U.PORTO

# 4D STRUCTURES FOR RAPID CONSTRUCTION OF A SHELTER IN CRISIS SITUATIONS

Luísa Alice Costa Henriques

Dissertation for the Master Degree in Product and Industrial Design

Supervision from
Prof. António Torres Marques (FEUP),
Prof. Bárbara Rangel (FEUP) and
Prof. Jorge Lino (FEUP)

Porto, July 2019

U.PORTO

MESTRADO EM DESIGN INDUSTRIAL E DE PRODUTO
UNIVERSIDADE DO PORTO

## O JÚRI

**PRESIDENTE**

Doutor Rui Mendonça

PROFESSOR AUXILIAR DA FACULDADE DE BELAS ARTES DA UNIVERSIDADE DO PORTO

**ORIENTADOR**

Doutor António Torres Marques

PROFESSOR CATEDRÁTICO DA FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

**ARGUENTE**

Doutor Bruno Acácio Ferreira Figueiredo

PROFESSOR ADJUNTO DA UNIVERSIDADE DO MINHO

# 19

19 JULHO 2019

**MESTRE** Alice Costa
MDIP/**67**

*To my parents and my sisters. To my best friend and partner.*
*Thank you for always supporting me in all my adventures.*

## ABSTRACT

The increasing number of internal displaced people (IDP) due to conflicts or natural disasters over the years represents the need to create structural solutions for first emergency shelter, that are currently supplied in tarpaulin and with structures improvised by the locals.

Innovative technologies like 4D-printing could overcome these problems, being possible to develop 3D structures with smart materials that react with environmental stimulus such as water, light, heat and others. Unlike 3D-printing, which is static, the factor "time" adds a dimension to the 4D, making the structures self-assembling, multifunctional or self-repairing.

Given this, the aim of this dissertation is to investigate the application of 4D-printed structures, for crisis situations, to speed up and ease the assembly process, replacing the structures currently used with one that integrates the emergency kit.

This research presents a review on emergency shelters, as well as on 3D and 4D printing processes, clarifying its definition and introducing a case study demonstrative of the process, by printing with shape memory filaments, specifically poly(lactic acid) (PLA) and shape memory polymers (SMP).

Finally, a concept was developed and validated, evaluating the possibility of applying 4D printing process in the development of structures that are easy to transport and assemble in emergency situations, using SMP material.

It was concluded that the SMP material had beneficial characteristics for the development of the concept. Therefore, as future recommendations, it is suggested the simulation of the concept and the improvement of the material properties in terms of specific strength and toughness, that can be achieved using, composite materials, for example.


**Keywords:** 4D printing, Emergency shelter, Shape memory effect (SME), Shape memory polymer (SMP), Social design

# RESUMO

O elevado número de desalojados devido a conflitos ou desastres naturais tem vindo a aumentar exponencialmente nos últimos anos. Este facto representa a necessidade de criar soluções estruturais em termos de primeiro abrigo de emergência, atualmente fornecido em lona e com estruturas improvisadas pelos locais.

Tecnologias inovadoras como a impressão 4D, podem vir a resolver dificuldades como a apresentada, onde é possível desenvolver estruturas 3D usando materiais com memória de forma que reagem posteriormente a estímulos ambientais como a água, luz, calor, entre outros. Ao contrário da impressão 3D que é estática, o fator tempo acrescenta uma dimensão ao 4D, fazendo com que estruturas possam ser auto-montáveis, multifuncionais ou até auto-reparáveis.

Deste modo, o objetivo desta dissertação passa pelo estudo da aplicação de estruturas desenvolvidas em impressão 4D, para situações de crise, visando facilitar e acelerar o processo de montagem do abrigo e substituindo assim as estruturas atualmente utilizadas por uma estrutura que conste no "kit" de emergência.

Esta investigação apresenta uma revisão sobre abrigos de emergência e sobre o processo de impressão 3D e 4D, clarificando a sua definição e, ainda, um caso de estudo demonstrativo do processo, através da impressão com filamentos de memória de forma, nomeadamente ácido polilático (PLA) e polímeros com memória de forma (SMP).

Por fim foi desenvolvido e validado um conceito sobre a possível aplicação da impressão 4D, utilizando o material SMP, no desenvolvimento de estruturas de fácil transporte e montagem, para situações de emergência.

Concluiu-se que o material SMP apresentava características benéficas no desenvolvimento do conceito, pelo que foram ainda delineadas, para futura investigação, sugestões para a simulação do conceito, bem como para a melhoria das propriedades do material, em termos de rigidez e resistência especifica que podem ser obtidas com a utilização, por exemplo, de materiais compósitos.


**Palavras-chave:** Impressão 4D, Abrigo de emergência, Efeito de memória de forma (SME), Polímero com memória de forma (SMP), Design social

## ACKNOWLEDGMENTS

First, I would like to express my sincere gratitude to Professor António Torres Marques, not only for all the accompaniment and support but also for his full availability in sharing his knowledge, during the development of this work.

I am also very grateful to professors Bárbara Rangel and Jorge Lino, for all the advice, support and availability to help along this work and also this master degree.

The development of this work was also possible thanks to a collaboration with Maria Moita, a specialist of post-conflict disasters, in the International Organization for Migration (IOM). A special thanks to Maria for all the information provided for solving the main problem of this research.

I also want to thank all the persons who contributed to the enrichment of the experimental work developed. A special thanks to Púria Esfandiari from ISEP, for all the assist and availability in using his precious 3D printer and ISEP laboratories. Many thanks to André Brandão and Leonardo Santana, from LDPS at FEUP, for all the patience and help with the 3D printing of the final models. I thank also Luís Oliveira, from INEGI, for his availability in sharing knowledge and advice.

To all my professors and colleagues that accompanied me in this journey, thanks for all the assistance, support, guidance, motivation and friendship.

A huge thanks to my family, in special my parents and sisters, thanks for all the love, dedication and support over the years. Mom and Dad, thanks for giving me the opportunity to take my master degree outdoors, all the effort was really worth it. My sister Laura, thank you for being by my side and supporting me in this adventure, you are amazing. My little sister Clara, thank you for always making me smile, I hope I inspire you. Finally, to my best friend and partner, thank you for all the love and support throughout the whole process.

## INSTITUTIONAL ACKNOWLEDGMENTS

Authors gratefully acknowledge the funding of Project NORTE-01-0145-FEDER-000022 - SciTech - Science and Technology for Competitive and Sustainable Industries, cofinanced by Programa Operacional Regional do Norte (NORTE2020), through Fundo Europeu de Desenvolvimento Regional (FEDER).

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF ABBREVIATIONS

| | |
|---|---|
| ABS | Acrylonitrile Butadiene Styrene |
| AFP | Automated Fiber Placement |
| AM | Additive Manufacturing |
| ASTM | American Society for Testing and Materials Standards |
| ATP | Automated Tape Laying |
| BSI | British Standards Institute |
| DIW | Direct Ink Write |
| FDM | Fused Deposition Modeling |
| FFF | Fused Filament Fabrication |
| FGF | Fused Granular fabrication |
| FRP | Fiber Reinforced Polymer |
| GFRP | Glass Fiber Reinforced Polymer |
| HDPE | High-density polyethylene |
| ICRC | International Committee of the Red Cross |
| IDPs | Internal Displacement People |
| IFRC | International Federation of Red Cross and Red Crescent Societies |
| IOM | International Organization for Migration |
| ISO | International Standards Organization |
| NFI | Non-food Item |
| PA | Polyamide |
| PAC | Printed Active Composites |
| PC | Polycarbonate |
| PE | Polyethylene |
| PEEK | Polyether Ether Ketone |
| PEI | Polyetherimide |
| PET | Polyethylene Terephthalate |
| PETG | Polyethylene Terephthalate Glycol |
| PLA | Poly(lactic acid) |
| PTFE | Polytetrafluoroethylene |
| PμSL | Projection micro-Stereolithography |
| SLA | Stereolithography |
| SLS | Selective Laser Sintering |
| SME | Shape Memory Effect |
| SMM | Shape Memory Materials |
| SMP | Shape Memory Polymers |
| SMS | Shape Memory Strip |
| SOK | Sealing Off Kit |
| STL | Standard Triangle Language |
| $T_g$ | Glass Transition temperature |
| TPU | Thermoplastic Polyurethane |
| UNHRC | United Nations Human Rights Council |

## LIST OF SYMBOLS

| | |
|---|---|
| $ | Dollar |
| € | Euro |
| cm | Centimeter |
| $cm^2$ | Square Centimeter |
| $cm^3$ | Cubic Centimeter |
| g | Grams |
| $g/cm^3$ | Gram per Cubic Centimeter |
| GPa | Gigapascal |
| $H_DD$ | Digital Hardness shore D |
| kg | Kilograms |
| km | Kilometer |
| kNm/g | Kilonewton meter per grams |
| m | Meter |
| $m^2$ | Square Meter |
| $m^3$ | Cubic Meter |
| mm | Millimeter |
| mm/s | Millimeters per second |
| $mm^2$ | Square Millimeter |
| $mm^3$ | Cubic Millimeter |
| MPa | Megapascal |
| Nm/g | Newton meter per Grams |
| °C | Degree Celsius |
| USD | United States Dollar |

# I. INTRODUCTION

# 1. INTRODUCTION

This dissertation describes an investigation to achieve an alternative solution for first emergency shelter, a solution that could provide an easy and fast assembly after a crisis situation, solving the constraints of the current structures developed with materials provided by humanitarian organizations, such as tarpaulin and bamboo.

The aim of this research is to make a contribution, developing an improved solution through the adoption of innovative and technologic solutions, such as additive manufacturing (AM) processes and 4D printing.

## 1.1. Context

In 2017, the number of internal displacement people (IDPs) related with cases of conflict and violence almost doubled from 6.9 million to 11.8 million, remaining 40 million persons at the end of the year. Approximately 8.5 million people of 23 countries have not found a long-term solution and related to disasters it was documented 18.8 million of new IDPs in 135 countries and territories (Figure 1). Considering this, there are currently a global total of 67.3 million persons displaced (IDMC 2018).

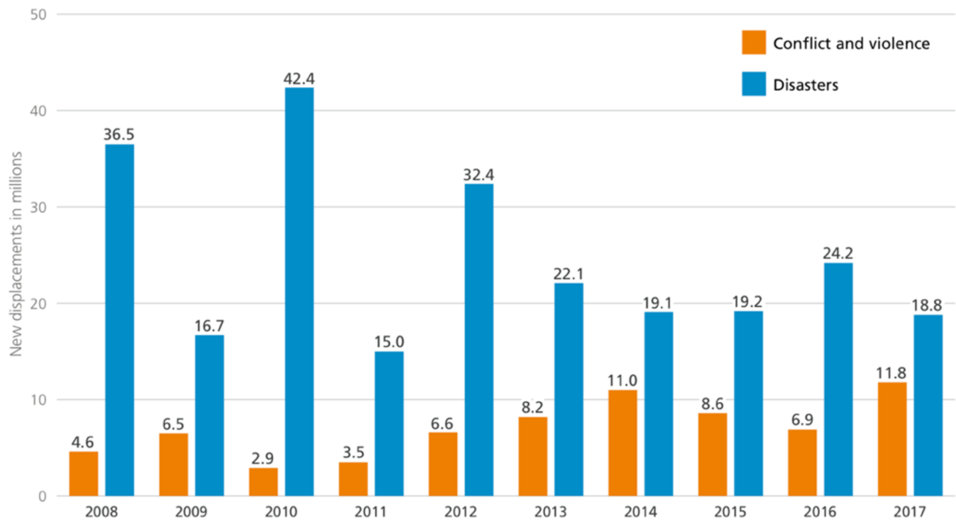


Figure 1 - New displacements due to conflict and disasters (2008-2017)(IDMC 2018)

The numbers of displaced people have not stopped increasing, due to natural disasters such as floods, earthquakes, droughts, tsunamis, hurricanes, tornados, fire, explosion and epidemics, or man-made conflicts, and these people are living in emergency or transitional shelter or in need for them.

This represents the necessity to provide shelter and support in emergency cases all over the world and be aware of how to find solutions for IDP's, establishing first care shelter for later reconstruction of long-term housing.

After a disaster or a conflict, the critical element for survival and rehabilitation is a shelter, due to its essence of a habitable place, being also a place where people can settle even if temporarily. The concept of a shelter goes beyond the provision of a physical structure involving the development and understanding of each case scenario.

Considering the numbers and concept, after disaster or conflict there is an instant response from the government and international organizations, such as International Organization for Migration (IOM), providing first emergency shelter through an emergency kit for building them. However, the structure for the construction of this shelter, with tarpaulin, is not included in the kit and IDPs normally use local materials, such as wood or bamboo poles, to construct them.

However, will the displaced people be able to build their own shelter after a conflict or disaster? How much time will they need to build a structure? Will the provided shelters offer the basic need for survival and also be resistant to extreme climate changes? Which materials are used to build the structures in the different countries? What is the resistance and durability of those structures? Is it possible to develop an easy and fast assemble structure using alternative technologies? Could the 4D printing process be a solution for the development of an emergency shelter?

These are some of the questions that lead to this research, in order to find a solution to the structure and tarpaulin for the first emergency shelter. A subject studied by scientists, architects, engineers and designers all over the world, claiming that appropriate shelter can save lives through the use of proper building techniques, innovative materials and appropriate technologies. The research aims to bridge the gap between humanitarian organization solutions and the latest innovative technologies, providing a contextualized solution that is quick and easy to build, being an alternative solution to the current one provided for the first emergency shelter.

Appropriate technologies concept, introduced by Schumacher (1973), sees technology not only as a way to reach an end, but as a path that should be designed in such way that promotes sustainability and also contributes to manufacturing processes that help the society in general. This concept was summed up as technology tailored to a location and to the necessities of each individual, aiming to improve the life quality of the poorest population, by implementing simple and sustainable technological methods to solve their needs. Appropriate technologies provide to researchers, engineers and designers, a new way to rethink concepts, in order to develop solutions that respond to real needs in less developed places (Schumacher 1973).

The MIT researcher Amy Smith (2006), founded the D-Lab MIT, a program focused on the design, development and dissemination of appropriate technologies for international development. Apologist of appropriate technologies and her concept "Simple designs to save a life", encourages her students in the development of useful and low-cost solutions to solve real problems in developing countries and in emergency situations, through the use of innovative technologies along with methodologies and local materials. According to Smith (2006), technology enhances value to design and development, being innovation and creativity crucial to survival.

Regarding these concepts, the purpose of this dissertation is to adapt innovative technologies and materials, such as 4D printing concept and composites, to support appropriate solutions for emergency shelter, through the development of structures that can be easy to transport and fast to build, or even assemble themselves as a reaction to a stimulus.

## 1.2. Objectives

Concerning the necessity of first emergency shelter and the solutions provided after disasters, the main objective of this investigation is the development of a practical and cost--effective solution that enables the fast construction of a shelter, replacing the current structures in tarpaulin and bamboo, and also considering the sustainability and reuse of the shelter.

The structure intends to be part of the emergency kit provided by the organizations in an emergency situation. So, in order to develop a material and a structure for the first emergency shelter and considering its requirements, several materials and techniques will be analyzed.

Nowadays, the main material for the development of the structures of emergency shelters is bamboo, due to its resistance and flexibility. Hence, the aim is to find a material with similar characteristics as bamboo's, at a competitive cost considering its lightweight, sustainability or reusability, easy assembly, transportation and manufacture process, as well as durability and adaptability.

Therefore, in order to solve the main question of this investigation, the objectives of the dissertation can be summarized in:

i. study the current shelters provided by the organizations and conceptual shelters, through a state of the art and market research;

ii. list the requirements for the emergency shelter, concerning the local needs and individual necessities of internal displaced people;

iii. search and introduce innovative materials and technologies, such as composite materials and 4D printing structures;

iv. analyze the costs and manufacturing process;

v. develop a project for a shelter for 2 or 3 persons, considering the relevance of IOM, its typologies and a laboratorial research;

vi. make an experimental plan to test the material, the structure and validate the 4D printing process.

## 1.3. Methodology

In order to guide this research, a methodology was established, beginning with a deep bibliographic revision and laboratory research to support the investigation, as well as a market research of conceptual shelter structures. Then, several case studies were explored, related with IOM typologies and from selected materials of the state of the art, followed by the analysis and tests of the materials for the posterior conceptualization of the product. And finally, the discussion of the results, as well as the conclusions and future recommendations will be presented.

The content of this investigation can be categorized in four chapters: Introduction, State of the art, Case studies and Conclusions.

In chapter 1, it is introduced the context, questions, problems and relevance of the theme, the objectives and innovative goals of the dissertation, as well as this methodology, developed to guide the project and dissertation. Also, the emerged constraints on this project are described.

In chapter 2, State of the art, is detailed a research about the emergency shelter currently provided by the humanitarian organizations and also on conceptual design solutions. From this, the materials and constructive processes are described, as well as the advantages/disadvantages of each solution. Beyond that, an analysis of 3D printing along with its applications in large scale, and the concept of 4D printing were presented, so that concepts like these could be used in the development of new solutions. Lastly, a review on composite materials for constructive solutions and lightweight composite structures is made, in order to compare the performance of these materials with the ones currently applied.

In chapter 3, Case studies, it is explained the relevance of the IOM organization, analyzing the problems and needs. Also, a standard shelter is prototyped at scale, to register the process of construction as well as the challenges of using the conventional materials, tarpaulin and bamboo. Besides this, several materials and shapes are tested in the concept of 4D printing, followed by the development of the product, focusing on what design can bring into the solution, as well as tests and results to validate the models.

In chapter 4, Conclusion, is presented a summary of the whole work, describing the achieved goals regarding the developed product, and its efficiency on responding to crisis scenarios. Some recommendations for further work and improvements will also be given.

### 1.4. Constraints

The project only concerns on the first emergency shelter, not on the transitional or permanent one and it is restricted to the standard rules and conditions imposed by the involved organizations for the first emergency kits.

The solutions of the humanitarian organizations responsible in providing first emergency shelter are extremely tested and validated, so it is hard to change or impose new concepts, regarding how innovative and outstanding the developed product could be. However, the regulations are considered and perhaps, in some circumstances, they could be modified in order to fit with the developed solution.

Despite the main constraint being the difficulty of implementing the solution in real case scenarios, due to the requirements imposed, another constraint is the fact that the technology applied in the project, 4D printing, is a recent technology and in this work the concept was only demonstrated using the materials available for FDM printing. However, the demonstration of the principle of shape memory effect (SME) could be applied for other materials and processes.

Being dependent on different 3D printers from ISEP, FEUP and INEGI laboratories for running the tests, the calibration of each printer used directly influenced the results and also the dimension of the printer limited the size of the pieces.

# II. STATE OF THE ART


Tibbits, S. 2014

# 2. STATE OF THE ART

## 2.1. Emergency shelter and settlements requirements

Organizations spread all over the world, such as IOM, provide first emergency shelters for those in need, right after disaster or conflict. The solution is mainly based on tents made with high quality tarpaulin, due to its easy way of construction, durability and impermeability.

The SPHERE Association was created in 1997 by humanitarian non-governmental organizations and the Red Cross and Red Crescent Movement, with the goal of improving work quality of humanitarian responses to emergencies. This association developed a handbook to assure minimum principles and foundations for the needs of each individual. A book that was made according to the SPHERE philosophies, defending that the affected individuals have the right to dignity and assistance. Besides that, all possible measures should be taken in order to relieve people's suffering due to each crisis situation (Association 2018).

According to SPHERE, shelter and settlement are concepts that should always be inter-related, "shelter" being the space for living, supporting the daily needs, and "settlement" the location where communities live. Therefore, shelter and settlement responses should provide safe living environment for individuals, supporting the community and promoting health.

Regarding the minimum standards imposed by SPHERE, the objective of primary emergency shelter is beyond providing survival, it is also ensuring dignity, privacy, access to water and sanitation facilities. The access to adequate shelter is protected by international law, and shelter support needs to be adapted according to the context of each situation, considering the requirements to build after a disaster or conflict. Additionally, determinant factors are the climate and social conditions, considering the scale of the crisis situation. Shelter and settlement are the fundament for people to carry their daily activities, so first emergency shelter should be accessible to everyone, offering the basic needs conditions and livelihoods. It must also assure safety, privacy and separation between gender, age groups and families, according to cultural and social standards.

First emergency shelter is part of the Non-Food Items (NFIs) distributed by IOM, in humanitarian response operations. Due to the constant increasing of ongoing responses, IOM and ICRC/IFRC lined some specifications for kits, based on laboratory testing and field experience. These kits (Table 1) are defined according to each country and there are different types of kits around the world, developed and adjusted to meet everyone's needs (IOM 2016).

Table 1 - IOM Standard Sealing off kit (SOK) (adapted from IOM 2017)


| Category | Items | Description | Qty | Unit |
|---|---|---|---|---|
| Sealing-off Materials | Plastic sheet | Shelter grade plastic tarpaulin, 4 m x 5 m | 2 | pcs |
| | Ply wood | size (1.8x122x244 $mm^3$) thickness 17 mm | 6 | pcs |
| | Square timber | 10x5 $cm^2$, 2meter, +/- 5 mm | 6 | pcs |
| Fixings | Rope | Plastic reinforced rope (roll), 1/4" Diameter (30m nylon rope) | 1 | pcs |
| | Wire Nails | Round Wire Nails Steel, length: 75 mm, 3 mm dia., supplied in a sealed bag. 1kg | 1 | pcs |
| Tools | Hammer | minimum length 35 cm | 1 | pcs |
| | Wood saw | minimum length 35 cm | 1 | pcs |
| | Measuring tape | 10 m | 1 | pcs |
| | Water hose | Nylon, 10 m | 1 | pcs |
| | Water goblet | For water scooping | 1 | pcs |
| | Silicone gun | For silicone, with metal handle | 1 | pcs |
| | Silicone tube | Weather proof silicone tube | 4 | pcs |
| | Bucket | Plastic bucket with handle | 1 | pcs |
| Optional items | First aid kit | 20 basic first aid items | 1 | set |
| | Fire extinguisher | 5 kg, ABC powder type | 1 | pcs |

During 2017, IOM coordinate 25 shelter country mechanisms and distributed a variety of items (Figure 2), reaching over 5.2 million affected individuals, in 49 countries (IOM 2018). As shown, the number of delivered timbers, poles and bamboos achieved the 1.452 million, items that were mostly used to provide structures for shelters, or to upgrade them.

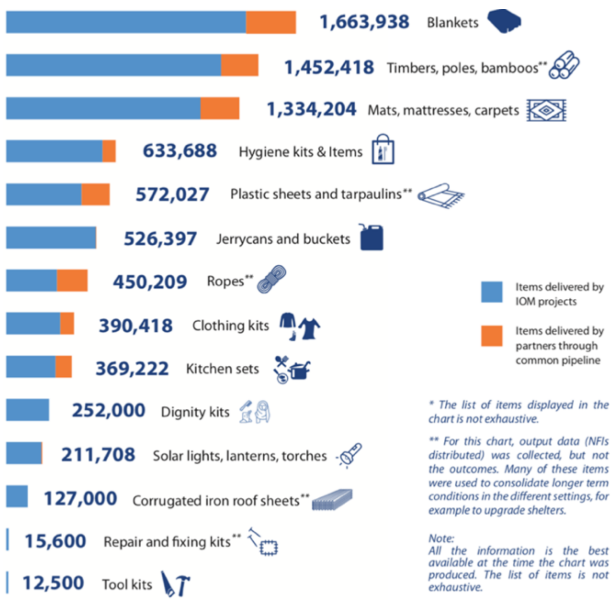



Figure 2 - NFIs delivered by IOM in 2017 (IOM 2018)

The kits contain basic items, such as construction materials, tools and personal and site safety equipment, to build a first shelter, as shown in Table 1. All the items are distributed in bales to save volume, and it is distributed one kit per family (max. 6 persons), costing between $250 to $300 per kit (ShelterCluster_Iraq 2018).

The tarpaulin distributed by the organizations should have the standard size between 4mx5m to 4mx6m, being the ideal size the 4mx6m, following the requirements shown in Figure 3, with reinforcement bands and printed with logo as specified below.

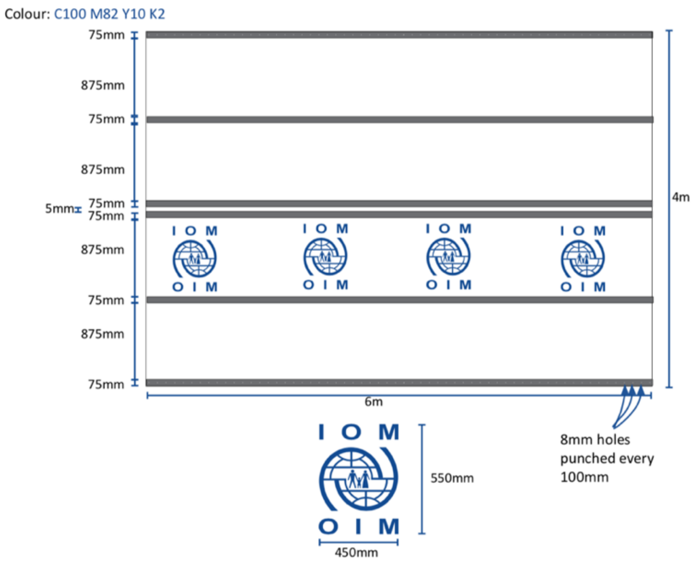



Figure 3 - IOM logo size and placement (IOM 2016)

Shelter structure construction usually depends on the materials, technologies and available resources of each place and since the emergency kit does not include a structure, it also depends on local materials or resources later provided by the organizations, such as timber or bamboo (Figure 4 and Figure 5).

Figure 4 - Shelter construction wood structure in Maiduguri, Nigeria (© M. Mohammed, IOM 2016)

Figure 5 - Bamboo construction shelter demonstrated in Myanmar Training Course (Shelter, ReciproBoo. 2017)

The current requirements (Table 2) for plastic sheeting are tested and established according standards from ISO (International Standards Organization), BSI (British Standards Institute), ASTM (American Society for Testing and Materials Standards) or the International Fabrics Association (CPAI-84 for flame retardance).

Table 2 - Standard specifications for plastic sheeting (IFRC and International 2007)

| | |
|---|---|
| **Basic specification:** | |
| Weight | 200g/m2 ± 5% (ISO 3801). Add 10% for reinforcement. (Lighter versions that meet the material performance specifications below might also be considered) |
| Woven fabric | HDPE, BLACK color (Black color provides privacy and reduces heating under the sheeting due to the sun). |
| Lamination material | LDPE, WHITE color on at least one side. (White color reflects heat better in hot climates). |
| **Either reinforcement bands (rolls and sheets) or eyelets (sheets only):** | |
| Sealed edges (with eyelets) | One strong aluminum eyelet every 1.00m ± 5% on edges. Sealed on all sides (or 2 sides heat sealed and two sides double stitched), with nylon or HDPE ropes in hem. |
| Reinforcement bands | 6 Grey bands of 7.5cm width made from black woven HDPE laminated on both sides. |
| **Material specification:** | |
| Tensile strength | Outside of reinforcement bands:<br>Minimum 500N (ISO 1421) or Minimum 600N (BS 2576 50 mm grab test)<br>(US equivalent test ASTM D751) (For reinforced tarpaulin only: Inside of reinforcement bands: Minimum 700N (ISO1421)) |
| Tear strength | Outside of reinforcement bands: Minimum 100N (under ISO 1421) (or BS 4303 wing tear). |
| Bursting strength | Not necessarily specified. (200N/cm2 (BS 4768)). |
| Welding | Maximum 1 welding along the middle.<br>Minimum 80% of the original tarpaulin strength in the weft. (This means that sheets / rolls are made from two panels). |
| UV resistance | Maximum 5% loss on original tarpaulin tensile strength (ISO 1421) after a minimum of 1500 hours UV under ASTM G53/94 (UVB 313 nm peak). |
| Temperature resistance | -20 to 800C where defined. (This is not necessary to define as HDPE/LDPE perform well within this temperature range) |
| Fire resistance | Ideally treated with fire retardant (CPAI 84-1995 section 6 >2000C). |
| Volatiles | This is not generally defined. (0.07% under ASTM D 1203) where defined. |
| **Printing:** | |
| Logo | On request. |
| Fabrication | Manufacturer name, month and year of production. |
| Markings | Markings every meter (to aid cutting and distribution). |
| **Packing:** | |
| Sheets | Packed in bales of 5 or 10, wrapped in polyethylene, sealed with a polyester band. |
| Rolls | Folded in the middle and wound. Wrapped in polyethylene and sealed with a polyester band. |
| Stacking | Criss cross stacking to avoid palette collapse. |
| Palettes | As per organizational standard.<br>Example: "plastic: size 120cm x 110cm x 13cm.<br>The packed goods must not exceed the length and width of the palette. |
| Shipping volumes sheets | Dependent on precise specification. Example below for 5mx4m sheets with eyelets.<br>3000 sheets / 20' container (without palettes)<br>6000 sheets / 40' container (without palettes)<br>2400 sheets / 20' container (with palettes) 5400 sheets / 40' container (with palettes) |
| Shipping volumes Rolls | Dependent on precise specification. Example below for 50mx4m rolls without reinforcement or eyelets.<br>256 rolls / 20' container (without palettes)<br>576 rolls / 40' container (without palettes)<br>250 rolls / 20' container (with palettes) 550 rolls / 40' container (with palettes) |

For fixing the plastic sheeting to a structure, rope is the most commonly used material, normally 5 mm to 14 mm diameter. Made from several types of material, such as polyamide (PA), polyethylene (PE) and natural fibers, rope properties can vary, from the most resistant and expensive one, the PA, up to the cheapest and with less considerable mechanic properties, but with high resistance to UV, the natural fibers.

Considering the materials specifications, the shelter or settlement construction require the following minimum standards (UNHCR 2018):

- guarantee the minimum of 3.5 $m^2$ living space per person and the height should be at least 2 m at the highest point;
- adapt the shelter solutions according to climate conditions, cultural and geographic context, and also with the local skills and materials;
- consider the lifetime of the material (at least two years in toughest conditions), recyclability and sustainability;
- always support individual family shelter over common accommodation, in order to provide privacy and safety;
- respect privacy amongst family members, subdividing the shelter if needed;
- protect against environmental issues, such as hazards zones or extreme weather, and assure privacy, security and protection of belongings;
- provide the minimum materials needed, blankets, mats and tarpaulin;
- shelter design should be, if possible, adaptable to fit its occupants' individual needs;
- if possible, provide the assistance and materials for IDPs to build a shelter on their own.

Every emergency scenario, either after disaster or conflict, requires a different type of shelter, from plastic sheeting to prefabricated shelters, and each one has its advantages and disadvantages, as described in Table 3. Therefore, several decisions should be taken when choosing the emergency type shelter or combining types of shelter, in order to respond to the situation in hands.

Table 3 - Advantages and disadvantages of each type of emergency shelter (UNHCR 2018)

| Shelter solution | Advantages | Disadvantages |
|---|---|---|
| Family tents | Traditional relief tent; lightweight; proven design; good headroom; can be winterized; large production capacities. | Inflexible; may be unstable in high winds or heavy snow, difficult to heat.<br>Where tents are used for long durations, provisions for repair materials should be considered. |
| Plastic sheeting | Most important shelter component in many relief operations; heavy duty; flexible; large capacities.<br>UV-resistant; lightweight, production | Collecting wood for shelters' support frames or stick skeleton can considerably harm the environment if collected from surrounding forests. It is therefore important to always supply frame material which is sufficient to support plastic. |
| Materials and tools for construction (shelter kits) | Suitable local materials are best, if available, and must be suitable for variance in the seasons, culturally and socially appropriate and familiar. | Required time and training |
| Prefabricated shelter and containers | Permanent or semi-permanent structures; long lasting. | High unit cost; long shipping time; long production time; transport challenges; assembly challenges; inflexibility; disregarc cultural and social norms. |
| Rental subsidies | Greater sense of independence; greater integration in a community; influx of income to host community. | Difficult to monitor that shelter meets standards; competitive market may result in exploitation and abuse; inflation and speculation may occur; upgrades or repairs may be needed. |

In cold climate conditions shelter is more expensive and complex to build, requiring specific standards such as:

- stabilize the structure in order to resist snow and wind;
- protect the walls, roofs, doors and windows from the wind loads;

- provide heating for shelter, kitchen and sanitation;
- develop a survival strategy for each individual, for living space and for heating.

The standard requirements referenced above were imposed by SPHERE association and should be considered in all operational emergency scenarios, preparing individuals for the next stage of sheltering, from temporary to permanent shelter.

### 2.1.1. Logistic and distribution of materials

Each organization have their own logistics, regarding its transportation, warehousing, distribution and monitorization. The air freighting is considered more expensive than shipping and it can cost more than the material itself, although it should be considered in urgent situations. The weight and volume of the material should be as minor as possible, in order to facilitate storage and transport. For example, the shipping volume to transport 5m x 4m sheets is 3000 sheets per container, without pallets, (IFRC and International 2007).

Plastic sheeting can come in rolls or sheets, depending on their designated use, so organizations distribute them for shelter, flooring, sanitation, latrines and other uses. The distribution of the items is made according to a beneficiary list, giving additional technical support about plastic sheeting construction. The distribution of plastic sheeting aims to achieve the major number of IDP's, ensuring the needs of these people are met, thus monitored by the organizations planning to assure that all the distribution reaches those in need.

### 2.1.2. Current structures built from emergency kits

Primary shelters, built with emergency kit materials, such as tarpaulin and rope, only provide minimum cover as living space and its structures are usually made with local materials. However, this can affect the local economy, local workers and the environment, as the material will be arranged from local manufacturers and extracted from nature. Also, sometimes resistant and quality materials might be unavailable in those contexts and, for this reason, alternative materials and production processes are used, although it should always consider the environmental and cultural impact.

Despite the first shelter construction methods, the materials and processes should provide the possibility to adapt or even upgrade the shelter to a long-term housing if needed. These adaptations must be supervised and made only if local material and tools are available.

#### 2.1.2.1. Shelter

Regardless its effectiveness, plastic sheeting/tarpaulin is not a constructive solution on its own. It needs a structure to support them. Therefore, local materials or distributed material by the organizations are used to build them, such as timber, poles and bamboo.

The distributed shelter kit only contains plastic sheeting and rope for making a shelter with local materials or still existing structures available. However, these structures are not ideal and, in some cases, do not provide sufficient conditions for living according to the circumstances.

The use of plastic sheeting, as well as the structure who supports it, is evaluated according to the climate conditions, establishing priorities from cold climates, insulating and waterproofing the environment, up to warm zones, providing protection from the sun and heat, as shown in the examples from Figure 6 to Figure 8.

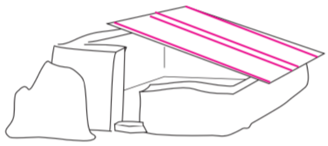


Figure 6 - Shelter repair kit following an earthquake (IFRC and International 2007)

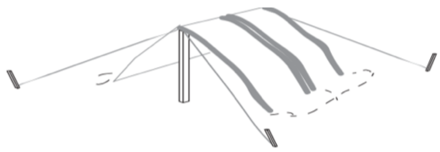


Figure 7 - Basic plastic sheeting shelter (with no ends) for hot climates (IFRC and International 2007)

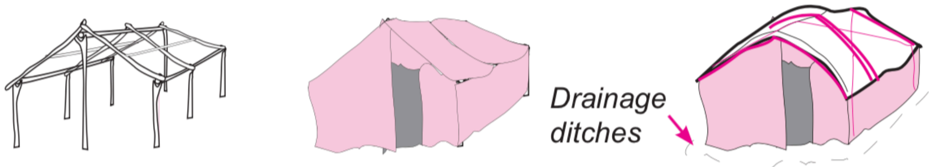



Figure 8 - Waterproof covering for a bush pole and grass matting shelter (IFRC and International 2007)

Sanitation should be beyond a latrine. It must provide dignity for people and also consider the conditions to reduce risks related with diseases. Commonly plastic sheeting is used for construction of latrines in emergency case scenarios. Nonetheless its requirements for each gender and age, latrines can vary from a minimum defecation field, trench latrines later upgraded with squat plates, towards the ideal individual family latrines (IFRC and International 2007).

Besides using plastic sheeting, the latrines structures are usually made with solid timber poles and nails, building a basic structure (Figure 9) or even a superstructure (Figure 10) of blocks of latrines to save material.

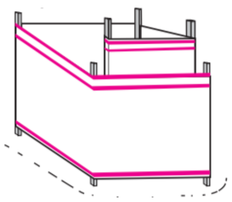


Figure 9 - Basic superstructure for latrine / washroom (IFRC and International 2007)

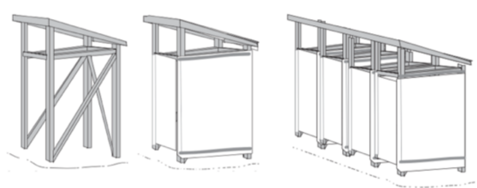


Figure 10 - Superstructure for latrine / washroom using plastic sheeting (IFRC and International 2007)

### 2.1.2.2. Timber and bamboo as construction material

When using timber or bamboo as a construction material for structures in humanitarian operations, several principles must be considered in order to use it properly. Principles such as planning before build, choosing materials properly without compromising the environment, design and construct for safety and recycle if possible, making it sustainable.

According to Nations et al. (2009), these structural materials are highly considered due to the lightweight, strength, flexibility, sustainability, recyclability and long lifetime and since they are a familiar material used and reused in construction, they can be easily adapted by people. Being natural materials, that derive from trees and plants, their properties can vary according to each specie. Hence it is important to identify the right one which attends the specifications for durability, hardness, density, flexibility, strength, and weight.

Timber and bamboo are used to design and build appropriate emergency shelter due to its beneficial properties, such as lightweight, flexibility, sustainability and recyclability. Also, these materials are natural and can last for a long time, being able to be used in permanent shelter. Different types of timber and bamboo are used to build versatile structures, sawn timber, timber composites, palm timber, bamboo and poles that are often used to construct simple structures (Figure 11). Regardless the type, it is essential to plan the structure according to the need and durability range, and also how much material is needed, Figure 12, (Nations et al. 2009).

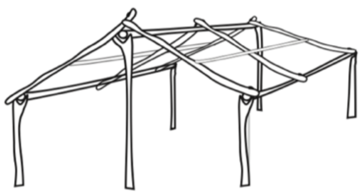


Figure 11 - Simple structure using different shapes of poles (Nations et al. 2009)

**How much timber is needed.**
Approximate volumes of timber in simple structures.

| | | | | |
|---|---|---|---|---|
|  Latrine (without slab) |  8m x 6m shed |  House / classroom |  Emergency ridge shelter |  Basic timber shelter |
| 0.4 – 0.8m³ | 3m³ | 2 - 4m³ | 0.1m³ | 0.3m³ |

Figure 12 - Structural material volumes (Nations et al. 2009)

To make an efficient use of timber or bamboo structures, designs should be well developed in order to use a reduced amount of timber in construction without compromising the safety and stability of the shelter. It is also important to support local building skills and offer technical assistance, because the affected people may not be able to build by themselves. If they are not able, the organizations should assist or hire contractors to do so. Organizations should assure that timber and bamboo provided should always be verified and sustainable, being delivered by local, national or international suppliers, varying the time of delivering respectively faster and cheaper to slower and more expensive, as shown in Figure 13.

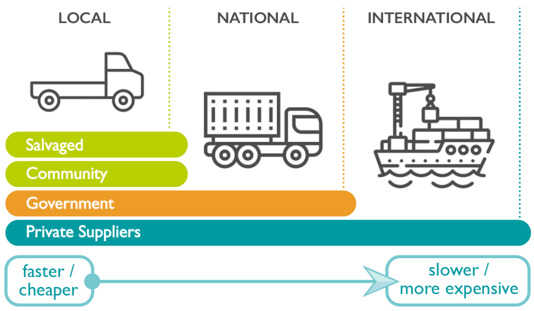



Figure 13 - Transport of timber and bamboo from local, national or international suppliers. (adapted from Nations et al. (2009))

Despite the considerable properties, such as strength and flexibility, for using timber or bamboo, the decision on whether to use one or other depends on several factors, including the local environment. If local timber or bamboo are scarce, they will be imported, taking longer time to build the shelter. However, alternative local materials can be considered if their properties can be equated to conventional material used, depending on the shelter designs.

### 2.1.2.3. Structure requirements

Organizations claim that before building new structures for plastic sheeting, the need for them must be settled according to each situation. Besides that, materials and design should be appropriate to local skills, climate conditions and cultural needs.

When using high quality plastic sheeting for construction of shelters the current principles for fixing it regardless of structure are:

- expand the load, spreading over large areas to avoid them from pulling;
- fixing through reinforcement bands or with rope folding a smooth stone inside;
- when fixing to the ground, use additional sheeting for burying in ditches;
- keep plastic sheeting tight and sloped to avoid flapping and water puddles;
- prevent contact with sharp points and friction;
- avoid structures that release heat, such as metallic or black surfaces;
- space the structures 2.5 times of their height, to assure privacy and also to prevent spreading in case of fire;
- select sustainable materials and processes that not damage the environment.

According to *Timber as a construction material in humanitarian relief* book, bamboo and timber are the main materials used for building structures. Consequently, the requirements applied to these materials are standard for emergency structures (Nations et al. 2009):

- durability (from 5 to +25 years depending on the treatment process);
- maximizing lifespan (depending on the time that timber or bamboo can perform);
- the material should be submitted to treatment processes, such as brushing, dipping or soaking, in order to increase its durability and lifespan;
- certified quality according to an International Standard (ISO)[1];
- respect the standard tolerances, derived from shrinkage;
- attend the dimensions specified, varying from shelter design, normally it is standard the dimension 10 cm x 5 cm x 2 m.

Considering the requirements to build a shelter in such emergency conditions, its structure must be as simple as possible, using fast and easy assembly methods. Also, all the materials should be sustainably obtained, considering its lifecycle.

[1] **Some relevant ISO standards** (available from www.iso.org.) (Nations et al. 2009):
- ISO 13912:2005: Structural timber. Machine strength grading. Basic principles (2006)
- ISO 21887:2007: Durability of wood and wood-based products. Use classes (2006) Also European standards: EN 335-2:2006 (definition of use classes) EN 351-1:2007 (preservative retention)
- ISO 9709:2005: Structural timber. Visual strength grading. Basic principles (2006)
- ISO 22156:2004: Bamboo. Structural design for Standardization (2006)

### 2.1.3. Family tent standard specifications

Tents are used to provide quick shelter since they contain the structure to support them. However, they are more complex and much more expensive, taking longer time to arrive at the local in opposition to plastic sheeting, that has significantly less volume. Nonetheless, tents should be considered in scenarios such as:

- local materials are scarce;
- existing structures are not in conditions to be used;
- constructions skills are insufficient;
- structures made with plastic sheeting do not provide efficient shelter to several climate situations;
- bigger structures are required.

The current model of tent provided is based on a commercial tent customized to respond to specific shelter needs. This family tent (Figure 14) has 16 m$^2$ and has been developed by ICRC and UNHRC, guaranteeing that the product fulfills the requirements imposed, being able to be used in all climates and produced at a minimum cost (IFRC 2011).

Figure 14 - Family tent (IFRC 2011)

The family tent is designed for a family of five individuals and it is essential to provide technical assistance so that people can assembled it properly. Each tent is delivered in packages with the following items (Table 4), weights approximately 55kg and costs CHF310, approximately 273,604 €, (IFRC 2011).

Table 4 - Family tent packaging list of standard tent package (IFRC 2011)

| | |
|---|---|
| outer tent x1 | inner tent x1 |
| ridge pipe of 4m in 2 pieces x1 | upright poles of 2.20m x2 |
| central pole of 2.17m x1 | side poles 1.25m x6 |
| door poles 1.40m x4 | guy ropes of 8mm x6 |
| angled iron pegs of 350mm x6 | guy ropes of 6mm x4 |
| candy cane pegs of 300mm x4 | pegs of 230mm x26 |
| hammer x1 | set-up instruction x1 |

Summing up this section, shelter solutions mainly depend on the local technologies and materials for construction, and also on available technical skills. Therefore, humanitarian organizations recognize the need for new ideas and concepts to simplify the shelter construction, making it possible to be built by locals without further assistance. Innovative technologies and materials, such as 3D and 4D printing, are analyzed, in the next sections, in order to develop a simple and cost-effective solution, using a shape memory effect (SME) material and provide at least 10m$^2$ area.

## 2.2. 3D Printing

Introduced as "Rapid prototyping", 3D printing concept has evolved and is nowadays known as "Additive Manufacturing" (AM). A process distinguished from traditional manufacturing processes due to the addition of material, layer by layer, instead of removing it.

In the XX century, 3D printing has evolved due to the large development of new polymers, and new technologies emerged, such as SLA (Stereolithography), FDM (Fused Deposition Modeling) and SLS (Selective Laser Sintering), technologies that still remain as main ones for polymers. However, at that time, the costs for using such techniques was very high, limiting its applications (Wohlers and Gornet 2014).

Currently, the investment on this process keep rising ( Figure 15), and major industries are realizing the potential of 3D printing technology. This and the fact that several competitive solutions appeared, highly influencing the significantly dropping of costs. From desktop 3D printers, to large scale printers and robotic arms, additive manufacturing technology is nowadays used to produce from prototypes to engineered components, using a wide range of raw materials, such as polymers, metal alloys, ceramics, glasses, and composites.

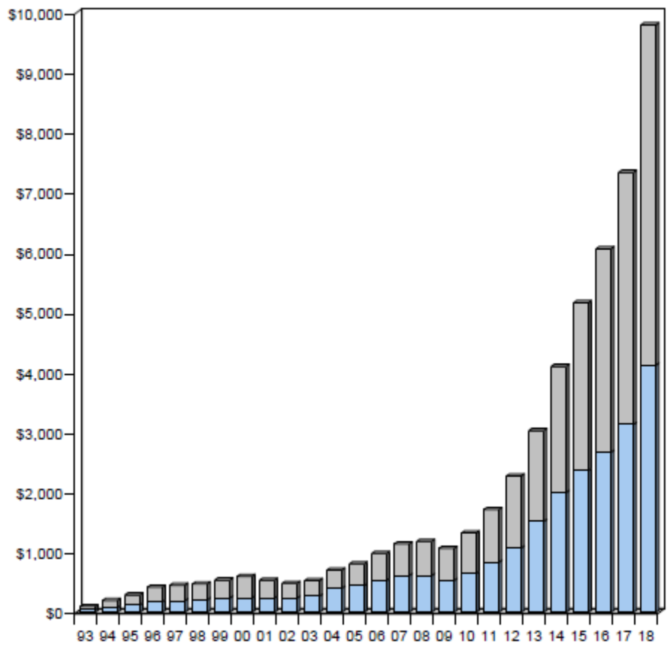



Figure 15 - Additive manufacturing industry growth versus price (in dollars), over the past years. The lower (blue) segment of the bars represent products, while the upper (gray) segment represents services. Neither category includes secondary pars or processes, such as molded parts and casting. (Wohlers Associates 2019)

### 2.2.1. Design and process

As the name describes, AM process is based on adding material until the desired shape is achieved. Yet, there are some design rules for 3D printing (Redwood et al. 2017):

- dimensional tolerance: ±0.5% (lower limit ±0.5 mm);
- support: overhangs with less than 45° require support structures;
- holes: minimum recommended diameter from 0.5 mm to 2 mm;
- connections require gaps;
- escape holes: minimum 4-5 mm diameter.

Material shrinkage and minimum tolerances should also be taken into account, as well as the mechanical properties of each material after printed, compared to the bulk material (Redwood 2018).

The process of AM occurs after designing a CAD model (solid file) that is then converted to a Standard Triangle Language (STL) file through a CAD software. STL files represent the object through its surface made with a set of triangles. After the STL file is obtained, it is uploaded in a "slicer" software in order to get a slicing model, represented by a G-code that contains all the printing process, like printing speed, layer thickness, infill deposition, temperature and support structures. To print a component, it is only needed to upload the G-code in a 3D printer and run the system. The AM processes are specifically described in section 2.5.4.

### 2.2.2. Applications in large-scale

There are a wide range of advantages in 3D printing, from freedom of shapes to rapid prototyping. This technology has been achieving many fields of research in the last few years. Applications that vary from education, automotive, aerospace, medical industry and also civil construction and engineering.

Major applications regarding the construction industry are also evolving to large-scale printing due to new engineering materials, such as composites (Stratasys 2017). Being this a benefit for the development of the emergency shelter proposed in this dissertation.

The exponential evolution of 3D printing it's happening every day, and it is even possible nowadays to print a 3D house, such as the example developed by Skidmore, Owings & Merrill LLP (SOM) architecture firm. An innovative shelter, fully 3D printed polymeric structure, that is intended for off-grid living, Figure 16, (Inhabitat 2016).

Figure 16 - World's largest 3D-printed polymer building from SOM (Inhabitat 2016)

Taking advantage of the 3D printing instant feedback, and rapid prototyping, it is possible to explore new shapes and analyze every possible design. This project, as so further several shelter designs, have been demonstrating that additive manufacturing can be considered as a solution for the construction industry, offering freedom of shapes and designs, with the combination of composite materials and its beneficial mechanical properties.

3D printing in civil construction was considered possible thanks to Contour Crafting (CC), Figure 17, one of the first technologies used in the field to the automated construction of a building, using layer by layer manufacturing process. An evolving technology that can significantly reduce costs in construction, around one fifth of conventional constructions. This reduction in costs is mainly due to the fast construction time, for example, a house of 185,8 $m^2$ can be built in less than 24 hours, saving also labor costs. Contour crafting can be applied in various types of building constructions, such as houses or commercial buildings, and also, it has been showing potential to be exploited on Mars (Khoshnevis 2004). A process also studied by Teixeira (2018), using 3D printing for extrusion of concrete (Figure 18), and envisioned by Soares (2018) for the development of 3D printing structures on Mars (Figure 19).

Figure 17 - Automated building construction using CC technology (Corporation, Contour Crafting 2017)

Figure 18 - 3D printing of a cylindric tower, assisted by a turntable (Teixeira 2018)

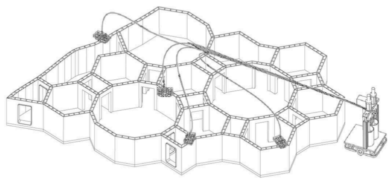


Figure 19 - Simulation of 3D climber robots printing a colony (Soares 2018)

Following this concept and in order to overcome architectural and construction limitations, the Institute for Advanced Architecture of Catalonia (IAAC), based in Barcelona, has been investigating the potential of 3D printing and its implementation in large scale. Researchers in IAAC had accomplished new developments using robotic fabrication associated with additive manufacturing, adding much more potential to this technique in large scale constructions. Illustrative of these new developments are the Minibuilders (Figure 20) and the On-site Robotics (Figure 21) projects, both using extrusion-based process, however with different materials and robotics methods.

The Minibuilders project was developed in order to be scalable, fabricating several structures regardless of its final shape. With no limitations, these small robots are mobile and can print large-scale structures, through the deposition of cement layers. A family of coordinated robots developed the assigned tasks for each phase construction, from footprint, walls, ceilings and reinforcements (IAAC 2015).

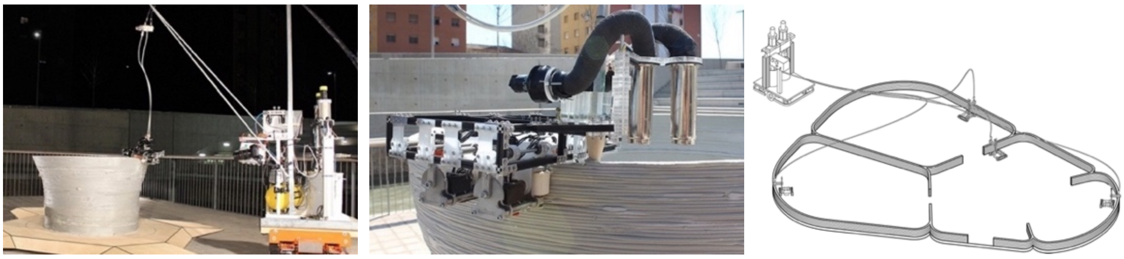


Figure 20 - Minibuilders, small robots printing big structures (IAAC 2015)

On site robotics was another project developed to demonstrate the potentials of AM and robotics in construction, combining technology and natural materials to construct sustainable and low-cost buildings. This project introduced also the large-scale printing of construction parts and small building, made from natural material such as earth. The system has a cable-driven robot with automated movement that can be assembled in several workplaces or directly on the construction site. Also, an extruder is integrated in the system, which enables the use of natural, biodegradable, recyclable and clay-based extrusion materials. The robot trajectories are generated through integrated CAD software (IAAC 2017).

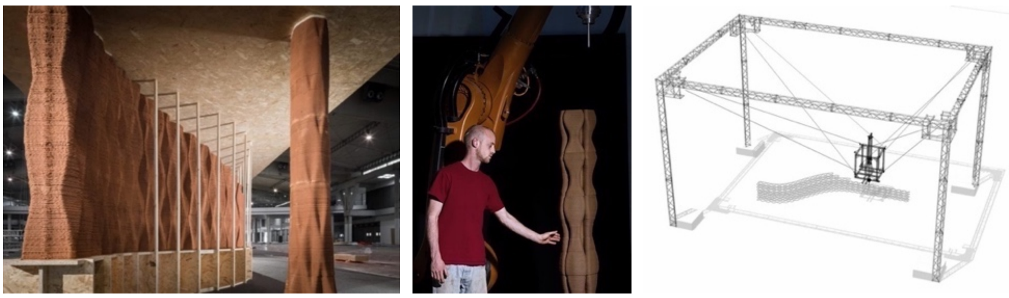


Figure 21 - On site robotics, construction with soil. Cable-driven robotic construction (IAAC 2017)

These two projects developed by IAAC aimed to revolutionize the construction and architecture industry, offering innovative possibilities of customization on site, reducing costs in production and enabling mass production of customized construction.

Proof of the application of large-scale printing is the VULCAN project (Figure 22), considered one of the largest 3D-printed structure, besides that its design was awarded a guinness world record. Created by the Beijing-based Laboratory for Creative Design (LCD), the equilateral triangle shape pavilion is 8.08 m by 2.88 m tall and it could be divided into three identic modules, making it flexible in terms of assembly on site. Inspired by the structural possibilities of the cocoons, the shape of the pavilion resembles a mushroom cloud formed during a volcanic eruption (Xu 2016).

Figure 22 - VULCAN Pavilion at Parkview Green, Beijing (Xu 2016)

The development of VULCAN's concept took three months, simulating its design in *Rhino 3D* and generating the code for printing. Then, 20 large FDM printers were connected for printing 1086 units in 30 days, that were posteriorly assembled on site by 15 people in 12 days. VULCAN pavilion was the main stage for Beijing Design Week opening ceremony, proving that concepts of large-scale printing can be performed in real case scenarios.

VULCAN's concept was a major achievement in large-scale 3D printing construction. However, several companies consider that building with 3D printers is a challenge, and to have precision and great performance in large scale it results on having larger machines and inevitably much more expensive. Hereupon, likewise the Minibuilders concept, AMBOTS company followed the thought of having small mobile robots building larger structures.

Marques, Williams, and Zhou (2017), the founders of AMBOTS, aimed to achieve scalability in 3D printing, thereby developed a mobile 3D printer, envisioning a cooperative 3D printing technology. The goal was to print outside the standard imposed dimensions, by having a mobile printhead on a robotic platform (Figure 23).

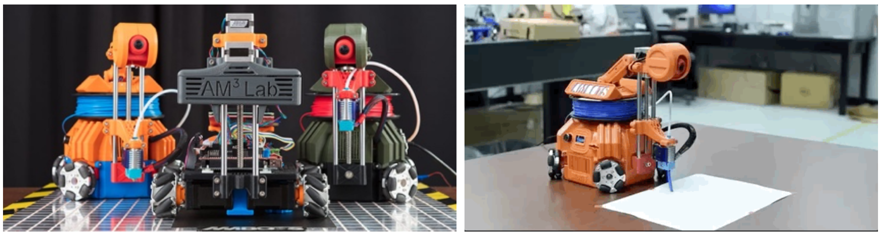


Figure 23 - AMBOTS mobile 3D printer robots (ambots.net/technology, 2018)

Breaking the barriers of the limited sizes to print, Marques, Williams, and Zhou (2017) also intended to achieve cooperative printing, where many mobile robots could work together by printing and assembling components autonomously. A cooperative printing test was made where two mobile printers have successfully printed at the same time as shown in Figure 24. The performed tests on cooperative printing demonstrated its potentialities for large-scale autonomous robotic printing as well as further developments towards autonomous digital additive manufacturing (ADAM), where mobile robots can work simultaneously to manufacture complex and large-scale constructions (Figure 25).

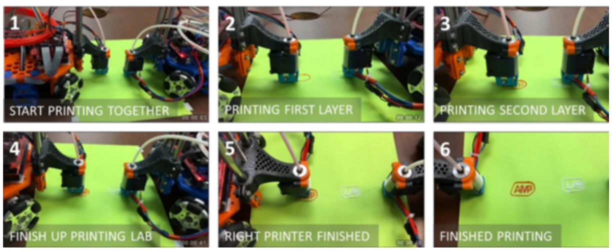



Figure 24 - Cooperative printing test: two mobile printers print together two words, in orange and white respectively (Marques, Williams, and Zhou 2017))

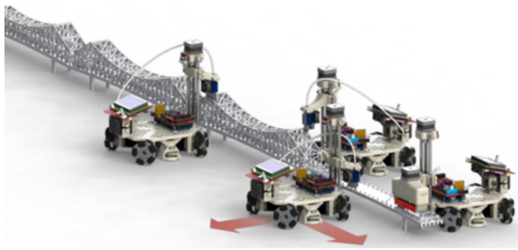


Figure 25 - ADAM process: several mobile robots work together to build a complex structure (Marques, Williams, and Zhou 2017)

A recent and innovative development in 3D printing of large-scale structures was MARSHA, the AI SpaceFactory's habitat (Figure 26), winner of the 2019 "NASA 3D - printed habitat challenge". This 3D printed habitat developed for Mars, can be built in 30 hours with nearly no human assistance and was designed to shelter four astronauts, with its construction respecting structural and construction techniques, as well as other requirements imposed by NASA (SpaceFactory 2019).

For the development of the habitat, they created their own recyclable and biodegradable material for in-situ utilization, a biopolymer basalt composite, based on natural materials from Mars, basalt extracted from Martian rock and biopolymer (PLA) processed from plants. This material with outstanding properties proved to be better than the other competitors which used concrete as construction material, passing with distinction the tests for impact, strength, resistance and durability.

An approximately 5 meters tall prototype was built, using a robotic arm through AM process, proving their concept and also the possibility of printing polymer-based material in large-scale printing. Also, they intended to build this year the first space habitat on earth, the TERA concept, using recycled materials from MARSHA to 3D print the new TERA. According to the CEO of AI SpaceFactory, the TERA concept aims to prove the use of natural and biodegradable materials from earth in the construction industry, eliminating the industry's waste materials, such as concrete (SpaceFactory 2019).

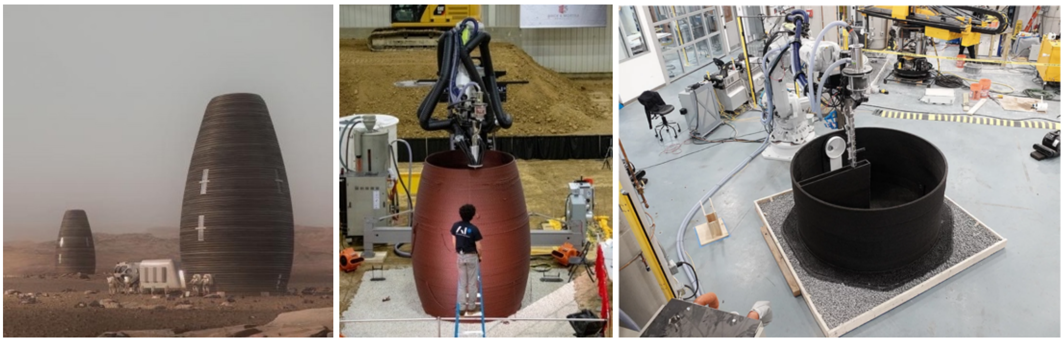


Figure 26 - MARSHA, AI SpaceFactory 3D printed habitat, winner of the 2019 NASA challenge (SpaceFactory 2019)

These examples are representative of the potential in 3D printing technology and its large-scale application in the construction industry. Thus, making it possible to achieve feasible solutions for emergency shelters in an imminent future.

#### 2.2.2.1. 3D printing using FGF (Fused Granular Fabrication)

Major 3D printing applications in large-scale use robotic arms or largest 3D printers through the process of FGF, a granulate based fabrication process with potential applications in product design, furniture design and in the industry field, due to the possible use of a wide range of materials, as long as they were supplied in granulated state for printing.

A process that instead of filament, extrude granules (Figure 27(1)), pressed through a nozzle (Figure 27(4)), where the nozzle controls the diameter of the material that is deposited. The process is quite similar to FDM printing, a model is built through the deposition of the material layer by layer. Each layer is added, and the piece is built by lowering the building platform (Figure 27(5)) until the model is finished (ManufacturingGuide 2019).

The granulated based printing at large scale offers endless possibilities to manufacturers, with time and cost-efficient fabrication in a short period of time. An ascending innovation in 3D printing and consequently in the development of the largest printers, that are appearing in a wide variety of sizes and from diverse manufacturers.

One of the biggest 3D printers developed so far was fabricated by BLB Industries, a company founded in 2015 (BLB_Industries 2018). THE BOX printer (Figure 28), is able to build up to 1,5x1,1x1,5 $m^3$ of volume, using FGF technology. However, BLB Industry is also able to customize machines for the development of bigger volumes, up to 5x5x5 $m^3$.

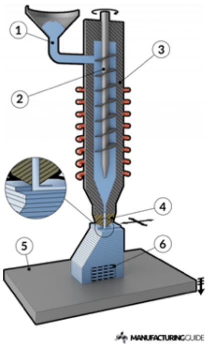



Figure 27 - Fused granular fabrication process (ManufacturingGuide 2019)

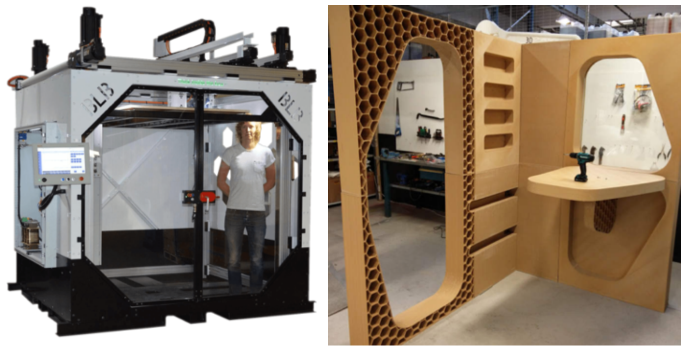



Figure 28 - THE BOX printer and a printed corner of a house module (BLB_Industries 2018)

## 2.3. 4D Printing

The evolution of 3D printing over the last few years and the wide application of this technology led to an innovative technology initiated by a research group on MIT, the concept of 4D printing (Figure 29). Introduced by Tibbits (2013), an approach of 3D printed structures that could change shape in function of time, as a reaction to an external stimulus.

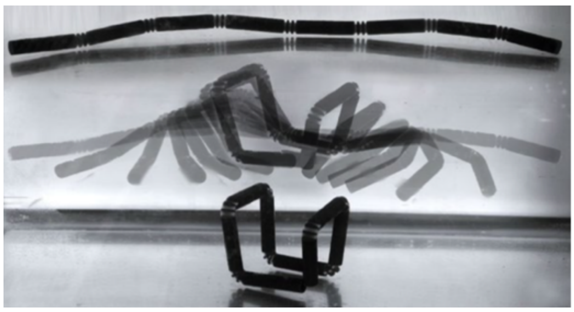


Figure 29 - 4D Concept - Transformation of 1D strand to 3D wireframe cube by self-folding after exposed to water (Tibbits, S. 2014)

4D printing technology could be appropriate in order to solve the main problem presented in this dissertation, the first emergency shelter, through the development of structures that can assemble themselves as a reaction to a stimulus, such as water, heat or light. A technology that emerged from the use of smart materials, programmed so their properties can change when exposed to a stimulus.

This technology combines science and engineering so that the 3D static structures can become dynamic structures with diverse shapes, properties, or functionality, achieving self-assembly, multi-functionality, and self-repair (Momeni et al. 2017). The process is almost the same as 3D printing. However, structures that were previously static after 3D printed, can now assume different properties and shapes after printed, due to the use of smart materials, being this the main difference between the two processes as illustrated in Figure 30.

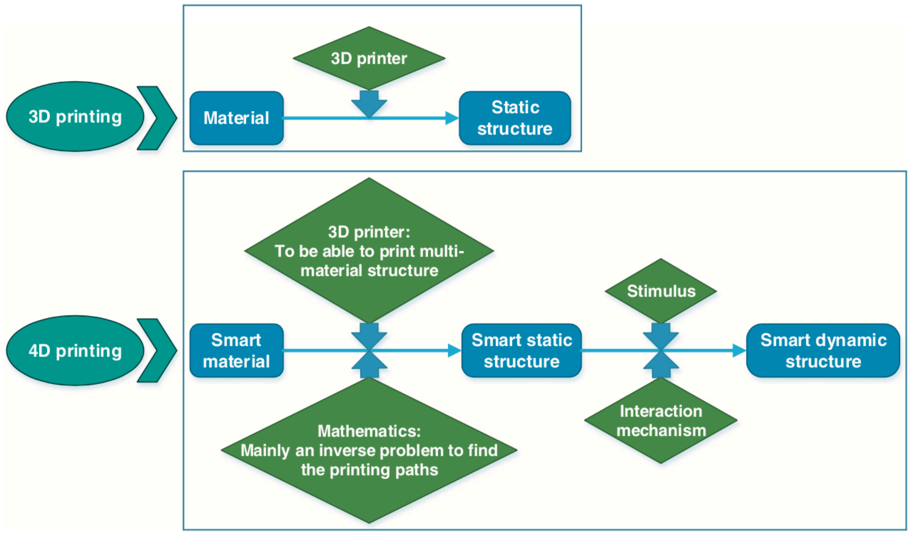



Figure 30 - The differences between 3D printing and 4D printing (Momeni et al. 2017)

Presenting beneficial potentialities such as simplification of design and manufacturing process, 4D printing also allows the possibility to achieve complex shapes. Besides, it reduces storage volume, facilitating transportation and its assembly, advantages that are desired for the final product of this dissertation.

As previously mentioned, the potential applications of 4D printing structures can be classified as self-assembly, multifunctionality and self-repair, being self-assembly the most advantageous attribute for the development of the emergency shelter.

The material's selection is a crucial process in 4D printing, being essential to analyze its smartness and printing capacity, as its response to a stimulus. Smart materials have beneficial properties, such as memory shape, that allows the material to return to its original shape after deformation, with the application of a stimulus. Smart materials or stimulus responsive materials can be classified into groups as demonstrated in Figure 31.

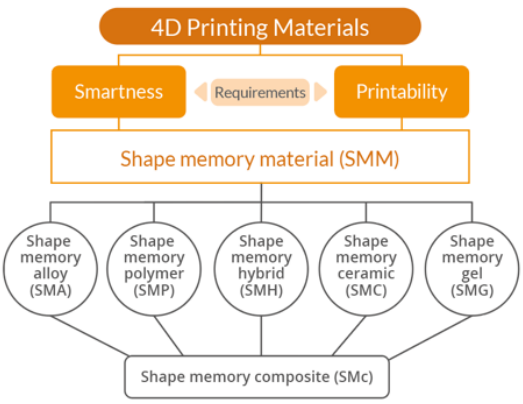



Figure 31 - Stimulus-responsive materials (adapted from Momeni et al. 2017)

So far, the mainly structural applications in 4D printing have used shape memory polymers (SMP) activated by heat (Figure 32) or water (Figure 33). However, shape memory composites with carbon fiber have been demonstrated by Hoa and Raju (2018), Figure 34, and wood composite structure presented by the MIT research group (Figure 35).

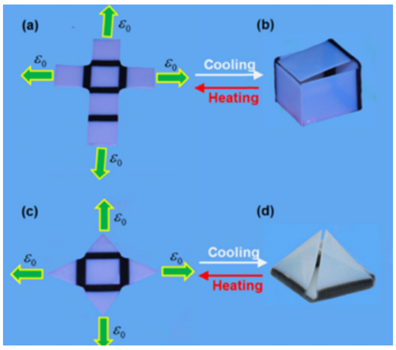



Figure 32 - SMP origami structure activated by heat (Ge et al. 2014)

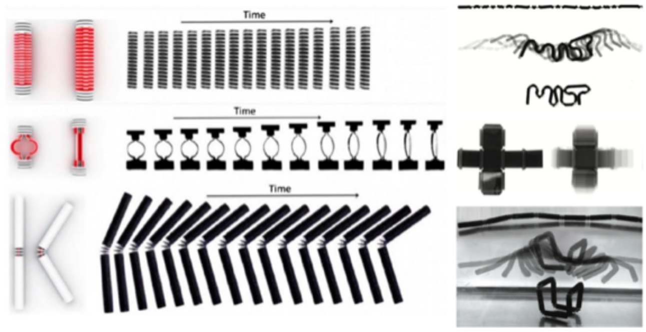



Figure 33 - Hydrophilic structures responsive to water (Raviv et al. 2014 and Tibbits 2014)

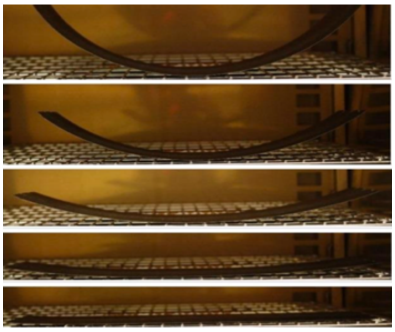


Figure 34 - Carbon fiber laminate reacting to different temperatures (Hoa and Raju 2018)

Figure 35 - Programmable wood composite (selfassemblylab.mit.edu)

The manipulation of smart materials applied to 4D printing process allows unlimited possibilities of constructive solutions in several fields and services (Figure 36). Furthermore, the development of these technologies can overcome constructive problems and solve structural needs, such as emergency and temporary shelter.

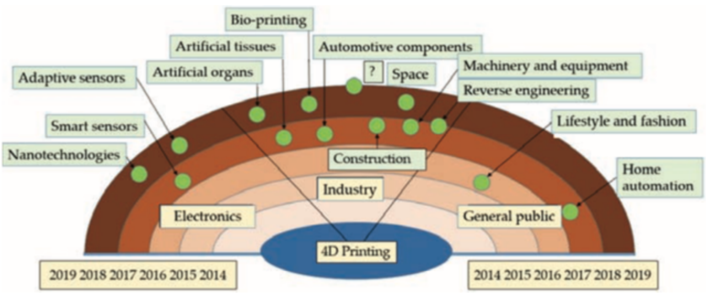



Figure 36 - Possible applications of 4D printing process (André 2018)

Regarding aforementioned, the 4D printing process, with the complement of FGF in large scale printing, is introduced as a possible application for the development of structures that are easy to transport and assemble. Such benefits are possible with the contribution of composite materials, that would allow the improvement of specific strength, specific stiffness and toughness of the structures.

### 2.3.1. Development of structures with smart materials

Smart materials are fundamental for the development of 4D printing structures. However, not all materials allow these structures to be durable and mainly to support load, a key point for solving the problem of emergency shelter structures. Considering these requirements, Chen et al. (2017), Bodaghi et al. (2016) and Mao et al. (2015) introduced some developments in SMP structures that could solve major constructive problems.

Mao et al. (2015) exploit the shape memory effect of thermoplastics for the development of self-folding structures, where the final shape can be obtained through temperature changes (Figure 37). These types of structures are produced with a multi-material Inkjet 3D printer, depositing material with variable stiffness, which allows flat printing to posteriorly 3D assembly. An advantageous process in reduction of volume and weight in transportation, compared to conventional objects. However, the developed objects do not allow possible reversibility calculation, so the final shape cannot be controlled with full precision and the load bearing capacity is not defined.

In the process of development of adaptive structures with self-deployment capacity, Bodaghi et al. (2016) come up with the association of 4D printing technology with these mechanisms, developing an actuator with printed polymeric shape memory fibers (SMPs), creating a flexible lattice that changes shape when exposed to different temperatures (Figure 38).

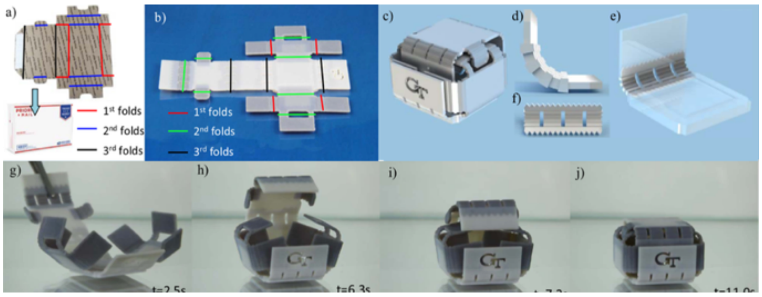



Figure 37 - 3D folding structures mimicking a mailbox. (a) Mailbox folded into a box by following a sequence of folding. (b) A programmed 3D printed sheet with different materials assigned at different hinges. (c–f) Model of the folding box with some details at the hinges. (g–j) Upon heating, the sheet folds into a box with self-locking mechanism (Mao et al. 2015)

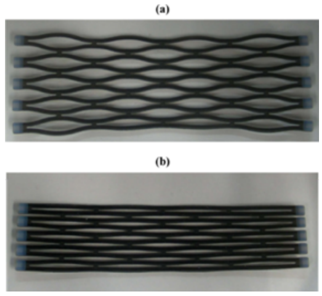



Figure 38 - SMP meta-material lattice: (a) schematic sketch; its configuration at the time associated with maximum deployment (b) and the end time (c) (Bodaghi et al. 2016)

Accordingly the same technology used by Mao et al., Chen et al. (2017) showed developments, aiming to overcome the established challenges, namely the load capacity and final shape of the structure, significant characteristics in several engineering areas, such as construction. These improvements are also beneficial for space lattice structures that can soon have the ability to be transported flat or in a coil, reducing their volume. Also, building facades, photovoltaic systems and implants can be adjusted and reconfigured automatically, adapting to specific needs.

Chen et al. intended to achieve load-bearing and deployable structures through the following approaches, the development of a bistable unit actuator and the design of hierarchical structures. The bistable actuator was developed based on the von Mises Truss (VMT)[2], with a bracket, four trusses and a pin, being the pin and middle part of the trusses produced in a rigid plastic and the joints in an elastomer material, thus allowing two configurations, retracted or extended (Figure 39).

The bistable actuator is used, for the development of load-bearing deployable structures, as a standard connector for the design of complex hierarchical structures. Since the actuator has two states, retracted or extended, the assembly of several actuators generates a multistable structure, being each actuator of the final structure independent, thus resulting in variable geometries (Figure 40). Regarding this, it is possible to create the desired geometry by considering the activation of each actuator, achieving different lengths simply with the variation of the Truss angle. Chen et al. study also showed that increasing the material stiffness it increases the actuator stiffness and, unlike the 3D process, the joints are no longer the weakest link.

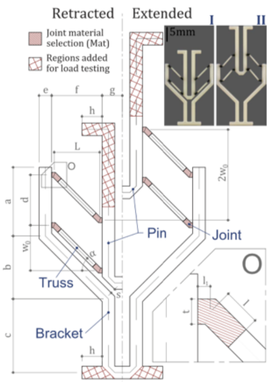



Figure 39 - Drawing of the proposed bistable unit actuator (Chen et al. 2017)

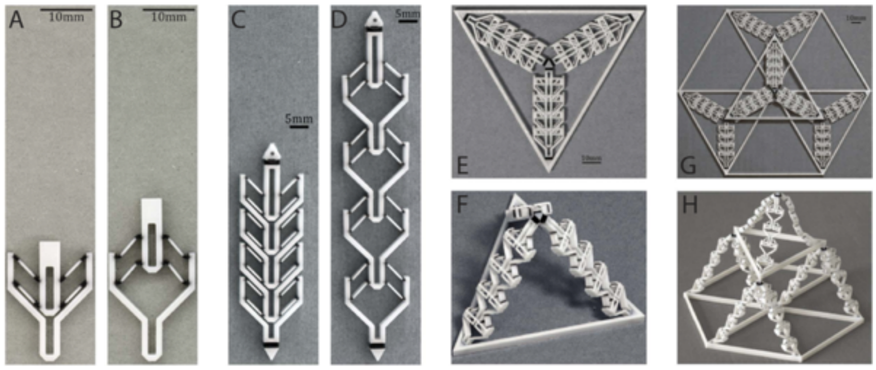



Figure 40 - Design hierarchy from a single unit actuator (E,F) to a tessellation of modules (G,H). (A,B) Unit actuator. (C,D) Four connected actuators. (E,F) The tetrahedron module. (G,H) Multiple tetrahedron units to demonstrate the deployment of a space frame (Chen et al. 2017)

These structures are printed flat, with the minimum material, achieving a hierarchical design with the assembly of 50 x50 mm$^2$ modules, like the ones shown in Figure 41. The structure is activated actuator by actuator, from the bottom to top, until the maximum height is achieved. Also, by changing the initial configuration of the actuators the final geometry can assume a positive or negative shape (Figure 41 C, H).

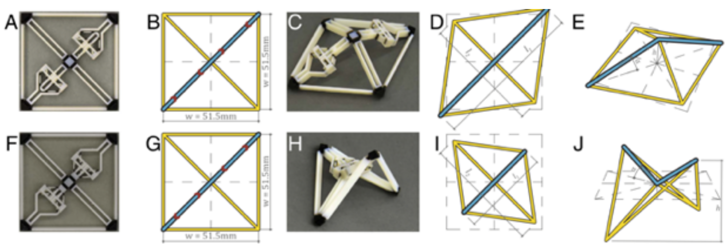



Figure 41 - A unit module consisting of two actuators in either the retracted (A) or the extended (F) configuration (50 by 50 mm). (B,G) The initial simulation configuration. (C,H) Activated state of (A,F), resulting in a positively or negatively curved surface respectively. (D,I,E,J) The simulation results in plan and isometric views (Chen et al. 2017)

[2] The von Mises Truss (VMT) was introduced in 1923 as a structure that features two pin jointed truss members with a vertical load at the apex. (Chen et al. 2017)

The singular modules shown in Figure 41 can be combined, resulting on structures like the following (Figure 42). The bigger the set of modules, the larger the structure, being also the dome bigger (Figure 42 C) and, consequently, the structure has higher stiffness.

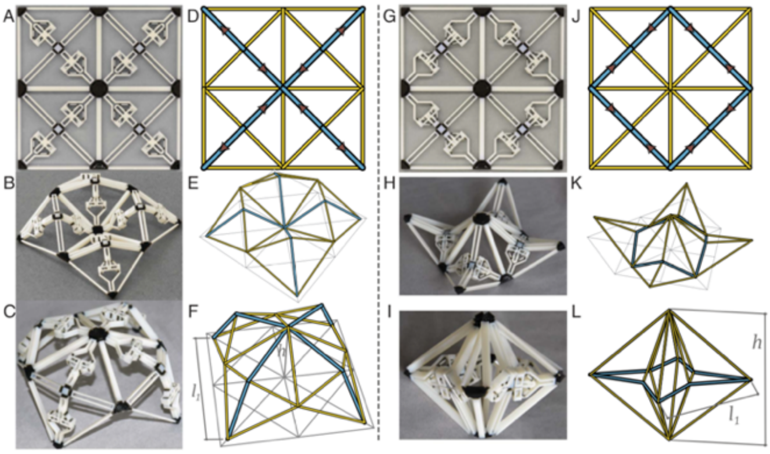



Figure 42 - The grid structure with actuators in the retracted (A) or the extended (G) configuration. The first activated unit modules (B and H), and the second show global behavior that form a dome (C) or an enclosure (I). Simulation is shown in (E, F, K, L) where the yellow members are rigid trusses, and the blue members are actuated trusses (Chen et al. 2017)

3D deployable structures and conceptual designs for deployable load-bearing structures with predictable and configurable geometries have been demonstrated by Chen et al. 2017.

Considering these concepts and taking advantage of 4D printing technology, Chen and Shea (2018) introduce a bistable programmable actuator, that allows the automatic deployment and reconfiguration of the structure, activated through temperature stimulus. This actuator is based on a shape memory polymer material, that reacts to temperature, providing the required strength to activate it (Figure 43), thus making the activated structures geometrically accurate and capable of bearing load. Besides this, the programmable actuator was designed to create larger scaled structures that could be applied in space exploration, construction industry and biomedical field.

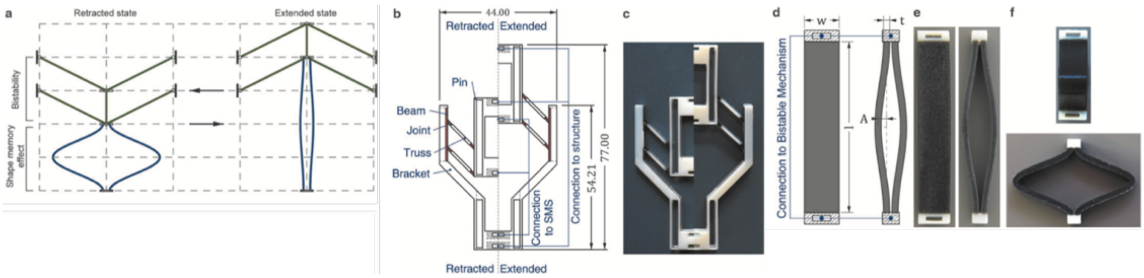



Figure 43 - Design of a heat-activated bistable unit actuator. (a) Schematic showing activation of the actuator. The actuator consists of a bistable mechanism and an SMS. The SMS provides the force to activate the bistable mechanism. (b) Design of the unit actuator showing the bistable mechanism (d) The SMS whose geometry is parametrically defined to provide both expansion and contraction to the actuator. (c, e, f) The fabricated specimens. SMS, shape memory strip (Chen and Shea 2018)

Following the same perceptive as demonstrated in the previous examples (Figure 42), the modules assembled create symmetrical hierarchical structures, with the use of programmable actuators (Figure 43). These structures can become self-assembled and reconfigurable, activated by environmental stimulus, and also capable of load bearing as their activation occurs, Figure 44, (Chen and Shea 2018).

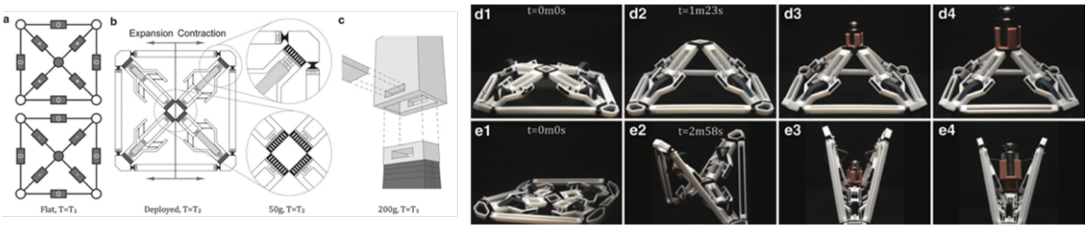


Figure 44 - Shape reconfigurable structures showing activation and load-bearing capability. (a) Schematic of the designs. Four actuators are integrated in a flexible frame, the first has four expansion actuators (+), and the second has four contraction actuators (-). (b) The physical design of the structures. (c) A detailed view of a universal connector between all parts of the assembly. (d, e) Video screen captures of the expanding and contracting structural deployment, respectively, (1) flat state, (2) activated state, (3) load-bearing capacity under high temperature, and (4) load-bearing capacity under operating temperature (Chen and Shea 2018)

Since 4D printing process is barely the same as 3D printing process, the major difference is the material that needs to be a shape memory material or a smart material in 4D process, the product development has the same advantages in time and cost reduction. Even better, due to the possibility of changing its shape, objects bigger than the printers can be printed and then unfold to larger shapes, reducing volume in production and thus consequently reducing costs. Also, 4D printing adds the potentiality of reusability, being beneficial to increase the life cycle of the product.

In conventional manufacturing, the more complex is a product, the most expensive it becomes to manufacture. However, in additive manufacturing, 3D or 4D printing, fabricating a complex shape does not require additional cost or time compared to a simple shape, thus making complexity of forms free. Additionally, since printing one unit costs the same as mass production of the same object, the manufacture of personalized products would be a major advantage for additive manufacturing, making a transition from mass production to mass customization, where products are personalized for the users without additional cost (Campbell, Tibbits, and Garrett 2014).

Figure 45 illustrates the cost analysis comparison between traditional manufacturing and additive manufacturing. According to Cotteleer and Joyce (2014)'s studies, the cost curves change for each unit manufactured, for traditional manufacturing, it is necessary to produce a great amount of units to economically reach the breakeven point and then profit, as demonstrated in the curve (black). In contrast, in additive manufacturing profit is not influenced by the number of units manufactured, thus allowing to achieve profitability even producing in small quantities, a major benefit for 3D and 4D manufacturing processes.

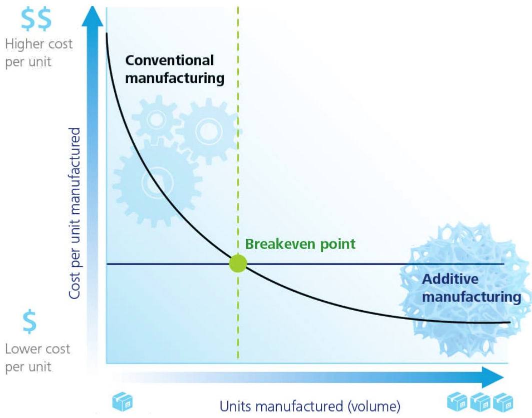



Figure 45 - Cost analysis comparing conventional and AM processes (Cotteleer and Joyce 2014)

### 2.3.2. Materials and methods

According to Kuang et al. (2018), 4D printing methods demonstrated so far use mostly polymers, likewise 3D printing processes and the most widely used methods that are extrusion-based, due to the range of materials that can be printed. From the AM techniques, FDM and SLA are the most used and investigated methods as shown in Figure 46.

As explained previously, 4D printing has the ability to save material and time, where objects can be developed with AM processes for several functional applications. Different material systems can be printed, and later respond to a predetermined stimulus to achieve the intended application. 4D printing categories, stimulus and elements are shown in Figure 47.

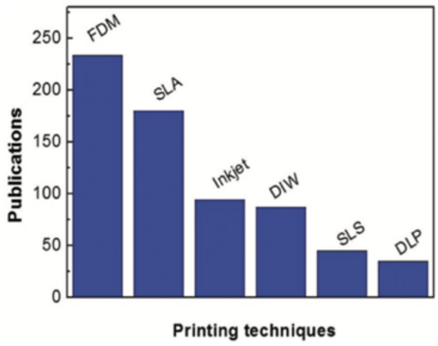



Figure 46 - Publications of 3D and 4D printing using different printing techniques for SMP. Data collected from Web of Science between 2013 and July 2018 (Kuang et al. 2018)

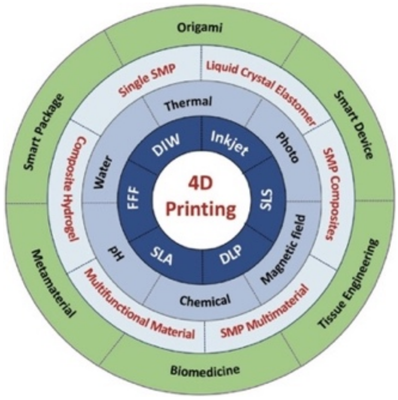
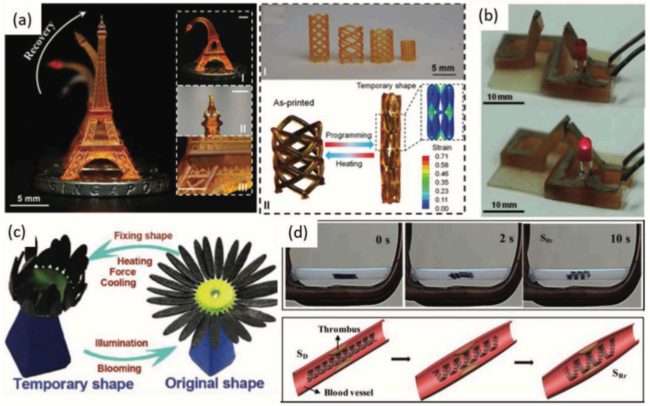
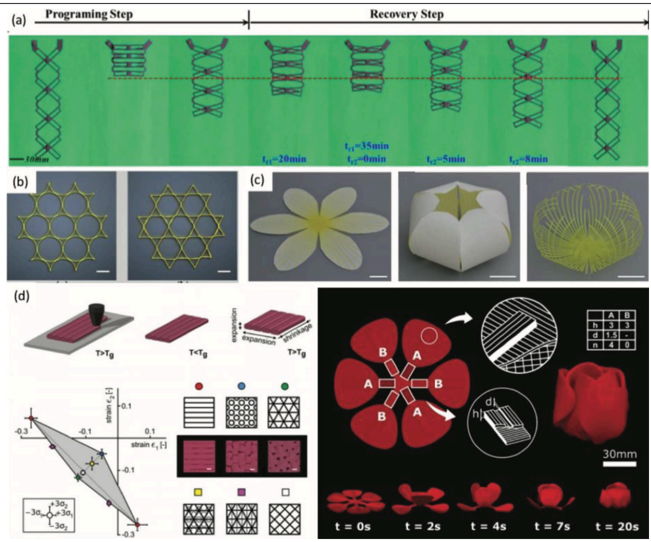
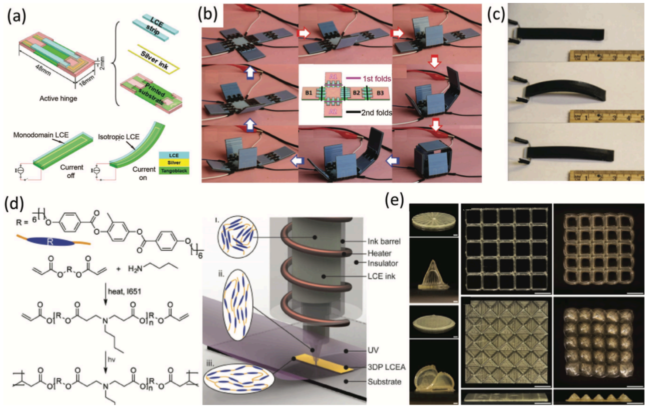
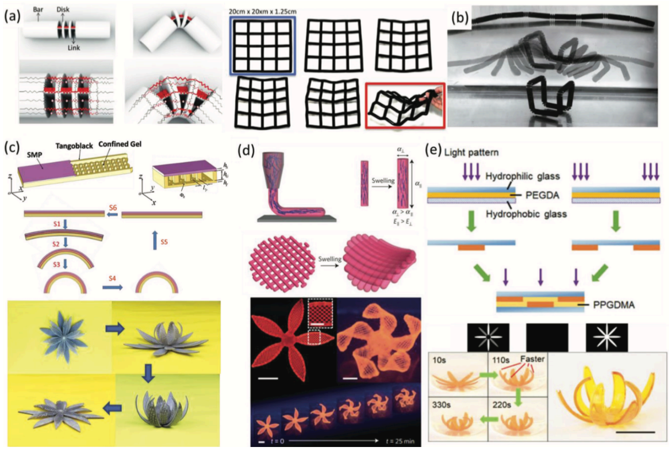


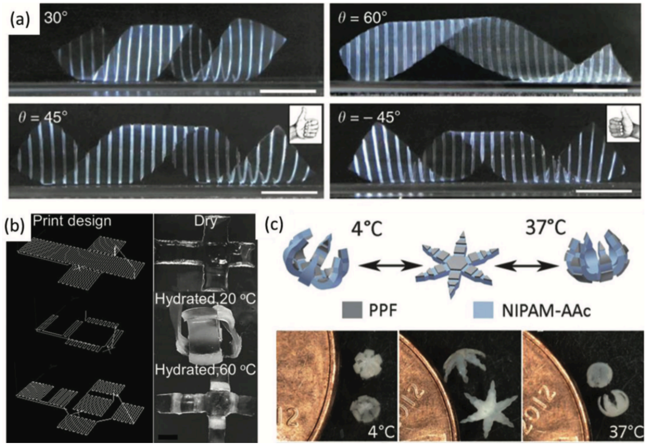
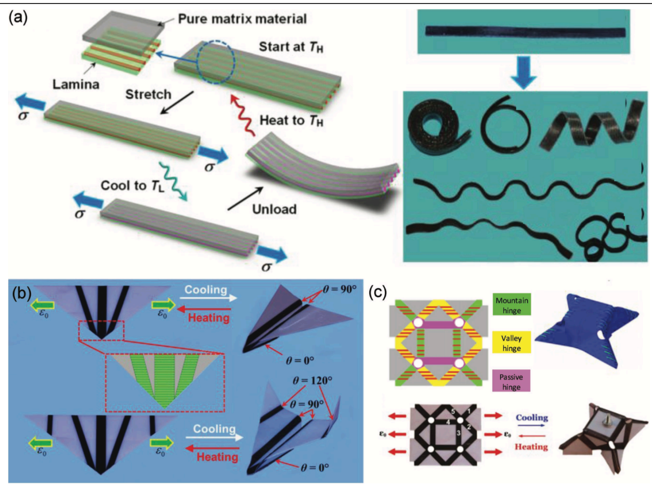

Figure 47 - Categories of 4D printing. 1) Methods; 2) Stimulus; 3) Materials; 4) Applications; (Kuang et al. 2018)

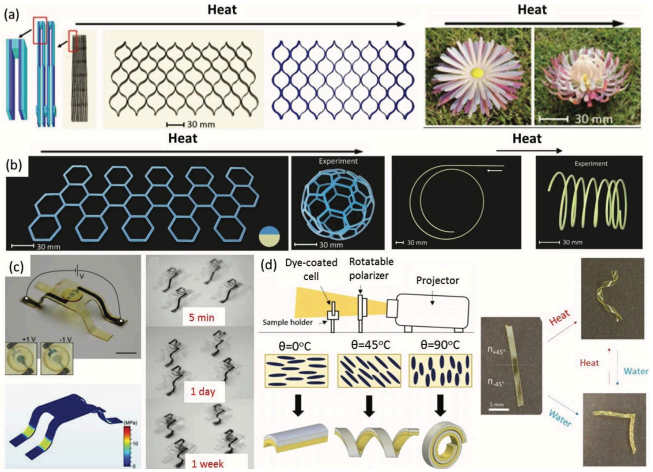
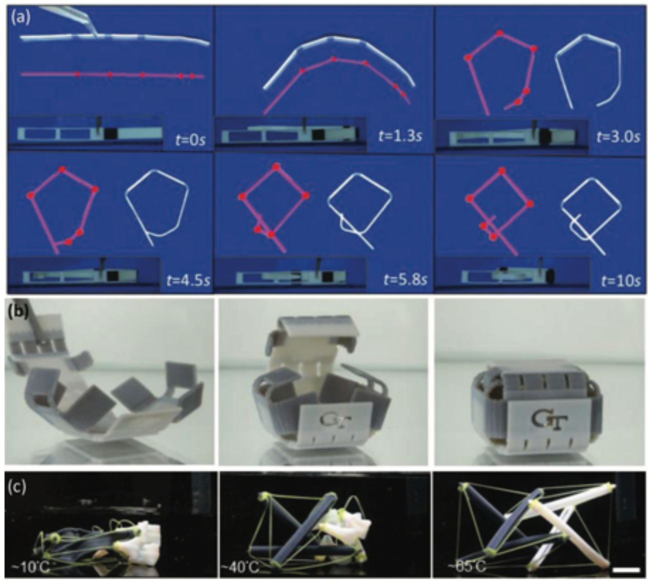
Until now, 4D printing generally uses polymers as base material, and since these can have potential application that are relevant for this research, they are categorized in this section. They go from a single material to multimaterials and composites, with respective stimulus response. In the following Table 5, the materials are detailed according to the demonstrations from Figure 48 to Figure 59.

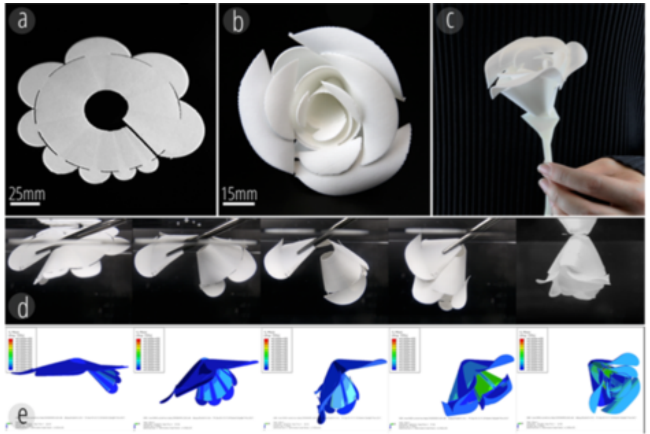
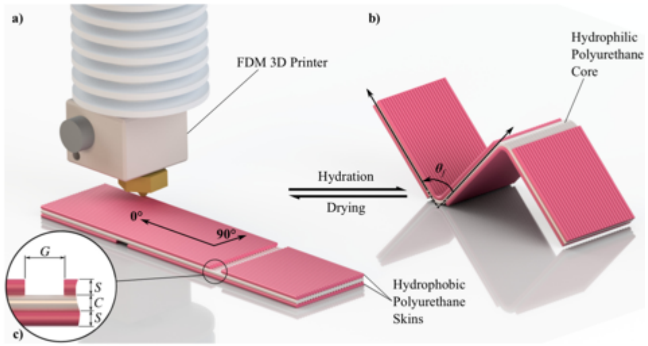
Table 5 - 4D printing materials according to demonstrations. (adpated from Kuang et al. (2018), An et al. (2018), Baker et al. (2019), Chen and Shea (2018) and Yang et al. (2015))

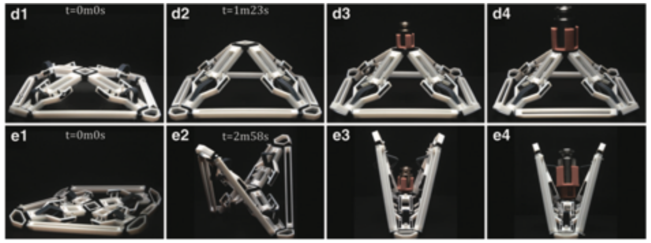
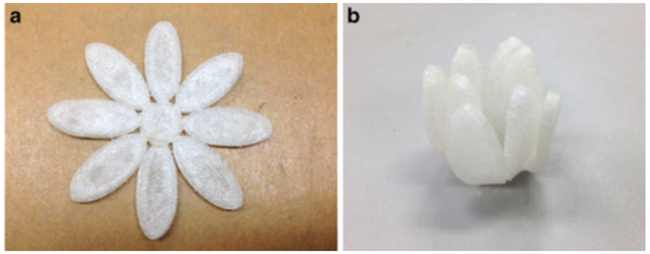
| Application | Material and details | Method | Stimulus |
|---|---|---|---|
|  Figure 48 - 4D printing of single SMP and respective printing techniques. (Kuang et al. 2018) | <u>Stimulus responsive Single SMP</u><br>Shape memory polymers (SMP) can be programmed to maintain a temporary shape and to recover its original shape in a presence of a stimulus.<br>**a)** SMP with benzyl methacrylate and several difunctional acrylate oligomers<br>**b)** Methacrylated polycaprolactone (PCL) in a heating vat to melt the crystalline oligomer<br>**c)** Photoresponsive SM and carbon black-reinforced polyurethane (PU)<br>**d)** UV cross-linking poly(lactic acid) (PLA)/$Fe_3O_4$ composite ink | a) PμSL<br>b) SLA<br>c) FDM<br>d) DIW<br>e) DIW | Heat<br>Light<br>Magnetism |
|  Figure 49 - Multiple and automatic shape shifting by single SMP (Kuang et al. 2018) | <u>Shape shifting by Single SMP and PLA</u><br>The automatic shape shifting of 3D printing structures with SMP material, can be achieved by exploiting the multi-shape memory effects (multi-SME) of the materials.<br>**a)** Triple SME in printed SMP truss structure<br>**b)** 2D lattice printed with PLA<br>**c)** Composite sheet with PLA strips, from PLA filaments<br>**d)** PLA filaments | a) Polyjet<br>b) FDM<br>c) FDM<br>d) FDM | Temperature<br>Heat<br>Cooling |

| | | | |
|---|---|---|---|
| <br><br>Figure 50 - 4D printing of crystal elastomers (Kuang et al. 2018) | <u>Liquid Crystal Elastomer (LCE)</u><br>LCE can experience large contraction under an external stimulus, so the placement of LCE strips in 3D printed objects enables shape shifting.<br>a) Laminated hinge containing LCE layer, conductive silver layer and soft rubber layer (TangoBlack)<br>b) Folding and unfolding of a box with LCE strips, when applying a current.<br>e) LCE actuators from 2D to 3D | DIW<br>d)Photopolymerizable LCE ink for high operating temperature<br>DIW | Current<br>Heat/Cooling |
| <br><br>Figure 51 - 4D printing hydrogels and composites responsive to water (adapted from Kuang et al. 2018) | <u>Water-Responsive Composite Hydrogel</u><br>Hydrophilic rubber (hydrogel) swells when exposed to water. Applications with other materials create water responsive composites.<br>a) Hinges with <u>rigid plastic</u> as base and <u>hydrogel</u> in the link joints (in red).<br>b) Representative of the concept a), a strand that folds itself into a cube.<br>c) <u>Hydrogels</u> sandwiched between <u>SMP</u> and an <u>elastomer</u>.<br>d) <u>Hydrogel composite ink</u>: containing an aqueous solution of N,N-dimethylacrylamide, photoinitiator, nanoclay, nanofibrillated cellulose (NFC), glucose oxidase, and glucose. (US Patent Application 20180251649).<br>e) hydrophilic/hydrophobic composite structures. | a/b/c)Polyjet<br>d) DIW<br>e) DLP | Water |

| | | | |
|---|---|---|---|
| <br>Figure 52 - Temperature-responsive hydrogel composites based on PNIPAm (Kuang et al. 2018) | <u>Thermal-responsive Composite Hydrogel</u><br>Similar to the previous one these type of hydrogel composites based on PNIPAm can shrink in response to temperature.<br>a) PNIPAm–PNIPAm/ PAMPS gel in a 1m NaCl solution<br>b) PNIPAm-based PEO–PU bilayer hydrogels, and resulting variations of temperatures for a cubic box<br>c) Poly(propylene fumarate) (PPF) segments and responsive poly(N-isopropylacrylamide-co-acrylic acid) (PNIPAm-AAc) hinges | DIW | Temperature |
| <br>Figure 53 - 4D printing examples of SMP composites (Kuang et al. 2018) | <u>SMP Composites – Fiber-reinforced active composites</u><br>Based on PAC, printed by multimaterial 3D printer it consists on a glassy polymer fiber (<u>VeroWhite</u>) and a rubbery matrix (<u>TangoBlack</u>)<br>a) Laminate architecture and the programming process of the PAC and the representative examples for folding.<br>b/c) SMP composite smart hinges connecting inactive plates of rigid plastic | Polyjet | Heat/Cooling |

| | | | |
|---|---|---|---|
| <br>Figure 54 - Bilayer SMP composites (Kuang et al. 2018) | Bilayer SMP composite<br>Direct 4D printing process based on SMP, more precisely a bilayer laminate strip printed with TangoBlack+ as the elastomer and VeroClear as the SMP.<br>a) Metamaterial lattice structure<br>b) Rod with composite cross-sections transformed into a 3D shape upon heating<br>c) Electrochromic element composite<br>d) LCE bilayer containing a water-responsive hydrophilic polymer (polyacrylic acid-PEGDA copolymer) | Polyjet | Heat<br>Water |
| <br>Figure 55 - Printing of SMP multimaterials (Kuang et al. 2018) | Multimaterial SMPs<br>Due to the different Tg values of SMPs, they could be utilized for sequential shape-shifting transformation. By distributing SMPs and using them as hinges, with the same recovery temperature, the SMP hinges that have higher Tg lead to sequential folding.<br>a) Comparison of experiments and the simulations of interlocking SMP component by 3D printing<br>b) 3D printed flat sheet folding into a box with self-locking mechanism<br>c) Deployable sequence of two-layer tensegrity using two different SMPs for the struts | Multimaterial 3D printing processes:<br>Polyjet or FDM.. | Heat |

| | | | |
|---|---|---|---|
| <br><br>Figure 56 - Self-folding rose: Thermorph process, from flat sheet (a) to self-folding (b-d), and simulation steps (An et al. 2018) | *Thermorph* composite (PLA and TPU)<br>A new composite material for low-cost FDM printing, the thermorph is built with 4 layers: 1 layer of TPU, as the constraining layer, and 3 layers of PLA as active layers.<br>This AM system allows the printing of flat thermoplastic composites **(a)** and its self-fold **(b-d)** when triggered with a stimulus (heat).<br>**e)** Thermorph editor is an interactive web-based platform that allows the simulation of the self-folding process, from 3D shapes to 2D patterns for printing. | FDM | Heat |
| <br><br>Figure 57 - Thermoplastic polyurethane hydrogel-elastomer trilayers (Baker et al. 2019) | Multi-material trilayers: hydrophobic polyurethane top and bottom skins (pink), with a hydrophilic polyurethane core (white)<br>A study that uses active hydrogel (Tecophilic™ TPU ) and a passive elastomer (NinjaFlex 85A), through low-cost FDM printing, creating a sandwich structure that returns to its original shape when submerging in water, from dehydration to hydration.<br>A hybrid 4d printing method demonstrated in origami patterns and with great potential to be explored in diverse shapes. | FFF / FDM | Water |

| | | | |
|---|---|---|---|
| <br>Figure 58 - Shape reconfigurable structures with load-bearing capability. (d-e) Video captures of the expansion/contraction of the structure, from flat to active and load-bearing capability under high temperature (Chen and Shea 2018) | <u>Shape reconfigurable load-bearing structure</u><br>A 3D printed programable structure, that responds to temperature changes, consisting of a shape memory polymer (FLX9895), a temperature resistant rigid plastic (RGD525), and an elastomer-like material (Agilus30). An actuator that amplifies the strength of the structure, providing the load-bearing capability. This autonomous shape reconfigurable structure, has diverse hierarchic configurations, as demonstrated on section 2.3.1. | Polyjet | Temperature |
| <br>Figure 59 - SMP flower: a) Unfolded flower; b) Folded flower after heating above Tg (Yang et al. 2015) | <u>SMP filament</u><br>In order to print SMP parts to be used for deployable structures, smart actuators and fast assembly, a thermal sensitive SMP filament was produced for FDM printing process.<br>Available at smptechno.com, this filament enables the production of pieces **(a)** that folds to a temporary shape **(b),** when heated above its $T_g$ (55°C). Also the original form (a) can be restored when heated again above 45°C. | FDM | Temperature |

## 2.4. Deployable structures and origami structures

Over the years and due to technological evolution, the aerospace industry has shown great interest for deployable structures and origami structures, for its easy transportation, lightness and fast assembly, properties that are also significant for the construction of emergency shelters. These dynamic structures are developed for several environments, featuring large-scale configurations that can expand or retract due to their geometry, material and mechanical properties. Owing to these characteristics and also because they are reusable, deployable structures are likewise recognized as sustainable (Adrover 2015).

Deployable structures are more durable when they have rigid components, such as lattice (Figure 60) or scissors mechanisms (Figure 61), being these of interest for this investigation, since they support structural concepts that use the minimum amount of material for the development of structures that can be used as shelters (Figure 62).

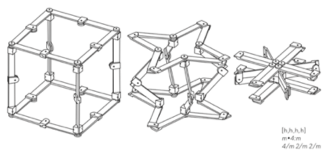


Figure 60 - Deployable structure using lattice mechanism (Adrover 2015)

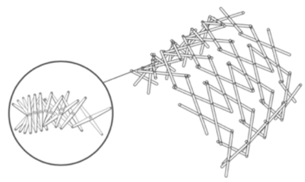


Figure 61 - Deployable structure using scissors mechanism (Adrover 2015)

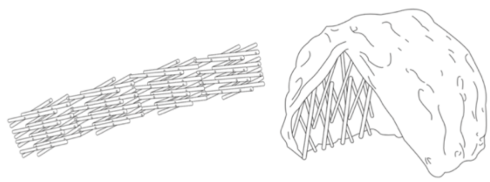


Figure 62 - Structural flat mechanism and used as tent structure (Adrover 2015)

Krishnan (2017) describes deployable structures as an interdisciplinary design process, a concept that could solve emergency shelter needs, due to its adaptability and fast assembly. For the design of these structures it is fundamental that the connector's mechanism and geometry of the structure provide the required movements and supports load. Example of this concept is the origami-based pavilion (Figure 63), a deployable origami structure with scissors mechanism (Krishnan 2017).

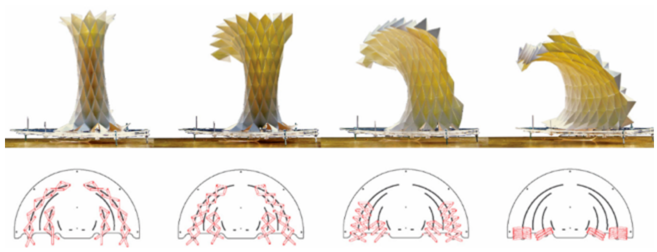


Figure 63 - Deployment sequence of origami-based pavilion facilitated by a base mechanism using polar scissors linkages (in red) (Krishnan, 2017)

As previously referred, deployable structures are mainly studied in aerospace industry, having significant developments for shelters in aerospace exploration, anticipating future exploitation on Mars. Illustrative of these is the "Deployable shelter for Mars" (Figure 64) developed by Häuplik-Meusburger et al. (2013). A concept based on origami folding techniques and scissors mechanisms, as the ones demonstrated by Adrover (2015), the "Deployable shelter for Mars" is self-assembled while inflated by internal air pressure till it achieves the final shape.

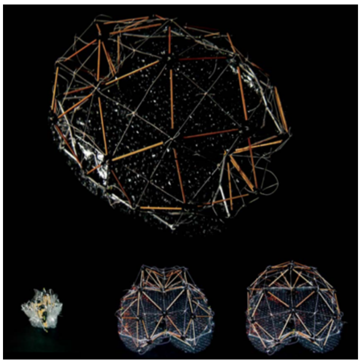


Figure 64 - Model 1:20 scale to test of the deployable shelter structure (Häuplik-Meusburger et al. 2013)

Once the structure is inflated, the shelter maintains its shape in case of losing pressure. This structure is developed to shelter two people, being also capable to adapt to several scenarios and irregular ground (Figure 65). The deployable shelter of Häuplik-Meusburger et al. (2013) is an illustrative example of the concept that could be achieved with 4D emergency shelter structures.

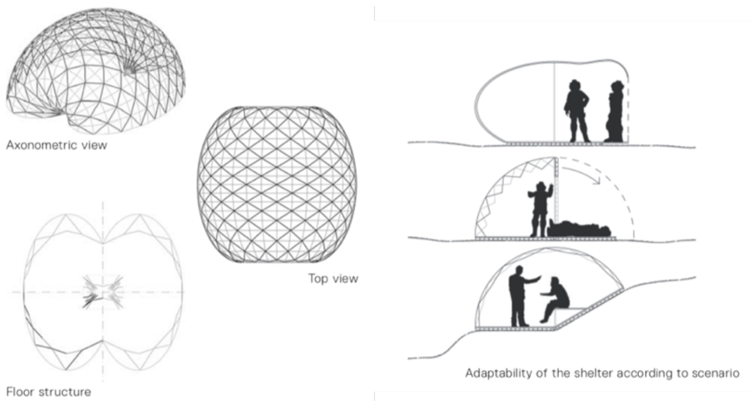



Figure 65 - Adaptability of the shelter according to different scenarios (Häuplik-Meusburger et al. 2013)

## 2.5. Composite materials and structures

Regardless its effectiveness, plastic sheeting/tarpaulin is not a constructive solution on its own and there is a need for a structure to support them, therefore could a 4D printed structure be a solution for emergency shelter? Imagine a structure that could be included in the emergency kit, providing not only the quick and easy assembly of the shelter but also replacing the tarpaulin. A structure that beyond structure could provide cover.

The evolution of 4D printing technology and smart materials has shown their potentialities along the years and, due to the possibility of printing almost every material, concepts of deployable autonomous structures with considerable mechanical properties could be achieved with composite materials.

Considering the aforementioned, composite materials were studied for the development of structures that are easy to transport and assemble, to be used in emergency situations. These materials are also analyzed to be used as smart composites in the 4D printing process, in order to improve specific strength and toughness of the structures developed.

### 2.5.1. General applications of composites in construction

Composites are a combination of two or more, macroscopic materials from different nature, with complementary qualities that usually creates a material with global characteristics superior to the respective constituents. These materials can be classified according to the matrix or the reinforcement. Despite this, composites can also be classified as natural, synthetic or hybrid, depending on their matrix and reinforcement. The matrix holds the fibers together protecting their surface and adding the necessary toughness. The reinforcement fibers offer beneficial mechanical properties, such as stiffness and strength, while the matrix stabilizes the fibers, transferring loads amongst the fibers.

Composite materials have been a matter of interest and research for the development and implementation of this advanced engineered materials in order to solve significant problems such as infrastructure deterioration, corrosion of steel, high labor costs, energy consumption, and environmental pollution.

The most popular application in civil infrastructure is fiber reinforced polymers (FRP), amongst other common composites like reinforced polymers (RP), Glass FRP and Carbon FRP. FRP are applied in shapes of panels, tubes, columns, rods, beams and cellular panels to support loads like vehicular and pedestrian bridges, and others (Mafeld and JEC 2017). Using composites in the construction industry have demonstrated more and more benefits over the years. The benefits of using such materials are summarized in Table 6.

Table 6 - The benefits of using composites in construction (adapted from Mafeld and JEC (2017))

| Primary Benefits | Resulting Secondary Benefits |
|---|---|
| Lightweight | Lower load on foundations or less supporting structure needed<br>Thinner structures can increase available space in the interior<br>Enables manufacture off-site (reduces building site material waste)<br>Ease of transportation, manipulation and installation<br>Speed of installation – less time and cost on site |
| Off-site manufacturing | Allows pre-fabricated parts and modular approach<br>Allows operations to be done which are difficult to do on site<br>Waste can be better controlled than on site |
| High strength to weight ratio | Allows designs that would not be possible with traditional materials due to weight<br>Useful in temporary structures where transportation will be important |
| Freedom of form | Allows the creation of forms not possible or difficult with other materials |
| Durability and lack of deterioration | Color can be provided via so-called gelcoat outside layer<br>Tests on composite parts exposed for thirty or more years have shown no fading |
| Excellent weathering and water resistance | Little or no maintenance is required<br>Composites do not support mildew<br>Composites do not rot<br>Composites are resistant to pests, such as termites |

| | |
|---|---|
| Built-in, no fade color | Composites have demonstrated through many years of use that they do not deteriorate and are very durable |
| Translucency | Composites can be translucent rather than opaque providing natural light |
| Fire resistance, low smoke emission and low toxicity | Composites can be tailored via use if specific resins and fire-retardant additives to meet specific fire performance and thereby pass all relevant fire tests<br>The material can be formulated to have no contribution to the fire, and only to carbonize |
| Thermal insulation | Composites do not conduct heat well and they can significantly reduce thermal bridging in buildings |
| Corrosion resistance | Long life in aggressive environment (e.g. near ocean/sea) |
| Non-conductive of electricity | Composites do not conduct electricity which can add safety during construction and in the building itself |
| Impact resistance | Composites are tough and if designed appropriately can resist impacts |
| Mechanical fixings can be designed to be built-in | If fixings are necessary, they can be incorporated in the molding process |
| Integration parts | By appropriate design composites can integrate into one part what would have been needed to be multiple parts when using other materials |
| Good compatibility with structural adhesives | Allows parts to be bonded together without having to use mechanical fixing |
| Ease of repair | As has been demonstrated in many other applications, for instance in boats, composites can be repaired easily |

### 2.5.2. Composites in lightweight structure construction

Composites represent a higher chance for a material to be used in the construction of emergency shelters due to its mechanical characteristics, performance and flexibility. Engineers, architects, and designers have been investigating this material in shelter construction in order to be approved by humanitarian organizations and facilitate the life of the displaced people. Examples of these applications are described next section (2.6) in Figure 79, Figure 80 and Figure 82, from Table 8.

Due to its lightweight and easy assembly, composites are used for several systems kits that can be used to construct a whole structure. Most systems developed are used to solve a specific part of a building, however, some engineers developed concepts and systems to build complete structures, modular, or even portable ones, in order to solve problems as the one presented. Representative of these systems are the following examples (Table 7), detailed from Figure 66 to Figure 73.

Table 7 - Lightweight composites constructions.

Figure 66 - Composite Modular Hangar (CMTH®) (Dasyc 2015)

The Composite Modular Transportable Hangar is assembled from prefabricated sandwich panels, made from a hard-polyurethane core between two glass fiber reinforced polyester (GFRP) resin laminate skins. The panels are easy to transport and can be assembled easily and fast, making it possible to be used for military or civil purposes, as storage facility or provisional space for vehicles, equipment, field hospital, and also as emergency response facility (Dasyc 2015). In order to create a structure with the same strength of concrete or steel building, the GFRP composite was chosen, building a structure capable of bearing the same loads as specified on conventional materials. Additionally, the material is a cost-effective solution, reducing labor due to the possible application of multiple layers at the same time.

Figure 67 - Inpod-Luxury modular building (modularbuildings.leadersgroup.co.in/)

Inpod is an award-winning modular building system, made with FRP composites. This portable building can be assembled in hours and it's classified as a temporary structure. Besides, it includes climate control, electrical fittings and lightning, a kitchen, bathroom, flooring and windows. Created with German technology, this product is fully composite, with structures lighter than wood and stronger than concrete ones, making it ideal for instant shelter solutions. FRP composite was chosen due to its fast build performance, making it possible to complete an approximately 9.3 $m^2$ structure in just 12 hours, in a controlled environment.

Figure 68 - Gable House, modular construction with thermoplastic composite panels. (Gardiner 2017)

Composite housing took another step with modular construction concepts, offering solutions of all types with a wide range of prices.

Gable House is a 45$m^2$ composite construction that took only seven days to be assembled. The chosen material for this construction were thermoplastic composite panels, specifically LitePan composite SIP with LiteTex thermoplastic composite skins. The development of this construction is based on modules that are easy to assembly, with a design system that can reduce the residential construction time by 88%. A concept that could be suitable for emergency housing, due to its lightweight and easy transportability (Gardiner 2017).

Figure 69 - A glass and carbon fibre-reinforced composites pavillion made by robots and drone. (JEC_Group 2017)

To explore large scale fabrication of glass and carbon fiber reinforced composites, a research pavilion was built using robots and a drone. A filament winding process developed by the Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart, benefiting from the characteristics of fiber construction, mainly the lightweight and high tensile strength that these materials offer. This project demonstrates the potential of computational design in construction through the autonomous robotic fabrication of structural fiber winding geometries, proving the possible large-scale fabrication processes of long-span structural composites, appropriate for architectural constructions. It also shows how future applications could evolve to introduce adaptive autonomous systems (JEC_Group 2017).

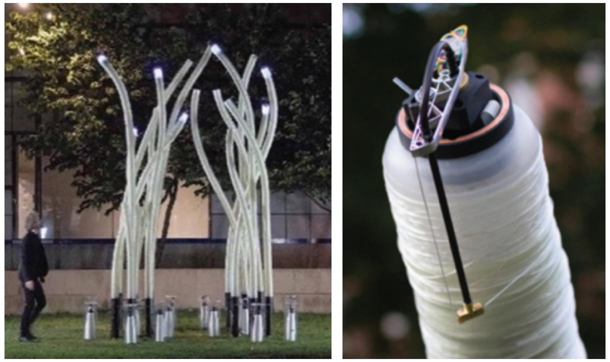


Figure 70 – An architectural-scale structure built using 16 identical *Fiberbots* operating in parallel over 2 days (Kayser et al. 2018)

Using also filament winding process, the Mediated Matter group from MIT Media Lab developed the Fiberbots project. Fiberbots consists on a group of 16 programmed robots developed to wind fiberglass filament around themselves, building strong tubular structures. The robots are mobile and have sensors to control the length and curvature desired for each tube, providing controllable design and autonomous construction. Offering also solutions for fast and easy construction in scenarios such as natural disasters. To demonstrate the potentialities of the Fiberbots, Kayser et al. (2018) used this system to create a projected architectural structure (Figure 70). The tubes vary in length from 2.5 to 4.1m and the overall structure took only 12 hours to assemble. To verify its performance within environmental conditions this structure remained on site, in Cambridge, Massachusetts, for 7 months, resisting from fall to winter.

Figure 71 – Temporary Cathedral of Créteil (Paris, France), based on a gridshell composite structure (ThinkShell 2014)

Gridshells were first introduced by a Russian engineer Vladmir Shukhov and later developed by several architects and engineers, using wood and steel. However, ThinkShell, a team at Navier Laboratory in Paris, shown that glass fiber based composites prove to be the ideal material for the building of gridshells, due to their lightweight and elasticity.
The Ephemeral Cathedral of Créteil is a temporary church, built in 2013 and used during the two years renovation of the permanent cathedral. The construction is based on a gridshell with 2 km of GFRP that covers a surface of 350 m$^2$. This temporary large-scale prototype was built by the locals themselves that took only one day to erect it, and represents an innovation for the construction industry, regarding the use of non-conventional material like composites for the development of structural applications.

Figure 72 - Temporary Church Roof after in Italy (Mafeld and JEC 2017)

In 2009 Maria Paganica Church was damaged by the earthquake, so in order to keep the original structure that was left of it and to preserve the artworks inside of the building, a roof of 32 m high, was developed and erected using pultruded fiber reinforced polymer (PFRP), covering 1000 m$^2$.
This temporary roof was developed in composites due to it lightweight and good mechanical properties, such as resistance to earthquakes and electrical insulation. It is a structure that is easy to assemble and to manufacture, being easy to transport and handle on site, without the need for large lifting equipment. A maintenance-free structure that could be applied to emergency scenarios, protecting what's left from the disaster occurred, in order to restore the remained structures and housing also the displaced people.

Figure 73 - 3D Roof Structures with Exel Composites Tubes (JEC_Group 2016)

The composite manufacture Excel composites, together with Australian based PT Architects Technology, developed a 3D roof structure with composite tubes. A concept that consists on three different diameter tubes in composite, being lightweight and also strong. Additionally, compared to traditional materials such as aluminum and steel, composites allow freedom and flexible designs, due to its bending radius of up to 6 m. The flexibility and adaptability of composite designed structures allow the rounded shapes like waves represented on this project, and its lightweight facilitates the installation process, reducing time and costs in construction. Excel composite tubes offer remarkable fatigue and durability properties, and also good weather resistance, concerning UV damage, moisture and extreme temperatures.

### 2.5.3. Manufacturing processes

Evaluation and selection of the appropriate choice of the composite material are also linked to its requirements and manufacturing processes, such as pultrusion, filament winding, compression molding, resin injection, and others. The several methods for manufacturing composites are chosen according to the design or shape and the final application intended, also depending on the materials for each particular part.

According to Compositeslab (2016), composites manufacturing processes can be divided into three types: open molding, closed molding and cast polymer molding.

Open molding (Figure 74) summarizes the processes where materials (resins and fibers) are placed in a mold and while exposed to air they cure or harden. Open molds tool costs are normally cheap, making this an effective inexpensive technique for a small production or for prototyping (Compositeslab 2016).


Figure 74 – Open molding processes (adapted from Compositeslab (2016))

In closed molding processes (Figure 75), composite materials are cured inside a mold with two sides (in a closed atmosphere) or inside a vacuum bag, on a process that can be easily automated. Demanding special equipment and thus being expensive, closed mold processes are considered when there is a need for a two-sided finish or when it is required a high-volume production (Compositeslab 2016).

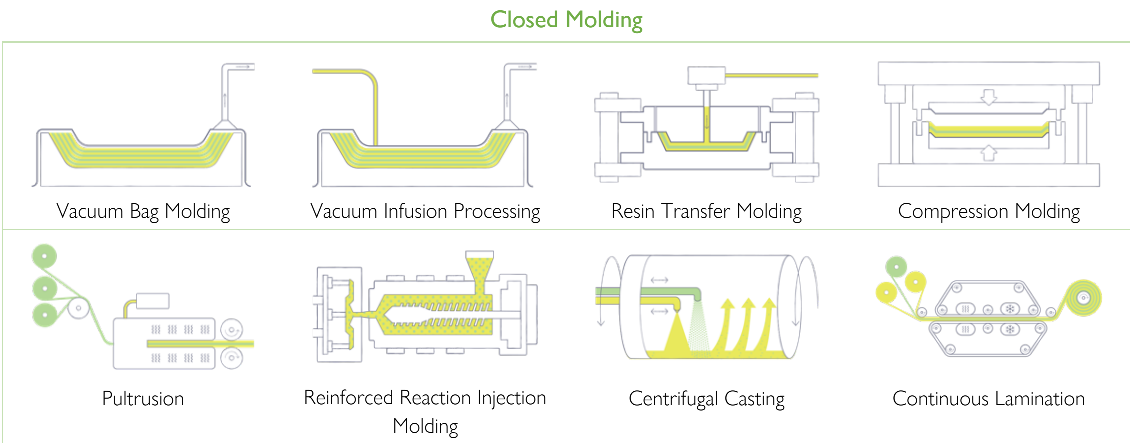



Figure 75 – Closed molding processes (adapted from Compositeslab (2016))

A unique method in the composites industry, cast polymers molding (Figure 76), is a method that can use open molding or closed molding, depending on the specific strength requirements for the final application. In this method, that normally do not have fiber reinforcements, a mixture of resin and fillers are poured to a mold where it cures or hardens, producing products of any size and shape (Compositeslab 2016).

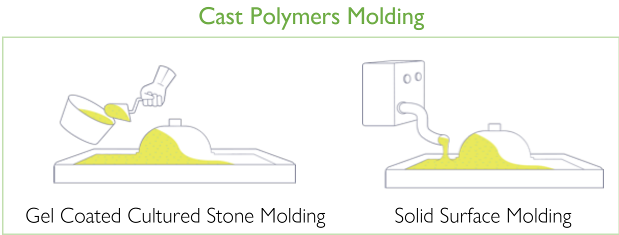



Figure 76 – Cast polymers molding (adapted from Compositeslab (2016))

Since this research points in the direction of using polymers for the development of the product, it is also fundamental to introduce some methods used for thermoplastic composites, such as thermosetting, an automated process where plastic is forced to a heated mold, forming a final shape. And also, advanced computerized methods of layup, such as automated fiber placement (AFP) and automated tape laying (ATP). Automated processes that offer considerable properties compared to conventional methods.

These methods were introduced considering that the development of the product could potentially benefit from the use of composite materials manufactured from such processes, in order to improve the material properties in terms of specific strength, stiffness and toughness.

### 2.5.4. Additive manufacturing processes

In order to reduce cost in prototyping and product development of composite parts, additive manufacturing processes emerged. Despite some composite manufacture processes, such as hot plate press and hand lay-up, could be considered additive manufacturing, the evolution of AM occurred with the introduction of 3D printing technologies.

Additive manufacturing, also known as 3D printing, is a method of highly interest in this dissertation, due to its fast production of three-dimensional structures directly from a CAD model. It is a process that can also be adapted to 4D printing technology when using smart materials, as referred previously.

According to Tofail et al. (2018), the success of AM depends on how well the manufactured product functions according to its designated use in the market. Besides this, additive manufacturing most recent developments, demonstrate the ability to fabricate complex and innovative products, taking advantage of the benefits of 3D printing, such as:

- quick translation from the design to element;
- customization of parts with no need for additional equipment or costs;
- possibility of manufacture complex internal shapes;
- fabrication of flexible and lightweight components with hollow or lattice structures;
- maximization of material utilization potentializing zero-waste manufacturing;

- the reduction of product development and fabrication time leads to the fast placement of the product in the market;
- reduction of the operational foot-print in manufacturing several parts;
- great scalability.

The International Organization for Standardization (ISO) / American Society for Testing and Materials (ASTM) 52900:2015 standard divides the AM processes into seven categories (Figure 77), in which the respective technologies and common materials are specified.

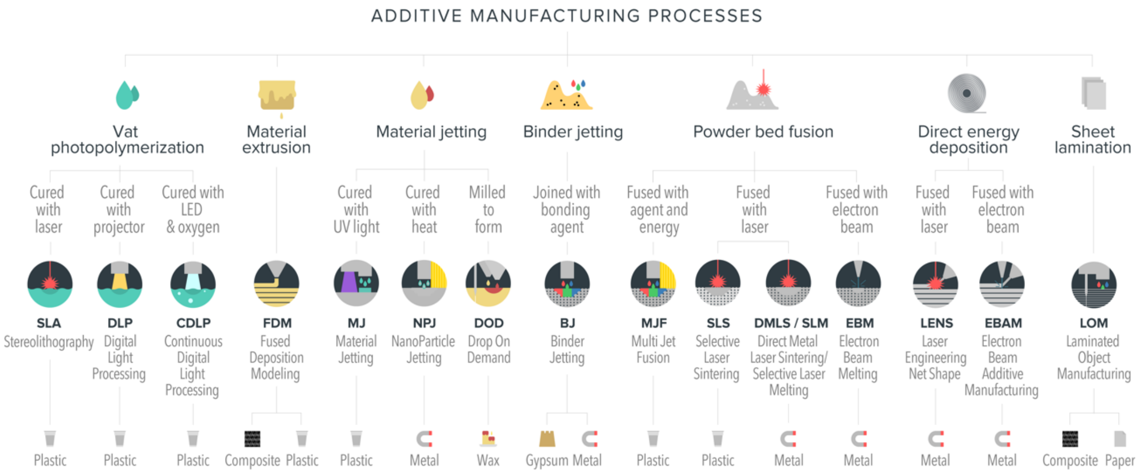



Figure 77 - Additive manufacturing processes (adapted from 3dhubs.com)

Flexible and customizable, 3D printing technologies have exponentially advanced in the past years, being mainly adopted for rapid prototyping and particularly influencing composites industry, in a way that some of AM technologies have shown potential in the production of composite parts, specifically extrusion-based technologies, such as Fused Deposition Modeling (FDM).

FDM is one of the most widely used AM processes, belonging to material extrusion category, in which objects are built by the deposition of melted material, through a programmed path, one layer at a time until it reaches the designated shape. An advantage of FDM is the wide variety of available materials, from the most common thermoplastics (e.g. ABS and PLA) to engineering-grade ones (like PA, TPU and PETG) and high-performance thermoplastics (such as PEEK and PEI), thus, increasing respectively in performance and cost. These common materials used in FDM process provide the basis for composite systems of high performance enabling more design freedom compared to traditional methods of manufacturing (Redwood et al. 2017).

Additive manufacturing processes were analyzed in order to better understand the fabrication methods and to select the most profitable to use in the development of the product. Considering this, FDM was the one selected since it was the process available to test the selected materials and also the most cost-effective.

## 2.6. Market research

In addition to the solutions provided by the organizations, there are several conceptual ideas and prototypes, projected by engineers, architects and designers, that studied this problem in order to find a sustainable and durable solution, improving the life of IDPs after conflict or disaster. Table 8 gathers several examples of shelter solutions designed to meet the needs of different emergency scenarios, detailed from Figure 78 to Figure 86.

Table 8 - Emergency shelter concepts

Figure 78 - Better Shelter; door lock; frame; shelter interior (BetterShelter 2019)

Better Shelter, developed in partnership with UN Refugee Agency, UNHCR, and the IKEA Foundation. A project initiated in 2010 and released in 2015, the Better Shelter was designed to meet the standard needs in terms of privacy, security and familiar environment with dignity, thus providing a basic living space.

This shelter is a low cost and durable solution, with an optimized transportation due to its flat packaging, costing about €1150 /unit, and with a lifespan of 36 months, that allows the adaptation in several areas, being a flexible shelter for different scenarios to be implemented when local solutions are not possible.

A modular post-emergency shelter designed according to Sphere standards for humanitarian shelter use (*The Sphere Handbook: Humanitarian Charter and Minimum Standards in Humanitarian Response).* Each unit is 17.5 m$^2$ and it can accommodate up to five persons. It can be built in 5-6 hours by a team of 4 trained people, assembling a galvanized high strength steel frame and involving it with semi-hard/opaque plastic panels (BetterShelter 2019).

Figure 79 - Anthony's Emergency Housing System (Nickels 2016)

According to its creator, Peter Anthony, this shelter is simple, lightweight and portable. Developed to solve the common problems among deployable shelters, the weight and strength issues, and in order to find a low cost and durable solution, a folding system with composite panels was created. The composite panels are built from a sandwich system of foam core and cellulose skins.

Anthony's Emergency Housing System weights less than 90.7 kg and provides a living space of 5,76 m$^{2,}$ thus housing up to two persons. However, its living space can be expanded to 14,6 m long by joining up to four units. Its transportability is easy and fast due to is collapsible characteristic, making it possible to transport flat and assemble it on site by two people in less than 30 minutes (Nickels 2016).

Figure 80 - Enviropod Dome Home (Enviropod 2019)

(Enviropod) is a FRP composite fiberglass dome unit, optimized for disaster relief or temporary shelter. A cost-effective solution, starting at $8.710 USD, that has the strength of conventional homes and resists to harshest environments. This portable and durable structure can be built in less than a day, with 29 $m^2$, is able to shelter 8 to 10 people (Enviropod 2019).

Providing quick and easy assembly shelter, with only basic tools, this solution has the lifespan of 30 to 50 years with basic maintenance, being also energy efficient. Its material, composite fiberglass, offers benefits in terms of durability and resistance, and also its lightweight provides the easy handle and transportation.

A safe and field-tested solution for temporary shelter, due to its fire, weather, water, moisture, wildlife and wind resistance, and its easy assembly.

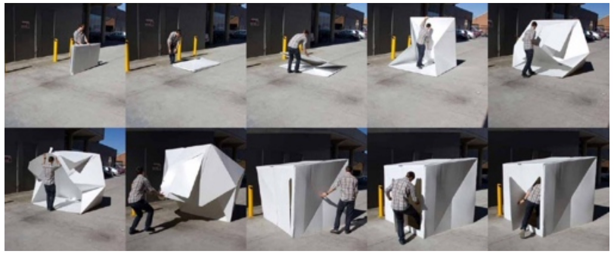


Figure 81 - Compact Shelter designed by Alastair Pryor (Borgobello 2014)

Compact Shelter is a durable and weather resistant shelter, designed by Alastair Pryor. A foldable and portable disaster relief shelter, easily assembled in two minutes, and able to house up to two adults and two children. A cost-effective solution, suitable for several emergency scenarios, this shelter was made with polypropylene, weights only 16 kg and it is easy to transport, due to its flat pack. When packed its dimensions are 200x100x7$cm^3$ and when erected it is 2x2x2 $m^3$.

A modular shelter that allows the joint with other units, creating larger shelters, in order to accommodate bigger families and provide privacy. And besides providing shelter this is also a 100% recyclable solution, by melting the material and reproducing it again (Borgobello 2014).

Figure 82 - Fold Flat Composite (Lippmann 2015)

Fold Flat Shelter is a lightweight composite structure, designed by Lippmann (2015) for after disaster situations. Developed to be foldable, this waterproof and fire-resistant shelter is transported flat and assembled on site by two people in less than five hours, with no need for any tools.

According to Lippmann (2015), the materials used are *Dibond©* or *Alucobond©* sheets for the roof and walls, the floor was made of *HeliPAN*, a sandwich panel of recycled plastic between perforated metal plates, and the substructure in GRP (glass fiber reinforced plastic).

A flat-packed shelter that is 3x1.5x0.3 $m^3$ when packed, weight 250 kg and when erected has an area of 8 $m^2$, thus housing up to three persons. This lightweight and durable material provides easy and fast assembly shelters that can be used as long-term housing. Besides this, its size can be extended up to 18 $m^2$, by joining units (Lippmann 2015).


Figure 83 - Cmax System (cmaxFoundation 2017)

Cmax system was developed by Nicolás García Mayor, to improve the life quality of displaced people. A shelter that combines the major advantages of tents and trailers, in a lightweight system that can be transported flat and assembled on site by two people in 11 minutes, without special tools or equipment.

This resistant shelter is made from polypropylene, aluminum, and polyester, containing survival kits and housing up to ten persons. It costs about $3.000 USD, being easy and quick to assemble and offering also three sanitary structures. A low-cost modular system, that can be reusable and stackable. The structure is raised above the ground which allows its adaptation to different scenarios (cmaxFoundation 2017).

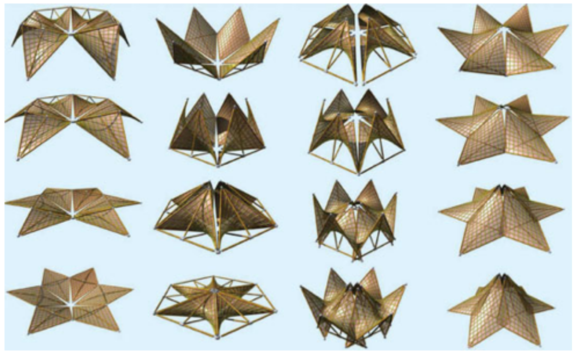


Figure 84 - Origami-Inspired Folding Bamboo House (Yoneda 2008)

Developed by Ming Tang, the origami inspired bamboo shelter was conceptualized in order to be cheap, easy to produce and eco-friendly, intended to be used as temporary shelter after an earthquake. These folding shelters are based in bamboo poles, taking advantage of its strength, to build a variety of rigid structures and then covered it with pre-consumer recycled paper (Yoneda 2008).

Regarding this concept, Krishnan (2017) also demonstrated a deployable sequence of an origami-based pavilion with scissors mechanism, previously described in section 1.1, Figure 63.

Origami-based structures have shown to be strong concepts to be applied in the development of structures for emergency shelters, due to its easy transportation and assembly, and also its adaptation to several environments.

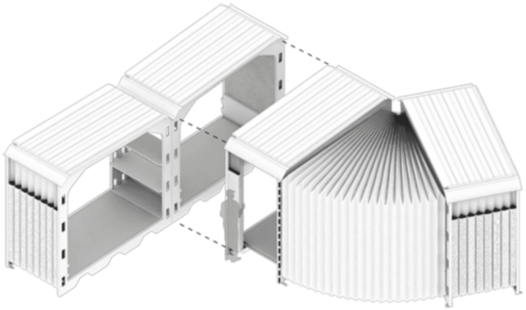


Figure 85 - SURI Shelter Unit for Rapid Installation (SuricattaSystemsSL 2017)

SURI is an emergency or transitional shelter designed by Urbana de Exteriores. A versatile and flexible shelter that can be transformed over time or extended by joining units, to build a variety of dimensional shelters depending on the number of people to house.

This low cost and lightweight modular system is sustainable and eco-friendly, created with recyclable, reusable or biodegradable materials. Also, the SURI system was tested in order to obey the European regulations.

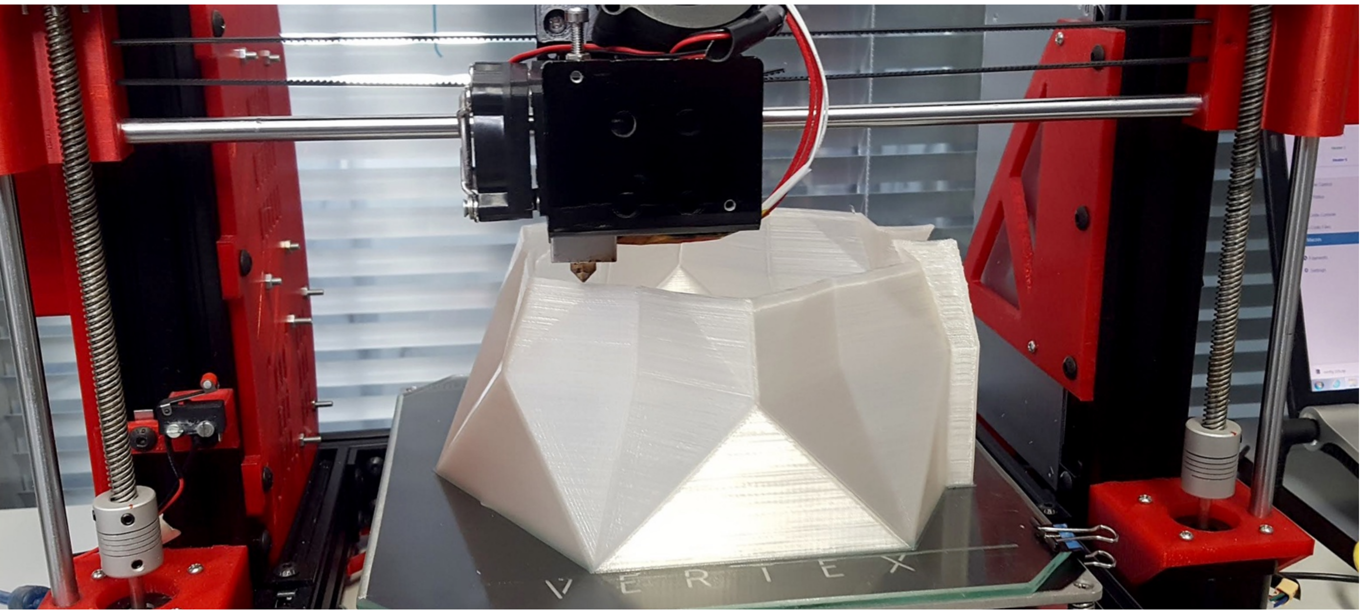
Each unit is transported flat with dimensions of 267x294x10 $cm^3$, weighing 110 kg, and it can be assembled by two people. When unfolded the unit is 244x270x130 $cm^3$, with an area of 3.5 $m^2$, thus sheltering one person. By joining 4 units it can shelter a family of four, and so on (SuricattaSystemsSL 2017).

Figure 86 - Recover shelter (Malone 2008)

Recover shelter, design by Matthew Malone is a temporary shelter for a post-disaster situation. A foldable shelter that is 100% recyclable, made from Coroplast (food grade polypropylene). Lightweight and easy to transport, due to its fold shape in a flat sheet, and quick to assemble on site by one person in minutes (Malone 2008). Its accordion design, similarly to the previous example (Figure 85), allows the shelter to achieve different shapes, providing the joint of structures, thus extending the shelter.

This concept of accordion-like shelters have been demonstrated by several authors, such as Tina Hovsepian, with the Cardborigami (2017), and Thrall and Quaglia (2013), that reviewed the accordion-based shelters developed by the US military.

# III. CASE STUDIES



# 3. CASE STUDIES

## 3.1. Context

After exploring the state of art, it became clear that IOM as other humanitarian organizations need a solution for the structure of the emergency shelters currently developed. A structure that could be not only flexible and adaptable to different emergency scenarios and environmental conditions, but also a solution easy and fast to assemble by the IDPs.

Because of this, the intent in this case study is to prove that concepts as the ones demonstrated in the state of art, namely 3D and 4D printing, could be the solution for an emergency shelter. In fact, the aim of this case study is to demonstrate the application of 4D printing structures in parallel to the development of a standard emergency shelter, analyzing the challenges of both processes for later development of the final product.

First, it was important to understand the relevance of IOM as one of the major humanitarian organizations in shelter operations. The way that this organization works and what they need, regarding the emergency shelter terminologies, materials and construction.

Then, related to 4D printing, PLA filaments were tested in order to achieve regular and controlled structures from flat to 3D. Also, SMP filament was studied, to develop 3D structures that could assume a temporary folded shape, later restored to a 3D shape, demonstrating the concepts evidenced in the state of art.

Following the experimental plan, after building the basic standard shelter and tested the materials and geometries, a concept for an easy and fast assembly shelter was developed, according to the shelter requirements established by IOM.

Finally, some 3D renders, representative of the concept developed, were shown and models at scale were developed, with posterior validation.

### 3.1.1. Relevance of IOM

Humanitarian shelter and settlement operations have been managed so far by IOM and other humanitarian organizations. However, IOM is in charge for most of the operations regarding natural disasters and conflicts, providing first emergency shelter, safety and dignity to the IDPs. Supported by national government and authorities, IOM's aims to guarantee quality in the operations, focus on people and their needs, support better practices and maintain long term aid while IDPs need assistance.

During 2017, IOM program assisted over 5.2 million individuals (Figure 87) in 49 countries, building about 53 thousand newly shelters. Also, IOM supports one third of the people assisted by the Shelter Cluster, being one of the biggest sheltering organization around the world, with a major role in the coordination of 25 shelter country activities (IOM 2018).

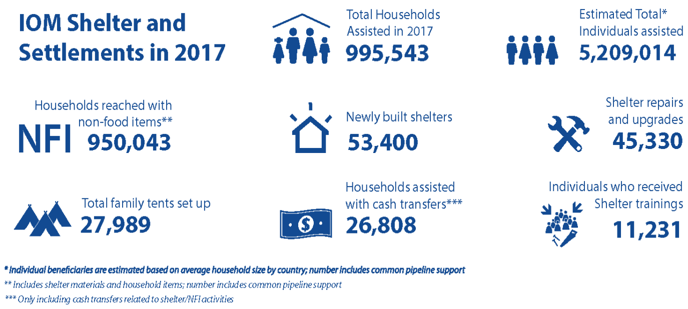



Figure 87 - IOM Shelter and Settlements in 2017 (IOM 2018)

IOM is the organization highlighted in this dissertation as the major distributor of shelter kits and technical assistance to build the first emergency shelter. As so, they currently need a solution to improve the structures developed for the emergency shelter, normally improvised with wood poles. Having this in mind, terminologies and developed shelter types were studied, in order to come up with an alternative solution that could provide structure and also cover.

### 3.1.2. Humanitarian organizations shelter terminologies

According to IFRC (2013), sheltering should be considered a process, not a product and terminologies are related to the context in which structure is intended to be built. Different scenarios after disasters or conflicts can be related to different terminologies (Figure 88), from emergency shelter to permanent housing, considering the phase of response and the context that the shelter is built on.

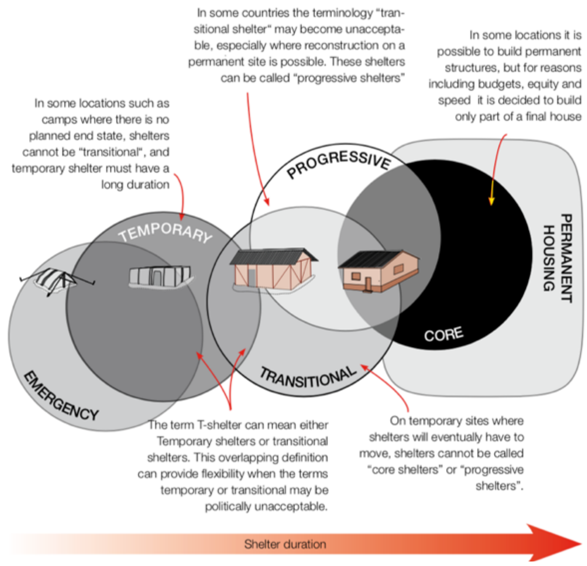



Figure 88 - Illustration of overlaps between some of the different shelter terminologies in use (IFRC 2013)

However, focusing on the design of the shelter and its process, after analyzing the context that they are built, IFRC recognized that these terminologies could be mentioned as:

- Emergency shelter: the first and most basic shelter provided right after a disaster or conflict, assuring lifesaving support. This shelter normally has a short lifetime.
- Temporary shelters: a rapid constructed household or shelter solution for post-disaster, with limited costs and consequently limited lifetime.

- Transitional shelter: post-disaster more durable shelter built with materials that could be reused or upgrade into a permanent structure. Also a shelter that can be relocated from temporary space to a permanent location.
- Progressive shelter: a shelter designed to be more durable and easily upgrade into permanent housing, making some transformation in its structure over time.
- Core shelters: a household design to be a future permanent housing, with at least two rooms and possible extension, providing more privacy and reaching permanent housing standards.

Deciding which terminology to use is influenced by several contextual elements, from the level of permanence that is expected for the shelter, to the materials the shelter is made and the location it is going to be built. Yet, emergency shelter is always referred as the first provided after a disaster, temporary and transitional ones should be designed bearing in mind that its relocation or reuse of the material, and progressive or core shelter should be built on permanent locations, aiming to become permanent housing.

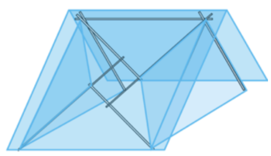
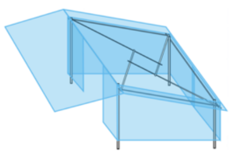
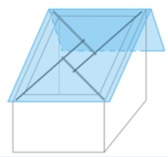
In this dissertation, it is referred the development of a first emergency shelter, although according to the context of the terminologies, it could be also seen as a temporary or transitional shelter due to the lifetime and durability envisioned for the product developed.

### 3.1.2.1. Emergency bamboo shelter types

From the terminologies mentioned above, the development of the shelters associated to emergency and temporary shelters normally consist on bamboo or timber frame, covered with tarpaulin. Given this, and to facilitate the construction of the shelter, IFRC developed a technical sheet with guidance and examples of emergency shelter and roof frames, suitable for different contexts.

In Table 9, three types of first emergency shelter are described according to IFRC standards, using only tarpaulin, bamboo poles and rope. The simplest shelter, built in two hours by three people and providing an area of 17.5m$^2$, is the standard bamboo shelter model, the main one considered and also prototyped at scale in the experimental plan of this dissertation.

Table 9 – Emergency shelter and roofs with bamboo frames (adapted from IFRC (2015))

| Standard bamboo shelter model | Elevated bamboo shelter model | Bamboo roof frame model |
|---|---|---|
|  |  |  |
| Basic shelter with a rectangular shape and oblique roof with structure build in bamboo poles and the walls and roof covered in plastic tarpaulin. | Rectangular shape shelter with slightly inclined roof. Its structure is in bamboo poles and its cover with plastic tarpaulin, with one entrance at front. | Sometimes there are some structures that can be used with only improvements in the roof. In these situations, the roof is made from a bamboo structure and tarpaulin. |
| **Materials:** shelter kit and bamboo poles<br>**Building time:** 2 hours<br>**Construction team:** 3 people<br>**Area:** 3.40 m x 5.15 m (17.5m$^2$) | **Materials:** shelter kit and bamboo poles<br>**Building time:** 4 hours<br>**Construction team:** 3 people<br>**Area:** 3.40 m x 5.60 m (19m$^2$) | **Materials:** shelter kit and bamboo poles<br>**Building time:** less than 1 hour<br>**Construction team:** 3 people<br>**Area:** 3.60 m x 3.60 m (13m$^2$) |

### 3.1.3. PLA and other FDM based materials for 3D and 4D printing

The growth of 3D printing market has triggered the appearance of new materials for FDM printing, mainly polymers and composites. However, polymers are the most used so far, being PLA and ABS the dominant ones. But the choice of the right type of material to print depends generally on the object to be printed as so the mechanical properties intended and visual quality. Currently, the main pure polymers in the market are PLA, ABS, PET, PA, TPU and PC. To make a choice between these polymers, there are key categories, besides cost and speed, that can sustain the decision, such as the ones classified in Figure 89.

Poly(lactic acid) (PLA) was one of the selected materials in the development of this case study, being the easiest polymer to print and providing good visual quality (Figure 90). Besides this, it is one of the cheapest materials for FDM printing, with good rigidity and high strength, but fragile.

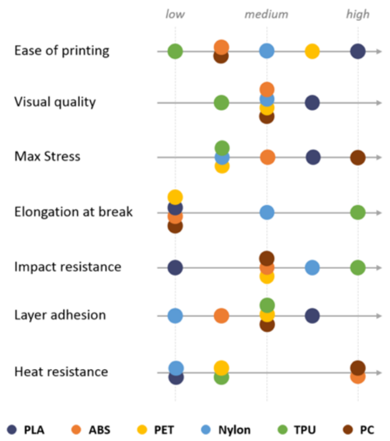



Figure 89 - Polymers for FDM printing, ranked by criteria from 1(low) to 5(high) scale (3DMatter 2016)

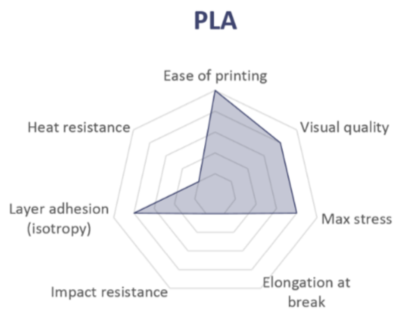



Figure 90 - PLA properties ranking for FDM printing process (3DMatter 2016)

According to Farah, Anderson, and Langer (2016), PLA is, so far, the most researched and used biodegradable polyester in human history, having several applications in medicine and in industry, with potential to replace conventional petrochemical based polymers. Made from renewable resources, PLA is recognized by the United States of Food and Drug Administration (FDA), as safe for use as food packaging applications, increasing also its use for other industrial applications.

PLA was successfully implemented in biomedical applications, showing not only better mechanical proprieties, but also more controlled surface properties than conventional polymers. Compared to other polymers PLA appears to be more advantageous, being eco-friendly, biocompatible and better processability than other biopolymers, requiring also less energy to produce compared to petroleum-based ones. These advantages in production directly affect its cost, making it a low-cost polymer. However, there are some limitations in its applications, like poor toughness, slow degradation rate and hydrophobicity.

The choice of a polymer is based on its respective properties. Mechanical and physical properties, as density and heat capacity, are influenced by the glass transition temperature ($T_g$). However, a significant property that directly influences major properties of the polymers, such as hardness, modulus, tensile strength, stiffness and melting point is the rate of crystallinity. In fact, polymers can be amorphous or semicrystalline, depending on their stereochemistry and thermal history. Yet, polymers cannot achieve complete crystalline material so there are always amorphous areas on semicrystalline polymers. Semicrystalline polymers present regular repeating units, thus giving higher tensile strength and stiffness than amorphous ones. Amorphous polymers flexibility reduces when cooled below its $T_g$. Concerning this, semicrystalline PLA is preferred when higher mechanical properties are desired, being its $T_g$ approximately 58°C and the melting temperature ($T_m$) varies from 130-230°C (Farah, Anderson, and Langer 2016). Summarized in Table 10 are the mechanical properties of PLA.

Table 10 - Properties of PLA (adapted from Farah, Anderson, and Langer (2016))

| Properties | | Unit |
|---|---|---|
| Polymer density (ρ) | 1.21 – 1.25 | $g/cm^3$ |
| Tensile strength (σ) | 21 – 60 | MPa |
| Tensile modulus (E) | 0.35 – 3.5 | GPa |
| Ultimate strain (ε) | 2.5 – 6 | % |
| Specific tensile strenght (σ*) | 16.8 – 48.0 | Nm/g |
| Specific tensile modulus (E*) | 0.28 – 2.80 | kNm/g |
| Glass transition temperature (Tg) | 45 – 60 | °C |
| Melting temperature (Tm) | 150 – 162 | °C |

Printing with PLA and other filaments has its challenges when fabricating complex objects, mainly in the Z axis, that needs support structures whenever the vertical angles are bigger than 45°. Thus leading to rough surfaces and unsuccessful printings. On the other hand, 4D printing appears to be a solution to the major problems of 3D printing, in a way that complex objects would be printed flat and later achieve the 3D shape when submitted to a stimulus. The evolution of 3D for 4D printing envisions to increase the production rate.

As described in section 2.2.2, 3D printing is achieving large scale, having demonstrated applications in the construction industry as well. Being large scale a possibility in 3D printing, it is intended to achieve also large-scale printing in 4D (Figure 91), as envisioned by An et al. (2018). A concept of large-scale printing of flat pieces triggered on site could make it possible to obtain the intended programmed shape. Thanks to the wide range of materials that can be printed nowadays, as engineering-grade materials, this vision is becoming a real possibility in a near future.

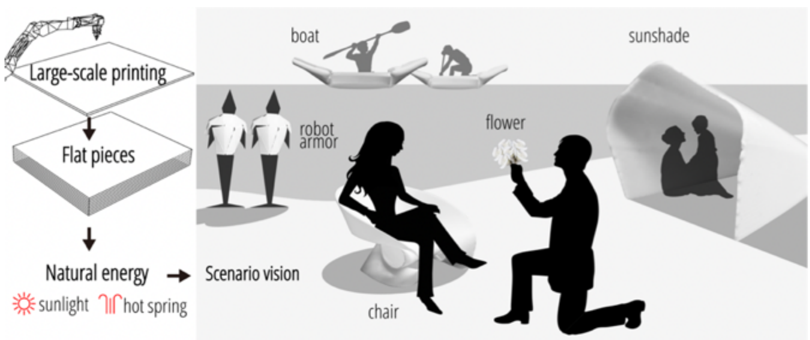



Figure 91 - Design vision for 4D printing on site. Concept from *Thermorph* (An et al. 2018)

#### 3.1.3.1. Deformation temperature and SME of 3D printed PLA

A study performed by Wu et al. (2017) showed the influence of process parameters, such as layer thickness, raster angle, deformation temperature and recovery temperature on the shape memory effect of 3D printed PLA. It was revealed that the shape memory effect (SME) is more influenced by the recovery temperature than the deformation temperature, with a demonstrated shape recovery ratio of 98%. However, the deformation temperature was a highlighted parameter more studied in the following section 3.3.2.

Being PLA a thermosensitive SMP it showed efficient SME phenomenon in the experiments developed (Figure 92). Presented by Wu et al. (2017), the SME process with PLA can be divided in development of the original shape, deformation to a temporary shape under high temperature, fixation at low temperature and recovery of its original and permanent shape at high temperature.

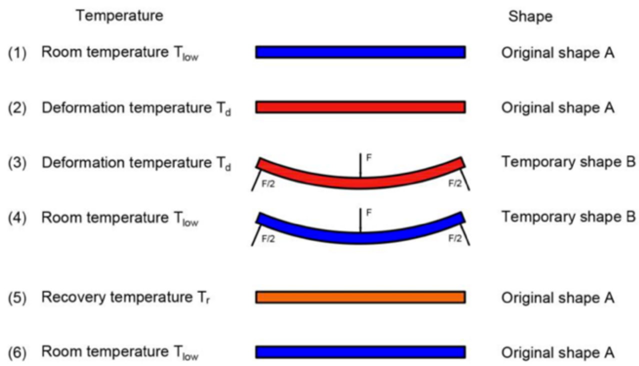



Figure 92 - Shape-memory effect experimental process of PLA rectangular sample measuring 95 x 15 x 2.4 $mm^3$ (An et al. 2018)

The SME of PLA was affected by many factors, being highlighted the deformation temperature ($T_d$), applied for the deformation of the material and the recovery temperature ($T_r$), applied in order to restore the original shape. Yet, the glass transition temperature ($T_g$) also influenced the SME of PLA, as well as the correlation between temperatures, frequency, stress and strain under several conditions. Demonstrating these properties, a dynamic mechanical analysis was performed (Figure 93) by An et al. (2018). Considering that the PLA used for the experiments had a $T_g$ of approximately 63.5°C, it showed a glass transition region when temperatures were ranging from 45° to 70°C and at temperatures higher than 70°C the material was in a rubbery state, showing a quite low storage modulus.

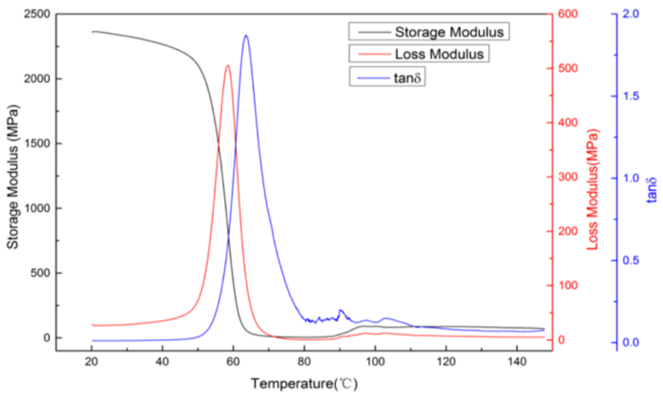



Figure 93 - Dynamic mechanical analysis of PLA (An et al. 2018)

From an investigation performed by Wijnen, Sanders, and Pearce (2018), concerning the deformation and warpage of PLA in FDM, it was pointed that residual stress and crystallinity are fundamental parameters for the deformation process. Besides this, it was also mentioned that for temperatures below the $T_g$, the objects did not shrink or crystallize. However, when achieved 90°C they shrink significantly and crystalize fast.

### 3.1.4. SMP filament properties and other applications

Presented in the state of art, SMP filament (Figure 59) showed also deformation with temperature as well as SME, advantageous properties for the development of an adaptable and flexible product. This filament (Figure 94) was developed by SMP Technologies inc., based on a polyurethane thermoplastic trademarked by Mitsubishi Heavy Industry as DiAPLEX, a smart material that changes its properties according to the temperature. The basic properties of DiAPLEX pellets from SMP Technologies inc., are listed in Table 11.

Table 11 - Basic properties of DiAPLEX pellets used in the fabrication of SMP filament (Yang et al. 2015)

| Properties | | Unit |
|---|---|---|
| Density (ρ) | 1.2 | g/cm$^3$ |
| Melting temperature (Tm) | 205~215 | °C |
| Recommended injection nozzle temperature | 195~205 | °C |
| Recommended 1st transition and metering section temperature | 190~210 | °C |
| Glass transition temperature (Tg) | 45 | °C |
| Hardness below Tg | 76 | $H_DD$ |
| Hardness above Tg | 30 | $H_DD$ |
| Tensile strength below Tg | 55 | MPa |
| Tensile strength above Tg | 10 | MPa |
| Price per kg (without shipping cost) | 55,5 | USD |

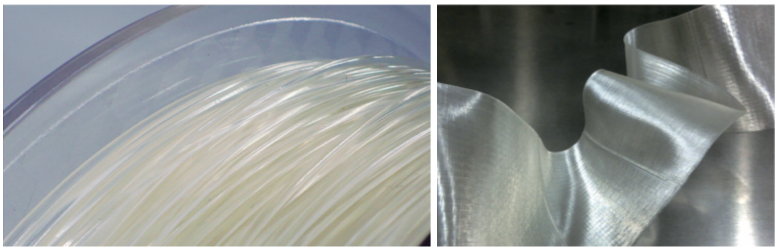


Figure 94 - SMP filament with customizable shape (SMPTechnologies 2018)

Despite the referenced SMP filaments, explored in this research, this material can be also provided as pellets, liquid solution, fiber, microbeads and foam. Therefore, different production techniques can be used, such as injection, extrusion and other forming techniques (SMPTechnologies 2018).

SMP filament was the first filament developed to be customizable after printing, soften when heated and harden at room temperature. It offers potential benefits for applications in the medical industry as well as space industry, in the development of self-deployable structures. Characteristics such as lightweight, low cost, easy processing and maximum strain up to 400%, show that this material could be applied in endless possible products, such as the development of an emergency shelter. In fact, the recovery and fixation state of the structures after printing could facilitate the packaging and transportation of the structures (SMPTechnologies 2018).

This filament is suitable for FDM process in hobbyist 3D printers (Figure 95), using almost the same printing conditions as PLA. In Figure 96, the relation between Young modulus and the temperature, shows that the objects are fixed after printing. However, they can be deformed when heated above $T_g$, thereby altering the shape of the printed object, in the rubbery state, to a temporary shape. The deformation applied could also be restored to its original shape, by heating the object also above the $T_g$. The process is the same for deformation and recovery of shape since it is made in the rubbery state of the material.

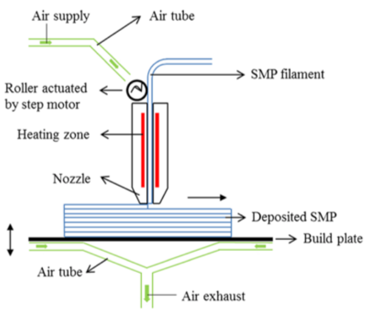



Figure 95 - Schematic of SMP's 3D printing process (Yang et al. 2015)

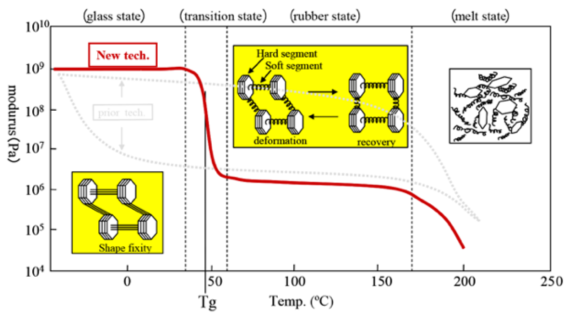



Figure 96 - Young modulus (E) changes with the temperature (SMPTechnologies 2018)

Besides the shape memory effects, this material also offers beneficial properties and applications such as the ones presented in the SMPTechnologies (2018) catalog:

- damping property, suitable for the development of lens and artificial blood vessel;
- gas or moisture permeability;
- volume expansion and recovery force, useful for inflatable solutions and deployable structures.

Also in SMPTechnologies (2018) catalog the concept for an inflatable material for aerospace applications was demonstrated (Figure 97), where the relative volume of the compact stowed structure was 30% to 40% of its original structure. As described before, the structure developed with SMP material can reduce its dimensions, compacting the structure in temperature above the $T_g$ of the material, admitting a temporary rigid state of hibernation that can be later restored by heating it at a temperature above the $T_g$. A process that is valuable for the topic discussed in this dissertation, the development of an emergency shelter.

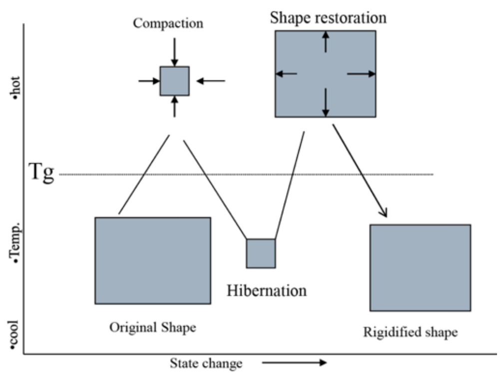



Figure 97 - Inflatable material, using SMP technology, for aerospace applications (SMPTechnologies 2018)

## 3.2. Methodology

The methodology applied in this case study derives from the most relevant data gathered in the state of art (chapter 2) and tests them in order to better understand the materials and structures that led to the final concept of the structure developed. Following this, an experimental plan (Figure 98) was developed to guide the whole process.

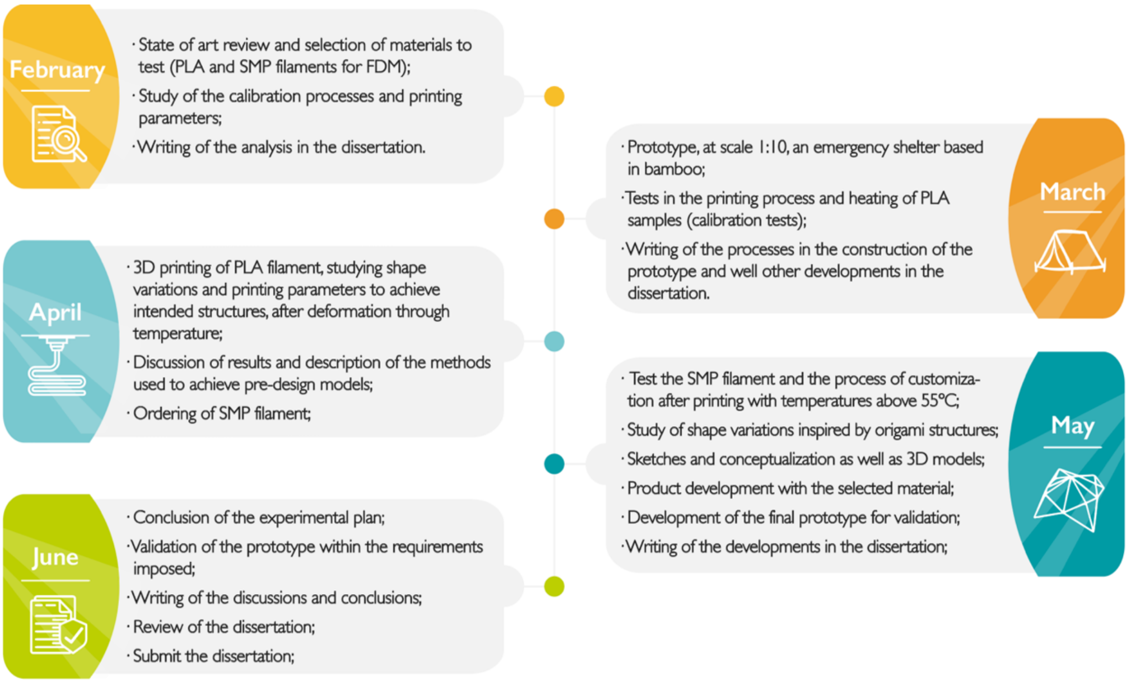



Figure 98 - Overview of tasks developed along the experimental plan

From the bibliographic research, the material that represented better possibilities to test and prove the 4D printing process was PLA filaments (Figure 49d). This material is easy to obtain and test in FDM printing since PLA is the most used and cheap filament. Representing the 4D process, after printing these filaments, the object can deform or shrink when submitted to high temperatures (70ºC-100ºC). Besides this, the SMP filament (Figure 59) was another relevant process, representative of the shape memory polymers, that have a reversible process after deformation, which means that after printing the object can be deformed to a temporary shape and recover its original shape when submitted to hot water (55ºC).

In parallel to the analysis of the 3D printing materials, it was important to understand also the main constraints when assembling a conventional emergency shelter, as so the material used for this construction. Given this, a standard shelter based in bamboo and tarpaulin was built, in order to register the difficulties, needs, strength, stiffness and other properties of the structure. Thus giving some ideas of what should be improved in the concept of the final product.

## 3.3. Experimental Plan

Regarding the context, an experimental plan was developed and the steps to achieve the final concept were strategically defined. The experimental plan illustrated in Figure 99 was a substantial point, guiding the process until the product development, adjusting the concept and the material to achieve better outcomes.

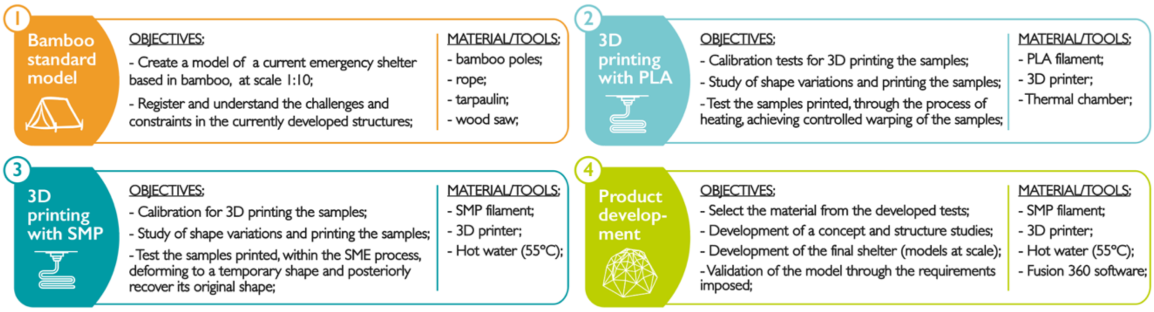



Figure 99 - Experimental plan tasks assignments

### 3.3.1. Building a basic emergency shelter based in bamboo

In order to better understand the challenges and steps of building an emergency shelter, a prototype was built according to IFRC (2015) instructions manual. The prototype developed was based on the simplest existing shelter, adopted by humanitarian organizations, the standard bamboo shelter model (Figure 100), as the example built by RSK Shelter (Figure 101).

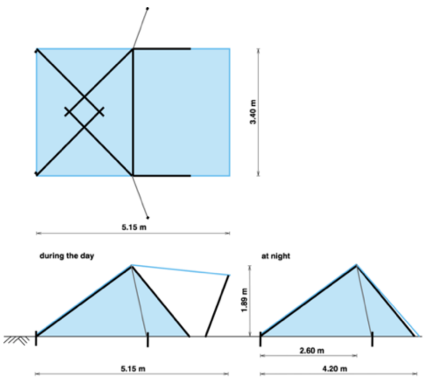



Figure 100 - Plans of the standard shelter model (IFRC 2015)

Figure 101 - Red Cross and villagers in Myanmar Delta build emergency RSK shelters 2017 (RSK Shelter 2018)

Respecting the materials and tools specified in Table 12, and since the prototype was built at a scale 1:10, the bamboo poles, the rope and the tarpaulin were cut with the respective dimensions at scale. Besides this, it was also studied the process of fixing the poles to each other, as represented in Figure 102 and Figure 103.

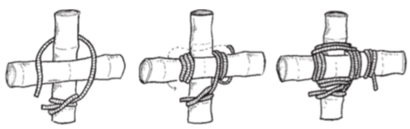


Figure 102 - Fixing two perpendicular poles together (IFRC 2010)

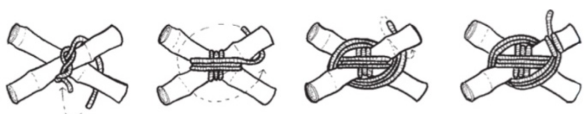


Figure 103 - Fixing two poles together in diagonal angle (IFRC 2010)

Table 12 - Materials and tools to build a standard shelter (adapted from IFRC (2015) and RSKshelter (2018))

| Materials and Tools to build a standard shelter | | |
|---|---|---|
| **Item** | **Specification** | **Q.** |
| SHELTER KIT | | |
| Tarpaulin | Size: 4x6m | 2 |
| Shelter tool kit | Tools and fixings<br>(nails, rope (30m), etc.) | 1 |
| STRUCTURE | | |
| Bamboo (roof frame) | Length: 2.90m<br>Diameter: 45 mm (range 30-60) | 4 |
| Bamboo (ridge pole) | Length: 3.50m<br>Diameter: 45 mm (range 30-60) | 3 |
| Bamboo (support pole) | Length: 2.45m<br>Diameter: 45 mm (range 30-60) | 2 |
| Bamboo (entrance)<br>*(optional)* | Length: 2.00m<br>Diameter: 45 mm (range 30-60) | 2 |

· Material and tools used by RSKShelter.

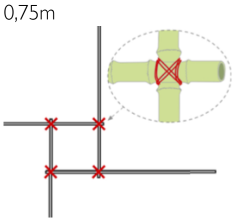
· Material at scale for building the prototype.

The process of assembling a standard bamboo shelter is simple, but it requires basic construction skills. So, after understanding the requirements and properties of a disaster relief structure, the installation of this standard shelter was made, following the instructions described in Table 13. Also in Table 13 is represented the prototype at scale 1:10, following the step by step construction.

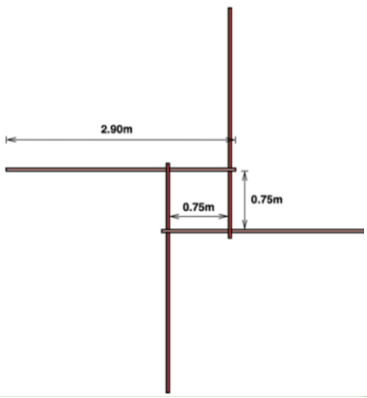
Table 13 -Steps to build a shelter and shelter prototype at scale 1:10 (adapted from IFRC (2015) and RSKshelter (2018))

**Step by step installation of the shelter and prototype at scale 1:10**

STEP 1. Roof frame
· 4 poles (2.90m)
· 4 lashings (2m)
· Intersect the 4 bamboo poles with a central square of 0,75 x 0,75m

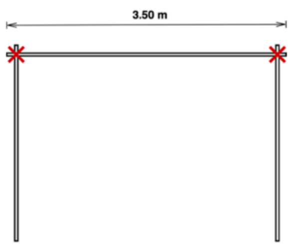


**Instructions**

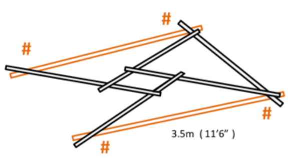



**Prototype (Scale 1:10)**

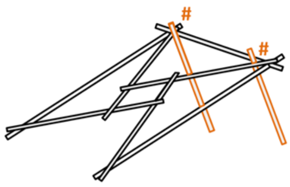
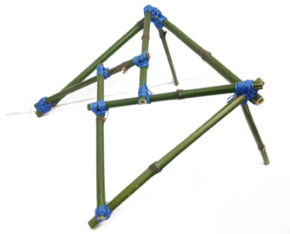
STEP 2. Support frame
· 1 ridge pole (3.50m)
· 2 support poles (2.45m)
· 2 lashings (2m)
· Join a 3.5m bamboo ridge on top of 2 support poles.



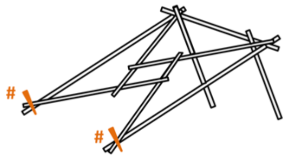

STEP 3. Attach two side poles
· 2 ridge poles (3.50m)
· 2 lashings (2m)
· Used to create the sides of the shelter (it is possible to use rope instead of poles, however it has less strength)



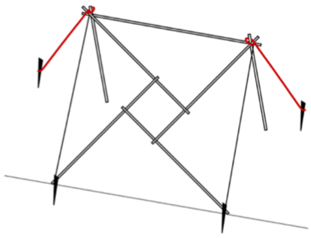

STEP 4. Assembling the roof frame to support frame
· Roof frame
· Support frame
· 2 lashings (2m)
· Lift one side of the roof frame and joint to the support frame with lashing rope

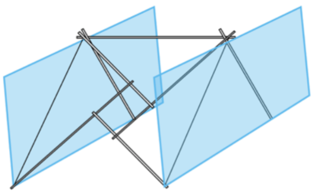
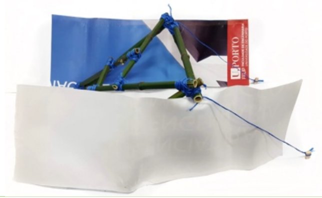
STEP 5. Anchor the base of the roof frame
· 2 wooden stakes (0.45m)
· 2 lashings (2m)
· Anchor the structure to the ground, placing the 2 stakes with 3.20m of distance from each other.



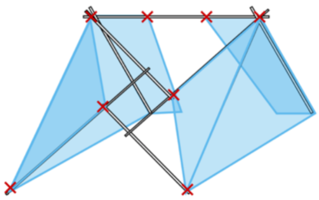

STEP 6. Anchor the base of the roof frame
· 2 wooden stakes (0.45m)
· 2 ropes (4m)
· Loop the ropes on the support pole's top and fix the pegs it to the ground on the sides of the structure.



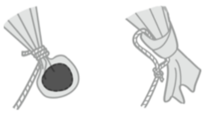
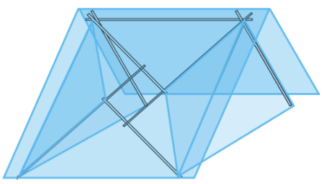
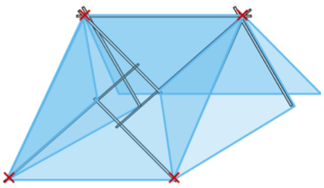
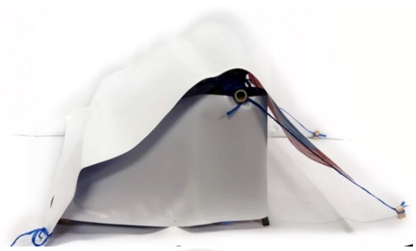

STEP 7. Cutting one tarpaulin in the middle
· 1 tarpaulin 4 x 6 m
· Cut the tarpaulin in the middle two obtain two pieces of 2 x 6 m and place them in the sides of the shelter.

STEP 8. Cutting one tarpaulin in the middle
· 2 sliced pieces of the tarpaulin
· 8 lashings (2m)
· Fold the tarpaulin over the frame and attach it at the places described in the figure.




STEP 9. Cover the rest of the shelter top and the shelter is complete
· 1 tarpaulin 4 x 6 m
· 4 – 6 lashings (2m)
· Place the tarpaulin on the structure and attached it in the 4 corners of the shelter frame.


After the prototype development, some obstacles were pointed out. First, the cut of the bamboo poles is not very precise due to the manual tools utilized (wood saw) and the irregularities of the surface in the poles. The lashing knots, despite the easy way of executing, they do no secure well the structure, making it unstable. Lastly, the tarpaulin does not have enough size to cover all structure properly and it is difficult to attach, sometimes ripping it. Thus, giving the idea that it may require some training for building the structure with precision and accuracy.

### 3.3.2. 3D printing of PLA filament

From the state of art, Figure 49d), Kuang et al. (2018) showed an approach based on the shape-shifting of programmed SMP, printed with simple desktop 3D printers and inexpensive materials such as PLA. An automated production process was presented by van Manen, Janbaz, and Zadpoor (2017), where planar shapes are printed and then triggered by temperature to achieve a pre-programmed 3D shape.

van Manen, Janbaz, and Zadpoor (2017) demonstrated a design strategy, using the heat transference concept, incorporating porosity and variation of thickness in the objects, thus programming the sequential shape-shifting of the object upon heating. A technique that could be used for a single shape or a combination of shapes, in order to achieve complex 3D shapes.

Using hobbyist 3D printers, the demonstrated process was based in FDM printing of PLA filaments (Figure 104a), the same process used in the experimental plan of this dissertation. The filaments were printed above the melting temperature (180ºC), stretching and then cooled, storing the memory of the material that shrinks when heated above its $T_g$. The obtained results, as the example in Figure 104f-g, were dependent on printing parameters and activation temperatures (Figure 104c-e), mainly layer thickness and combinations of directions of the printing layers. Verified that printing parameters highly influenced the shape-shifting behaviors, these parameters were also considered in the calibration tests and shape studies detailed in the following sections.

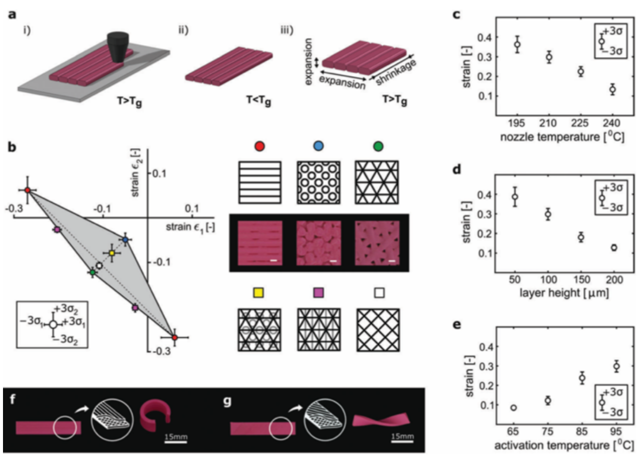



Figure 104 - PLA shape-shifting process. (a) i) The filament is extruded and it stretches and bonds with the previously printed layer; ii) the stretching of the filament is stored as memory in the material, after cooling below Tg; iii) heating above Tg, the material relaxes, resulting in shrinkage in the longitudinal direction and expansion in both other directions. (b) The printing pattern of multi-ply square panels regulates their in-plane strains. The grey area shows the range of possible directional strains measured for multipattern panels. (c–e) Printing and activation parameters control the shrinkage of multi-ply panels. (f) Basic shape-shifting in self-bending strips made by combining a longitudinal shrinking top layer with a semi-passive bottom layer. (g) Changing the orientation of the top layer results in self-twisting (van Manen, Janbaz, and Zadpoor 2017)

### 3.3.2.1. Calibration tests for a circular shape

Considering the case study of 3D printing with PLA filament, the concentric deposition was the first studied due to the fact that circular geometries were less propitious to uncontrolled warping effects. Following the case study context, the combination of thickness and direction of filament deposition was analyzed to study the effect of shrinkage and expansion operations. Concluding that in the direction of the material's deposition it tends to shrink.

Given this and to verify the 4D printing process with PLA, three circular samples with the same geometry were 3D printed with a combination of thickness (0,6 mm and 0,8 mm) and concentric deposition. As shown in Table 14, the three pieces were submitted, after printing, to a thermal stimulus for 3 minutes, which transform them into a conic geometry.

These calibration tests were made to study the influence of different temperatures in the process of shrinkage and expansion of the structures. Therefore, the temperatures of 75°C, 85°C and 95°C were defined, as they were above the $T_g$ of PLA, thus allowing the transformation of the pieces. From these temperatures, and as observed in Table 14, the 95°C was the temperature that has shown better results in a controlled uniform deformation of the shape from flat to a conic geometry with bigger height (12 mm).

Table 14 - 3D printing experiences with PLA. The same geometry with respective results after submitted to different temperatures

| 3D printed circular sample | After heating at 75° C | After heating at 85° C | After heating at 95° C |
|---|---|---|---|
|  |  |  |  |
| Diameter: 50 mm<br>Thickness: 0,6 mm and 0,8 mm | Max. Diameter: 46 mm<br>Min. Diameter: 44 mm<br>Max. Height: 8 mm | Max. Diameter: 45 mm<br>Min. Diameter: 42 mm<br>Max. Height: 9 mm | Max. Diameter: 44 mm<br>Min. Diameter: 39 mm<br>Max. Height: 12 mm |

Also in the calibration process, the printing parameters (Table 15) were studied and defined to generate the g-code of the three pieces, as well as for the following pieces designed in the study of shape variation, presented in the next section 3.3.2.2.

Table 15 - Printing parameters used to generate the g-code for printing the pieces in PLA

| Print setup parameters for *BQ Prusa i3 Hephestos* printer (g-code generated in *Ultimaker Cura*) | | | |
|---|---|---|---|
| Layer Height | 0.2 mm | Flow | 100% |
| Infill and Shell Pattern | Concentric | Print Speed | 90 mm/s |
| Printing Temperature | 190°C | Build Plate Adhesion | None |

### 3.3.2.2. Study of shape variations

The calibration tests revealed that the concentric deposition of layers multiples of 0,2 mm was the path to follow in the next assays. Regarding this, a study of shape variations was made in order to better understand the layer variation and thickness that is needed to achieve a regular shape, the required angles and a controlled height of the structure.

In these experiences, the methodology was to print a set of calculated designs in a *BQ Prusa i3 Hephestos* printer (Figure 105), with PLA filament in a concentric deposition, and later heat the pieces in a *Thermotron* temperature and humidity controlled chamber (Figure 105), to observe and register the effects of contraction and expansion of the material.

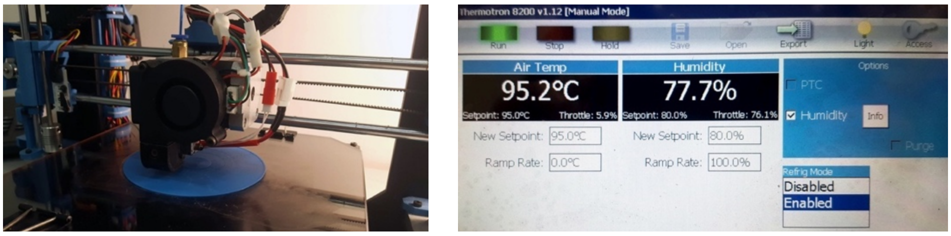



Figure 105 - BQ Prusa i3 Hephestos printing one sample for test and Thermotron settings for heating the samples

For the study, all samples were heated at 95°C for 3 minutes, because it was verified in the calibration experience that this temperature offers the most uniform warping of shapes.

ASSAY PLA 1

**Material:** PLA filament;
**Tools:** 3D printer – BQ Prusa i3 Hephestos and thermal chamber;

**Description:**
The first sample tested (Figure 106) was a circular shape with no size layer variation and two perpendicular joints to observe if the joints hold the deformation regularly. However, the warping process was uncontrolled, as shown in Figure 106c).

ASSAY PLA 1

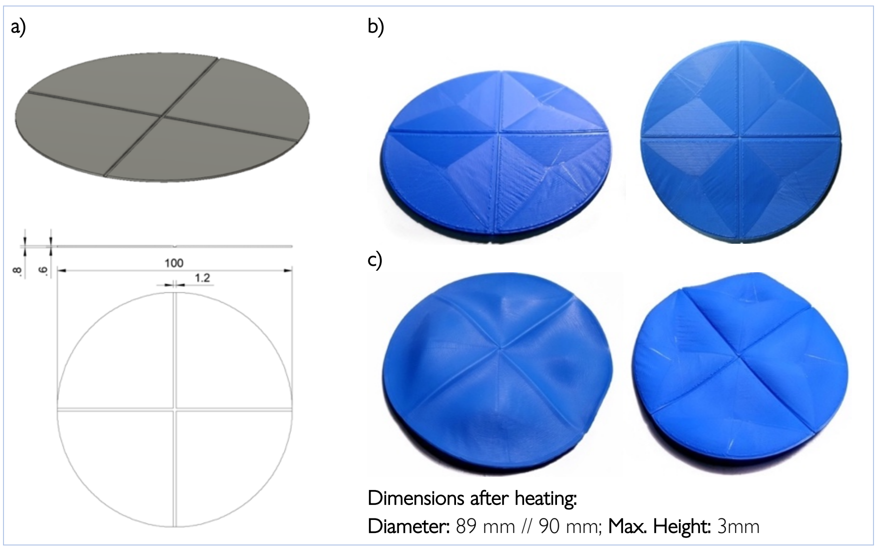



Figure 106 - Sample with 0,8 mm thickness and two perpendicular joints. **a)** 3D model made in Fusion 360; **b)** 100 mm diameter sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**
The joints were too thin, and the shrinkage was not regular, excluding this process over the variation of layer thickness as the previous experiments of calibration. As seen in Figure 106, there was low warping after heating (Figure 106c) and it was not regular, also with low height achieved. The diameter after heating varied from 89 mm to 90 mm, and the maximum height was 3 mm.

## ASSAY PLA 2

**Material:** PLA filament;
**Tools:** 3D printer – BQ Prusa i3 Hephestos and thermal chamber;

**Description:**
After verifying that the joint process did not work to warp the circular shape as it was supposed, the layer variation was used for this and the following tests. This way, a sample with 8 similar divisors (45°) was made, intercalating the thickness in 0,6mm and 0.8mm. This design (Figure 107) has 100 mm diameter and after heating the base of the structure becomes 67mm x 71 mm with diagonals of 88 mm and a maximum height of 16 mm.

ASSAY PLA 2

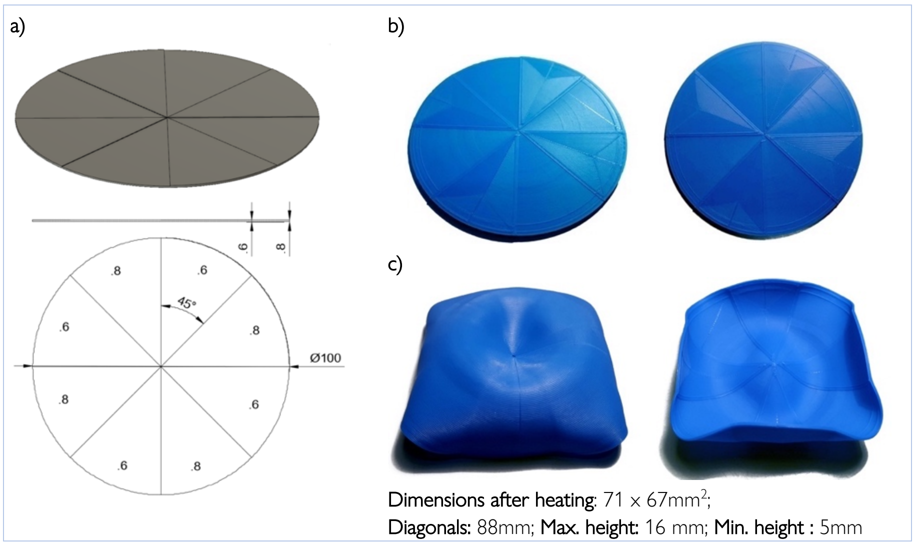



Figure 107 - Sample with 8 intercalating variation of thickness from 0,6 mm and 0,8 mm. **a)** 3D model, dimensions and layer thickness variation; **b)** sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**
In this test, it was intended to achieve the same behavior as the calibration tests. However, the center did not raise in this sample, probably due to the bigger diameter, the core needed more material. This was a challenge pointed out to be solved in the following studies.

## ASSAYS PLA 3 and 4

**Material:** PLA filament;
**Tools:** 3D printer – BQ Prusa i3 Hephestos and thermal chamber;

**Description:**
Maintaining the circular shape, the following examples (Figure 108 and Figure 109) were designed to see the behavior of the core with less and more material, as so with intercalating layer size thickness and different angles.

ASSAY PLA 3

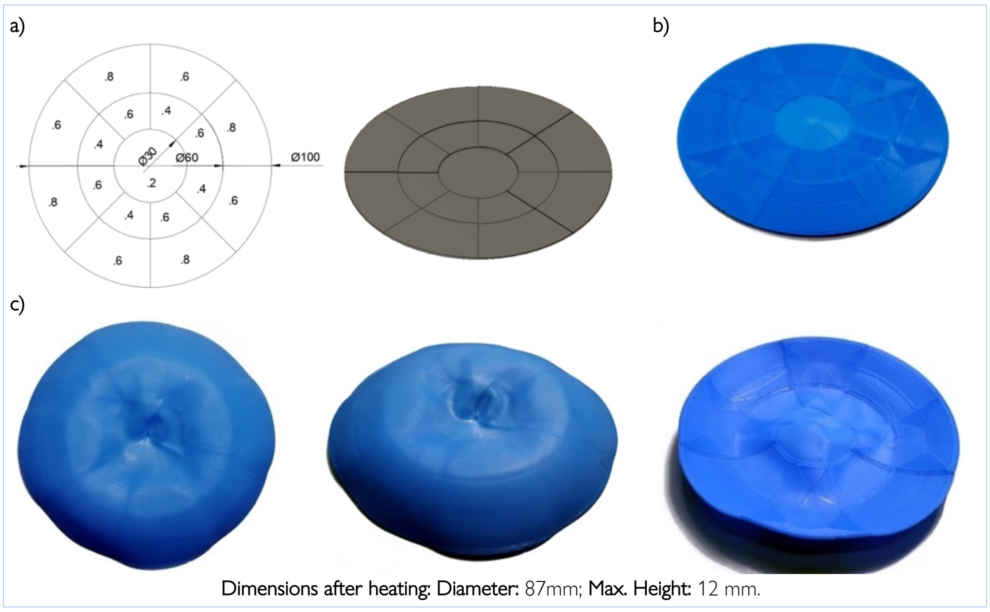



Figure 108 - Sample with 8 x 3 divisors and thickness variation from 0,2 mm to 0,8 mm. **a)** 3D model, dimensions and layer thickness variations; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

ASSAY PLA 4

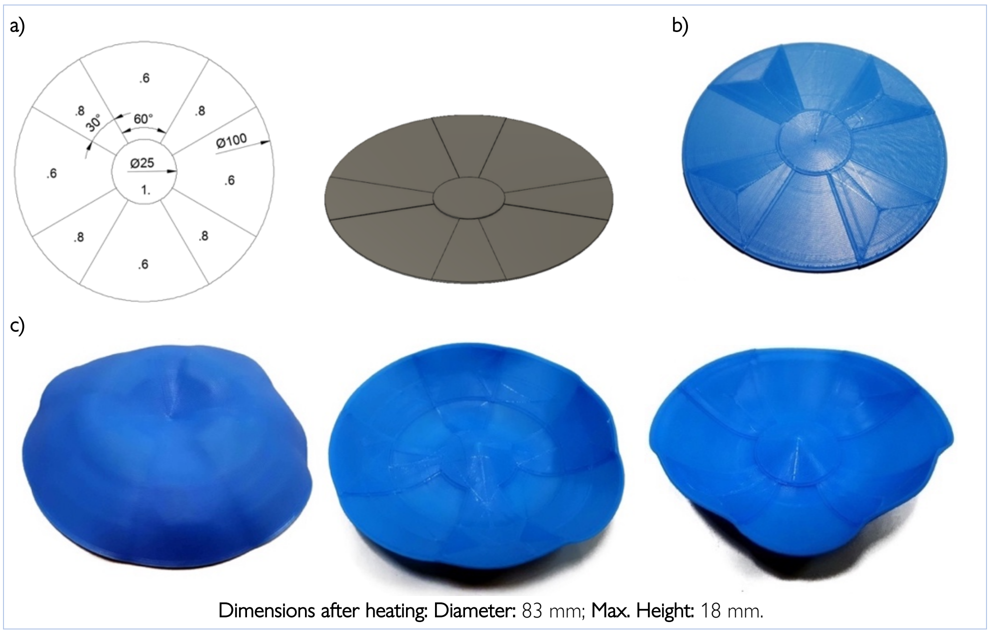



Figure 109 - Sample with 8 divisors varying from 0,6 to 0,8 mm thickness layer and a 25 mm diameter core with 1 mm thickness. **a)** 3D model, dimensions and layer thickness variations; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

### Conclusion / Improvements:

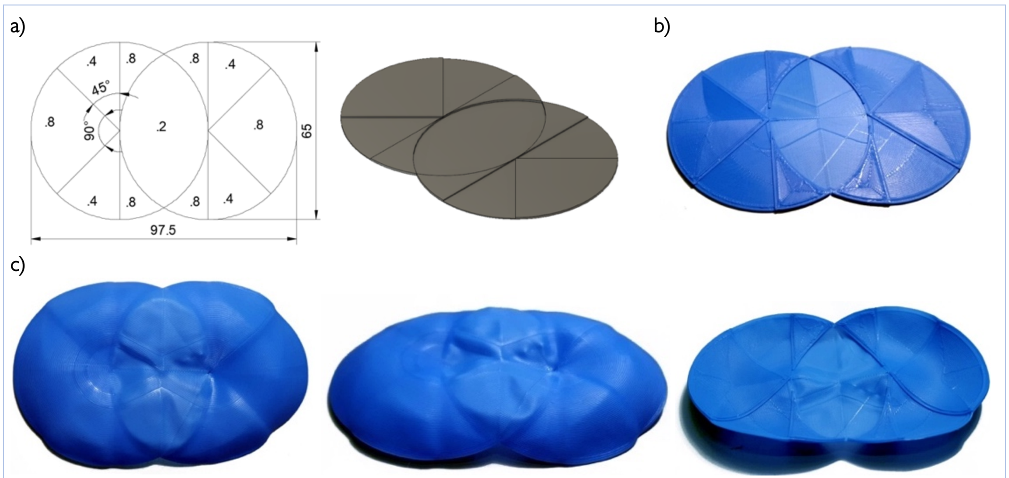
In these two assays (Figure 108 and Figure 109) almost the same behavior occurred. The core of the structure did not elevate and the warping was irregular, not achieving a conic shape as intended. Still, when the core of the piece had more material (Figure 109), it became more regular in the warping process and a maximum height was achieved (18 mm). Thus, indicating that the core might need the intersection or overlapping of geometries, in order to achieve more height.

## ASSAYS PLA 5 and 6

**Material:** PLA filament;
**Tools:** 3D printer – BQ Prusa i3 Hephestos and thermal chamber;

**Description:**
As understood from the previous tests, in order to achieve more height new designs were experimented (Figure 110 and Figure 111), with intersection and overlapping of circular shapes. It was also tried the layer thickness variation, with less and more material, respectively, in the core of the piece.

ASSAY PLA 5

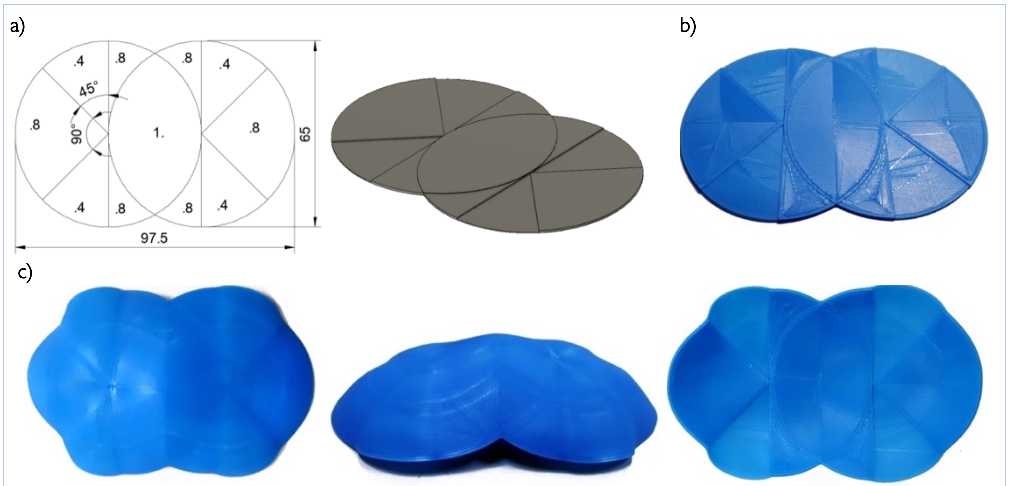



**Dimensions after heating:** 87 x 54 mm²; **Center:** 50 mm; **Max. Height:** 8mm.

Figure 110 - Sample with overlapping of circular sketches and thickness variation from 0,2 mm to 0,8 mm, the core with less thickness (0,2 mm). **a)** 3D model and dimensions; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion and Improvements for Assay 5:**
The designed piece (Figure 110a)), after heating (Figure 110c)) showed an uncontrolled warping and only 8 mm height. This behavior probably occurred by the fact that the center of the piece had less thickness. To validate this the same design was replicated with more thickness in the core-shell (Figure 111).

ASSAY PLA 6




**Dimensions after heating:** 84 x 54 mm²; **Center:** 47mm; **Max. Height:** 19mm.

Figure 111 - Sample with overlapping of circular sketches and thickness variation from 0,4mm to 1mm, the core had more thickness (1 mm) **a)** 3D model and dimensions; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements for Assay 6:**
Given the improvements in the designs, it was concluded that more stiffness, with overlapping geometries, in the core of the piece results in a more controlled warping and also bigger height (19 mm), as observed in Figure 111c). This sample (Figure 111) was the first one that proved symmetric and controlled warping after heating, achieving a visual shape that meets what was in mind in the process of designing the model from flat to 3D pre-programmed shapes.

In this phase of the experimental plan, it was understood that the effect of layer overlap, thickness variation and direction of deposition directly influence the final shape after heating. Thereby, the following studies on shape variation had this in mind.

Having *know-how* about the process and in order to achieve a bigger area where the roof of the piece was higher, new sketches were made, bearing in mind mainly the fact that more thickness in core made it regularly plane. The new sketches also continued on using circular shapes as base, overlapping them and consequently attributing variable thickness.

## ASSAY PLA 7

**Material:** PLA filament;
**Tools:** 3D printer – BQ Prusa i3 Hephestos and thermal chamber;

**Description:**
Given the conclusions derived from the previous assays and in order to achieve more volume, this model was created (Figure 112a) and b)), where the core was designed with two thickness (0,8 mm and 1 mm) and by crossing deposition directions.

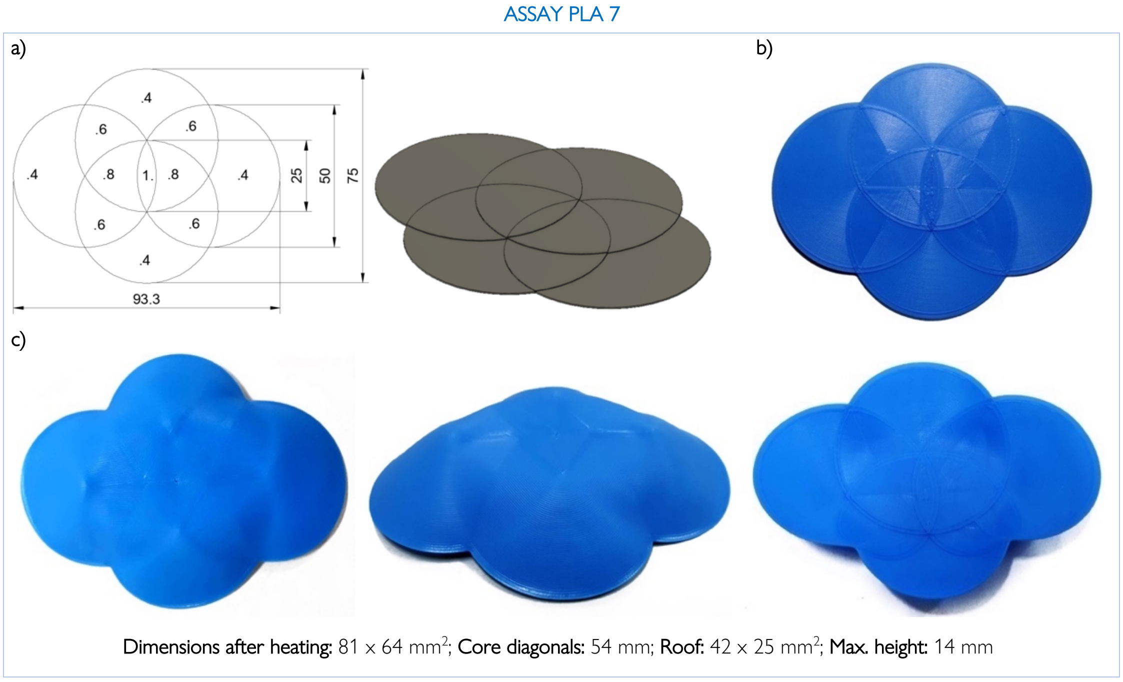



Figure 112 - Sample with overlapping of circular sketches and thickness variation from 0,4 mm to 1 mm, the core with two crossed thickness (0,8 mm and 1 mm). **a)** 3D model and dimensions; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**
This assay has shown a controlled warping of the piece after heating (Figure 112c)), where the dimensions from the flat piece (Figure 112b)) shrink in approximately 14% in area when heated, achieving a height of 14 mm where the roof area was 42x25 mm$^2$.

This shape, as well as the following ones presented, was designed considering the product development and aiming to achieve a shape that resembles a shelter, the focus of this dissertation. Given this, semi-spherical shapes, igloo shapes and dome shapes were tried to achieve, from the design of a flat 3D model with circular overlapping to heating into the intended shape.

## ASSAY PLA 8

**Material:** PLA filament;
**Tools:** 3D printer – BQ Prusa i3 Hephestos and thermal chamber;

**Description:**
Following the method used in assay 7 (Figure 112), a larger scaled geometry was replicated, proportionally increasing its dimensions and thicknesses (Figure 113a)). With this sample (Figure 113), it was intended to prove that proportionally scaling the design would result in the same warping effect, and as observed in (Figure 113c)) it did in fact occurred.

ASSAY PLA 8

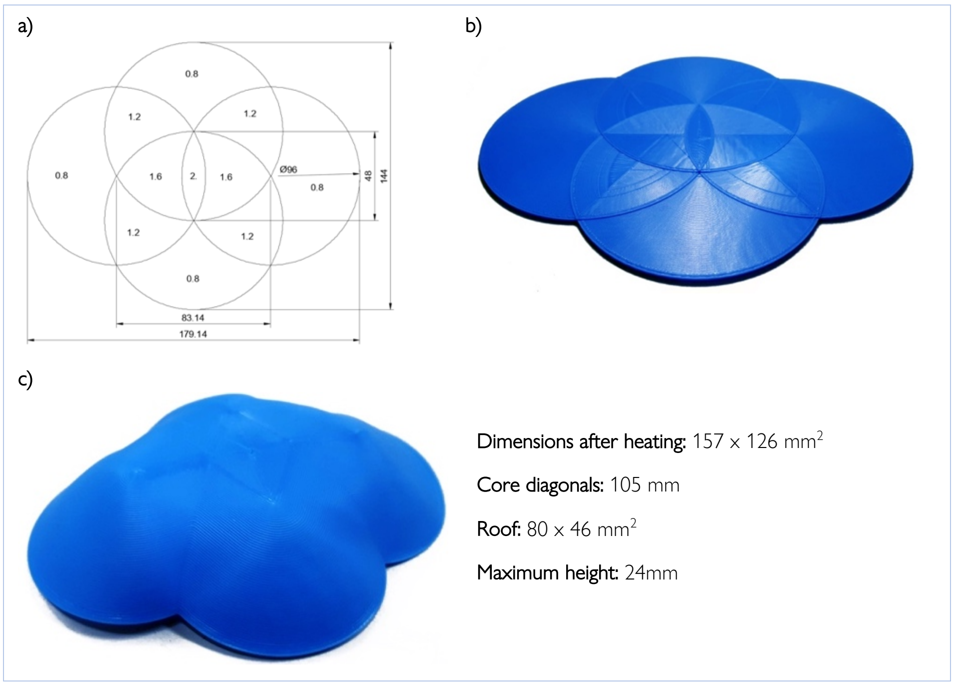



Figure 113 - Replication at scale from Figure 112. Sample with overlapping of circular sketches and thickness variation from 0,8 mm to 2 mm, the core with two crossed thickness (1,6 mm and 2 mm). **a)** Sample dimensions; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**
In this sample (Figure 113c)) it occurred as expected, a controlled shrinkage of the dimensions of the area, from flat to 3D, in approximately 12%, almost the same percentage as the previous scaled sample. Subsequently after heating a height of 24 mm was reached.

## ASSAY PLA 9

**Material:** PLA filament;
**Tools:** 3D printer – BQ Prusa i3 Hephestos and thermal chamber;

**Description:**

As the purpose of this dissertation was the development of an emergency shelter, it was fundamental to test samples with openings, representing such as doors and windows. Considering this, it was replicated a previous successful sample (Figure 112), with thoughtful cuts in dimensions that would represent at scale the door and windows (Figure 114).

ASSAY PLA 9

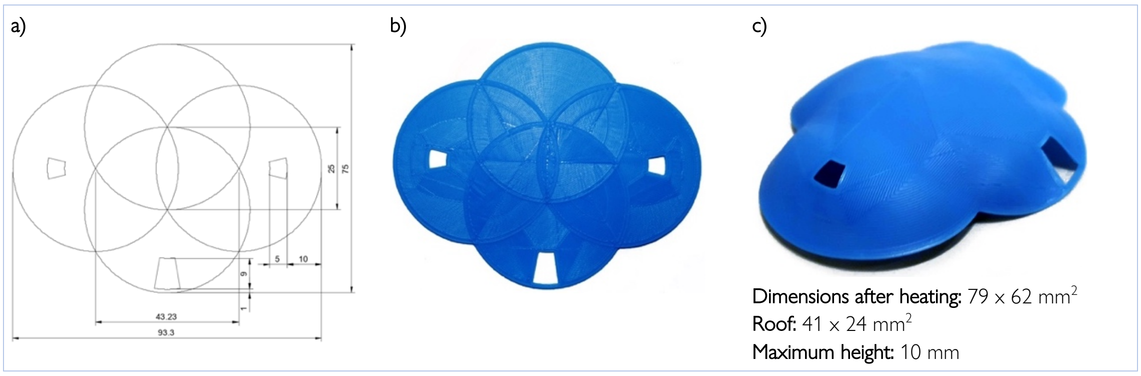



Figure 114 - Replication of a successful previous assay 7 (Figure 112) with openings, representing a door and windows. **a)** Sample dimensions; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**

This sample showed a controlled warping (Figure 114c)) as expected, however, the height only reached the 10 mm, the roof area was minor and not all flat as the previous assay (7).

## ASSAY PLA 10

**Material:** PLA filament;
**Tools:** 3D printer – BQ Prusa i3 Hephestos and thermal chamber;

**Description:**

In order to obtain a more circular geometry, with higher volume, it was studied a combination of the previous shape (Figure 113). Thus resulting in a sort of igloo shape as demonstrated in Figure 115. A geometry that has shown a controlled warping after heating, and shrinkage of area in about 22% to 28%.

ASSAY PLA 10

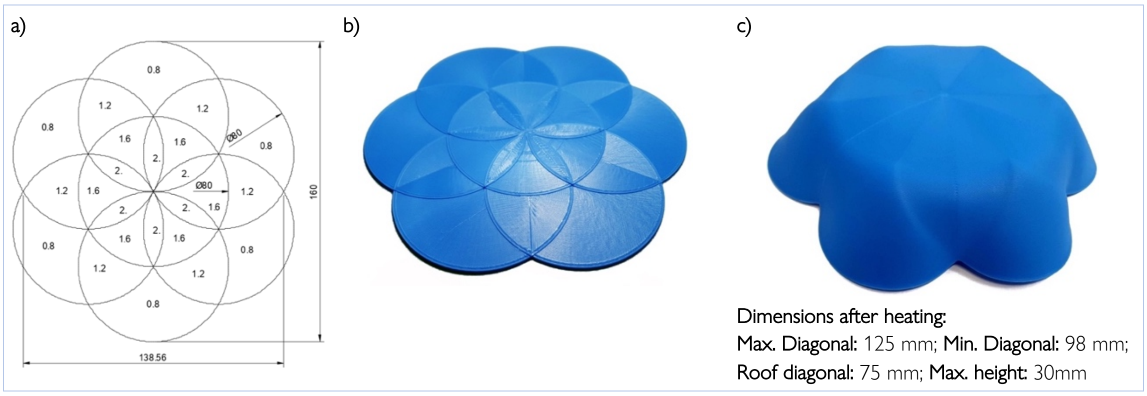



Figure 115 - Sample with overlapping of circular geometries resembling an igloo shape. **a)** Sample dimensions with variable thickness from 0,8 mm to 2 mm; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**
In this phase of the case study, it was better understood that, besides a controlled warping, the area with more thickness (1,6 mm and 2 mm) remained flat while the areas with less thickness (0,8 mm and 1,2 mm) shrink towards to the stiffer zone or, in this case (Figure 115), towards the core of the piece.

## ASSAY PLA 11

**Material:** PLA filament;
**Tools:** 3D printer – BQ Prusa i3 Hephestos and thermal chamber;

**Description:**
Once again, to prove the applicability of this process to the shelter development, some cuts were made in the previous model (Figure 116a) and then printed (Figure 116b) and heated to compare the dimensions of both structures. However, the warping process was different.

ASSAY PLA 11

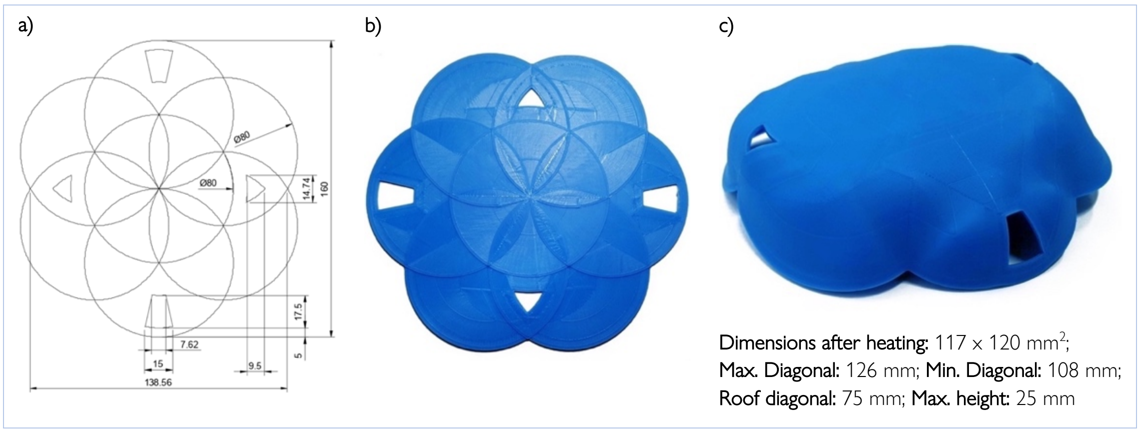



Figure 116 - Sample replicated from Figure 115, with openings for doors and windows. **a)** Sample dimensions with variable thickness from 0,8 mm to 2 mm; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**
The warping process occurred differently from the previous assay (10), maybe due to the openings that consequently modify the deposition of the material (Figure 116b)), influencing directly the shrinkage of the structure and reaching less height than the previous sample tested. Despite that, the result obtained (Figure 116c)) was positive, meeting the concept that was intended to achieve, such as a dome shape.

After these assays were made, an opportunity for using the printers from LDPS at FEUP emerged. Making it possible to increase the scale of the samples due to the two sizes of 200m$^2$ and 300m$^2$ available to print, using an *Alpha 8 printer* and a *Creality CR-10* printer.

## ASSAY PLA 12

**Material:** PLA filament;
**Tools:** 3D printer – Alpha 8 printer and thermal chamber;

**Description:**
To confirm that the process would have the same behavior in these printers, the previous two tests (Figure 115 and Figure 116) were repeated, using the same STL model and printing parameters.

ASSAY PLA 12

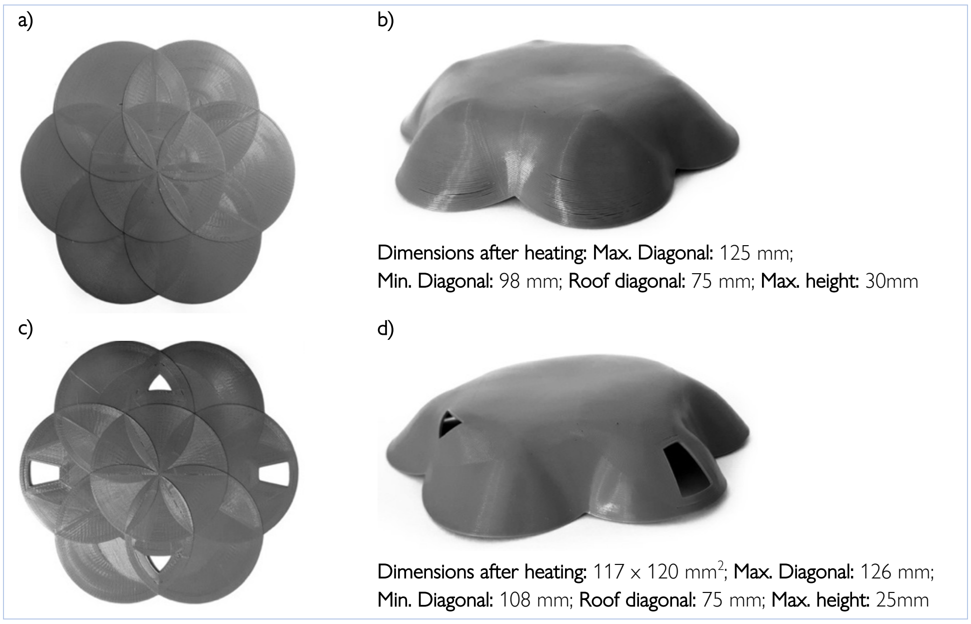



Figure 117 - Reprinting of the samples demonstrated in Figure 115 and Figure 116. **a)** and **c)** Samples after printing; **b)** and **d)** Samples after heating at 95°C and respective dimensions.

### Conclusion / Improvements:

After printing, they were heated and, as shown in Figure 117b) and d), the warping process occurred the same way achieving the same results as the assays 10 and 11.

## ASSAY PLA 13

**Material:** PLA filament;
**Tools:** 3D printer – Creality CR-10 and thermal chamber;

### Description:

Verified that the process was valid for different printers, using the same printing parameters, it was increased the size of the piece and its thickness proportionally, as represented in this assay (Figure 118a)). The piece was also heated at 95°C during 3 minutes (Figure 118b)) and the dimensions revealed shrinkage in approximately 20% to 23%, almost around the same shrinkage as the respective scaled sample tested previously (Figure 115).

ASSAY PLA 13

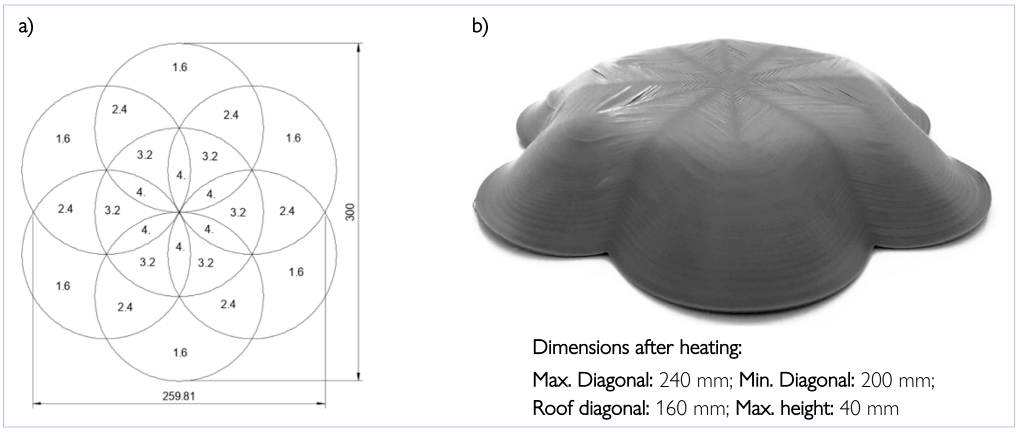



Figure 118 - Redesigned sample with increase of dimensions and thickness proportionally from Figure 115. **a)** Dimensions and thickness for printing; **b)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**

This test was fundamental to understand that the process is valid for large-scale-printing, as long as the dimensions and thicknesses are increased proportionally, and the printing parameters are the same, as defined in Table 15.

Despite the geometric shape reached meeting what was desired, the height at a proportional scale did not reach the 2 meters required for a standard basic shelter. Given this, it was tried to achieve a bigger height in the structure after heating, with the development of a new set of tests based on the circular geometry presented in Figure 115, varying the core diameter as well as the arcs that connect the core to the perimeter of the structure. Three assays, using approximately 200 mm diameter, were made in the process of achieving bigger height.

## ASSAY PLA 14

**Material:** PLA filament;
**Tools:** 3D printer – Alpha 8 printer and thermal chamber;

**Description:**

In this sample it was applied the same geometry as Figure 115, but with a smaller core diameter (60 mm), as specified in Figure 119a).

ASSAY PLA 14

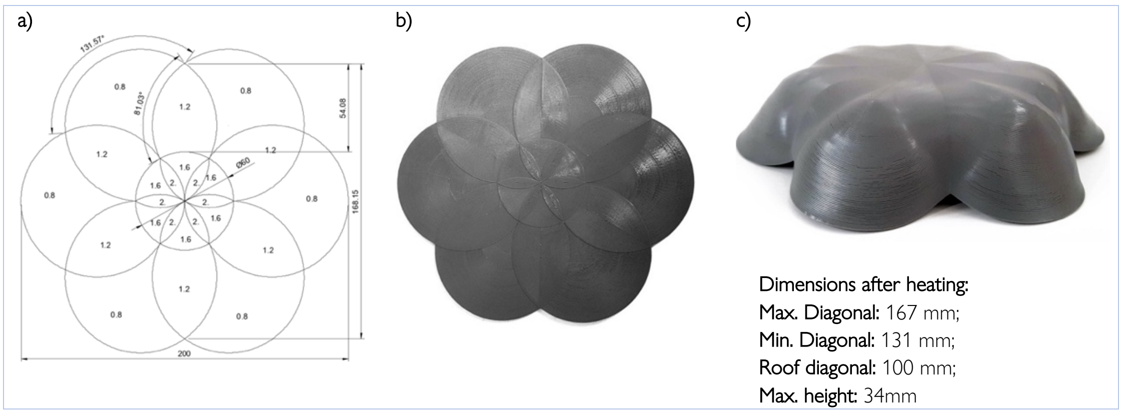



Figure 119 - Replicated sample with smaller core diagonal. **a)** Sample dimensions with variable thickness from 0,8mm to 2mm; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**

The dimension after heating warped in approximately 17% to 22%, thus reaching to a height of 34 mm. A controlled shrinkage occurred, yet the height was small compared to proportionally scaled dimensions. So, it was understood that the core diameter did not influence directly the height.

## ASSAY PLA 15

**Material:** PLA filament;
**Tools:** 3D printer – Alpha 8 printer and thermal chamber;

**Description:**

Perceived from the previous test (Assay 14) that the core did not influence much the height, but the roof diagonal, other changes were made in the geometry. As detailed in Figure 120a), the arcs with 1,2 mm thickness were increased in length and amplified the angles, making the minor diagonals closer to the major ones.

ASSAY PLA 15

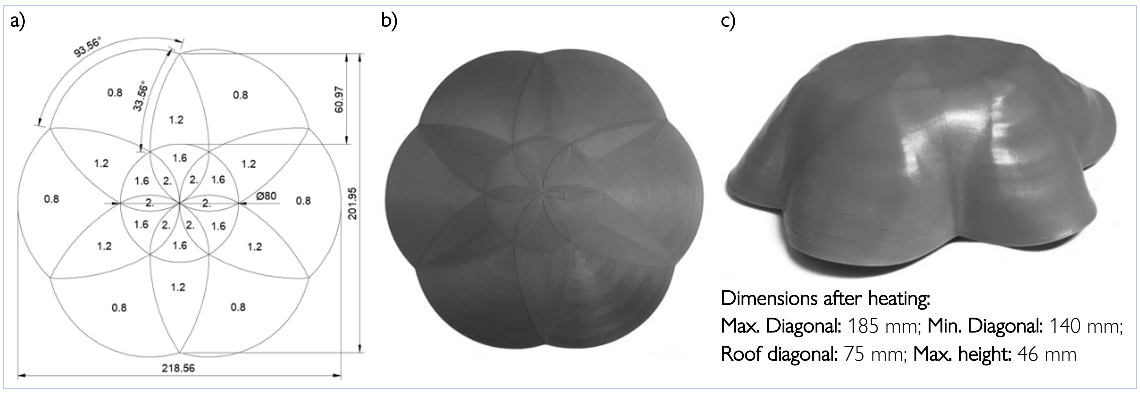



Figure 120 - Replicated sample with longer length arcs (represented by thickness 1.2 mm). **a)** Sample dimensions with variable thickness from 0,8 mm to 2 mm; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**

This changes in geometry resulted in a bigger height (46 mm) and minor roof diagonal after heating (Figure 120c)). However, the height should be bigger, and it was thought that it could be possible maybe from a combination of this and the previous assay (14).

## ASSAY PLA 16

**Material:** PLA filament;

**Tools:** 3D printer – Alpha 8 printer and thermal chamber;

**Description:**

Regarding the previous two tests conclusions, it was studied a combination of both samples. A geometry where the core diameter was minor and the arcs connecting to the major perimeter were increased in length, as sketched in Figure 121a).

ASSAY PLA 16

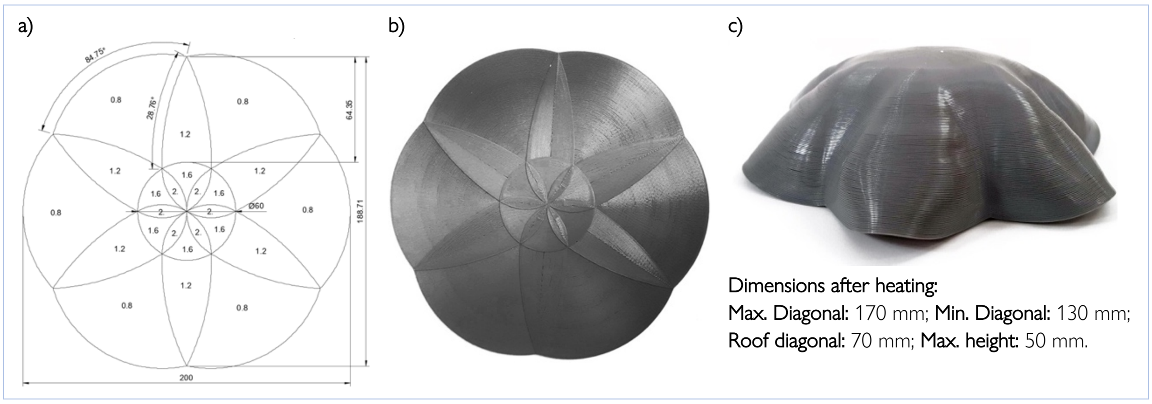



Figure 121 - Replicated sample with longer length arcs (represented by thickness 1.2 mm) and less core diameter (60mm). **a)** Sample dimensions with variable thickness from 0,8 mm to 2 mm; **b)** Sample after printing; **c)** Sample after heating at 95°C and respective dimensions.

**Conclusion / Improvements:**

Repeating the process for assembling the structure, the printed sample (Figure 121b)) after submitted to 95°C (Figure 121c)), reached the intended height of 50 mm, the exact 2 meters height if we scaled the sample at 1:40. Proving to be the better sample with proportionally scaled dimensions at 1:40, representing a kind of igloo shelter with approximately 21m$^2$ area.

Overall the 3D printing of predesigned geometries with PLA, through the overlapping of circular shapes and variation of thickness, proved to be a valid and advantageous process in assembling structures from flat to 3D. An innovative process, that when used, could accelerate the production rate and also ease the transportation of volumetric structures, by transporting them flat and then assembling on site.

Despite that, scaling the process to real dimensions of a shelter would imply the transportation of at least 4m$^2$ plates, thus being a challenge for the transportation of an emergency shelter that should respect the pallet dimensions for shipping. A way to overcome this challenge would be to fold the structure after printing. However, PLA printed objects do not have that ability. Given that, SMP filament, presented in the state of art, was studied in the next section 3.3.3. A filament that offers major benefits compared to PLA and other conventional filaments after printing.

### 3.3.3. 3D printing of SMP filament

SMP material offers several possibilities in the development of flexible solutions, in terms of design as well as compact and assembling properties. The fabrication of SMP filament for use in 3D hobbyist printers, demonstrated by Yang et al. (2015), had also proven to be an advantage in the development of products that could change its properties with heat.

Given that, it was analyzed the possibility of buying such filament to test and use in the development of the product presented in this dissertation. It was found that (SMPTechnologies) fabricated SMP filament and in order to obtain more information about the filament as well as price and delivery to Portugal, an email was sent. The information gather is detailed in the next section 3.3.3.1.

After evaluating the information of SMP filament, its properties and possibilities, as well as the price, it was considered advantageous, not just for the development of this dissertation, but also for other projects that could be further developed by FEUP. Therefore, the filament was ordered, so that tests could be made and also the prototypes for the final product would be developed.

#### 3.3.3.1. SMP filament technical information

By contacting the manufacture of SMP filament, we had the following possible option for buying this filament (Table 16). In both options, the filament shipping delivery time was one to two weeks. Since the major cost was shipping fee, it was chosen to buy more quantity of rolls, ordering 5 rolls, with a total cost of USD 771.00 (approximately 688,28€).

Table 16 - Cost options for ordering SMP filament

| | Option 1 (5 rolls) | Option 2 (1roll) |
|---|---|---|
| Price | USD 395.00 (352,62€) | USD 158.00 (141,05€) |
| USP Shipping fee | USD 376.00 (335,66€) | USD 200.00 (178,54€) |
| Total | USD 771.00 (688,28€) | USD 358.00 (319,59€) |

Besides the price options for ordering the filament rolls, (SMPTechnologies) had also provided the technical information for printing SMP, detailed in Table 17. Parameters that could be applied in the 3D printers at FEUP, thus being used in the specification of the parameters detailed in the next section, the calibration test.

Table 17 - SMP technical information for printing

| | |
|---|---|
| Material | SMP |
| Length (per roll) | 100m |
| Color | Transparent |
| Diameter | 1,75 mm ± 0,1 mm |
| Printing Temperature | 195°C - 210°C |
| Glass transition temperature (Tg) | 55°C |
| Table temperature | Not use |

### 3.3.3.2. Calibration test and printing parameters

In this phase, it was studied the technical information provided from (SMPTechnologies), as well as the printing process and parameters used by Yang et al. (2015), presented previously in the state of art (Figure 59), to prove the 4D printing process.

From this analysis, the parameters for printing the SMP pieces were defined (Table 18) and a simple cylindrical shape was tested (Figure 123), for calibration of the parameters used in the following tests of shapes studied. This and the other following samples tested in this section were printed in an *Alpha 8 printer* (Figure 122) and the respective g-code was generated in *Simplify3D*.

Table 18 - Parameters used to generate the g-code for printing the SMP pieces

| Print setup parameters for *Alpha 8* printer (g-code generated in *Simplify3D*) | |
|---|---|
| Layer Height | 0.24 mm |
| Infill and Shell Pattern | Rectilinear |
| Printing Temperature | 200°C |
| Infill | 0% |
| Flow | 100% |
| Print Speed | 80 mm/s |
| Build Plate Adhesion | 45°C |
| Nozzle | 0,4 mm |
| Fan speed | 20% |

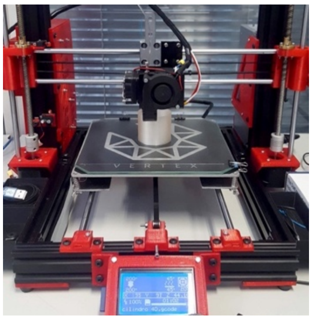


Figure 122 - Alpha 8 printer from LDPS at FEUP

Using these parameters (Table 18), a cylindrical shape of 50 mm by 50 mm and 2 mm thickness was printed (Figure 123a)). Then, to prove the shape memory effect of the material, the sample was heated in hot water (Figure 123b)), and pressed right after removing from the water (Figure 123c)), achieving a temporary rigid state at room temperature. After the sample was cooled, it was heated again (Figure 123d)) to restore its original shape. However, this first sample did not restore the original shape completely (Figure 123f)), maybe due to the uncontrolled temperature of heating, that consequently made the walls of the sample stick to each other in one point when pressed, or due to the thickness used compared to the size of the sample, that made it difficult to press it.

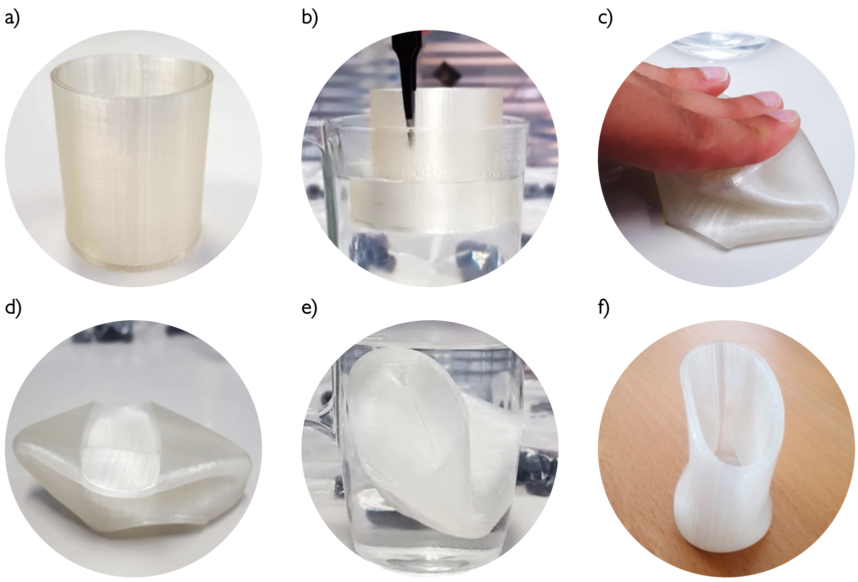


Figure 123 - First test of a 3D printed sample using SMP filament, from the process of deformation to recovery of shape. **a)** Cylindrical shape printed with 50 mm length and 2mm thickness; **b)** Heating the sample in hot water; **c)** Pressing the shape; **d)** Temporary rigid state, folded sample; **e)** Recovery of the shape through the immersion in hot water; **f)** Semi restored shape.

This test was essential to define the parameters, mainly the thickness used in the following samples tested. Finding that the thickness was too much, when compared to proportional dimensions used in this first sample tested, it was defined that for dimensions less than 100x100x100 $mm^3$, the thickness should be less than 1 mm.

Regarding this, two methods were defined for testing the next samples, the vase method and two-perimeter thickness. In the vase method, the infill was 0% and it printed only one perimeter, that is approximately 0,48 mm thickness. The other method was the two-perimeter thickness, that is translated in approximately 1mm thickness, using also 0% infill.

#### 3.3.3.3. Study of shapes and the process of deformation and recovery

Bearing in mind the parameters defined in the previous section, a study of shapes that would facilitate the folding process after heating, was made. The shapes designed were inspired by origami structures, tensegrity structures, dome structures and deployable structures, concepts also described in the state of art, as flexible in terms of volume reduction for transportation.

Besides the folding characteristic, it was also considered that the angles of the walls in the designed structures should be less than 45° to 55°, due to the fact that bigger angles would need support structures for printing.

For the development of the following structures, the dimensions were carefully thought to correspond at scale to a structure with 4 m diameter and at least 2 m height. Assuming this, a semispherical shape with the desired dimensions for the shelter development was designed, at scale (Figure 124), with dimensions of 100 mm diameter by 64 mm height and 1 mm thickness.

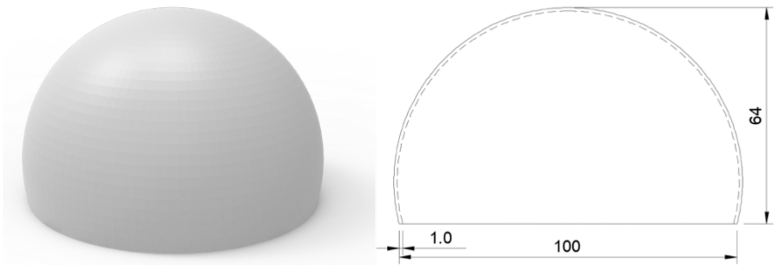



Figure 124 - 3D model and dimension (mm) of the semi-spherical sample printed.

## ASSAY SMP 1

**Material:** SMP filament;
**Tools:** 3D printer – Alpha 8 printer and hot water (55°C);

**Description:**
The 3D model (Figure 124) was printed using the method described in the calibration as the two-perimeters, corresponding to 1 mm thickness of the printed structure (Figure 125a)). To test the sample within the shape memory effect process, it was prepared a container with hot water, at temperature between 55°C and 65°C (Figure 125b)). Then, the sample was heated (Figure 125c)) and folded into a temporary rigid state at room ambient (Figure 125d)). After cooled, the sample was heated again (Figure 125e)) and restored its original shape as intended (Figure 125f)).

ASSAY SMP 1

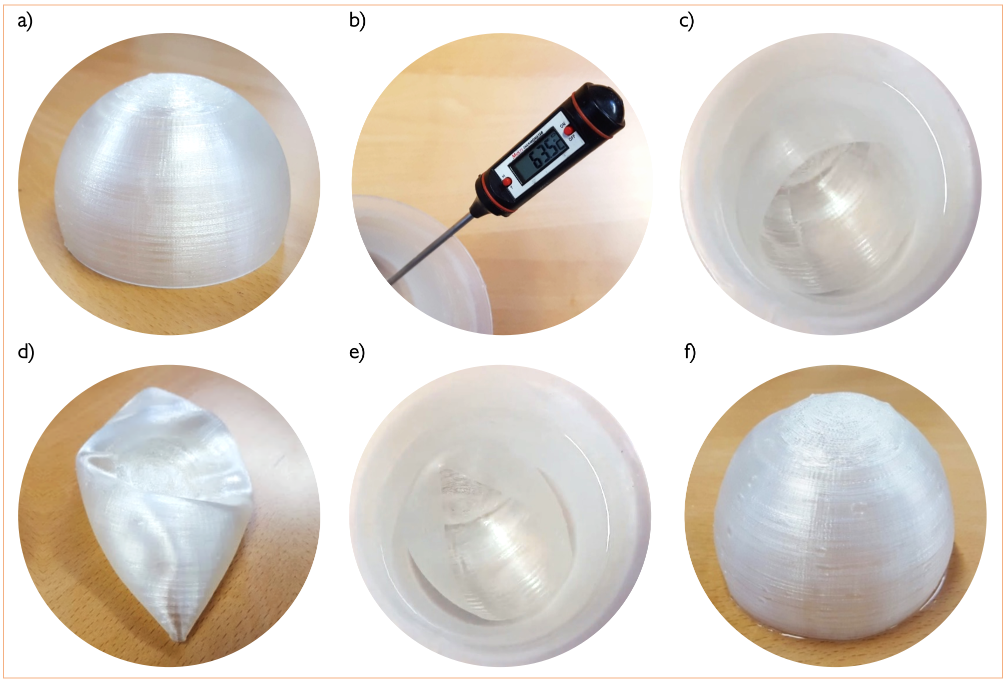



Figure 125 - Process of deformation and recovery of the sample printed from the 3D model of Figure 124.
**a)** Printed sample with 1 mm thickness; **b)** Temperature control; **c)** Heating the sample to fold; **d)** Folded sample at a rigid temporary state; **e)** Heating the folded sample to restore its original shape; **f)** Restored shape.

**Conclusion / Improvements:**

With this sample, it was proved the concept of SME, intended for the development of the product in this dissertation, where a structure can be folded into a temporary shape and then restore its shape when heated on site. However, the folding process needed to be better studied to fold the structure easily and as much smaller as possible.

Given this, the following model (Figure 126) was designed, using triangular shapes in different oblique angles, between 20° to 40°. A dome inspired structure with 100 mm width by 68 mm length, dimensions that at proportional scale would correspond to a real width of 4 m.

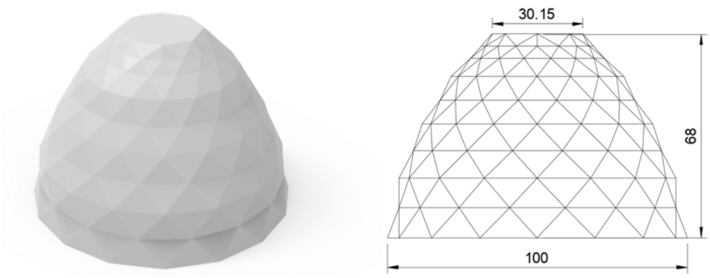



Figure 126 - 3D model and dimension (mm) of the sample printed.

This model was printed two times, using the two methods described in the calibration tests, the vase method and the two-perimeters method.

## ASSAY SMP 2

**Material:** SMP filament;
**Tools:** 3D printer – Alpha 8 printer and hot water (55°C);

**Description:**

This sample was printed using the vase method (Figure 127a)), corresponding to a thickness of 0,48 mm. Then, it was submitted to the process of folding into a temporary shape (Figure 127b)) and recovery to its original shape, but the recovery process failed (Figure 127c)).

ASSAY SMP 2

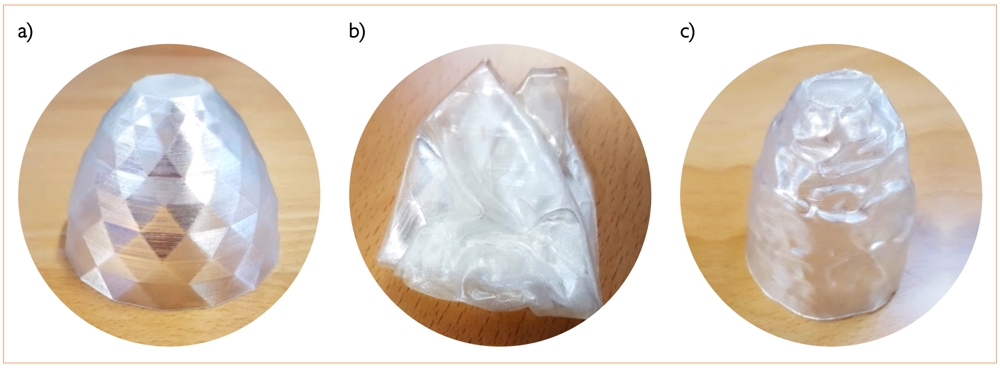



Figure 127 - Process of deformation and recovery of the sample printed from the 3D model of Figure 126. **a)** Printed sample using vase method (0,48 mm thickness); **b)** Temporary shape, folded after heated above 55°C; **c)** Semi restored shape.

**Conclusion / Improvements:**

It was found that this sample did not restore completely maybe due to the low thickness, thus making the sample stick in some points and making it impossible to restore the wall geometry.

## ASSAY SMP 3

**Material:** SMP filament;
**Tools:** 3D printer – Alpha 8 printer and hot water (55°C);

**Description:**

Observing that the vase method was too thin, which made it difficult to restore the original shape, it was printed the same model using two-perimeters (1mm thickness) (Figure 128a)). The model was tested under controlled temperature (Figure 128b)), within the same process as the previous tests. However, in opposition to the last sample tested with this model (Figure 127), this sample restored completely from the temporary shape (Figure 128d)) to its original shape (Figure 128f)).

ASSAY SMP 3

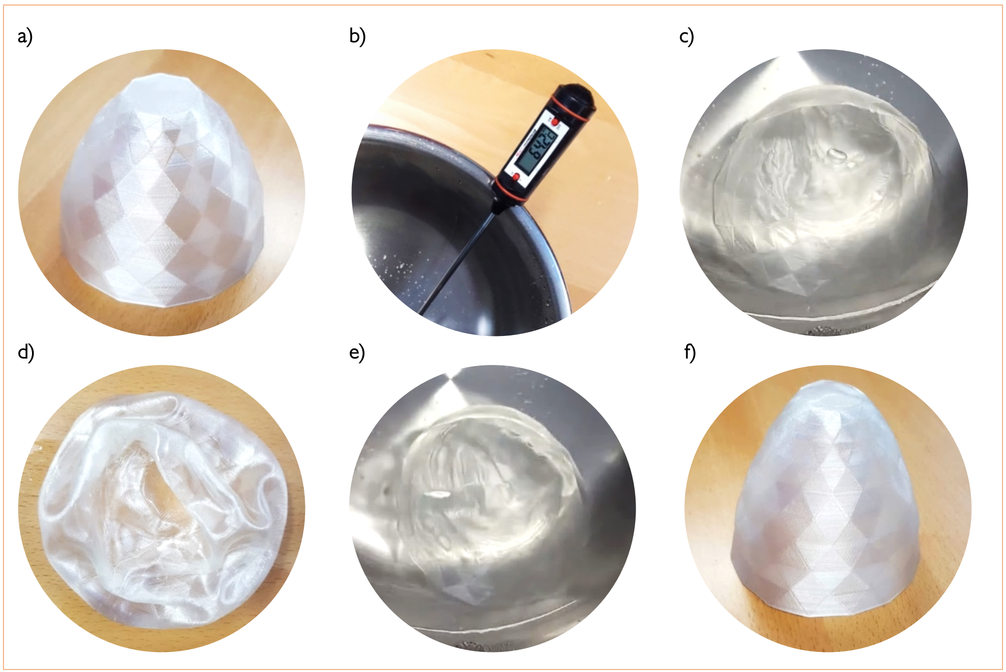



Figure 128 - Process of deformation and recovery of the sample printed from the 3D model of Figure 126. **a)** Printed sample with 1 mm thickness; **b)** Temperature control; **c)** Heating the sample to press; **d)** Pressed sample at a rigid temporary state; **e)** Heating the pressed sample to restore its original shape; **f)** Restored shape.

**Conclusion / Improvements:**

Comparing the results from both samples printed with different thickness, it was established that the 1 mm thickness should be the standard thickness used for samples with less than 100 mm width, as it has shown better results, not only in this model, but also in the semispherical sample tested before (Figure 125), restoring always its original shape after deformation.

## ASSAY SMP 4

**Material:** SMP filament;
**Tools:** 3D printer – Alpha 8 printer and hot water (55°C);

**Description:**

Since the process of deformation and recovery of shape can be repeated as many times as desired, the same sample, from assay 3, was reheated and folded into another temporary shape (Figure 129a)). When the temporary shape was cooled, the process was repeated, heating again the sample (Figure 129b)), and the original shape was successfully restored (Figure 129c)).

ASSAY SMP 4

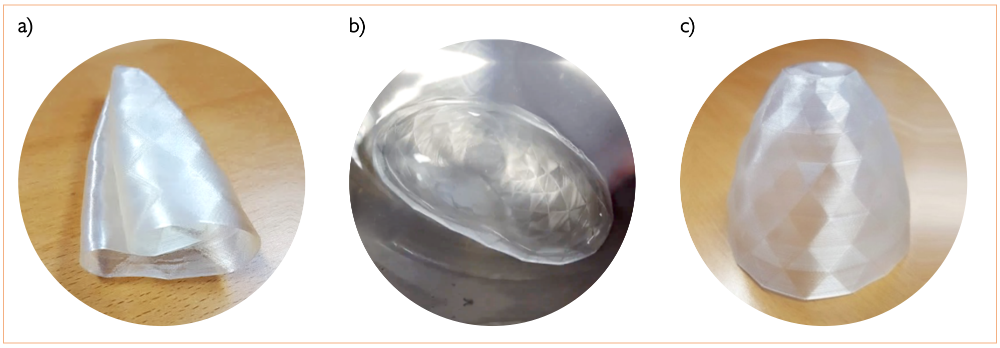



Figure 129 - Repeating the process described in assay 3 Figure 128, folding the sample instead of squeezing it. **a)** Folded sample after heated, rigid temporary state; **b)** Recovery of the sample through the immersion in hot water (above55°C); **c)** Recovery sample to its original state.

**Conclusion / Improvements:**

The samples tested had successfully validated the concept of 4D printing and SME. However, for developing the final product the geometry of the structure needed to be better studied, in order to facilitate the folding process.

## ASSAYS SMP 5 and 6

**Material:** SMP filament;
**Tools:** 3D printer – Alpha 8 printer and hot water (55°C);

**Description:**

Considering that the process of SME was demonstrated, while developing the concept for the final product, it was tested this sample using the base design wanted for the structure of the emergency shelter. A model that was made from studied dimensions of the previous tests, with a hexagonal shape as ground and angled walls to simplify the folding process and also provide more living area when assembled. The dimensions from this model (Figure 130) were proportionally scaled from real dimensions, the width of 100 mm and the length of 65 mm are respectively equivalent to 4 m diameter and 2,6 m height.

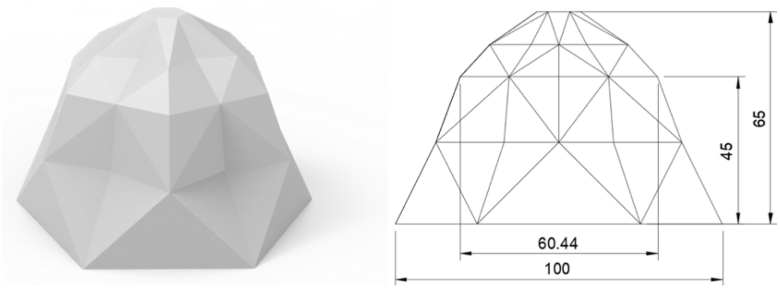



Figure 130 - 3D model and dimension (mm) of the sample from the product development progress.

The model was printed (Figure 131a)) using 1 mm thickness and the parameters defined in Table 18, and through the same process as the previous ones it was heated and folded, assuming a temporary shape (Figure 131b)). The process was repeated, reheating the sample (Figure 131c)) and thus recovering its original shape (Figure 131d)).

ASSAY SMP 5

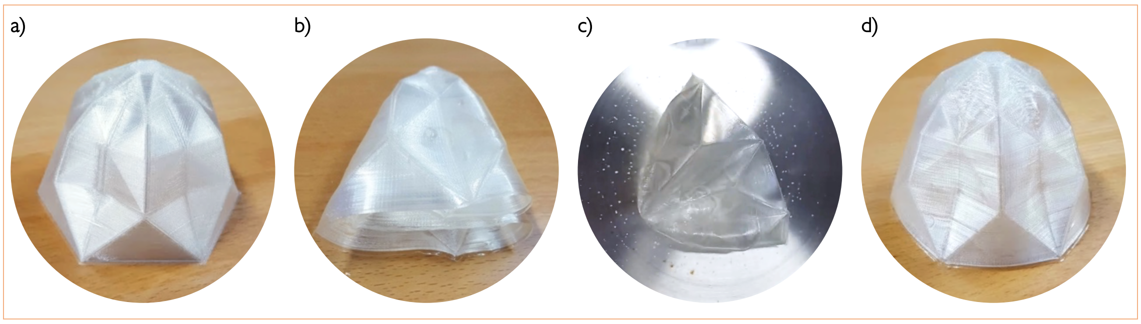



Figure 131 - Process of deformation and recovery of the sample printed from the 3D model of Figure 130 **a)** Printed sample with 1 mm thickness; **b)** Folded sample at a rigid temporary state; **c)** Heating the folded sample to restore its original shape; **d)** Restored shape.

Since the purpose of using this process is to fold the structure to transport and assembled on site, the folding process was repeated in this sample, in order to fold as much as possible. As shown in Figure 132a), the sample was fold using a PTFE sheet, to assure that the walls would not stick when folding and pressing the structure. The folded structure achieved the dimensions of 50 mm by 65 mm, and 20 mm thickness, thus reducing significantly its volume for transportation (in scale). The process of recovery had also shown to be successful (Figure 132b)), even with more folds compared to previous tests.

ASSAY SMP 6


Figure 132 - Repeating the process described in Figure 131, using a PTFE sheet to assure more folds without sticking the object walls. **a)** Folded sample after heated, rigid temporary state; Dimensions of the folded structure: 50 x 65 x 20 $mm^3$ **b)** Restored sample to its original state.

**Conclusion / Improvements:**

The sample tested two times, in assay 5 and 6, restored completely its original shape, demonstrating that the structure can be reused several times. For the development of the product, this structure was successfully validated, and its progress is sustained in the next section 3.4.

## ASSAY SMP 7

**Material:** SMP filament;

**Tools:** 3D printer – Alpha 8 printer and hot water (55°C);

**Description:** Besides the immersion tests in hot water, used in the previous experiments, it was made an assay with running water (55°C~65°C) to prove that the folding and recovery process would be successfully accomplished. This was validated with the following experiments (Figure 133).

ASSAY SMP 7

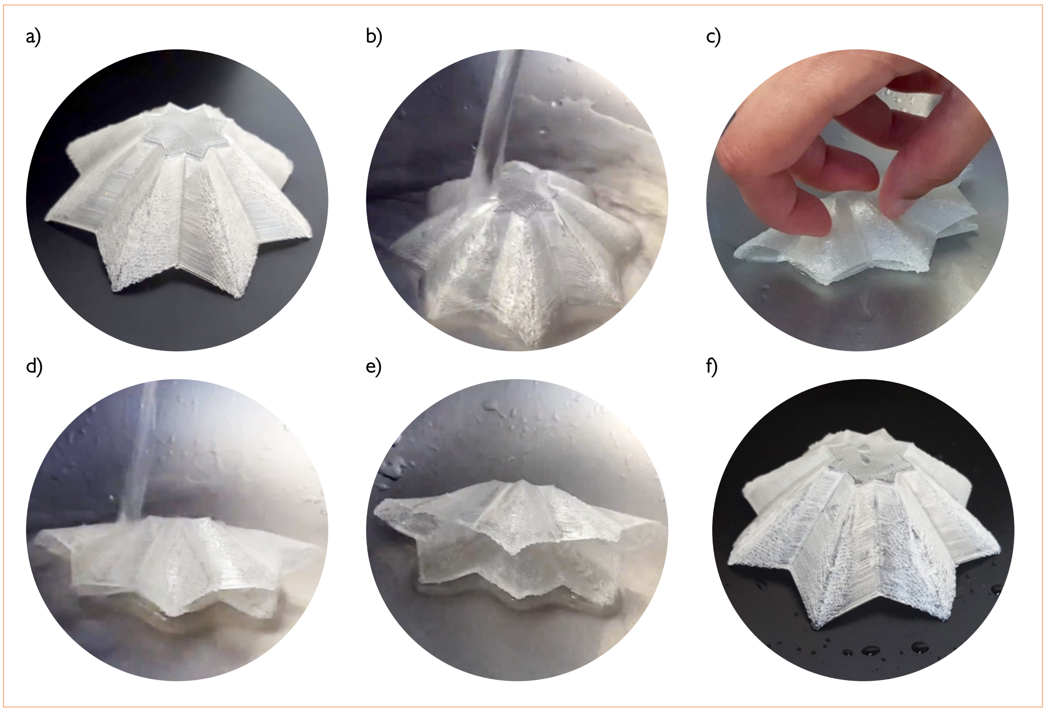



Figure 133 - Deformation and recovery of a sample with running hot water. **a)** Sample printed; **b)** Sample wet with hot water; **c)** Folding the sample to a temporary shape; **d)** Sample wet again with hot water; **e)** Recovery of shape; **f)** Sample completely restored to its original shape (a).

**Conclusion:**

This assay proved that not only the process of SME can occur with the immersion of the sample, but also with running hot water, thus proving also that in large scale the structures can be assembled with just spilling hot water in the sample, not needing to immerse the whole structure.

## 3.4. Product development

The presented assays were made in parallel to the development of the product, a concept for a structural and cover solution that could be provided as a first emergency shelter. However, thermic and acoustic insulation could not be fully guaranteed since the material mechanical and physical characteristics do not provide that, needing to be improved.

The concept emerged from sketches considering several ideas and geometries, being developed according to imposed requirements. Throughout the experimental process, the concept had evolved leading to the final product presented in this chapter.

### 3.4.1. Shelter requirements

Summarized from section 2.1, the concept for the emergency shelter in this dissertation should be developed in order to attempt the following requirements:

- guarantee the minimum of 3.5 $m^2$ living space per person and at least 2 m height;
- if using tarpaulin, assure the use of standard size of 4 m by 6 m;
- make the shelter adapted to climate conditions and cultural/geographical context;
- if possible, use local skills and materials;
- always consider the lifetime, recyclability and sustainability of the material;
- support family shelter over common one, assuring privacy, safety and protection;
- provide assistance and material for IDPs to build on their own;

Considering these requirements, the development of the product presented is also based on humanitarian emergency basic shelters, such as the one prototyped at scale in the next section 3.4.2.6, using the relation between area and height as standard sizes for the concept developed. Given this, additional requirements were established:

- the developed shelter should be adaptable or modular in order to fit the sizes of the emergency kits currently distributed by the organizations;
- to facilitate the transportation either local, national or international, the packaged shelter or kit containing the shelter should fit the dimensions of the distribution pallets (120 × 110 $cm^2$);
- the chosen material should be tested and validated according to standards established by the humanitarian organizations in charge;
- if possible, the developed shelter or structure should weigh less than 50 kg and cost less than $300 (approximately 270€).

### 3.4.2. Development of the emergency shelter

The development of the emergency shelter was made in order to come up with a solution to replace the current tarpaulin and bamboo structures, like the ones from section 3.3.1 (Table 13). It was intended to develop an alternative to these structures, with a solution that could be both the structure and the cover, using technologies such as the ones demonstrated in the experiments of the previous section 3.3.3.3. Also, the developed structure was supposed to be included in the emergency kit, and for that the shelter was supposed to be foldable, using the 4D printing process, to be later assembled fast and easy on site. However, it is known that the developed structure will not be able to provide higher acoustic and insulation properties, due to the characteristic of the material.

#### 3.4.2.1. Concept

Besides the considered concepts from the state of art, a moodboard (Figure 134) of ideas from shelters, structures and geometric shapes was made, in order to inspire and guide the development of the final product. Concepts such as domes, tensegrity structures and origami structures were emphasized due to the easy assembly and folding capability.


Figure 134 - Moodboard of inspirational designs. (Images from: archdaily.com, cnet.com, modlar.com and designplaygrounds.com)

From the moodboard's inspiration, a concept was sketched, derived from a hexagonal based dome with studied wall angles to ease the folding process of the structure. Some sketches representative of the concept development are illustrated in Figure 135.

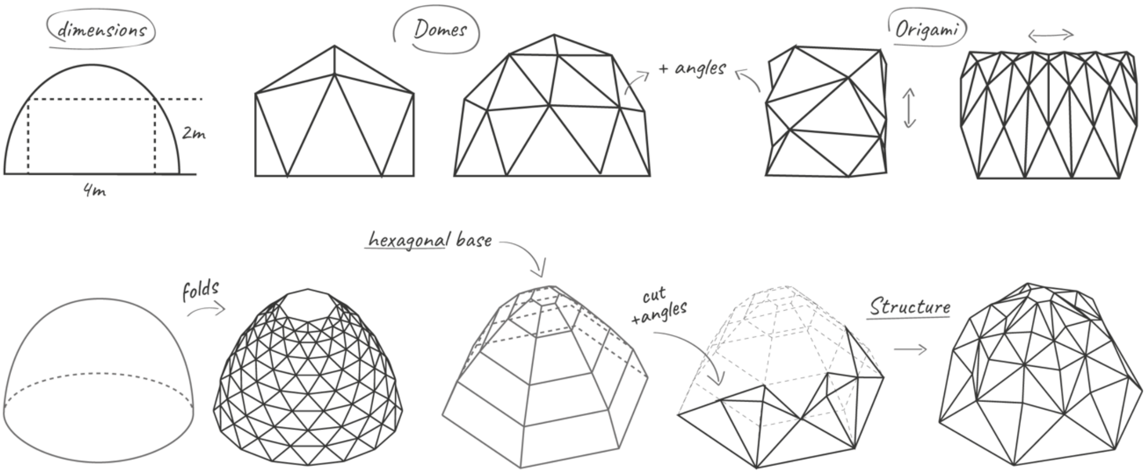



Figure 135 - Concept development sketches.

### 3.4.2.2. Structure development

The development of the structure was carefully dimensioned, in order to guarantee at least 10 $m^2$ of living area. To achieve the structure design in the concept development, a hexagonal shape with 2 m radius was sketched, being extruded and sliced with the studied angles, as demonstrated in the step by step construction of the 3D model (Figure 136). The final model achieved an area of approximately 10,4 $m^2$ and 2,6 m high, as detailed in the technical drawings of ANNEX A.

Step by step construction of the structure _ 3D model developed in *Fusion 360*

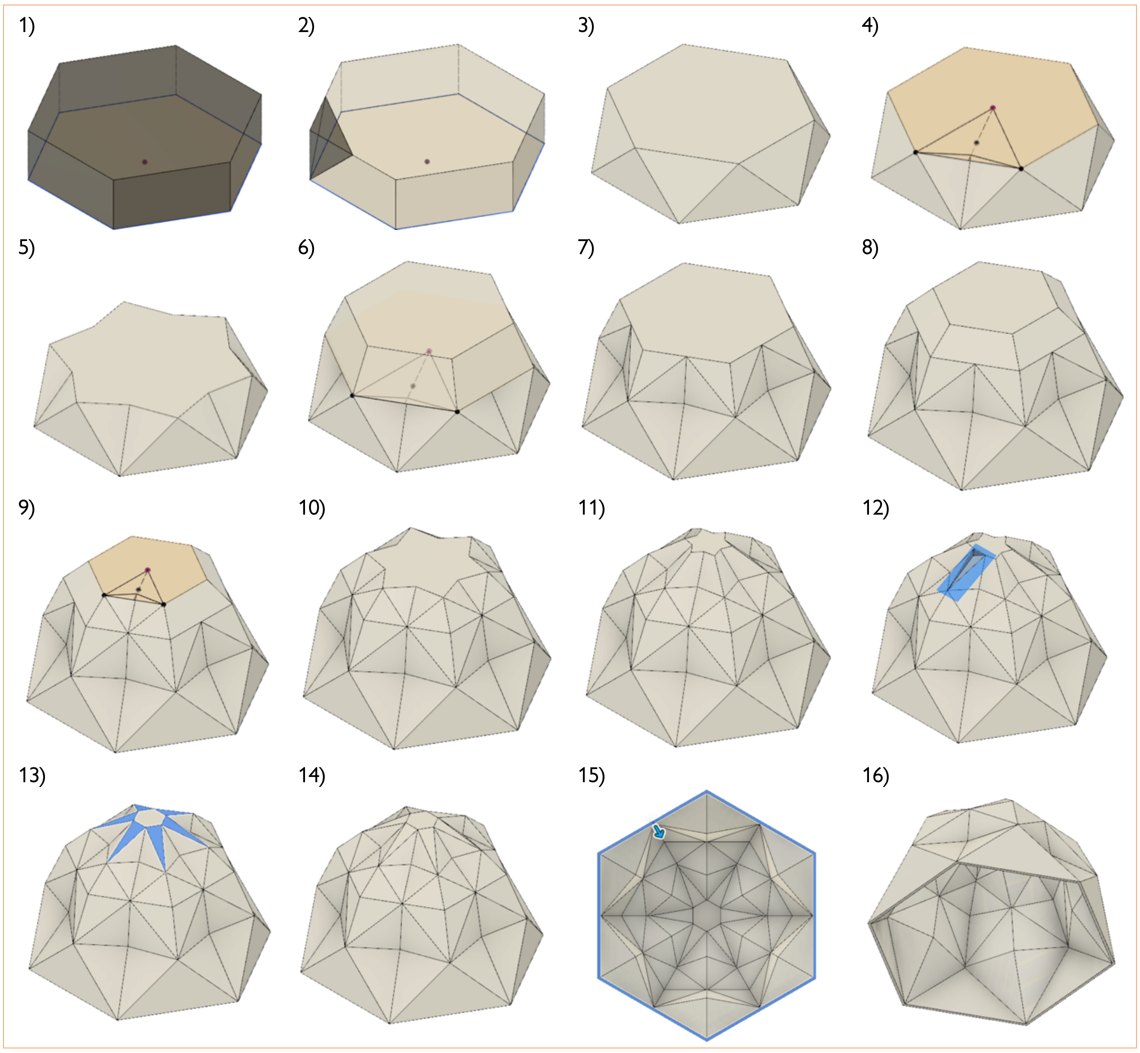



Figure 136 - Steps of the construction of the 3D model representative of the structure. **1)** Extruded an hexagon; **2)** Sliced the face from a plan interesting the middle points from two consecutive edges; **3)** Circular pattern, repeating step 2); **4)** Sketch and loft-cut the face; **5)** Circular pattern repeating the step 4); **6)** Extrude the top face; **7)** Loft-cut the face from the sketch made in 4) and circular pattern repeating the process; **8)** Extrude the top face; **9)** Sketch to loft-cut the face extruded; **10)** Circular pattern, repeating the step 9); **11)** Extrude the top face; **12)** Slice the face from a plan interesting the middle points from two consecutive edges of the top face; **13)** Circular pattern, repeating the previous process; **14)** Final component; **15)** Create a shell (4 mm) from the bottom face, creating thickness of the whole structure; **16)** Final component with 4 mm thickness.

While developing this concept it was considered also the requirements for FDM printing, such as the maximum angles a wall could be printed without the need for support structures. Given this, the structure wall angles should be smaller than 45° to 55° from vertical, as shown in Figure 137 this was estimated, despite the final angles exceeding a bit to close the structure.

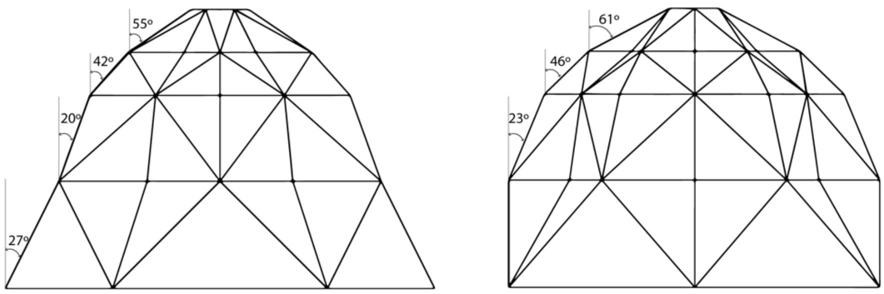



Figure 137 - Wall angles of the final structure.

Concluded the model of the structure and successfully tested at scale through the 4D printing process, as validated in the assay 5 and 6 (Figure 131 and Figure 132), it was idealized and modeled an opening for the door (Figure 138), extruded and cut from selected edges of the structure. In the final model, the door opening has a maximum height of 1,8 m and its dimensions are further detailed in ANNEX B.

Step by step construction of the door opening _ 3D model developed in *Fusion 360*

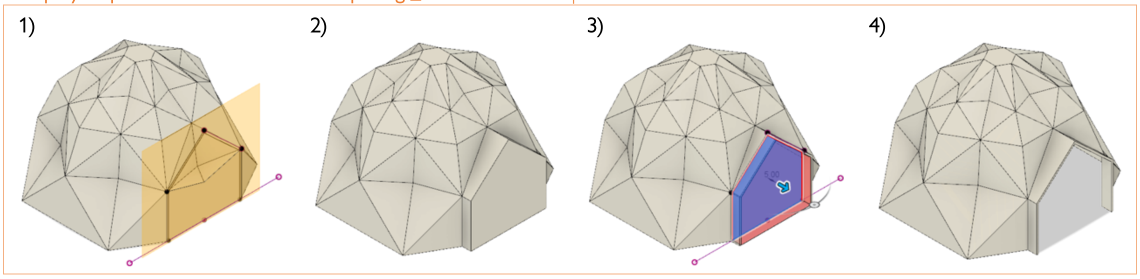



Figure 138 - Steps of the modeling of the door opening. **1)** Created a plan from two vertical edges, slicing the faces and created the door sketch; **2)** Extruded the door sketch; **3)** Extrude-cut the opening for the door with 4 mm thickness; **4)** Final model with the door opening.

### 3.4.2.3. Project

In this phase of the case study, the dimensions for the final concept of the shelter were defined and detailed in ANNEX B. This final model (Figure 139) was designed with a living area of approximately 10 $m^2$, providing shelter for 2 to 3 persons.

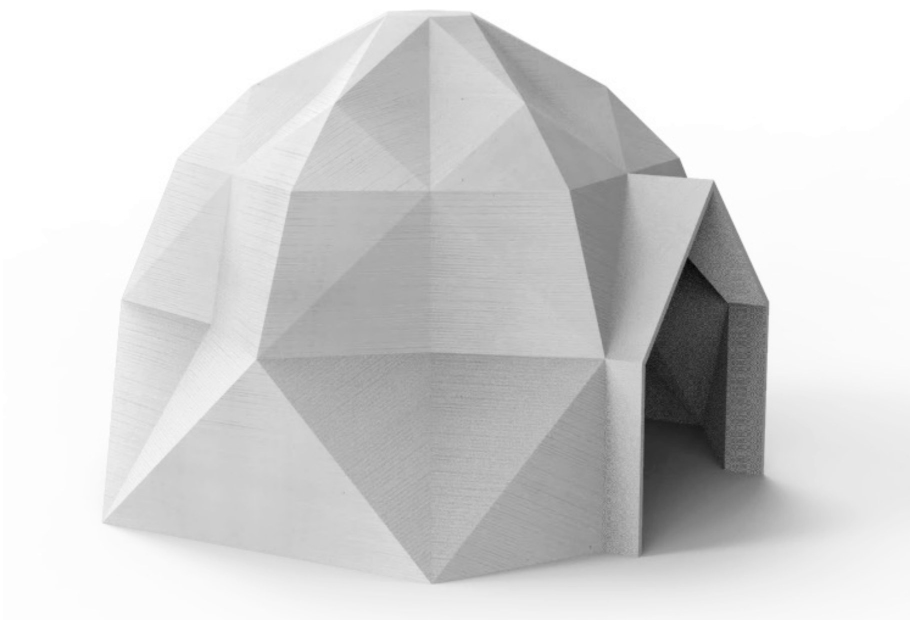


Figure 139 - Final model with door opening.

Besides this concept it was also idealized the possibility to be extensible and modular, with the combination of two shelters (Figure 140), achieving 20 $m^2$ of living space, thus sheltering bigger families up to 6 persons. For this concept it was designed a model with two openings in order to connect to the previous model, its dimensions are further detailed in ANNEX C.

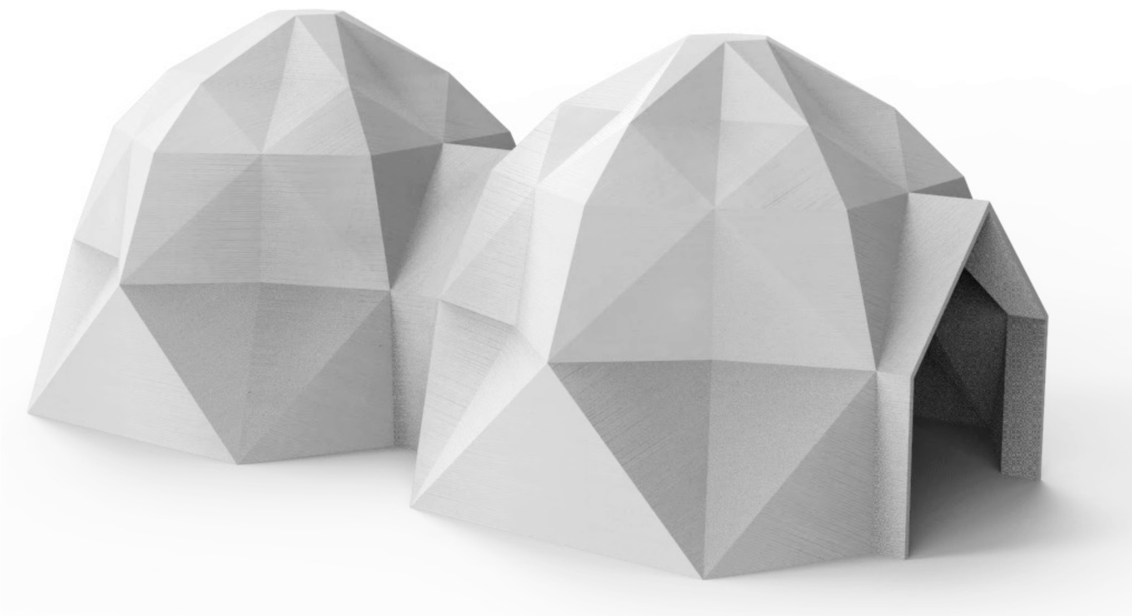


Figure 140 - Connection of two models.

Additionally, a door was conceptualized to be further included in the model (Figure 141), intended to be printed also with the same material and posteriorly connect to the rest of the structure on site.

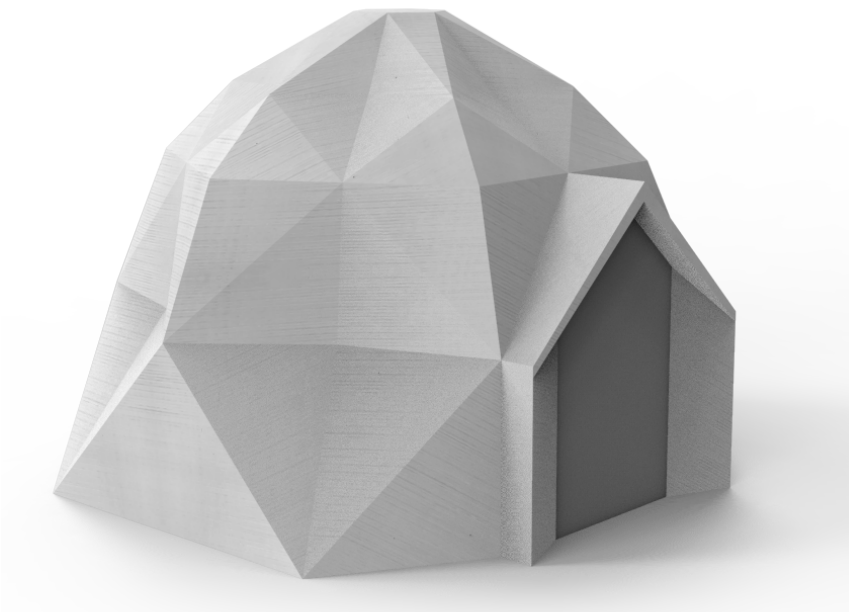


Figure 141 - Model with projected door.

To demonstrate the scale and application in real case scenarios, some renders, illustrative of these concepts were also developed (Figure 142, Figure 143 and Figure 144).

Figure 142 - Render of the shelters, simulating its application in a real case scenario. (Background image from: newsweek.com)

Figure 143 - Render of a set of shelters simulating its application. (Background image from: 680news.com, Photo: Jerome Delay)

Figure 144 - Render of a set of shelters, simulation of a refugee's camp. (Background image from: http://inthefray.org)

### 3.4.2.4. Selection of material

The SMP material was chosen mainly due to its SME property. However, it offers other beneficial characteristics, such as lightweight, low-cost and easy processing. These are advantageous properties for the development of the concept presented.

This concept was developed using SMP filament. However, in large-scale applications, it should be considered the FGF process, using SMP pellets (Figure 145) available from SMP Technologies, or even study the possibility of developing a composite material from an SMP matrix, in order to achieve considerable mechanical properties and a cost-effective solution. SMP pellets properties were previously shown in Table 11, where it is also detailed the cost per kg of SMP pellets, thus being cheaper than SMP filaments, USD 55,5 (approximately 49,31€), representing a significant decrease in costs for the final solution.

Figure 145 - SMP pellets (MM type) (SMPTechnologies 2018)

### 3.4.2.5. Development of the product

As described previously, the development of the product was made using FDM process with SMP filament. In order to validate the concept, two pieces from the designed model were printed (Figure 146) at scale, 1:40 and 1:20 respectively from the model detailed in ANNEX B. However, the thickness was not scaled proportionally, once the minimum dimension for 3D printing without compromising the sample was 1 mm, as demonstrated in the calibration process.

The printed models at scales 1:40 and 1:20 from the concept detailed in ANNEX B, were validated through the SME process in the next section 3.4.2.6. Yet, the list of material quantity, time and cost for the developed models are detailed in the following Table 19. The material quantity and manufacture time were simulated in the slicer software Simplify3D, and the cost was calculated from the price per roll detailed in Table 16.

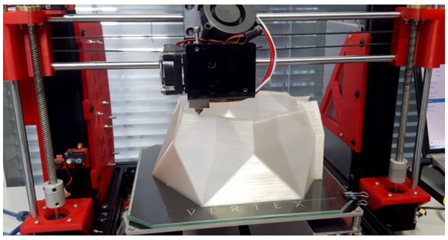


Figure 146 - 3D printing of the sample at scale 1:20.

Table 19 - List of material quantity, manufacture time and calculated cost in the development of the models, using SMP filament.

| | 100 mm model | 200 mm model |
|---|---|---|
| Material Quantity | 21,53g | 162,34 g |
| Manufacture Time | 1h38 | 7h26 |
| Cost* | ~USD 5,7 (5,10€) | ~USD 42,7 (38,25€) |

*calculated from option 1 price per 300g roll (~USD79), presented in Table 16, without shipping cost included. Simulated in *Simplify3D* software.

In order to estimate the weight and cost of the final product, it was also simulated in Table 20 the material quantity needed for real scale models assuming different thickness. The variation in thickness was made in order to find the one that provided the 50 kg maximum weight per piece, a requirement imposed in the previous section 3.4.1. The material quantity was calculated from the volume of the 3D Model, given by *Fusion 360* software, multiplying per density of the material (1,2 g/cm$^3$). From this simulation, it was observed that, if the defined thickness was 1.5 mm, it would weight approximately 45,78 kg and assume a final cost of approximately 10691€ per shelter.

Table 20 - Simulation of material quantities and costs for the real scale model, assuming different thickness.

| | Real scale model (4 mm thickness) | Real scale model (3 mm thickness) | Real scale model (2 mm thickness) | Real scale model (1,8 mm thickness) | Real scale model (1,5 mm thickness) |
|---|---|---|---|---|---|
| Volume* | 0,1016 m$^3$ | 0,07623 m$^3$ | 0,05085 m$^3$ | 0,04577 m$^3$ | 0,03815 m$^3$ |
| Material Quantity** | 121,9 kg | 91,4 kg | 61 kg | 54,9 kg | 45,8 kg |
| Cost*** | ~USD 32 059.7 (28 455,87€) | ~USD 24 038.2 (21 336,07€) | ~USD 16 043 (14 239,61€) | ~USD 14 438.7 (12 815,65€) | ~USD 12 045.4 (10 691,38€) |

*estimated volume given by *Fusion 360* software.
**volume x density (1200 kg/m$^3$)
***calculated from option 1 price per 300g roll (~USD79), equivalent to ~USD263 per kg. Shipping cost is not included.

However, this cost could be reduced when developing at industrial scale, more units, reducing consequently the cost of the material, that becomes cheaper when ordering more quantities. Or exploiting FGF method, using pellets (Table 21) instead of filament, reducing its cost to 2256€, a cost that can be also reduced when ordering bigger quantities of material.

Table 21 - Estimated cost calculated from material quantities, using SMP pellets.

| | 100 mm model | 200 mm model | Real scale model (1,5 mm thickness) |
|---|---|---|---|
| Material Quantity | 21,53g | 162,34 g | 45,8 kg |
| Cost* | ~USD 1,19 (1,06€) | ~USD 9 (8,01€) | ~USD 2541.9 (2256,17€) |

*calculated from price per kg (~USD 55,5), presented in Table 11, without shipping cost included.

Additionally, as illustrated in section 2.2, the investment in the AM process ( Figure 15) have been increasing exponentially over the last years. Given this, it is expected the evolution of materials and consequently the growth of manufacturers in the market, thus reducing significantly its costs. Hence, it looks like this solution is viable and with great potential to be implemented.

### 3.4.2.6. Validation of model

As described in the previous section, a model representative of the concept developed (Figure 139), detailed in ANNEX B, was 3D printed at two different scales (1:40 and 1:20) to be validated within the deformation and recovery process.

Validation of the model at scale 1:40

**Material:** SMP filament;
**Tools:** 3D printer – Alpha 8 printer and hot water (55°C);

**Description:**
The first model tested was the 1:40 scale, with 100 mm diameter (Figure 147). Submitted to the same process as the previous SMP assays, heated in water (Figure 147b)) and folded into a temporary shape (Figure 147c) and d)), assuming dimensions of 65x55x20 $mm^3$. After cooled, the sample was heated again (Figure 147e)) restoring its original shape (Figure 147f)).

Validation of the 100 mm diameter Model (scale 1:40 from real model detailed in ANNEX B)

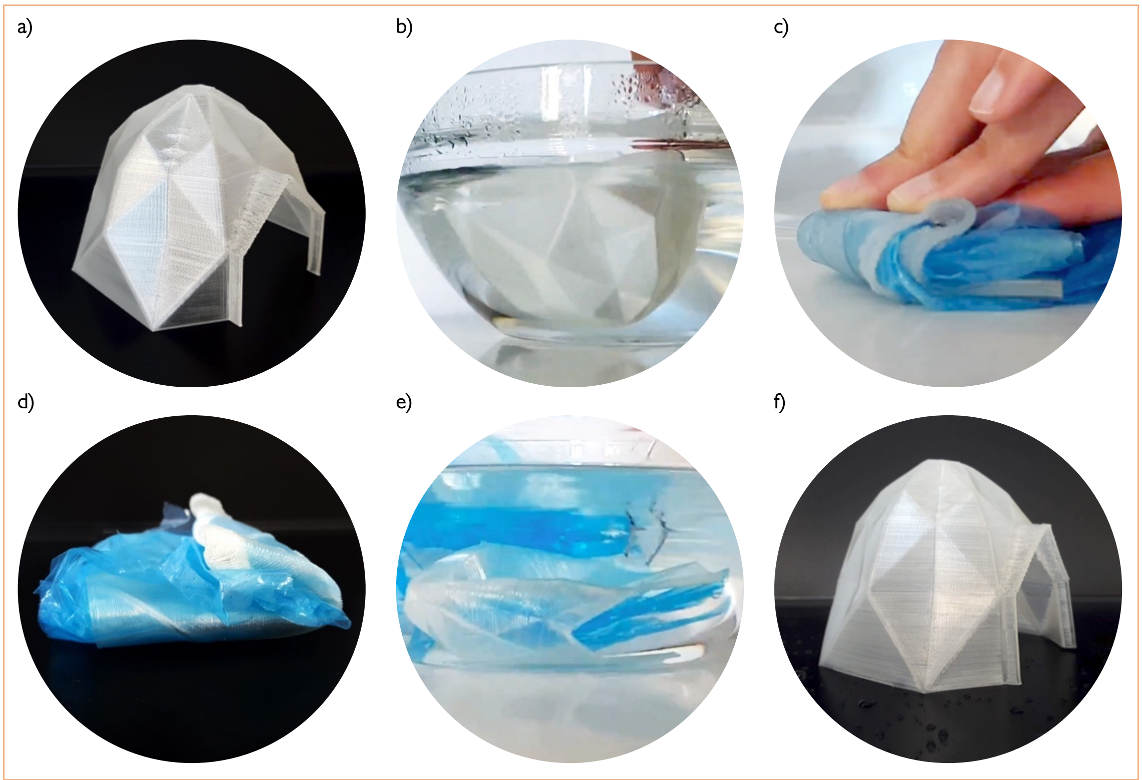



Figure 147 - Model at scale 1:40, tested within the deformation and recovery process. **a)** Printed sample; **b)** Sample heated in hot water (55°C); **c)** Folding the sample; **d)** Folded sample (dimensions of 65x55x20 $mm^3$); **e)** Process of recovery of shape in hot water (55°C); **f)** Restored sample.

**Conclusion / Improvements:**
The process of deformation and recovery of shape, as well as the concept of 4D printing, was successfully validated. The dimensions of the folded sample achieve at real size 2,6 m x 2,2 m x 0,8 m, thus reducing its dimensions for transportation. However, the dimensions should be much more reduced to fit the transportation pallets, in order to accomplish that, it should be increased the scale of the sample to be folded more times.

## Validation of the model at scale 1:20

**Material:** SMP filament;
**Tools:** 3D printer – Alpha 8 printer and hot water (55°C);

**Description:**
Aiming to better fold the structure, this sample was printed at scale 1:20 (Figure 148), assuming 200 mm diameter. After printing, the sample was tested under the same conditions as the previous assay.

Validation of the 200 mm diameter Model (scale 1:20 from real model detailed in ANNEX B)

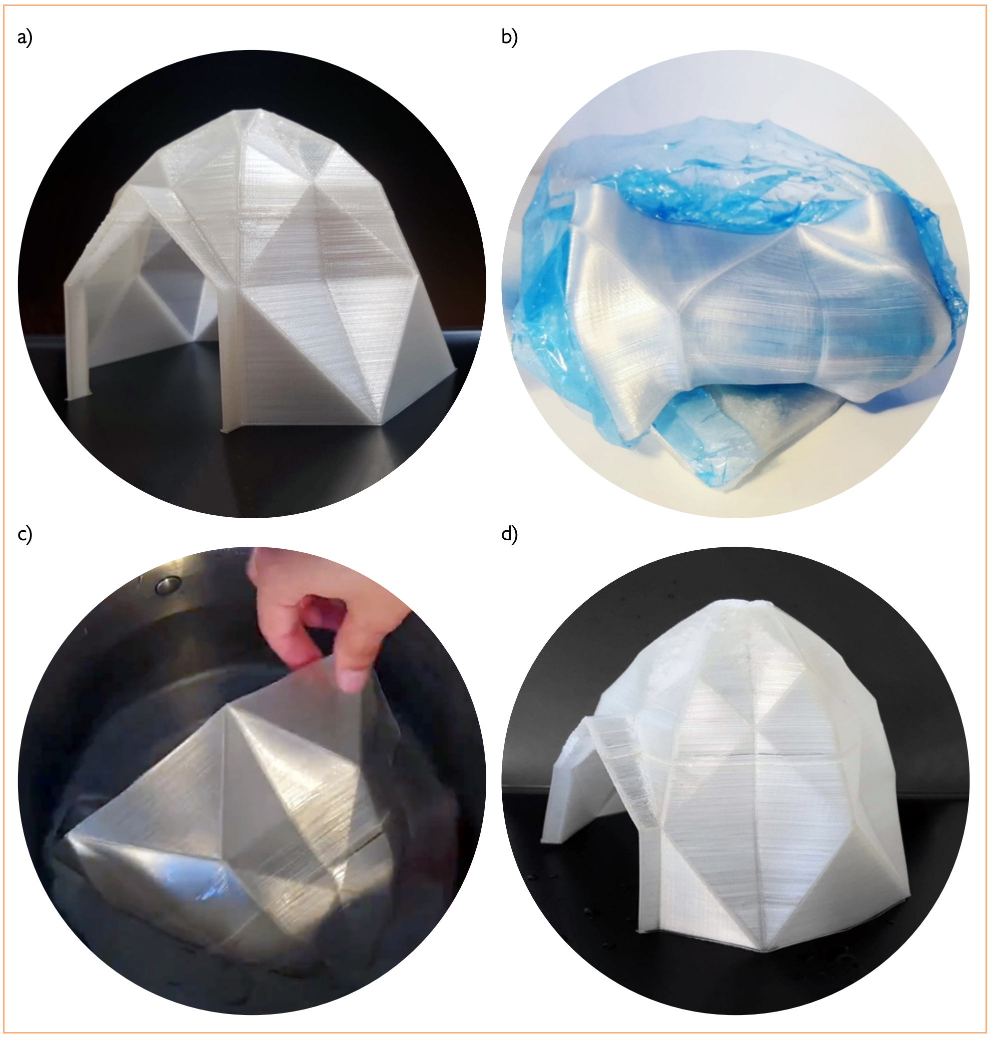



Figure 148 - Model at scale 1:20, tested within the deformation and recovery process. **a)** Printed sample; **b)** Folded sample (dimensions of 60 x 120 x 45 $mm^3$); **c)** Process of recovery of shape in hot water (55°C); **f)** Restored sample.

**Conclusion / Improvements:**
Once again the process of deformation (Figure 148b)) and recovery ((Figure 148c) and d)) was validated. The sample was much more folded, achieving the real sizes of 1,2 m x 2,4 m x 0,9 m, reducing significantly its dimensions for transport.

The validation of these two samples (Figure 147 and Figure 148) prove that with the increase of the size of the structure it could be better folded in smaller dimensions to fit correctly in the shipping pallets size.

### 3.4.2.7. Validation of requirements

Validated the developed concept within the 4D printing process, accomplished with the SMP material, it was also confirmed some of the requirements imposed in the development of this research. This validation is detailed in the following Table 22.

Table 22 - Validation of requirements imposed as well as how they were validated.

| Requirements | Validation | How it was validated |
|---|---|---|
| Minimum of 3.5 $m^2$ living space per person and at least 2m height. | ✓ | The developed shelter (Figure 139) provides a living area of approximately 10 $m^2$ and 2,6 m height. Being also possible to extend the shelter, assembling two structures, as demonstrated in Figure 140, achieving the double of living area (approximately 20 $m^2$). |
| If using tarpaulin, assure the use of standard size of 4 m x 6 m. | ✗ | Not used. |
| Make the shelter adapted to climate conditions and cultural/geographical context. | ✗ | Besides the gas and moisture permeability, the selected material was not tested yet against climate conditions. |
| If possible, use local skills and materials. | ✗ | Not needed. |
| Consider the lifetime, recyclability and sustainability of the material, in order to maximize its lifespan. | ✓ | The material intended to use (SMP) make possible to reuse the structure several times, due to its SME property, folding the structure for storage or transportation and assemble on site when needed. |
| Support family shelter over common one, assuring privacy, safety and protection against environmental issues. | ✓ | The developed concept offers accommodation for 3 persons, or through the assembly of two structures, it can accommodate bigger families, up to 6 persons. |
| Provide assistance and material for IDPs to build on their own. | ✓ | The shelter is assembled through the application of a stimulus (hot water, at 55ºC to 65ºC). Thus providing an easy and fast assembly of the shelter, so IDP´s do not need any technical assistance to assemble it. |
| Adaptable or modular in order to fit the emergency kit dimensions and shipping sizes in pallets (120 x 110 $cm^2$). | ✓ | The used material enables the possible folding of the structure to a temporary shape for transportation. In fact, within the validation tests, it was achieved the dimensions of 60x120x45 $mm^3$, corresponding to 1,2x2,4x0,9 $m^3$ at scale, thus validating the concept for transportation within shipping size. |
| The material should be tested and validated according to standards established by the humanitarian organizations in charge. | ✗ | The mechanical properties of the material needed to be further study and characterized, so it is not possible to validate them yet, thus being suggested for future work developments. |
| Weight less than 50 kg. | ✓ | From the estimation of weight, made in the development of the product (section 3.4.2.5), if the shelter thickness is 1.5 mm, the shelter would assume a weight of 45,8 kg (Table 20). However, this was just a simulation made in order to weigh less than the imposed 50 kg, when using tarpaulin for the construction of the shelter. Given this, the thickness should be further studied in order to find the ideal thickness that would provide a resistant shelter with less weight as possible. |
| Cost less than \$300 (approximately 270€). | ✗ | Calculated from the weight of 45,8 kg and thickness of 1,5 mm the cost using SMP filament was approximately 10691€ per shelter. A cost that can be reduced to 2256€, when exploiting FGF process, using SMP pellets. Other ways to reduce the costs would be developing a composite material with SMP, and also manufacturing at industrial scale, ordering bigger quantities of material consequently reduces its cost. |

## 3.5. Summary of the case studies

**Standard shelter (scale 1:10)**
[developed model at scale from a standard bamboo and tarpaulin shelter, to describe the process and constraints, as well as understand the dimensions and living area]

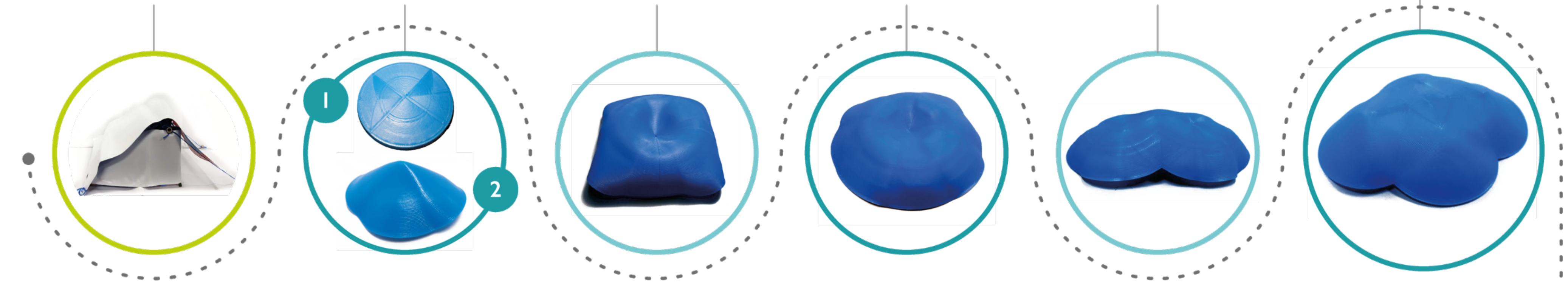
**Circular PLA sample**
(1) sample printed and heated at 95°C, achieving a conic shape (2)

**+ diagonals**
Sample with 8 intercalating variation of thickness from 0,6 mm and 0,8 mm

**+ diagonals and divisors**
8 divisors varying from 0,6 to 0,8 mm thickness layer and a 25 mm diameter core with 1 mm thickness

**Achieving + height**
overlapping of circular sketches and thickness variation from 0,4mm to 1mm, the core had more thickness (1 mm)

**Achieving ++ heigh**
overlapping of circular sketches and thickness variation from 0,4 mm to 1mm, the core with two crossed thickness (0,8 mm and 1 mm)




**Achieving 2m height and + living area = better sample**
Replicated sample with longer length arcs and less core diameter

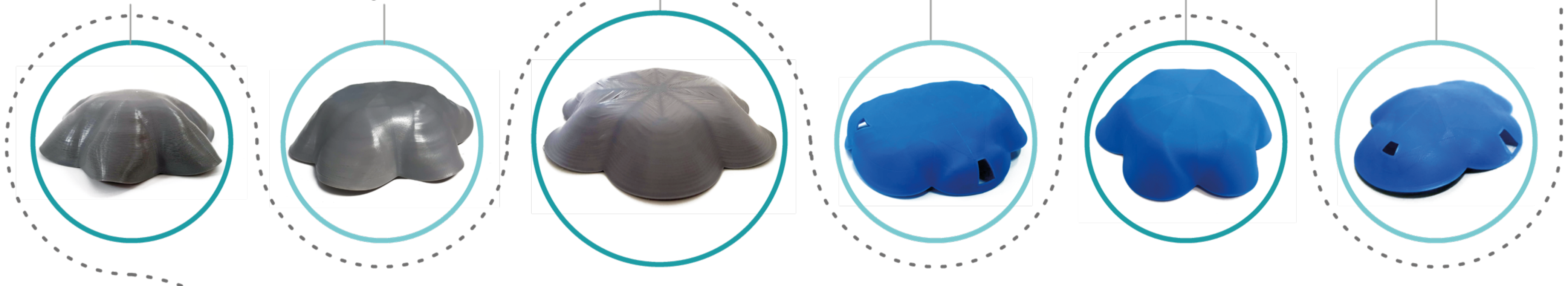
**Achieving + height and + living area**
Replicated sample with longer length arcs

**Bigger scale**
Redesigned sample with increase of dimensions and thickness proportionally

**Shelter concept**
Replication model from igloo shape with openings, representing a door and windows

**+ Area // Igloo shape**
Sample with overlapping of circular geometries to achieve an igloo shape

**Shelter concept**
Replication model with openings, representing a door and windows



### 3D printing with PLA and the process of warping

[3D printing samples with PLA filament from studied models through the overlapping of circular shapes, in order to achieve conic, dome or igloo structures, from flat printed shapes (1) to 3D (2) after heating at 95°C]
// The samples here presented are the results after heating for 3 min,

**Semi-spherical model**
Sample tested within the SME process. The printed sample (1) was heated and folded into a temporary rigid state(2). After cooled, the sample was heated again and restored its original shape (3)

**Origami based model**
Model based in origami shapes to ease the folding process. Sample printed and tested two times, restoring its original

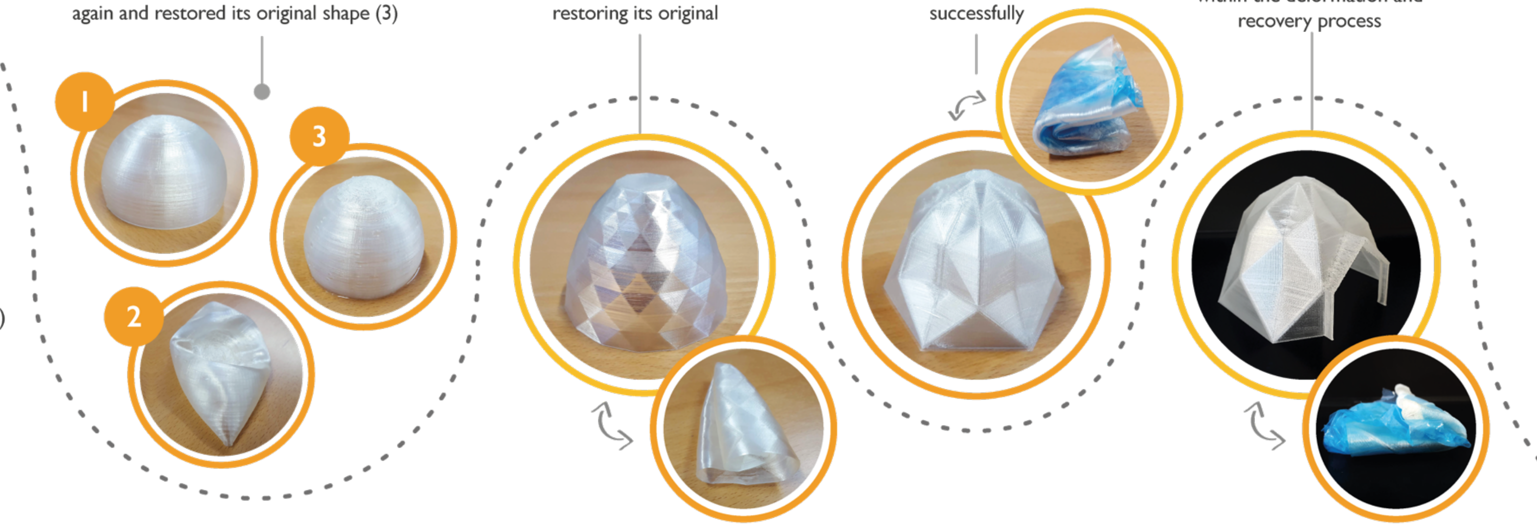
**Concept shape model**
Model developed using the base design and dimensions wanted for the structure of the emergency shelter. SME validated successfully

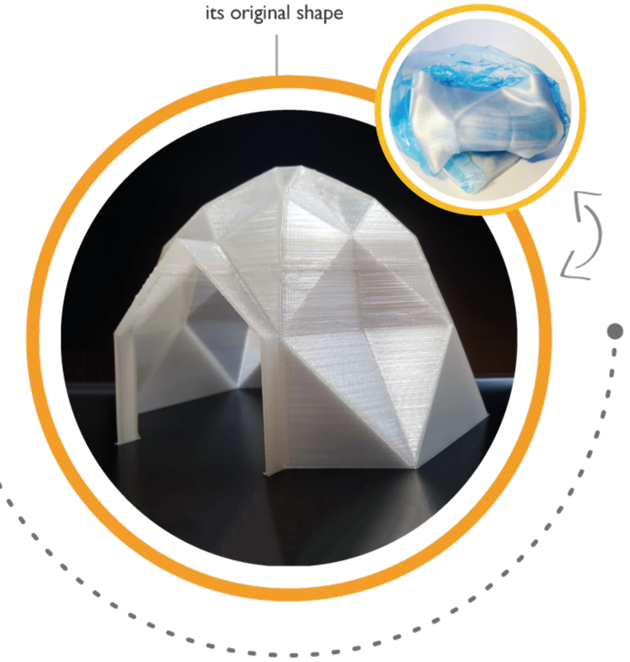
**Final model at scale 1:40**
Validatio of the final model within the deformation and recovery process

**Final model at scale 1:20**
Validation of the final model within the SME process. The sample was folded into the dimensions of 60 x 120 x 45 mm³ and restored successfully to its original shape

### 3D printing with SMP and the process of shape memory effect

[3D printing samples with SMP filament from studied models, that could be printed at the desired shape (1), folded into a temporary shape (2) when immersing in hot water (55°C) and later restored to its original shape (3) by heating the sample again]



# IV. CONCLUSIONS

# 4. CONCLUSIONS AND FUTURE RECOMENDATIONS

Due to the exponential increase of internal displaced people (IDPs) after crisis situations, such as conflict or natural disasters, there is current and urgent need to provide shelter, providing survival, basic conditions, privacy and dignity. Despite fulfilling the imposed requirements, the emergency shelter currently distributed by humanitarian organizations, does not have a structural solution solved, being improvised by IDPs with local materials, such as bamboo, covered with tarpaulin. However, IDPs may not be able to build on their own such structural solution, needing technical assistance.

This research aimed to make a contribution, to develop an improved alternative solution to replace the structure and ease its assembling process. In the process of developing the structural solution, innovative technologies, such as 3D and 4D printing processes, emerged as mechanisms that could enable the development of adaptable and flexible structures capable of solving the exposed problem.

The 4D printing concept here studied and presented, came up as a solution for the easy transportation and fast assembly of structures on site, since it only needed a stimulus, like water or heat to build them. This process was validated in the developed case studies using two materials that displayed shape memory effect, namely PLA and SMP filaments. However, the shape memory process of both materials occurs differently.

PLA shape memory effect was demonstrated through the development of studied geometries and designed shapes, with pre-determined thickness, combination of directions and deposition of the filament. Flat-printed designed models achieved the final pre-programmed 3D shape through heating at 95°C for 3 minutes. Despite its validation, its beneficial properties and possible application at large scale printing, this concept presented a challenge regarding its transportation, that in fact is impracticable to transport a 4 $m^2$ flat rigid plate in the shipping methods used by the humanitarian organizations.

Considering the transportation constraints manifested from the PLA case study, the SMP appeared as a solution. Due to its advantageous SME process, where the structure can be printed in the designed final shape and posteriorly heated with hot water (55°C), to be folded as intended, assuming a temporary shape, that can be restored to its original shape, by heating it again. A process that presented a solution for the developed shelter concept, in a way that the structure can be printed at its real dimensions, folded into dimensions that fit the emergency kit for transportation, and then assembled fast and easy on site after a crisis situation. The developed concept was validated within models that at real scale can provide a living area of 10 $m^2$, housing up to 3 persons, with the possible extension to double of the area through the joint of two models.

Summarizing, the main goal of this dissertation was accomplished. It was developed an alternative solution for first emergency shelter, in order to replace the current structures from tarpaulin and bamboo. It was achieved a conceptual product that can be part of the emergency kit, providing not only cover but also structural support. It was also possible to validate some of the requirements imposed, such as guaranteeing the minimum living space and ease the assembly process so that IDPs can build it on their own. However, the calculated cost was too high, even when using FGF process. Yet, it is known that it can be reduced when manufacturing more units, due to the fact that ordering more quantities of material reduces significantly its cost.

Also, composite materials and manufacturing processes were studied envisioning their potential application in further development of the product. It will be an alternative to improve its performance and mechanical properties. Moreover, it will open the possibility for hybrid composites and hybrid solutions.

In spite of the main goal achieved, in order to accomplish a functional solution, this research could be further developed following the detailed recommendations:

i. analyze and characterize the mechanical properties of the material (SMP filament and SMP pellets);

ii. determine how to hold the structure to the different types of soil;

iii. study the attachment of the door to the rest of the structure;

iv. test the models for several climate conditions, as well as UV test and fire-retardant test;

v. simulate the process of shape memory effect from a designed concept, in order to predict the shape that the concept should be printed and posteriorly folded and restored;

vi. estimate the durability of the shelter;

vii. improvement of the concepts design in order to facilitate the printing process that might display some challenges at large scale in the walls angles bigger than 45°, needing support structures;

viii. improvement of the material properties in terms of specific strength, stiffness and toughness that can be achieved using composite materials, for example;

ix. study the possible effect of creep or relaxation in the shape memory process;

x. consider the possibility of developing a composite material from SMP matrix, reducing the weight and cost of the developed structure;

xi. develop a real scale functional prototype using FGF method, to validate the concept within the requirements imposed, and be accepted by humanitarian organizations, such as IOM, in order to use the developed shelter after crisis situations;

## REFERENCES


3DMatter. 2016. "What is the best type of plastic for my 3D printing application?", Last Modified July 8, 2016, accessed April 2019. https://my3dmatter.com/what-is-the-best-type-of-plastic-for-my-3d-printing-application/.

Adrover, Esther Rivas. 2015. Deployable Structures. United Kingdom: Laurence King Publishing Ltd.

An, B., H. Wu, T. Zhang, L. Yao, Y. Tao, J. Gu, T. Cheng, X. Chen, X. Zhang, W. Zhao, Y. Do, and S. Takahashi. 2018. "Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces." Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18.

André, Jean-Claude. 2018. From Additive Manufacturing to 3D/4D Printing 3. Edited by Jean-Charles Pomerol. Great Britain: ISTE Ltd.

Association, Sphere. 2018. The Sphere Handbook: Humanitarian Charter and Minimum Standards in Humanitarian Response. 4 ed. Geneva, Switzerland.

Baker, A. B., S. R. G. Bates, T. M. Llewellyn-Jones, L. P. B. Valori, M. P. M. Dicker, and R. S. Trask. 2019. "4D printing with robust thermoplastic polyurethane hydrogel-elastomer trilayers."  Materials & Design 163. doi: 10.1016/j.matdes.2018.107544.

BetterShelter. 2019. "Better Shelter at DIHAD 2019." accessed March 2019. http://bettershelter.org/.

BLB_Industries. 2018. accessed May 2019. http://blbindustries.se/.

Bodaghi, M., R A. Damanpack, and H W. Liao. 2016. "Self-expanding/shrinking structures by 4D printing." Smart Mater. Struct. 25 (105034):1-15. doi: 10.1088/0964-1726/25/10/105034.

Borgobello, B. 2014. "Collapsible Compact Shelter pops up in under two minutes." New Atlas, accessed March 2019. https://newatlas.com/collapsible-compact-shelter-disaster-relief/32531/.

Campbell, Thomas A., S. Tibbits, and B. Garrett. 2014. "The Programmable World."  Scientific American 311 (5):60-65. doi: 10.1038/scientificamerican1114-60.

Cardborigami. 2017. "Shelter + Dignity = Hope." accessed March 2019. https://www.cardborigami.org/.

Chen, T., J. Mueller, and K. Shea. 2017. "Integrated Design and Simulation of Tunable, Multi-State Structures Fabricated Monolithically with Multi-Material 3D Printing."  Sci Rep 7 (45671):1-8. doi: 10.1038/srep45671.

Chen, T., and K. Shea. 2018. "An Autonomous Programmable Actuator and Shape Reconfigurable Structures Using Bistability and Shape Memory Polymers."  3D Printing and additive manufacturing 5 (2):91-101. doi: 10.1089/3dp.2017.0118.

cmaxFoundation. 2017. "Temporary urbanization for immediate response." accessed March 2019. http://cmaxfoundation.org/innovations/.

Compositeslab. 2016. "Composites Manufacturing Processes." accessed February 2019. http://compositeslab.com/composites-manufacturing-processes/.

Cotteleer, Mark, and Jim Joyce. 2014. "3D Opportunity." accessed January 2019. https://www2.deloitte.com/insights/us/en/deloitte-review/issue-14/dr14-3d-opportunity.html.

Dasyc. 2015. "Composite Modular Transportable Hangar (CMTH®)." accessed December 13. http://www.dasyc.gr/wp-content/uploads/2015/07/Hangar-Presentation_May-2015-site.pdf.

Enviropod. 2019. "Enviropod Dome Homes - FRP Composite Fiberglass Domes." accessed March 2019. https://www.enviropod.ca/.

Farah, S., D. G. Anderson, and R. Langer. 2016. "Physical and mechanical properties of PLA, and their functions in widespread applications - A comprehensive review." Adv Drug Deliv Rev 107:367-392. doi: 10.1016/j.addr.2016.06.012.

Gardiner, Ginger. 2017. "Thermoplastic composite panels deliver affordable housing solutions." CompositesWorld. Inside Manufacturing., August, 56-62.

Ge, Qi, K Conner Dunn, Jerry H Qi, and L Martin Dunn. 2014. "Active origami by 4D printing." Smart Mater 23 (094007):1-15. doi: 10.1088/0964-1726/23/9/094007.

Häuplik-Meusburger, Sandra, P. Petrova, S. N. Evetts, C. Sivanesan, Gernot Groemer, and S. H. Lu. 2013. "Deployable and portable emergency shelter for mars." Proceedings of the International Astronautical Congress, IAC 3:1777-1787.

Hoa, Suong V., and Victor A. Raju. 2018. "Contribution of resin shrinkage to deformation of laminates made by 4D printing." 18th European Conference on Composite Materials, Athens, Greece, 24-18 June 2018.

IAAC. 2015. "Small robots printing big structures." accessed March 2019. http://robots.iaac.net/#.

IAAC. 2017. "On Site Robotics." accessed March 2019. https://iaac.net/project/on-site-robotics/.

IDMC. 2018. "Global report on internal displacement."

IFRC. 2010. IFRC shelter kit guidelines. IFRC.

IFRC. 2011. "Shelter instruction flyer." www.ifrc.org.

IFRC. 2013. "Post-disaster shelter: Ten designs." In. www.ifrc.org.

IFRC. 2015. IFRC bamboo frame for emergency shelters and emergency roofs.

IFRC, and Oxfam International. 2007. Plastic Sheeting.

Inhabitat. 2016. "SOM debuts "world's largest 3D-printed polymer building" designed for off-grid living." accessed December. https://inhabitat.com/som-debuts-worlds-largest-3d-printed-polymer-building-designed-for-off-grid-living/.

IOM. 2016. IOM Logistics Emergency Catalogue. edited by IOM. Geneva.

IOM. 2017. "IOM Iraq - Shelter Programme 2017." Last Modified June, accessed December 2018. https://www.iom.int/sites/default/files/our_work/Shelter/documents/IOM%20Iraq%20-%20Shelter%20Programme%20-%20June-2017.pdf.

IOM. 2018. "IOM Shelter and Settlements 2017 Highlights."

JEC_Group. 2016. "Lightweight, durable 3D roof structures with composites tubes." Last Modified 17 Feb 2016, accessed December 2018. http://www.jeccomposites.com/knowledge/international-composites-news/lightweight-durable-3d-roof-structures-composites-tubes.

JEC_Group. 2017. "A glass and carbon fibre-reinforced composites pavillion made by robots and drone." Last Modified 18 Apr 2017, accessed October 2018. http://www.jeccomposites.com/knowledge/international-composites-news/glass-and-carbon-fibre-reinforced-composites-pavillion-made.

Kayser, M., L. Cai, S. Falcone, C. Bader, N. Inglessis, B. Darweesh, and N. Oxman. 2018. "Design of a multi-agent, fiber composite digital fabrication system." Science Robotics 3 (22):2. doi: 10.1126/scirobotics.aau5630.

Khoshnevis, Behrokh. 2004. "Automated construction by contour crafting—related robotics and information technologies." Automation in Construction 13 (1):5-19. doi: 10.1016/j.autcon.2003.08.012.

Krishnan, Sudarshan. 2017. "Deployable Structures: An Interdisciplinary Design Process." ASEE Conference and Exposition, Columbus OH, 25 - 28 June 2017.

Kuang, X., D. J. Roach, J. Wu, C. M. Hamel, Z. Ding, T. Wang, M. L. Dunn, and H. J. Qi. 2018. "Advances in 4D Printing: Materials and Applications." Advanced Functional Materials 29 (1805290):23. doi: 10.1002/adfm.afdm201805290.

Lippmann, Adrian. 2015. "Fold Flat Shelter." foldflat.de, accessed March 2019. http://www.foldflat.de.

Mafeld, Andrew, and JEC. 2017. The future of building - The growing use of composites in construction and architecture. 1 ed: Frédérique Mutel.

Malone, M. 2008. "Recover shelter." accessed March 2019. https://www.coroflot.com/mmalone/recover-shelter.

ManufacturingGuide. 2019. "Fused Granular Fabrication, FGF." accessed May 2019. https://www.manufacturingguide.com/en/fused-granular-fabrication-fgf.

Mao, Y., K. Yu, M. S. Isakov, J. Wu, M. L. Dunn, and H. Jerry Qi. 2015. "Sequential Self-Folding Structures by 3D Printed Digital Shape Memory Polymers." Sci Rep 5:13616. doi: 10.1038/srep13616.

Marques, G. L., A. R. Williams, and W. Zhou. 2017. "A Mobile 3D Printer for Cooperative 3D Printing." 28th International Solid Freeform Fabrication Symposium, Austin, Texas.

Momeni, Farhang, Seyed M.Mehdi Hassani.N, Xun Liu, and Jun Ni. 2017. "A review of 4D printing." Materials & Design 122:42-79. doi: 10.1016/j.matdes.2017.02.068.

Nations, United, Office for the Coordination of Humanitarian Affairs (OCHA), International Federation of Red Cross and Red Crescent Societies (IFRC), and CARE International. 2009. Timber as a construction material in humanitarian relief.

Nickels, L. 2016. "Shelter from the storm." Reinforced Plastics 60 (6):413-416. doi: 10.1016/j.repl.2015.06.044.

Raviv, D., W. Zhao, C. McKnelly, A. Papadopoulou, A. Kadambi, B. Shi, S. Hirsch, D. Dikovsky, M. Zyracki, C. Olguin, R. Raskar, and S. Tibbits. 2014. "Active printed materials for complex self-evolving deformations." Sci Rep 4 (7422):1-8. doi: 10.1038/srep07422.

Redwood, Ben. 2018. "Dimensional accuracy of 3D printed parts." accessed December 2018. https://www.3dhubs.com/knowledge-base/dimensional-accuracy-3d-printed-parts#variables.

Redwood, Ben, Filemon Schöffer, Brian Garret, and 3D Hubs B. V. 2017. The 3D Printing Handbook. Technologies, design and applications: 3D Hubs.

RSKshelter. 2018. "Standard Bamboo RSK Emergency Shelter Assembly Guidelines." In.

Schumacher, E. F. 1973. Small is Beautiful: Economics as If People Mattered. London: Blond & Briggs.

Shelter, ReciproBoo. 2017. ReciproBoo Shelter Kit (RSK) Instructor Training Course Myanmar. ReciproBoo Shelter Health and Education Charity and the Community Development Association (CDA) Myanmar.

ShelterCluster_Iraq. 2018. "SOK Technical Guidance." Last Modified September 2018, accessed January 2019. https://www.sheltercluster.org/sites/default/files/docs/sok_technical_guidance_v02.pdf.

Smith, Amy. 2006. "Simple designs to save a life." TED conference.

SMPTechnologies. 2018. "Shape Memory Polymer." accessed December 2018. http://www.smptechno.com/index_en.html.

Soares, Filipa F. 2018. "Going Mars, the beginning of a printed living machine." Master, Product and Industrial Design, Universidade do Porto.

SpaceFactory, AI. 2019. "AI SpaceFactory Wins 1st Place Prize for NASA 3D Printing Habitat Challenge." accessed May 2019. https://www.aispacefactory.com.

Stratasys. 2017. "Introduction to Additive Manufacturing for Composites." In. https://energygroup.it/getattachment/dd11d248-7452-4b60-a6b4-c075ab2dc697/Come-progettare-per-il-Direct-Digital-Manufacturin.aspx (accessed January 2019).

SuricattaSystemsSL. 2017. "SURI Shelter Unit for Rapis Installation." accessed March 2019. http://www.suricattasystems.com/en/suri/.

Teixeira, João. 2018. "Impressão 3D com extrusão de materiais cimentícios." Master, Product and Industrial Design, Universidade do Porto.

ThinkShell. 2014. "Temporary Cathedral in Paris 2013." accessed December 2018. http://thinkshell.fr.

Thrall, A. P., and C. P. Quaglia. 2013. "Accordion shelters: A historical review of origami-like deployable shelters developed by the US military." Engineering Structures 59 (2014):686–692. doi: 10.1016/j.engstruct.2013.11.009.

Tibbits, S. 2014. "4D Printing: Multi material shape change." Architectural design 84:116-121.

Tibbits, Skylar. 2013. "The emergence of "4D printing"." TED conference.

Tofail, Syed A. M., Elias P. Koumoulos, Amit Bandyopadhyay, Susmita Bose, Lisa O'Donoghue, and Costas Charitidis. 2018. "Additive manufacturing: scientific and technological challenges, market uptake and opportunities." Materials Today 21 (1):22-37. doi: 10.1016/j.mattod.2017.07.001.

UNHCR. 2018. Emergency shelter standard. In Emergency Handbook.

van Manen, T., S. Janbaz, and A. A. Zadpoor. 2017. "Programming 2D/3D shape-shifting with hobbyist 3D printers." Mater Horizons 4 (6):1064-1069. doi: 10.1039/c7mh00269f.

Wijnen, B., P. Sanders, and Joshua M. Pearce. 2018. "Improved model and experimental validation of deformation in fused filament fabrication of polylactic acid." Progress in Additive Manufacturing 3 (4):193-203. doi: 10.1007/s40964-018-0052-4.

Wohlers Associates, Inc. 2019. Wohlers Report 2019.

Wohlers, Terry, and Tim Gornet. 2014. History of additive manufacturing. WOHLERS ASSOCIATES, INC.

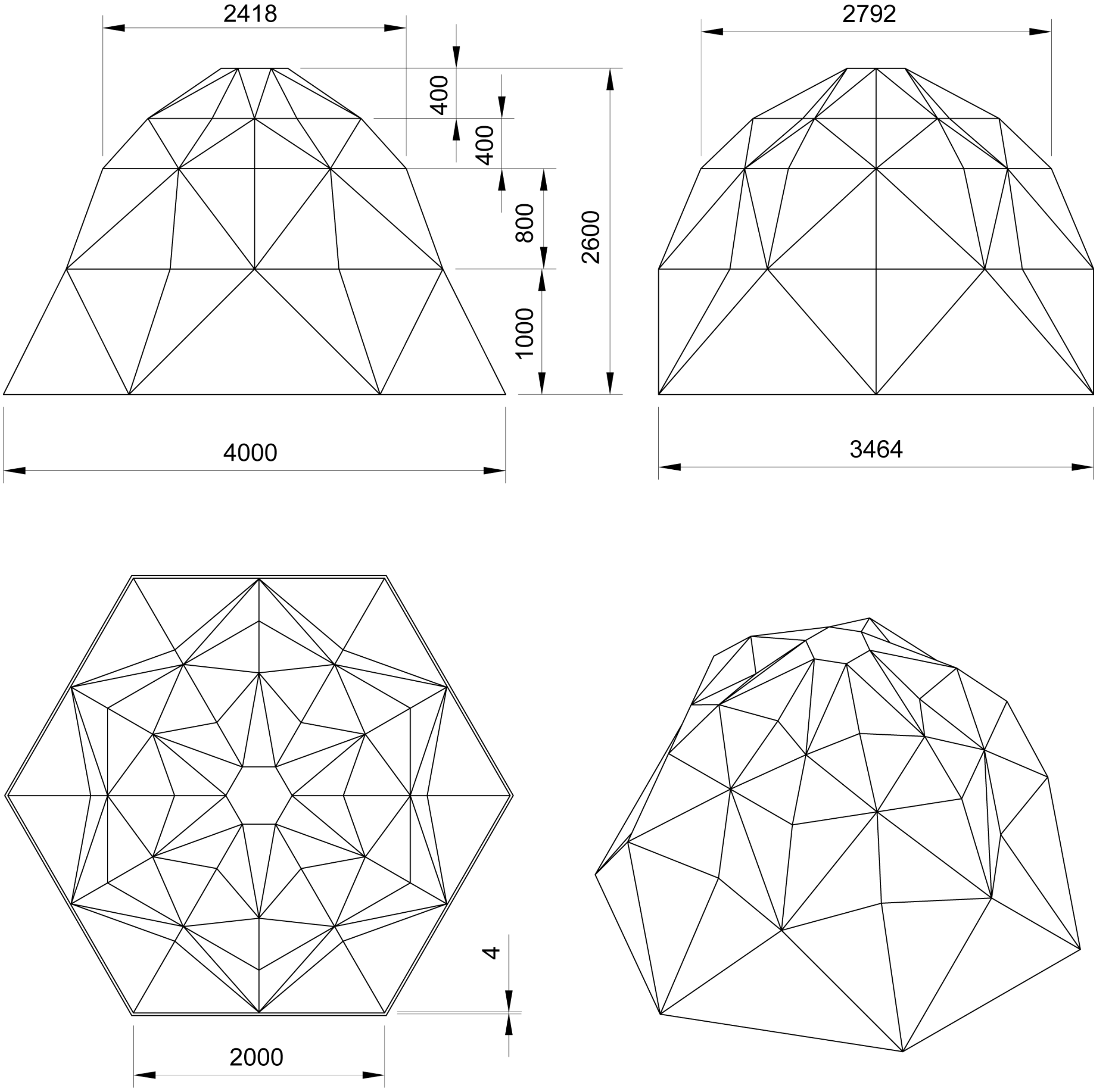
Wu, W., W. Ye, Z. Wu, P. Geng, Y. Wang, and J. Zhao. 2017. "Influence of Layer Thickness, Raster Angle, Deformation Temperature and Recovery Temperature on the Shape-Memory Effect of 3D-Printed Polylactic Acid Samples." Materials (Basel) 10 (8). doi: 10.3390/ma10080970.

Xu, F. 2016. "VULCAN. Closing the Loop in 3D-Printed Architectural Design." Architectural Design 86 (5):84-91. doi: 10.1002/ad.2093.

Yang, Y., Y. Chen, Y. Wei, and Y. Li. 2015. "3D printing of shape memory polymer for functional part fabrication." The International Journal of Advanced Manufacturing Technology 84 (9-12):2079-2095. doi: 10.1007/s00170-015-7843-2.

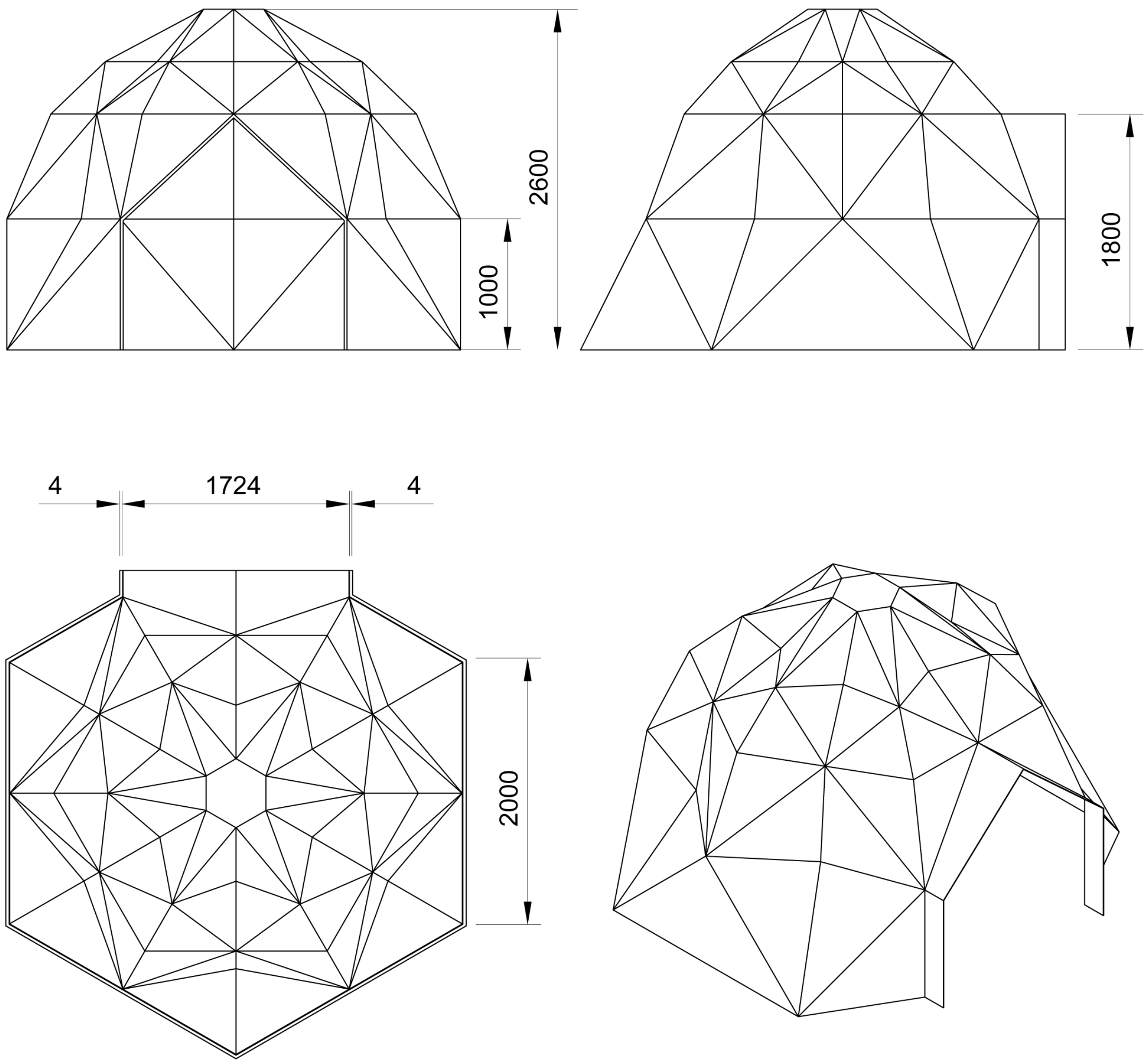
Yoneda, Yuka. 2008. "The Origami-Inspired Folding Bamboo House." accessed March 2019. https://inhabitat.com/origami-inspired-folding-bamboo-house-by-ming-trang/.

# ANNEX A: technical drawing of the final structure



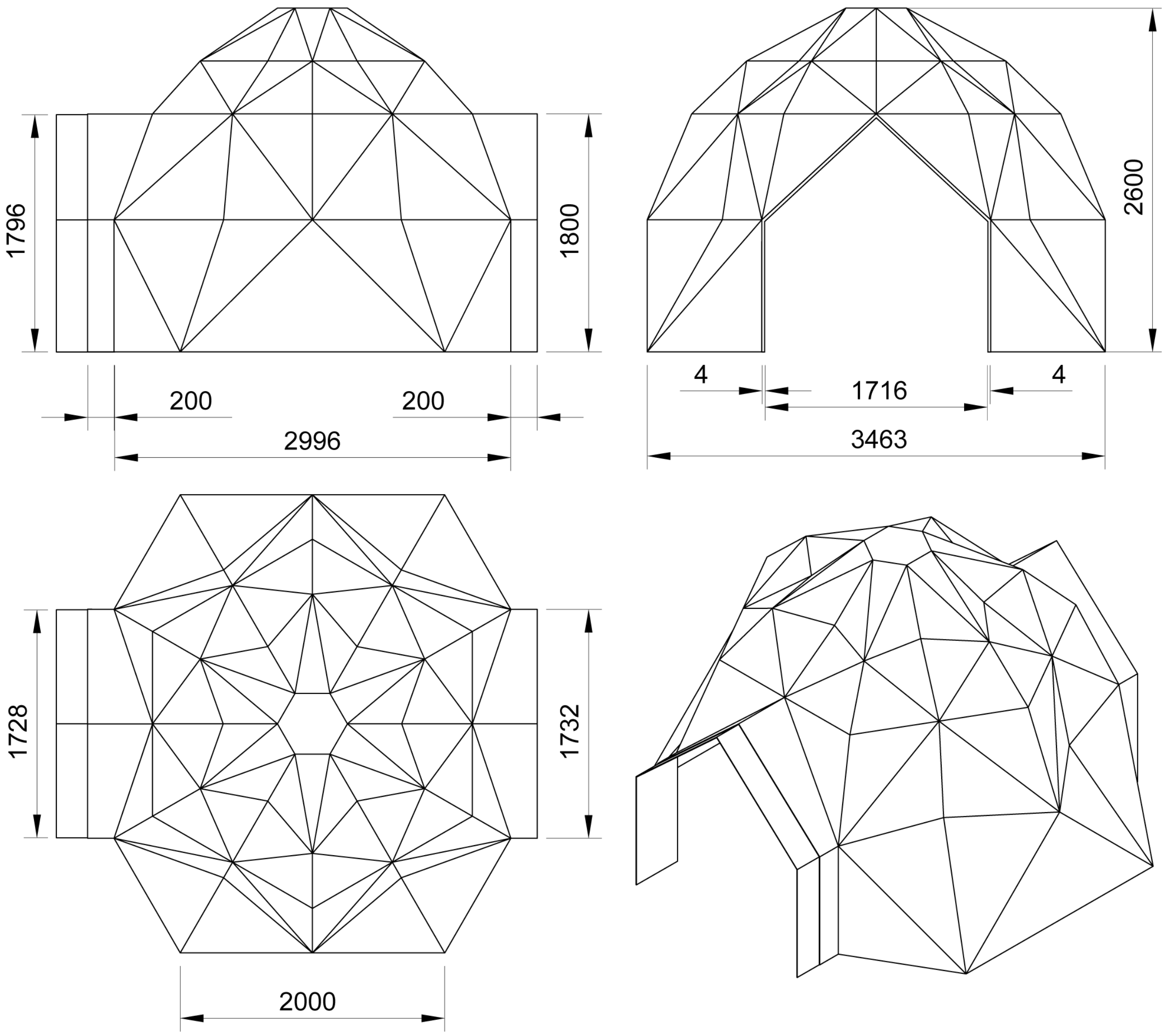

| | |
|---|---|
| Structure study model | June 2019 |
| Alice Costa | Scale 1:50 |

# ANNEX B: technical drawing of the final structure with door opening




| | |
|---|---|
| Model with door opening | June 2019 |
| Alice Costa | Scale 1:50 |

# ANNEX C: technical drawing of the structure with two openings used for expanding the shelter




| Model with two openings for connection | June 2019 |
| --- | --- |
| Alice Costa | Scale 1:50 |