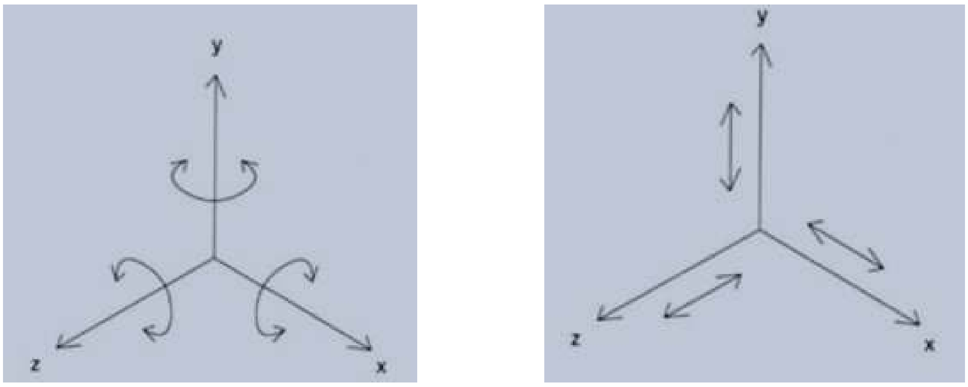
3.5.1. Trials and Ideas

A parallelogram, the simplest shape, is selected to be used as a shelter because of some distinctive characteristics such as symmetricity, the simple shape for living, and the possibility of changing its dimensions. Moreover, the symmetrical movement should be applied throughout the folding process.

Table 3.1 General parameters of the design

Parameter	Specifications
Volume and area dimensions	Maximum shelter height =2.69 m The area is enough for three people at least
Materials	Aluminium, steel and sandwich panels. Fire resistance, water resistance, isolator
Construction time and workers number	10 to 20 minutes and not more than 3 workers
Ground situation	Preparing the foundation for each shelter so that max a=0 degree (a is ground slope angle)
Weight	Each unit should be as light as possible

Cardboard was used in the design of a parallelogram cutting each parallelogram into sheets (plates) to use in the folding process. The movement axes allow three degrees of freedom (x, y, z) and the combination of movements means that a connection can have one to six degrees of freedom as shown in Figure 3.1 (Werner, 2013).



(a) (b)

Figure 3.1 Degrees of freedom (a) rotational (b) translational (Werner, 2013)

Mechanical movement in rigid elements (see Figure 3.2) can be limited to the types of movement discussed: rotation, translation and combined (rotation and translation). Generally, these movements are performed through basic mechanisms which only allow one degree of freedom: a hinge for rotation and a rail for sliding (Werner, 2013).

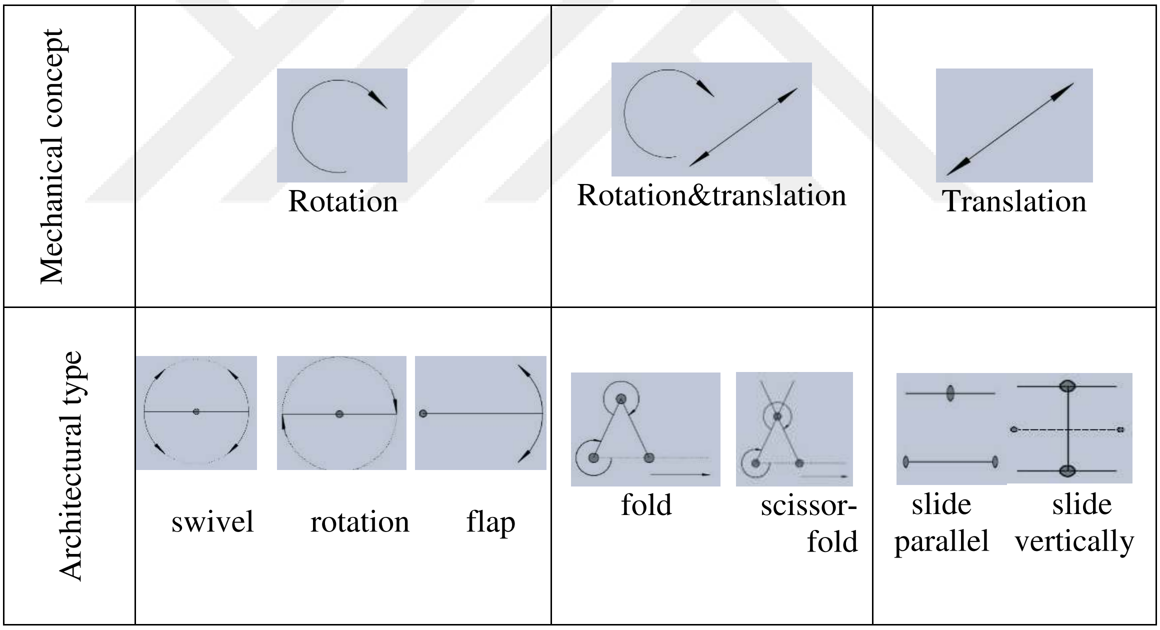
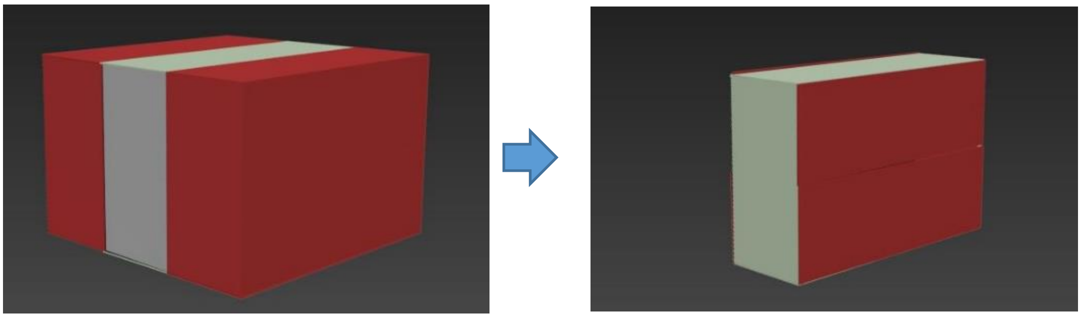


Figure 3.2 Movements in rigid buildings elements (Werner, 2013)

3.5.1.1. First Idea for Shelter

The idea here is to convert a parallelogram into a smaller parallelogram by dividing it into three units and trying to fold the side units into the main box using the symmetry feature as shown in Figure 3.3



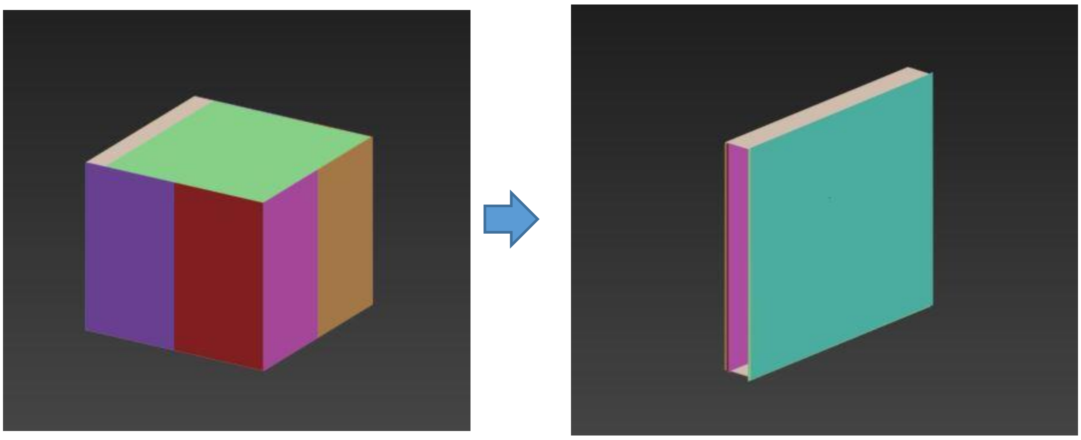
(a) (b)

Figure 3.3 Folding for first design (a) input, (b) output

The next step is dividing each side unit into sheets to allow it to be foldable. The dimension of each folded unit must be fit to the transportation container (the maximum height of the package should be less than 2.69 m), depending on the internal standard container dimensions (12.032m length, 2.35m width, 2.697m height), in order to maximize the number of the folded units which can be carried in a standard transportation container and deliver up at a time, the maximum width of each folded unit should be less than 1.17 m.

3.5.1.2. The Second Idea for Shelter

The idea here is to convert a parallelogram into a rectangular prism by folding the side panels first then the upper and lower panels after dividing all sides into many sheets according to the folding design as shown in the Figure 3.4

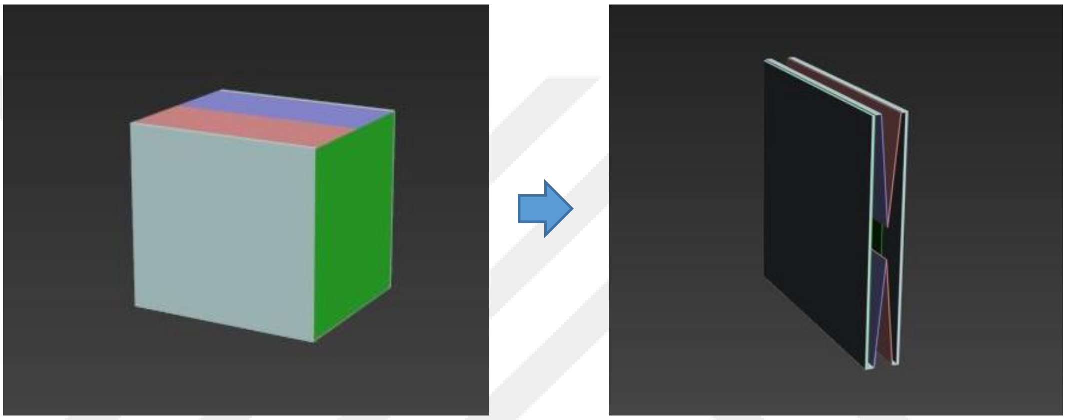


(a) (b)

Figure 3.4 Folding for second design (a) input, (b) output the dimensions of each folded unit must be fit to the transportation container which internal dimension is (12.032 length, 2.350m width, 2.697m height), as in the previous example (the maximum height of the package should be less than 2.69 m, the maximum width is 1.17m).

3.5.1.3. The Third Idea for Shelter

The idea here is to convert a parallelogram into a rectangular prism by folding the sides of the parallelogram, using the accordion instrument folding system as shown in Figure 3.5



(a) (b)

Figure 3.5 Folding for third design (a) input, (b) output

the dimensions of each folded unit must be fit to the transportation container which internal dimension is (12.032 length, 2.350m width, 2.697m height), as in the previous example (the maximum height of the package should be less than 2.69 m, the maximum width is 1.17m).

3.5.2. Adding Thickness to Folds

While dealing with paper origami folding might be simple due to zero thickness, applying origami folding techniques onto real-life thick structures could be challenging. However, the axis-shift method, in which a thick structure is made rotatable through adding a hinge system similar to that of doors, is one of the existing solutions adopted in this study. Figure 3.6 illustrates the shift in the rotational axis when adding thickness to the folds. The rotation axis shifts to the top or the bottom side of the folding mechanism, allowing a rotation between 0-180 degrees (Samuelsson and Vestlund, 2015).

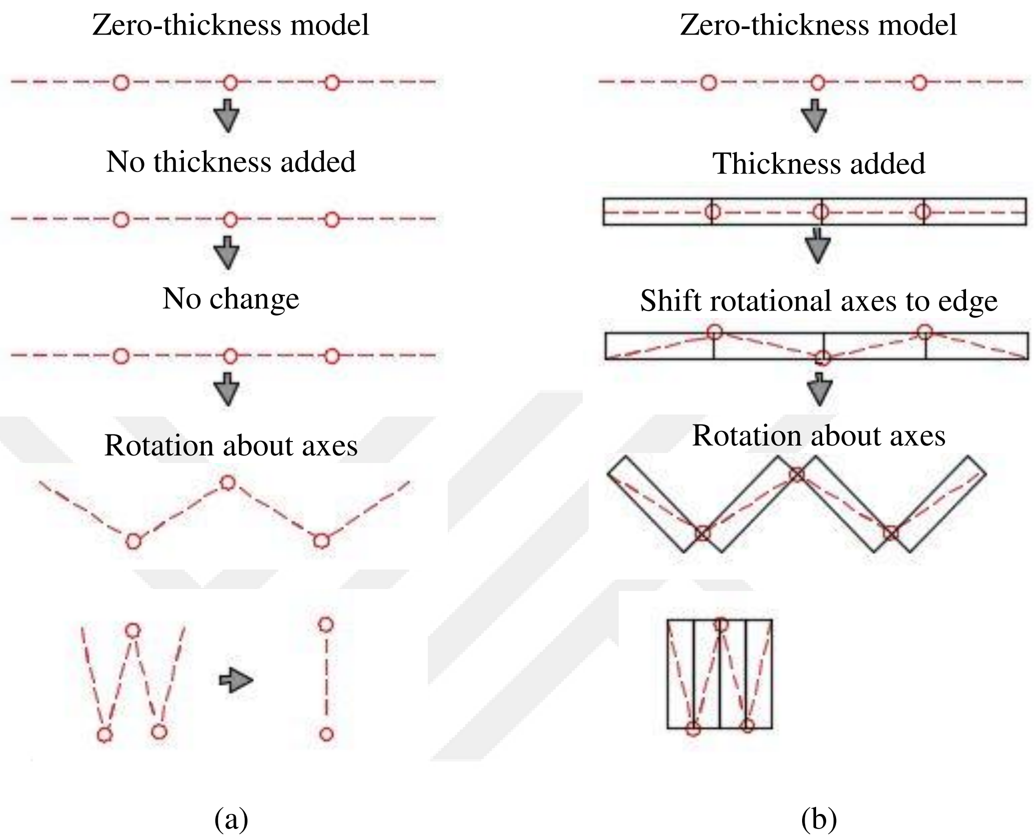


Figure 3.6 Axis-shift method (a) folding with no thickness, (b) folding with thickness

3.5.3. Movable Connection

On a foldable structure, static elements are connected by movable joints, transforming them into mobile components. Taking this into account, mobile joints not only connect two elements but also transfer loads allowing relative motion in some directions while constraining motion in others. The type and direction of motion are related to the extent of freedom allowed by each joint (Werrner, 2013).

To improve the suggested foldable unit, Invisible hinge model as shown in Figure 3.7 is adopted in this study and used for doors and windows and between folded plates of units. This hinge model is perfect for any door and special applications due to the highly important features it provides such as the perfect fit, small size and smooth operating mechanism. Uniquely designed and engineered, Invisible hinges move like no other hinges while remain hidden when closed. In addition to their high durability and beautiful design, Invisible hinges have the following features:

- exceptional appearance, since they cannot be seen after locking,
- high security and safety,
- fire resistance,
- adjustability even after installation is possible using an Allen wrench,
- the possibility to be used both in solid and hollow core planes,
- the possibility to open completely by180 degrees and in one direction
- high-quality manufacturing
- wide range of hinge size

In this study, Invisible hinge is applied because it can be used both in solid and hollow core doors and in wood or metal applications that are minimum 2″ thick. (UIP, 2006). Apart from this, cracks resulting from the folding process are covered with elastic rubber to protect the structure from dirt and rainwater leakage.

Figure 3.7 Invisible hinge (UIP, 2006)

For the door and window handles, unfoldable regular handles do not allow full folding, leaving spaces between plates. Therefore, the Debar lock and handle is used to avoid problems during the folding process. Debar combines classic aesthetics with a robust, functional design using the handles simplicity.

Debar lock and handle can turn either by 180 degrees or 160 degrees depending on the convenient position. The Debar Robus and Steel Lock both feature the following:

- the door is lockable from inside and/or outside on any configuration,
- locking with a key is possible,
- slim body,
- bolts shoot 23 mm,
- threaded rod connection provides easy adjustment up to 15 mm,
- they can be used in conjunction with Verso & Vivo handles
- corrosion protected (see Figure 3.8) (Bifold-hardware, 2014).

Figure 3.8 Debar bi-fold lock (Bifold-hardware, 2014)

3.5.4. Panel Materials

Sandwich panels which are used in mobile structure by Gomez and Colligon (2004) are also considered in this study. The materials of the walls, roofs and floors of the mobile structures are made of outer aluminum sheets, an intermediate isolating layer of polyurethane foam and an inner cover of separated material such as laminated wood with aluminum frames, plastic and tapestry. All sandwich panels layers are surrounded by aluminum frames. Advantages of sandwich panel are:

- Resistant to shock and corrosion
- Easy to remove clean
- Light weight
- Long life at low maintenance cost
- High speed erection of buildings
- Sound insulation (Panelplast, 2010)

Disadvantage of sandwich panel are:

- lack of ability to withstand the extra load
- low thermal capacity
- credited cosmetic damage
- freezing at the seams (Help repair, 2019)

CHAPTER 4

PROPOSED DESIGNS

4.1. Introduction

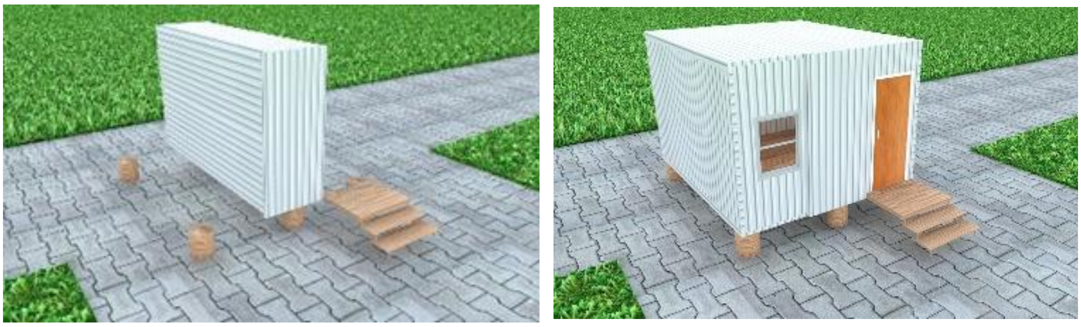
This chapter discusses the total results of experiments conducted through this study using zero thickness materials. In this research, a total of three different designs, modular foldable shelter units, were studied in two different modes: the first mode used zero-thickness materials while the second one used materials with thickness. This study also sheds the light on the structural configuration of each design and its expandability using incremental architecture.

Both folding techniques and incremental architecture are used to fulfil the desired results in accomplishing an easily assembled housing system that is sustainable, reusable or relocatable, restorable in compact packaging and upgradable in order to obtain convenient space and shape according to the variable needs. Moreover, this housing system can cater for the most important needs of comfort, safety, dignity and security.

4.2. Winged Shelters (WS) Design

4.2.1. Module Description

The Winged Shelter (WS) is a foldable housing unit which consists of an expandable parallelogram. The four symmetrical folded plates are the wings which are connected to long sides of the parallelogram by hinge joint system. Each wing is joined by two foldable plates. One of these two foldable plates is folded to the long edge of the wing, and the other is folded into the short edge of the wing using a hinge system so that it can freely rotate at a 90 degree angle. Figure 4.1 shows folded and unfolded WS unit.

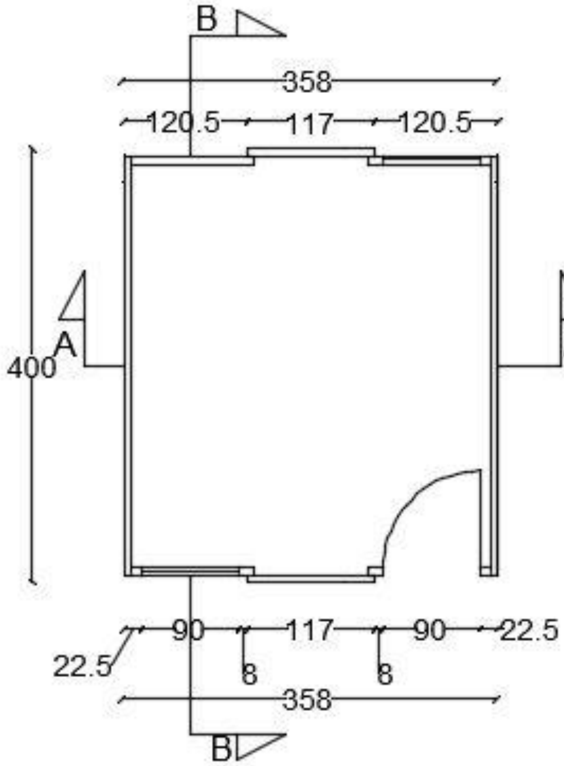


(a) (b)

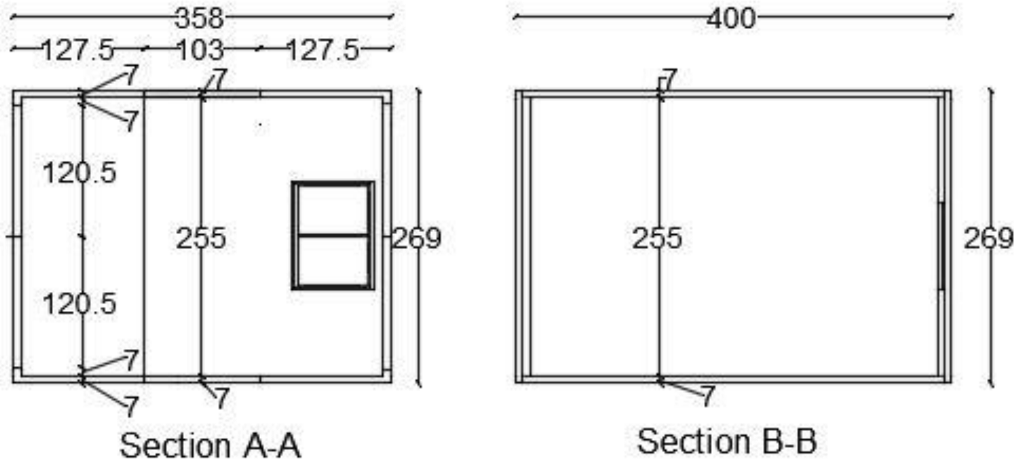
Figure 4.1 WS design (a) folded unit, (b) unfolded (after erected) unit

4.2.2. Geometry and Dimension

The suggested shelter structure is derived from a simple technique of folding. When the WS design is erected (opened), the base unit will be 400 cm long, 358 cm wide, 269 cm high. the unit supports 14.32 m^2 living floor area. The plane and sections views of the WS design is shown in Figure 4.2. The shape of this design is a parallelogram. It is a purely geometric shape which consists of flat sides. Flat surfaces give the ability to use standard prefabricated panels. In addition, they have flexibility to create openings like doors and windows to provide good lighting conditions to the unit.



(a)



(b)

Figure 4.2 The plane and section views of WS design (All dimensions in cm)

4.2.3. Conceptual Design

The basic idea of the concept is using folding and interlocking technology with the same modular composition system unit. The use of folding techniques makes the system more flexible, easily transportable, restorable and expandable.

As shown step by step in Figure 4.3, the installation procedure begins with the preparation of the foundation and ground where the unit will be placed on ground as shown in image1. Next, he wings are unfolded at a 90 degree angle to form the roof and floor as shown in image 2 and 3. After that, each wing is unfolded from the long edge at a 90 degree angle to form side walls (see image 4 and 5). It is noted that two plates from two different wings meet to form a side wall. The result of this step is two opposite walls of the unit. Then, the second plates of two of the wings are unfolded to the short edge at a 90 degree angle to make two vertical plates forming the backside walls as shown in image 6 and 7. Finally, the second plates of the other two wings are unfolded at a 90 degree angle to form front window and door panels as shown in image 8 and 9. In this case, the desired erected (unfolded) unit is ready to shelter people.
The unit can be unfolded to make it available within an hour by only three persons. As a summary, the steps of the unfolding process will occur in quick stages as following:

- Prepare the ground and foundation where the unit will be placed.
- Unfold the wings which constitute of floor and ceiling panels and two of wall panels.
- Open the other wall panel to obtain the whole unit.

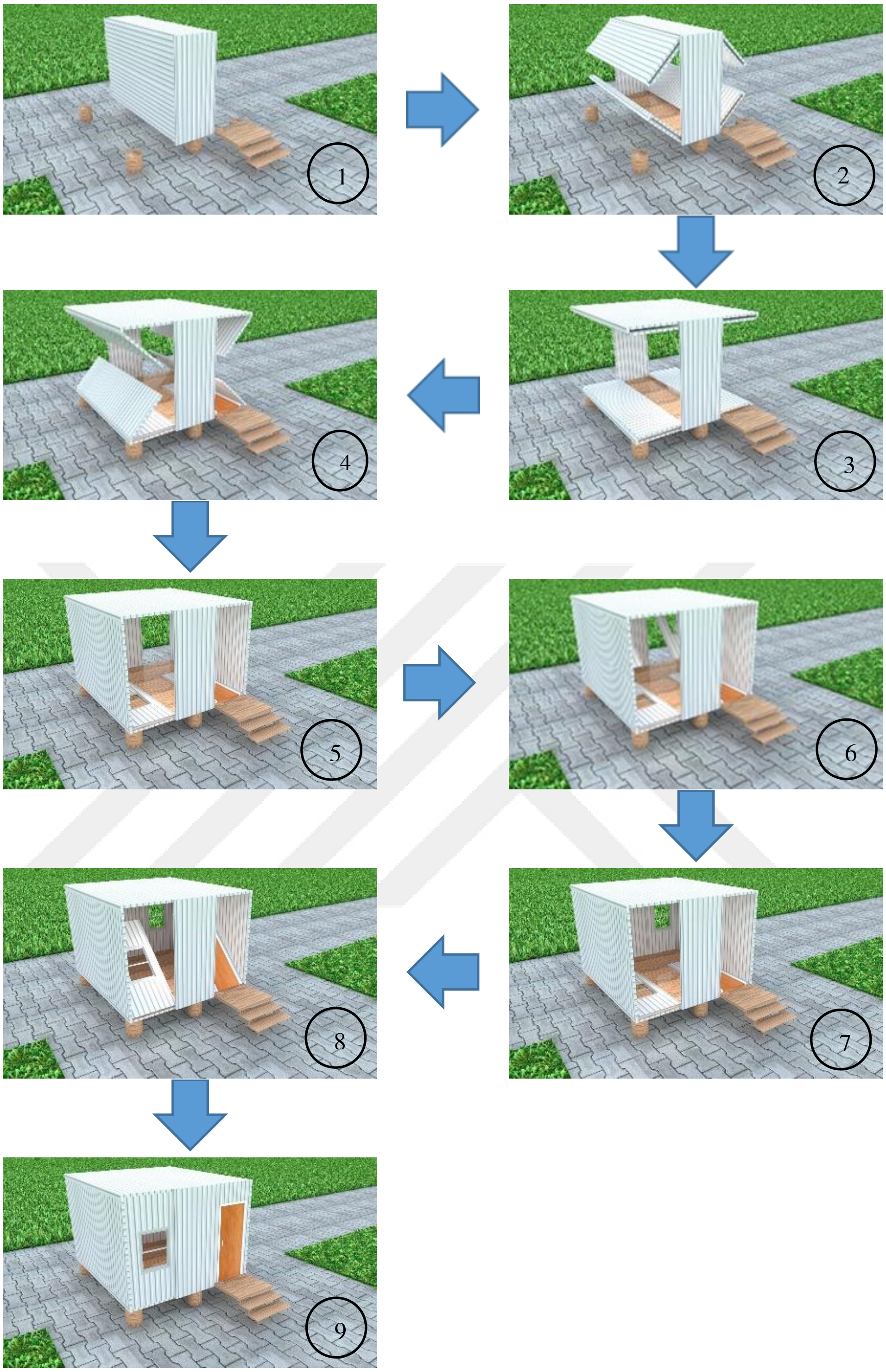


Figure 4.3 Unfolding process of WS unit

4.2.4. Transportation

In order to minimize the transportation cost and fast delivery of the unit and to the maximize the number of units carried in one transportation container to a remote campsite, the folded unit dimension must fit the transportation container (the maximum height of the package should be less than 2.69 m), depending on the internal standard container dimensions (12.03 length, 2.35m width, 2.69m height) (Council, 2017).

The suggested shelter structure can be folded into a small package to facilitate transportation. The package dimension of the basic unit is 400cm length, 117cm width, 269 cm height. Six basic unit package can fit in a standard transportation container and be delivered up at a time as shown in Figure 4.4.

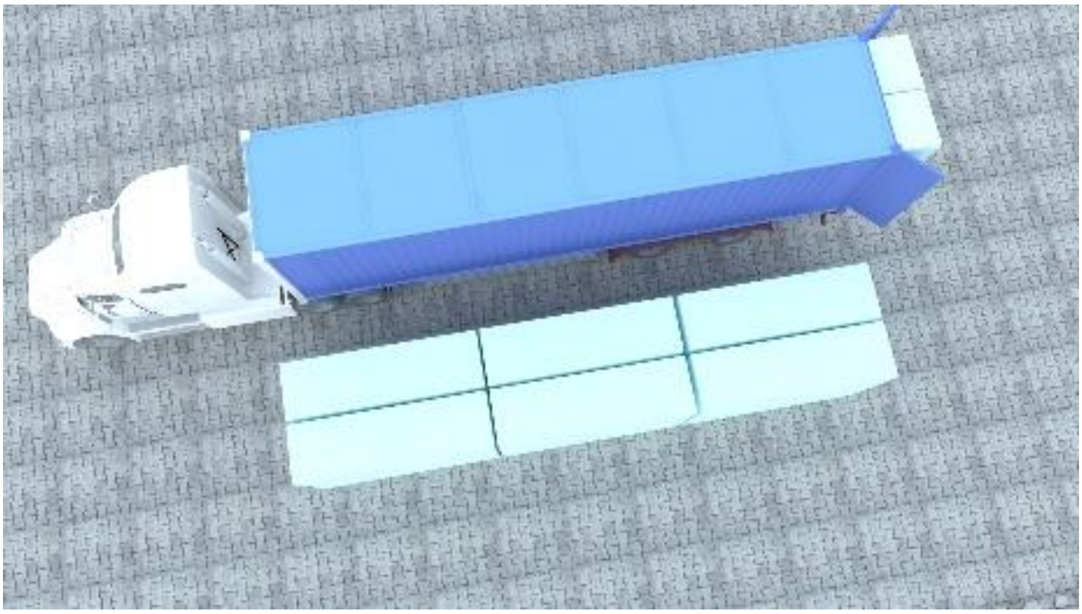


Figure 4.4 Transportation of WS units

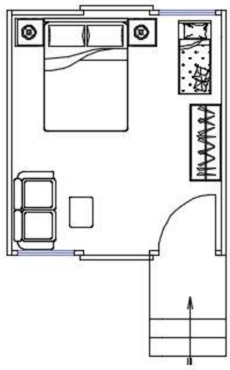
4.2.5. Incremental Housing Process

After receiving relief, affected families usually begin looking for more space to be used for daily activities. In incremental housing concept, the base unit is considered as the first step to be used in emergencies. Families can expand their shelter according to their needs, such as adding a bathroom or a kitchen unit or both.

The expansion will occur according to incremental architecture, which is a step-by-step process using addition, subtraction and substitution to obtain the required configuration. The core structure which is a bedroom with a baby-room space unit; this phase is called *emergency phase* (is a place for people to live temporarily when they cannot live in their previous residence, similar to homeless shelters) see Figure 4.5. The unit in the *emergency phase* (single unit) has the following features:

- Easily and quickly transported
- Easy to set up and quick to construct
- The unit can fit for 3 to 4 people
- Relocatable as necessary
- Upgradable size

(a)



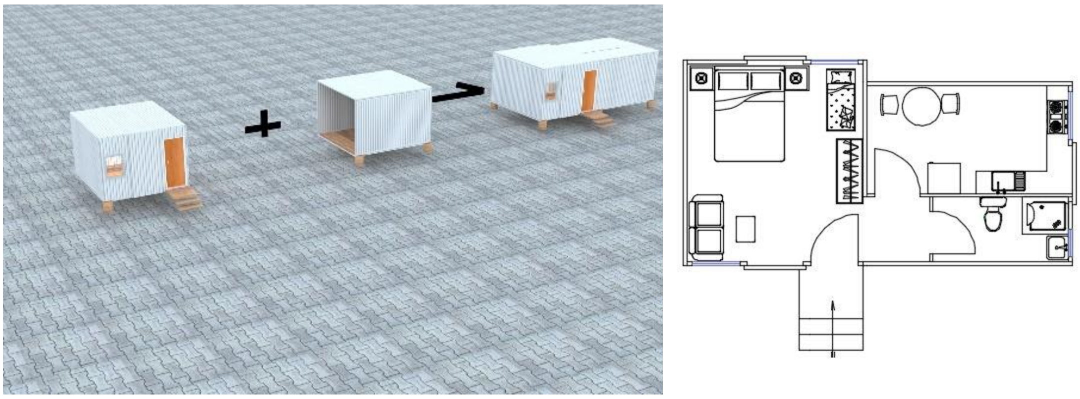
(b)

Figure 4.5 First level of **e**xpansion of WS design, (a) Main module (*emergency phase*), (b) Plan of the main module

When it is required, it is possible to connect additional modules (including bathroom, kitchen or another bedroom) to the core structure. This phase represents the *temporary phase* (double unit) and is illustrated in Figure 4.6

In this phase, one of the modules contains a kitchen and a bathroom, separate from each other. The unit in this *temporary phase* has the following features:

- People at this stage will begin searching for a larger area to cover more purposes such as a kitchen, a bathroom and a living room etc.
- The added unit can easily function as a kitchen or a bathroom by connecting it to the water supply system in the site or providing a water tank for each shelter.



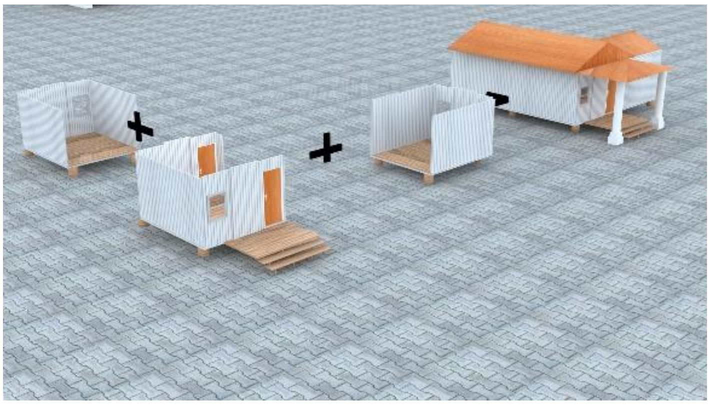
(a) (b)

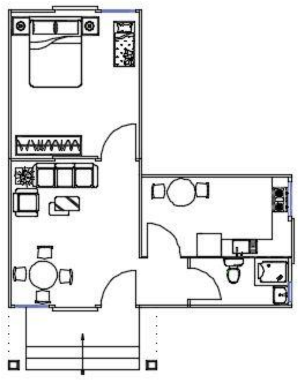
Figure 4.6 Second level of expansion of WS design, (a) Two module (*temporary phase*), (b) Plan view of two modules.

The third level of expansion program is called the *transitional* or *semi-permanent phase* (triple unit) in which we add another module to the unit in the previous phase (temporary phase). In this phase one of the modules represents the entrance - a living room with a dining room space unit as shown in Figure 4.7.

The system in the *transitional* or *semi-permanent phase* has the following features:

- After a long recovery from the disaster, the transitional stage will require more space for different purposes. 2-3 years later, users using this shelter will need more area to improve their living conditions. Systems designed to provide better living conditions can be upgraded not only horizontally but also vertically.
- Needs for more area increase during time. At this stage, the family can upgrade their unit size in order to have more space for living and dining area. However, adding more units will depend on the size and economic situation of each family.
- Adding an entrance to enhance privacy and protection.



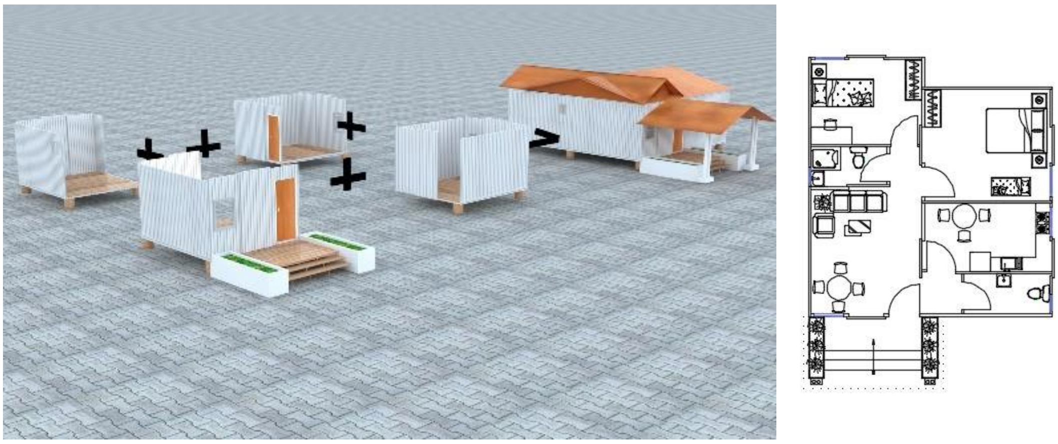


(a) (b)

Figure 4.7 Third level of **e**xpansion of WS design, (a) Three modules (*transitional phase*), (b) Plane of three modules

In the fourth level of expansion program, the permanent housing phase happen by adding another module to the *transitional phase*. In this phase, one of the modules contains a baby room and a bathroom using a separator between them as shown in Figure 4.8. The system in the *permanent* or *final phase* (quadruple unit) has the following features:

- This stage may come after years of use. The system should be more durable to work for a permanently and provide better life conditions.
- Adding more space is possible in this stage, and the unit is upgradable to ensure the space necessary for normal living conditions. Still, adding more units depends on the number of family members and their economic condition.
- In this stage the unit could be connected to the electric power system in the site or provided with solar panels system to each unit as a solution for a more sustainable house. Moreover, each unit is designed to be easily connected to the water distribution system.



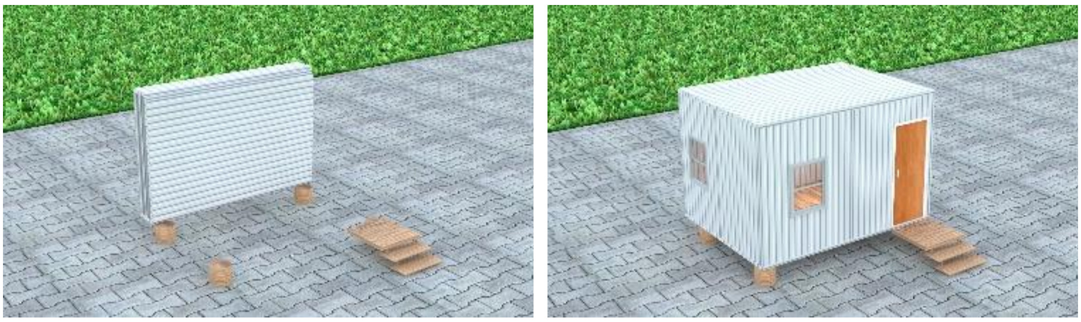
(a) (b)

Figure 4.8 Fourth level of **e**xpansion of WS design, (a) Four modules (*permanent phase*), (b) Plan view of four modules

4.3. Compact Shelter (CS) Design

4.3.1. Module Description

This design as shown in Figure 4.9 is called the compact shelter. The backside wall is a square-bracket shaped monolithic panel. Floor and roof are monolithic panels as well. The side walls and front facade consist of two panels each. The folded unit consists of a square-bracket shaped panel “the main panel” ([ ) and two folded plates connected to the side edges of the main panel. These two folded plates, which consist of three attached plates each, are connected to the main panel and to each other by the hinge joint system in order to allow these plates to freely rotate by 90 or 180 degrees. Moreover, there are two other plates connected to the upper and lower edges of the main panel using hinge joint system that allows the plates to rotate by 90 degrees.

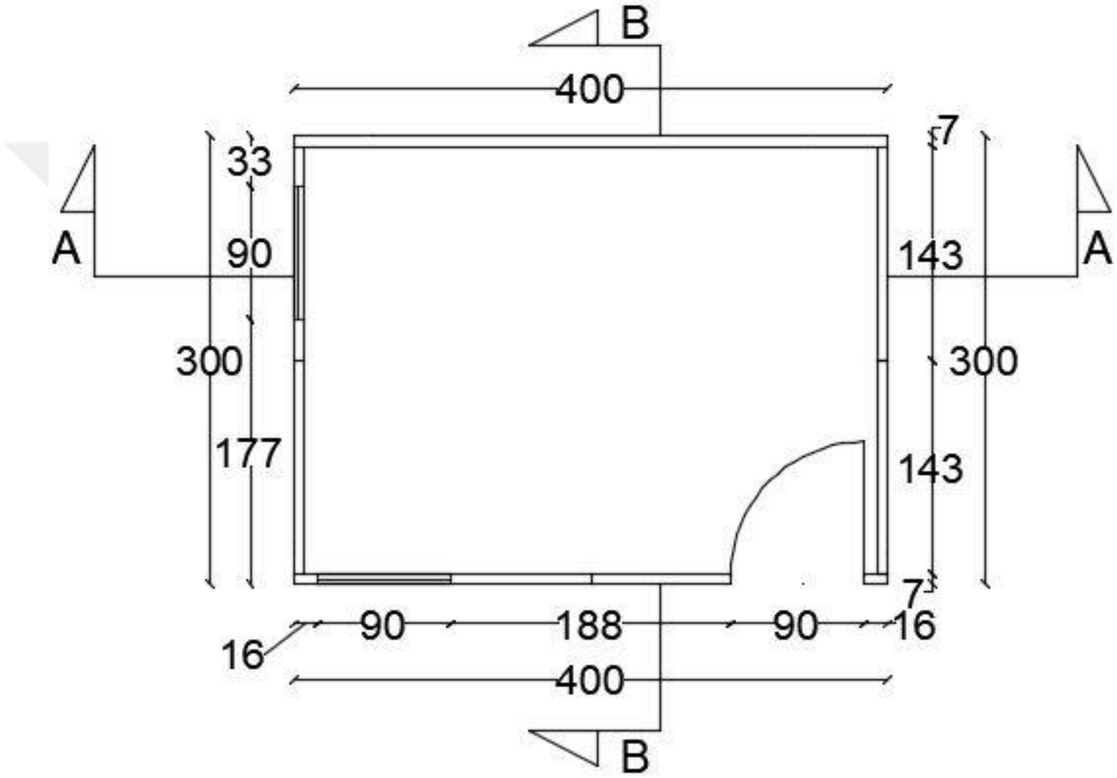


(a) (b)

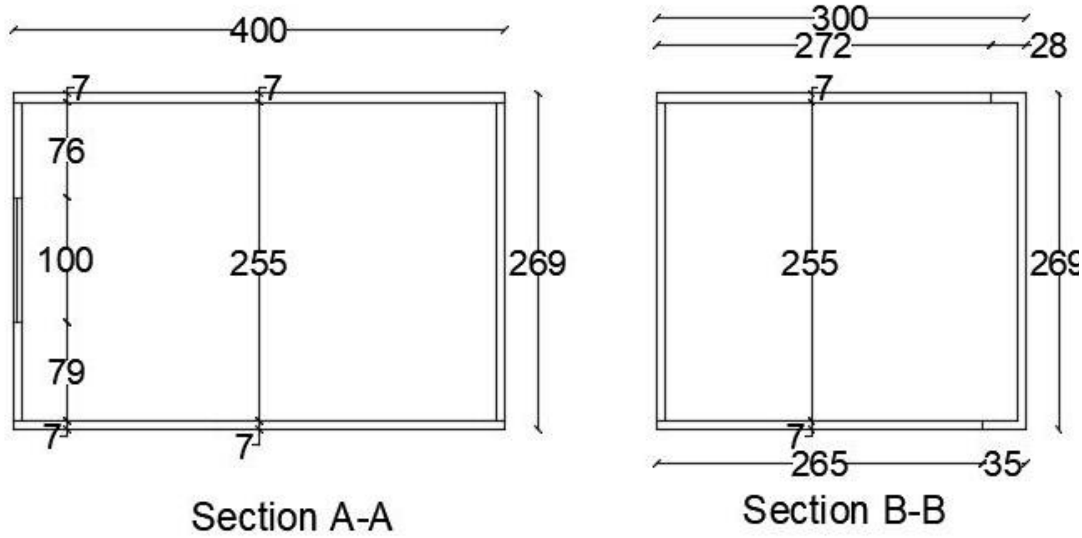
Figure 4.9 CS design (a) folded unit, (b) unfolded unit

4.3.2. Geometry and Dimension

When CS design is erected (opened), the base unit will be 400 cm long, 300 cm wide, and 269 cm high. The plan and section views of CS design are shown in Figure 4.10. The unit supports a 12 m^2 living floor area. The shape of this design is a parallelogram. It is a purely geometric shape which consists of flat sides. Flat surfaces provide the ability to use standard prefabricated panels. In addition, they have flexibility to create openings like doors and windows to provide good lighting conditions to the unit.



(a)



(b)

Figure 4.10 The plan and section views of CS design (All dimensions in cm)

4.3.3. Conceptual Design

As shown step by step in Figure 4.11, the installation procedure begins with the preparation of the foundation and ground where the unit will be placed on ground as shown in image 1. Next, the installation of the pack starts with the gradual unfolding of the plate connected to the lower edge of the mother plate at a 90 degree angle to form the floor as shown in image 2 and 3. After that, the plate connected to the upper edge of the mother plate is gradually unfolded at 90 degrees to form the roof (see images 4 and 5).

Then, the side plates, which consist of three attached plates each, are gradually unfolded in three steps. Firstly, the first plate is unfolded at a 90 degree angle to form the first part of the side walls of the unit represented in images 6 and 7. Secondly, the second plate is unfolded at a 180 degree angle to form the last part of the side wall as represented in images 8-10. Finally, the third plate is unfolded at a 90 degree angle to form the front facade as shown in images 11 and 12. Summary of the steps of the unfolding process:

- Prepare the ground and foundation where the unit will be placed.
- Unfold the floor and ceiling panels.
- Open the other wall panel to obtain the whole unit.

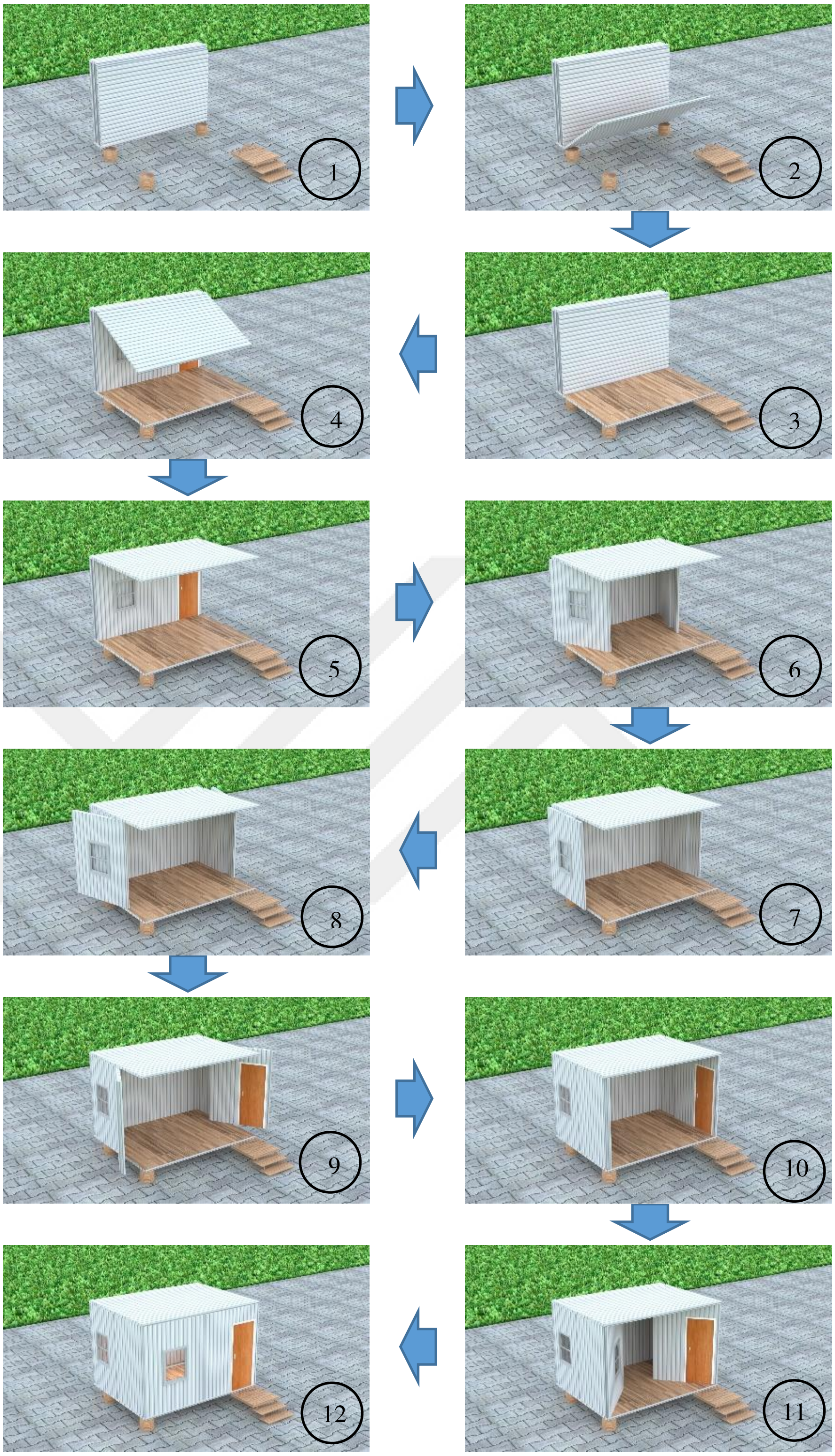


Figure 4.11 Unfolding process of CS unit

4.3.4. Transportation

The folded unit is 400cm long, 42cm wide, and 269cm height. Fifteen basic unit packages can deliver up at a time in a standard transportation container as shown in Figure 4.12.

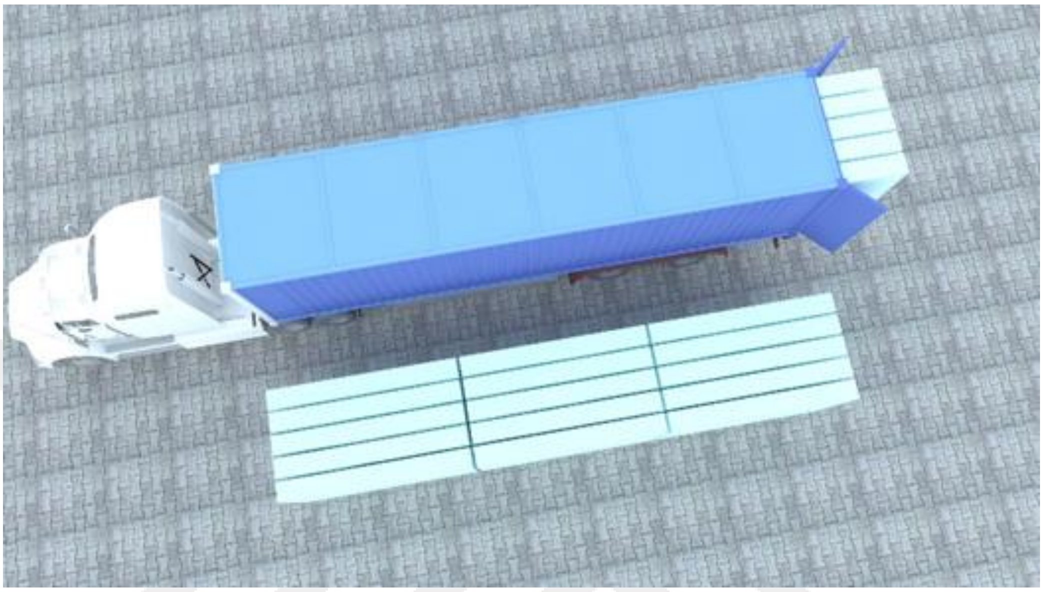
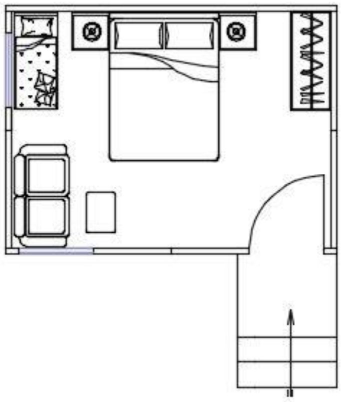


Figure 4.12 Transportation of CS units

4.3.5. Incremental Housing Process

The expansion in this proposed design will occur in the same way as in the previous design The expansion system will follow the same steps as the previously proposed design by adding units to the main unit to develop the system from the phase of the emergency to the phase of permanence.

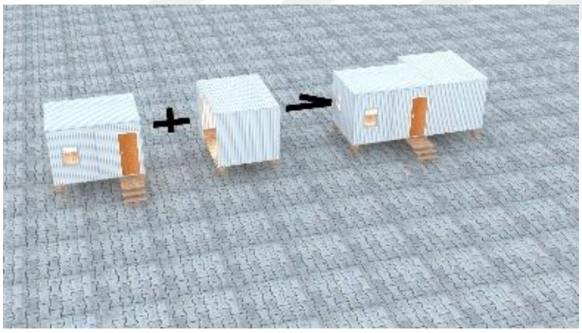
In this proposed design, Figure 4.13 represents the *emergency phase* in which the system has the same features as those in the previous design proposal.

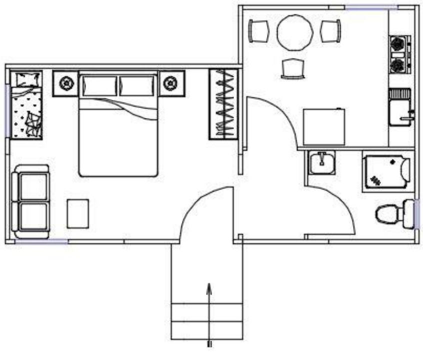


(a) (b)

Figure 4.13 First level of expansion of CS design, (a) Main module (*emergency Phase*), (b) Plan of the main module

Furthermore, Figure 4.14 represents the *temporary phase* in which the system has the same features as those in the previous design proposal and is similarly produced by adding a unit to the core structure that represents the state of emergency.

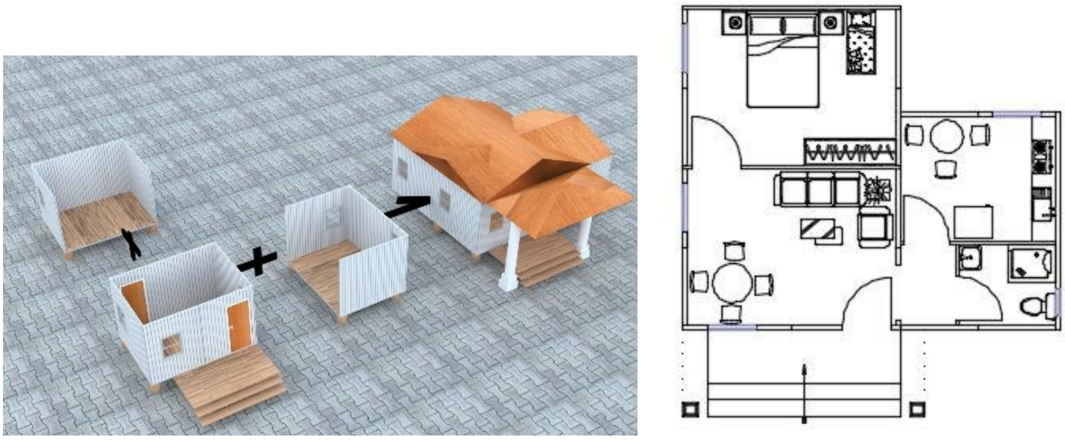




(a) (b)

Figure 4.14 Second level of expansion of CS design, (a) Two module (*temporary phase*), (b) Plan of two module

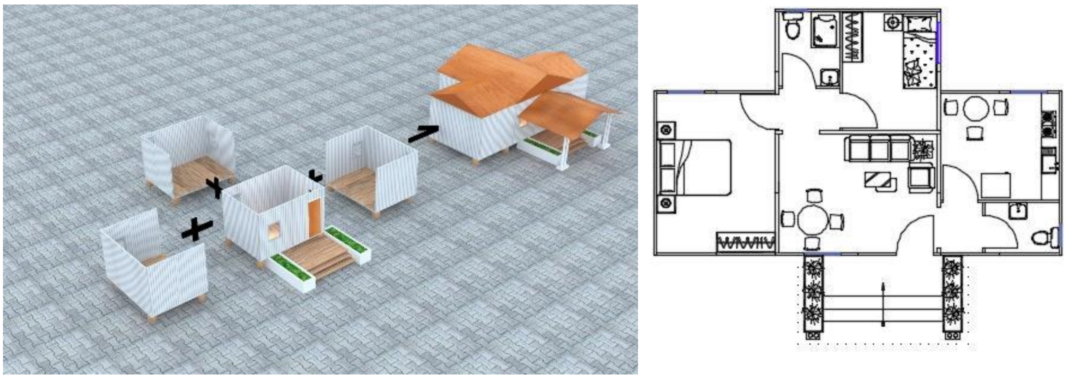
When adding another unit to the shelter temporary phase, the shelter moves into the *transitional phase*. Figure 4.15 shows that this phase has the same features as the previously proposed design.



(a) (b)

Figure 4.15 Third level of expansion of CS design, (a) Three module (*transitional phase*), (b) Plan of three module

The last step to access the permanent phase shown in Figure 4.16 by adding additional units to shelter of the *transitional phase*, and the *permanent phase* in this proposed design has the same characteristics as previously proposed design.



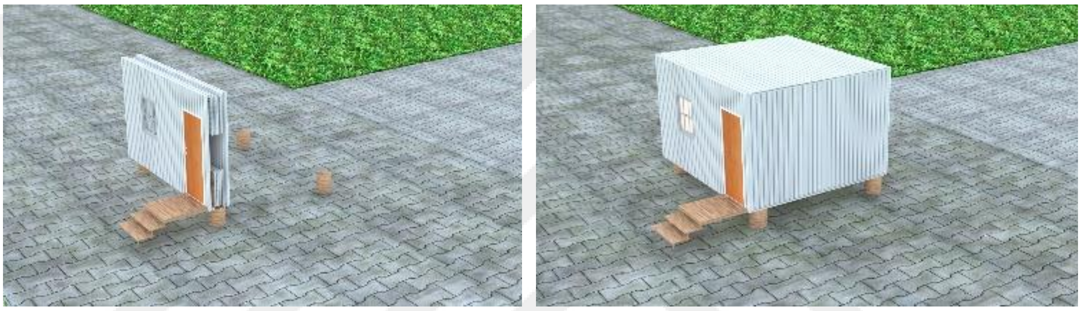
(a) (b)

Figure 4.16 Fourth level of expansion of CS design, (a) Four module (*permanent phase*), (b) Plan of four module

4.4. Accordion Shelter (AS) Design

4.4.1. Module Description

The unit is a foldable pack which can unfold in the same way as the accordion instrument, so the unit is called the accordion shelter. This shelter consists of two square-bracket shaped walls (main panels), which form the vertical sides of the accordion connecting the ceiling and floor. The ceiling and the floor consist of two plates, each divided into foldable plates resembling the folds of the accordion. The side walls are formed by two unfolded plates connected to the mother panels. Figure 4.17 shows the unit before and after unfolding process.

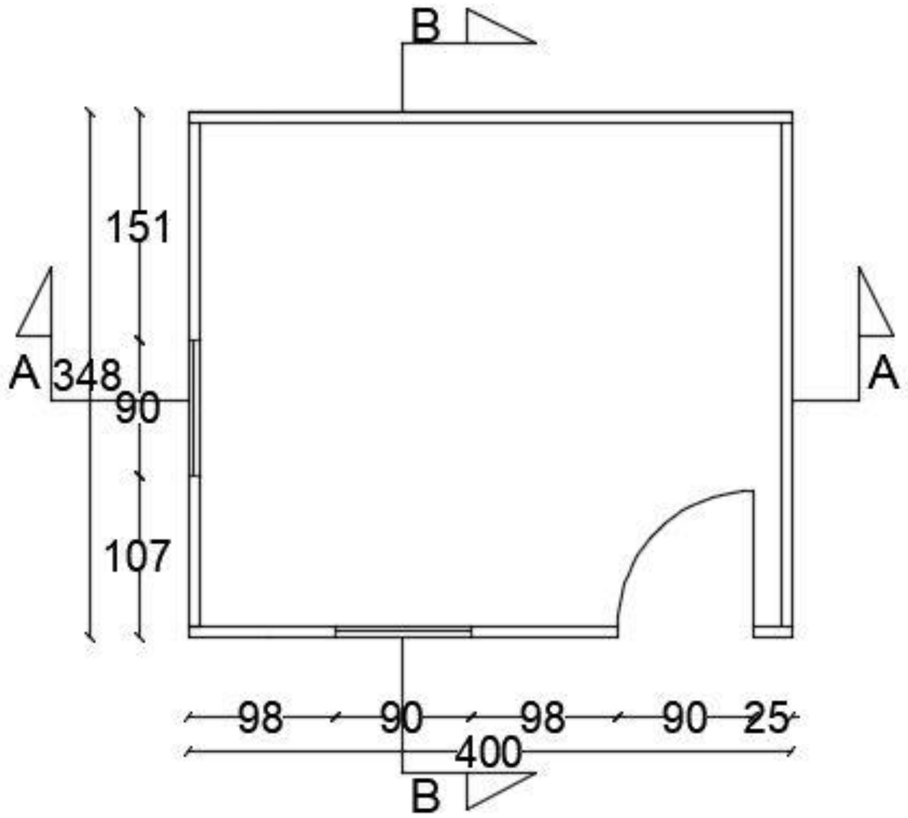


(a) (b)

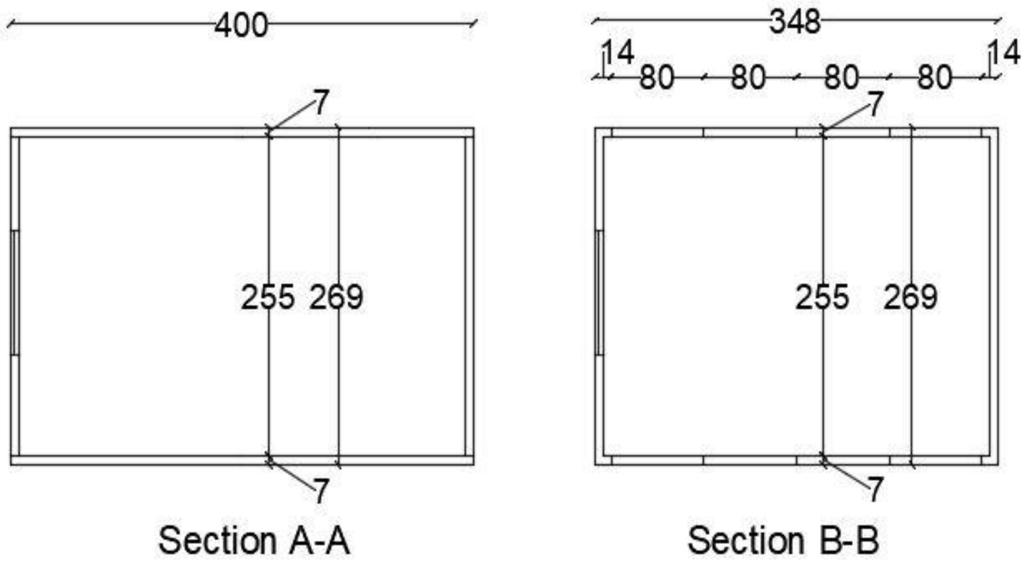
Figure 4.17 AS design (a) folded unit, (b) unfolded unit

4.4.2. Geometry and Dimension

When the accordion shelter is erected (opened), the base unit will be the 400cm long, 348cm wide, and 269cm high (see Figure 4.18). The unit provides 13.92 m^2 living floor space. The shape of this design is a parallelogram. It is a purely geometric shape which consists of flat sides. Flat surfaces provide the ability to use standard prefabricated panels. In addition, they have flexibility to create openings like doors and windows to provide good lighting conditions to the unit.



(a)



(b)

Figure 4.18 The plan and section views of AS design. (All dimensions in cm)

4.4.3. Conceptual Design

As illustrated in Figure 4.19, the installation procedure starts by preparing the foundation and ground where the unit will be installed as shown in image 1. Next, the ceiling and floor accordion-shaped plates are unfolded by pulling one or both of the square-bracket shaped walls represented in images 2-5. Thus, the roof and the floor of the unit are installed. The next step is to get the whole unit ready by unfolding the remaining folded walls at a 90 degree angle one after the other to avoid collision between these walls during the unfolding process as represented in images 6-9. All these stages can be done by up to 3 people within approximately one hour, so each family can set up their unit in a relatively short time. And the steps of the unfolding process will occur in these quick stages as following:

- Prepare the ground and foundation where the unit will be placed.
- Unfold the casing of two vertical walls and the floor and ceiling.
- Open the other wall panel to obtain the whole unit.

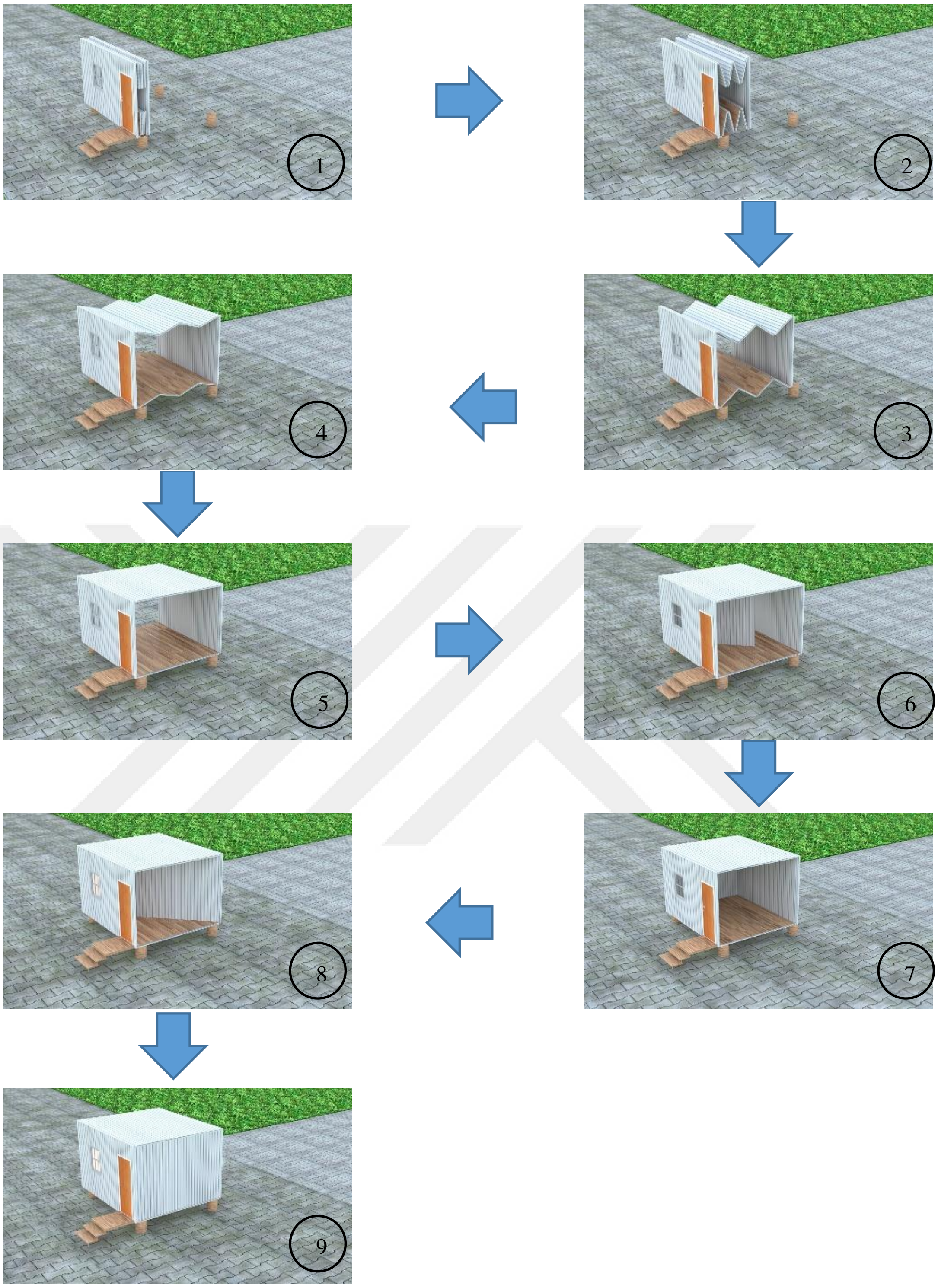


Figure 4.19 Unfolding process of AS unit

4.4.4. Transportation

The folded unit is 400cm long, 56cm wide, and 269 cm high. Twelve basic unit package can deliver up at a time in a standard transportation container as shown in Figure 4.20.

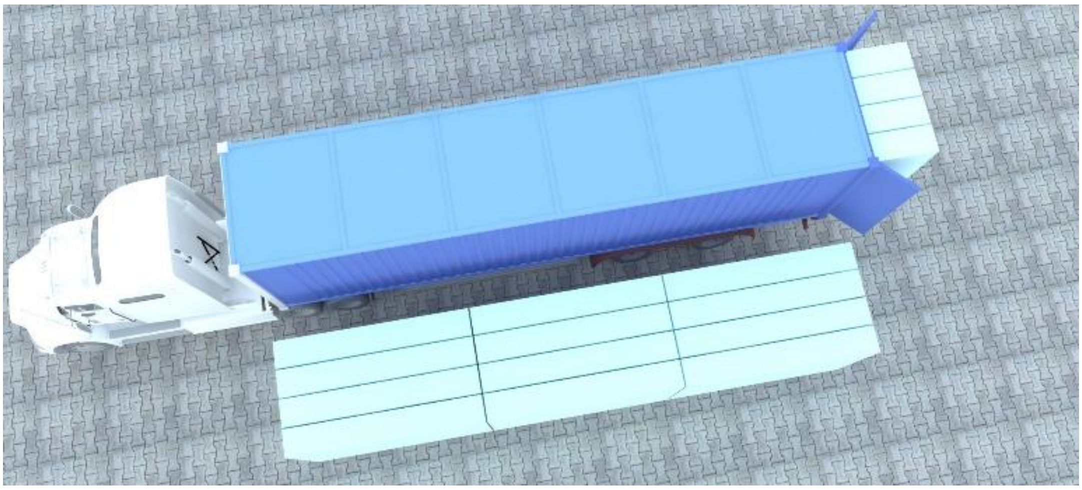


Figure 4.20 Transportation of (AS) units

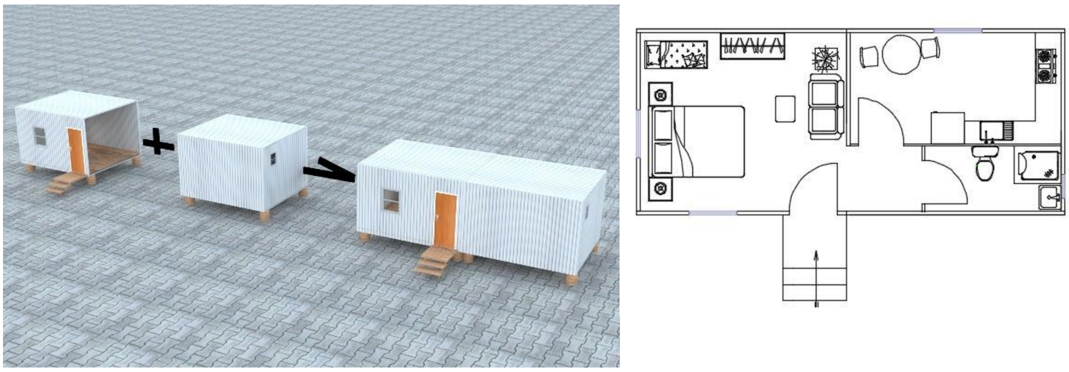
4.4.5. Incremental Housing Process

The expansion in this proposed design will occur in the same way as in the previous design using the process of incremental architecture, which is a step-by-step process using addition, subtraction and substitution to obtain the required configuration. The core structure is a bedroom with a baby-room space unit. This phase is called the *emergency phase*. As shown in Figure 4.21

(a) (b)

Figure 4.21 First level of **e**xpansion of AS design, (a) Main module (*emergency phase*), (b) Plan of the main module

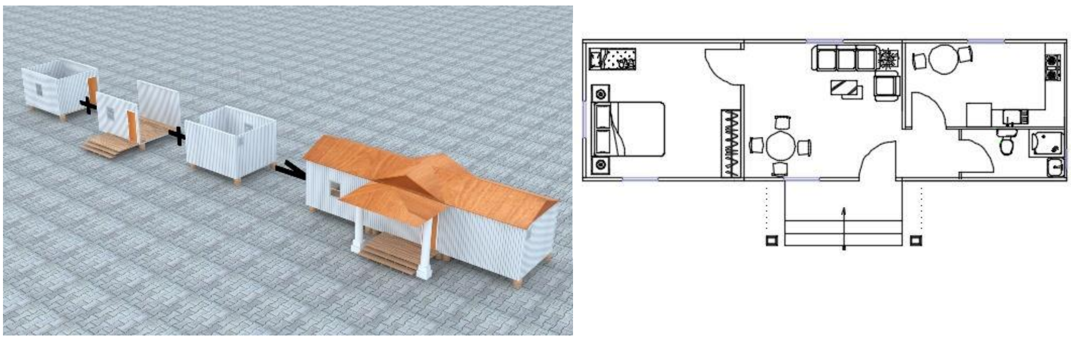
Figure 4.22 represents the shelter in the *temporary phase* which also has the same features as in the previous design proposal and is produced in the same way by adding a unit to the core structure that represents the state of emergency.



(a) (b)

Figure 4.22 Second level of **e**xpansion of AS design, (a) Two module (*temporary phase*), (b) Plan of two modules

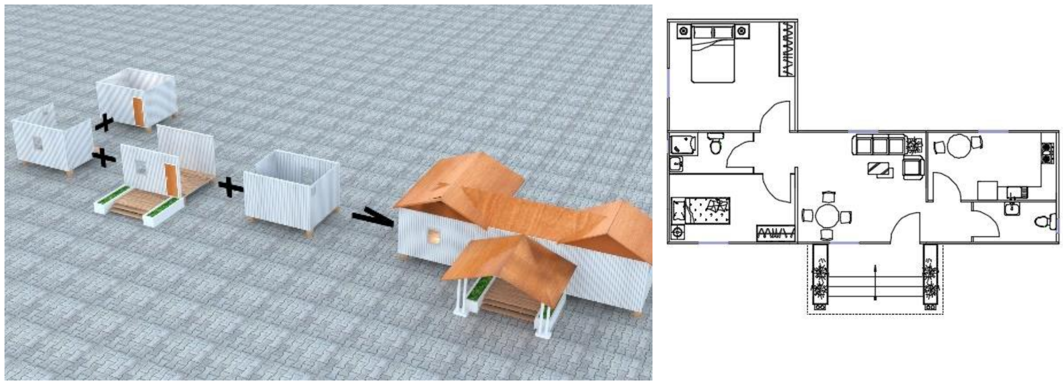
By adding another unit to the temporary phase, the shelter becomes in the *transitional phase or semi-permanent phase*. Figure 4.23 shows that this phase has the same characteristics as the previously proposed design.



(a) (b)

Figure 4.23 Third level of Expansion of the (FS), (a) 3 Module (*Transitional phase*), (b) Plan of 3 Module

The last step to access the permanent stage (shown in Figure 4.24) is through adding extra units to the *transitional phase* units. In addition, the *permanent phase* in this proposed design has the same features as in the previously proposed design.



(a) (b)

Figure 4.24 The fourth level of expansion of AS design, (a) Four module (*permanent phase*), (b) Plan of four modules

CHAPTER 5

CONCLUSION

To understand the characteristics of the mobile shelter, first of all, we need to understand the shelter system and its categories. Furthermore, in order to provide a successful shelter, it is necessary to consider the user's prospects and other factors such as safety, lifespan, size, comfort, privacy, etc. Still, these factors change depending on the situation, society, culture and economy.

As a result, three creative ideas are proposed for foldable mobile shelters used for various purposes, especially as temporary residences. The main advantage of these designs, which are different from the existing temporary shelter systems, is that they can be folded in a very compact form with an opening and closing mechanism. These modular designs can also be repaired and maintained making them more effective and efficient compared to regular temporary shelters. It is also possible to expand the structure as necessary by connecting additional units.

One of the main features of the proposed structures is that they are designed to cover all of the disaster recovery phases, so mobile shelter units can be utilized from the emergency phase up to the last phase, the permanent housing phase. To serve both short-term and long-term sheltering plans, these structures were designed to include the following features: they are easy to transport and set up, the area is adequate to accommodate 3 to 4 people during emergencies, and they can be relocated as necessary and upgradable in size and living conditions. To add more, structure storage is very simple since the structure is foldable to reach a much smaller size than the original size, which makes it easy to transport.

This paper also shows that it is possible to optimize the architectural functionality of the sheltering system while, at the same time, maintain its structural stability through the utilization of folding techniques in the design and implementation of the proposed sheltering systems.

Finally, shelter solutions should provide the opportunity for affected families to gradually move from emergency, temporary solutions to durable, permanent ones within the shortest possible time, taking into consideration the accessibility to the extra resources necessary.

REFERENCES

Asefi, M., Sirus, F.A. (2012). Transformable shelter: Evaluation and new architectural design proposals. *Procedia-Social and Behavioral Sciences*, **51**, 961-966.

Ashmore, J., Fowler, J., Kennedy, J. (2008). Shelter projects. *IASC Emergency Shelter Cluster, UN-HABITAT, Nairobi.*

Babaei, M., Sanaei, E. (2010). Geometric and structural design of foldable structures. *In Symposium of the International Association for Shell and Spatial Structures (50th. 2009. Valencia). Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures: Proceedings.* Editorial Universitat Politècnica de València.

Baldwin, Y.C., Clark, B.K. (2000). *Design Rules, The Powerity of Modularity,* The MIT Press Cambridge, Massachusetts, London, England.

Bakbak, D., Özakça, M., Göğüş, M.T. (2016). Design of Transitional Shelter Using Foldable Panels, *Proceedings Architecture in Emergency: Rethinking the refugee crisis conference,* November 17-19, İstanbul Kultur University, Turkey.

Bashawri, A., Garrity, S., Moodley, K. (2014). An overview of the design of disaster relief shelters. *Procedia Economics and Finance*, **18**, 924-931.

Bifold-hardware. (2014), DEBAR robus locking solution for bi-fold door. Available at: https://bifold-hardware.com/. Accessed: 06.06.2019

Council, W.S. (2017). Dry Cargo Container. Available at:

http://www.worldshipping.org/. Accessed: 01.01.2019

Da Silva, J. (2007). Quality and standards in post-disaster shelter. *Structural Engineer*, **85(14)**, 25-32.

DFID, Department for International Development (2009). *Transitional Shelter Prototypes Project,* Shelter Center

DesRoches, R., Comerio, M., Eberhard, M., Mooney, W., Rix, GJ. (2011). Overview of the 2010 Haiti earthquake. *Earthquake Spectra*, **27(S1)**, S1-S21.

de Zeen, (2016). Architect for Society designs low-cost hexagonal shelters for refugees. Available at: https://www.dezeen.com/. Accessed: 16.01.2019

do Nascimento, J.I.G. (2015). *Transitional architecture in emergency scenarios: click house case study: modular shelter made of advanced composite material*s. Master's thesis in Architecture, Instituto Superior Técnico of University of Lisbon.

Farrugia, P. (2008). *Kinematic analysis of foldable structures.* Doctoral dissertation, University of Surrey, United Kingdom.

Félix, D., Branco, J.M., Feio, A. (2013). Temporary housing after disasters: a state of the art survey. *Habitat International*, **40**, 136-141.

Goethert, R. (2010). Incremental housing. *Monday Developments*, **9**, 23–25.

Collignon, C.G.E. (2010). *Mobile structure* U.S. Patent No. 7,673,424. Washington, DC: U.S. Patent and Trademark Office.

IFRC/RCS, International Federation of Red Cross and Red Crescent Societies (2011), *Transitional shelters – Eight designs*, IFRC/RCS, Geneva,

IFRC/RCS, International Federation of Red Cross and Red Crescent Societies. (2013). *Post-disaster shelter: Ten designs*. IFRC/RCS, Geneva,

IFRC/RCS, UN-HABITAT and UNHCR. (2013). *Shelter Projects 2011-2012*. Available at: www.ShelterCaseStudies.org. Accessed: 02.03.2019

IFRC/RCS, UN-HABITAT and UNHCR. (2013). *Shelter Projects 2010.* Available at: www.ShelterCaseStudies.org. Accessed: 02.03.2019

Inhabitat, (2008). The Origami-Inspired Folding Bamboo House. Available at: https://inhabitat.com/origami-inspired-folding-bamboo-house-by-ming-trang/. Accessed: 07.04.2019

Inhabitat, (2008). Design for disaster: the accordion recover shelter. Available at: https://inhabitat.com/matthew-malone-recovery-shelter/. Accessed: 05.05.2019

IOM, International Organization for Migration (2012). *Transitional Shelter Guidelines*, Shelter Centre, Geneva Switzerland.

Isawsomethingnice, (2016). An Awesome Project: Hex House. Available at: http://www.isawsomethingnice.ch/2016/03/an-awsome-project-hex-house/.Accessed: 15.03.2019

Jelle, **BP**. (2011). Traditional, state-of-the-art and future thermal building insulation materials and solutions–Properties, requirements and possibilities. *Energy and buildings*, **43(10)**, 2549-2563.

Kirsch, **TD**., Wadhwani, C., Sauer, L., Doocy, S., Catlett, C. (2012). Impact of the 2010 Pakistan floods on rural and urban populations at six months. *PLoS currents*, 4.

Kronenburg, R. (2009) Mobile and flexible architecture: solutions for shelter and rebuilding in post-flood disaster situations. *Proceedings of blue in architecture 09: Water, climate change and architecture focus and debate on a fluid and sustainable future*. Università Iuav di Venezia, September 24-29th. Venezia, Italy

Lebée, A. (2015) From Folds to Structures, a Review. *International Journal of Space Structures*, **30**, 55-74.

Norman, **LR**. (1989). *Instantly Stable, Quickly Erectable and Quickly Collapsible Portable Structure.* U.S. Patent No. 4,825,892. Washington, DC: U.S. Patent and Trademark Office.

Johnson, **AF**., Sims, **GD**. (1986). Mechanical properties and design of sandwich materials. *Composites*, **17(4),** 321-328.

Samuelsson, C., Vestlund, B, (2015). *Structural Folding: A Parametric Design Method for Origami Architecture*, Master's thesis, Department of Applied Mechanics, Chalmers University of Technology, Sweden).

Shen, T., Nagai, Y. (2017). An Overview of Folding Techniques in Architecture Design. *World Journal of Engineering and Technology*, **5**, 12-19.

Smith, RE. (2010). *Prefab Architecture: A Guide to Modular Design and Construction*. John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

Šekularac, N., Ivanović-Šekularac, J., Čikić-Tovarović, J. (2012). Folded structures in modern architecture. *Facta Universitatis-series: Architecture and Civil Engineering*, **10(1)**, 1-16.

UIP (Universal Industrial Products), (2006), Strong… Beautiful… Invisible! SOSS® Invisible Hinges and Magnetic Door Holder. Printed in USA. Available at:

https://www.robertscoinc.com/pdf/SOSS%20CATOLGY.pdf. Accessed: 04.06.2019

UNHCR, United Nations High Commissioner for Refugees (2015). *Handbook for emergencies 4th edition*. UNHCR, Genova, Switzerland.

UNHCR. United Nations High Commissioner for Refugees, (2017). Global trends: forced displacement in 2017. Available at: www.unhcr.org/globaltrends2017/. Accessed: 08.07.2019

UNHCR The UN Refugee Agency, (2014). Al za'atari refugee camp shelter assessment. Available at:https://reliefweb.int/sites/reliefweb.int/files/resources/REACH_UNHCR_AlZaatari%20Shelter%20Assessment_June2014_final.pdf. Accessed: 05.03.2019

UN-HABITAT, IFRC/RCS, International Federation of Red Cross and Red Crescent Societies, (2010).Shelter Projects 2009. Available at: https://unhabitat.org/books/shelter-projects-2009-2/ Accessed: 05.02.2019

Werner, CDM. (2013). *Transformable and transportable architecture: analysis of buildings components and strategies for project design*, Master's thesis, Escuela

Técnica Superior de Arquitectura de Barcelona, Universitat Politècnica de Catalunya, Spain.