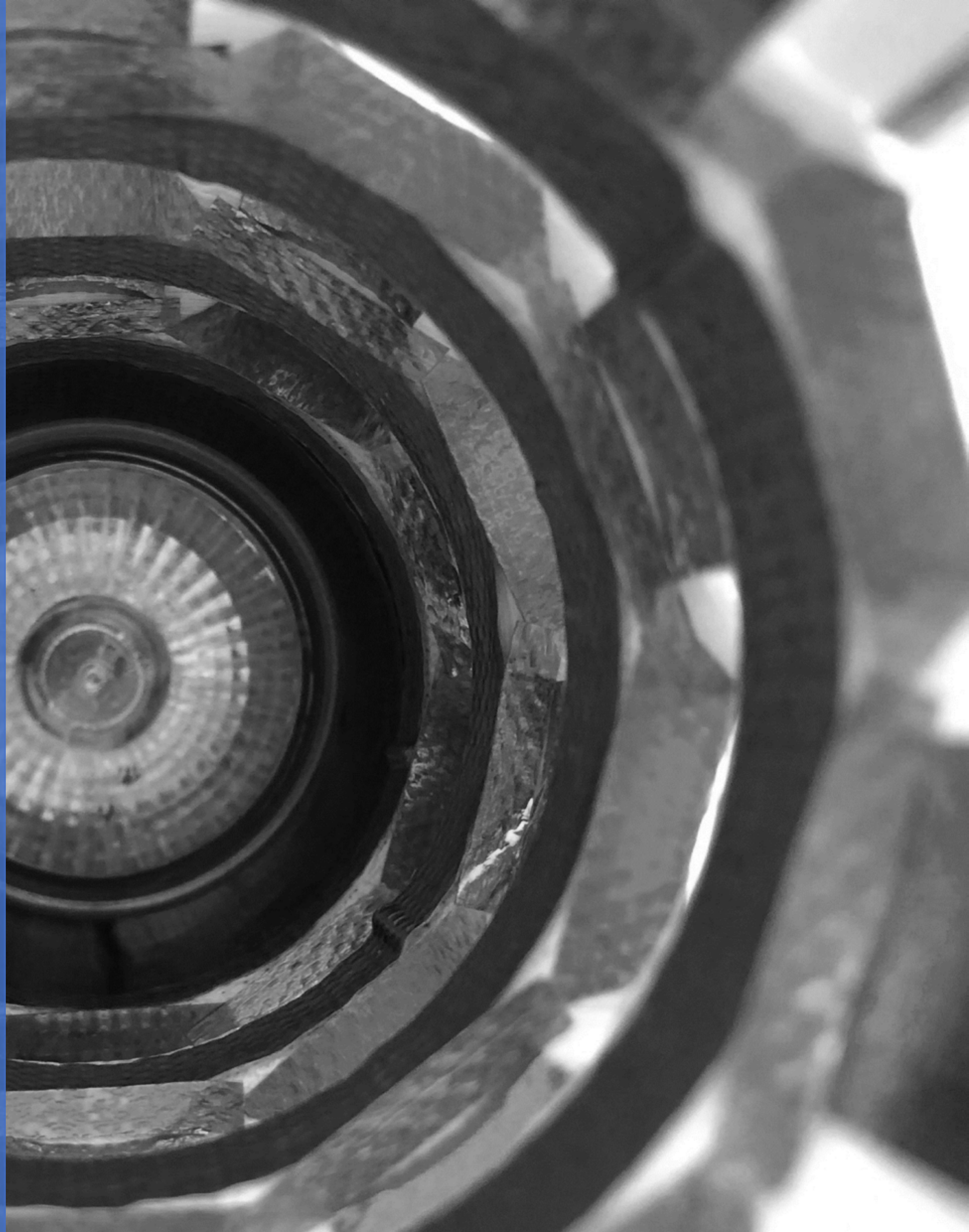
DESIGNING 3D-PRINTED DEPLOYABLE STRUCTURES WITH SHAPE MEMORY POLYMERS



Master thesis

Jesse Holierhoek

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Delft University of technology

For further information contact:

AUTHOR
Jesse Holierhoek

DELFT UNIVERSITY OF TECHNOLOGY
Faculty of Industrial Design Engineering
Landbergstraat 15
2628 CE Delft
The Netherlands

Email: info@tudelft.nl
Website: www.io.tudelft.nl

CHAIR
Dr. Sepideh Ghodrat, MSc.
Department: Sustainable Design Engineering

MENTOR
Silje Dehli, MSc.
Department: Design, Organisation and Strategy

Figure 1 DAWN: the shape memory wake-up light, in closed state (left) and open state (right)

EXECUTIVE SUMMARY

This report describes a graduation project performed at the faculty of Industrial Design Engineering of the Delft University of Technology for the master program Integrated Product Design. The aim of this project was to get a better understanding of the shape memory behaviour of 3D-printed polymers, and the different parameters which affect this, with the ultimate goal to apply shape memory in product design.

This project started with a literature study on shape memory polymers and 3D-printing. The material properties, different types of shape memory and different actuation methods were investigated, as well as different 3D-printing techniques and using shape memory polymers in 3D-printing. Existing applications and concepts using shape memory polymers, as well as recent studies in applying these materials were also investigated.

In parallel to the literature study, testing was done on the influence of different parameters on the shape memory behaviour of one of the most common FDM 3D-printing materials: PLA.

Through an iterative process, a test sample was designed which was used to test parameters related to material (different types of PLA), manufacturing (printing settings), and design (geometry and orientation of models).

Knowledge gained through the literature research and testing was combined to create design guidelines for manufacturing shape memory objects using 3D-printing.

To demonstrate how the shape memory capabilities of 3D-printed PLA could be applied in product design, A product concept was developed. With a vision as a starting point, ideation and concept development was started by first having a brainstorm session with different people to learn how people not involved with the project envisioned shape memory in product design. Moving on from this, useful results from this session were taken into an ideation phase, where a multitude of different ideas were thought up. From these ideas, four were chosen to be developed into concepts, of which one was chosen to be further developed into a physical prototype.

The chosen concept was a wake-up light which uses the heat of the lightbulb inside the lamp to heat the shape memory material and initiate shape recovery, which resulted in the lamp gradually giving off more light. This would wake up the user in a natural way.

The concept, which was given the name ‘’*DAWN*’’, was developed into a physical demonstrator, and the shape memory parts were printed based on the established guidelines. This also served as a test for the guidelines to see how they could be applied in the design process. After testing several printed prototype parts, a final design for the demonstrator was created and produced. At the end of the project, the process and results were evaluated and recommendations were given for further research into 3D-printing shape memory objects.

ACKNOWLEDGEMENTS

This graduation project concludes my years of study at the faculty of Industrial Design Engineering at the TU Delft. While being an individual project, it could not have been accomplished without the support and guidance of different people, which I would like to mention.

First and foremost, I would like to thank my supervisory team for helping me these past months. Sepideh: thank you for giving me the opportunity to work with shape memory materials. Before this project, this topic was practically unknown for me, but with your knowledge and enthusiasm, I have learned a lot of new and exciting things about shape memory materials, but also about doing material research and testing. Silje, I would like to thank you for coaching and advising me on how to structure the process, and helping me keep an overview while working on this project. Your guidance really helped me to keep a cool head and get a grip on the project while working on it.

Apart from my supervisory team, I would like to thank some people who helped me with different aspects of my project. First, I would like to thank Vahid for giving me a starting point for my research, and providing me with important insights early on in the project. Second, Leo, for supporting me with analysing my test results. I would also like to thank the people from the applied labs for supporting me with the use of different equipment for my tests, and the people who participated in my creative session, for helping me kickstart the creative part of my project.

Lastly, I would like to thank Fabia and my family for supporting me on a daily basis to keep on going, especially in these trying times.

I hope you all enjoy reading this report.

CONTENT

APPENDICES

1 INTRODUCTION

In the chapter, the project is introduced. First, an overview of the project is given, describing the aim of the project and the overall structure. After this, the approach of this project is discussed. Here, the method and starting point of the project are further explained.

1.1 PROJECT OVERVIEW

This report serves as a visual and textual documentation of a graduation project for the Integrated Product Design (IPD) master's degree, conducted at the faculty of Industrial Design Engineering at the Delft University of Technology.

Shape Memory Polymers, or SMP's for short, are a specific type of polymer based materials which have the ability to change shape as a reaction to an external stimulus like heat, light or electricity. These polymers are capable of remembering a specific shape they were trained to adopt, and can retrieve this shape when being exposed to an external stimulus after deformation. While numerous applications have already been defined, SMP's have still almost exclusively been applied in very specific fields such as the medical industry. In general, these materials are relatively unknown, also in design. Insufficient research has been done to prove the materials capabilities, hindering widespread application and production. Due to this, the threshold for designers to use this material is high. To make the use of SMP's more widespread, it is important to research these materials, and inspire and enable designers to work with these kinds of materials.

3D-printing is a promising method to manufacture SMP-objects. However, 3d printing of SMP's is still in its infancy. (practical) research still needs to be done on both 3D-printing as a manufacturing method for SMP objects and the properties of 3D-printed SMP objects, like accuracy and reliability.

The aim of this project is to improve the understanding of the shape memory properties of 3d-printed Shape memory polymers (SMP's), and the parameters that influence these properties. Through systematic testing, the parameters which influence this are identified and researched. The results are used to create a deployable structure which will serve as a demonstrator showing the capabilities of SMP's, as well as a set of design guidelines for designing 3d-printed SMP structures.

In this project, research is done on the parameters that influence the shape memory properties of 3d-printed structures. The project focuses on the printing parameters and material properties, to get a better understanding on how to manipulate the shape memory properties to serve a specific purpose and what the possibilities are for applying these properties in design.

Based on the research done in this project, two deliverables are created: a demonstrator and a set of guidelines, with the demonstrator being a 3d-printed deployable structure, which shows the capabilities of the SMP in terms of shape memory ability and design possibilities. The guidelines are an extension of the Material Driven Design (MDD) process, in the sense that they are meant to provide other designers with the knowledge needed to design 3d-printed objects with the Shape memory properties of these materials as the central driver for the design.

Both these deliverables combined are meant to serve as inspiration and a way to lower the threshold for designers to start working with these kinds of materials and manufacturing technique. Next to this, the data generated during this project will be valuable for models aimed at simulating and predicting the behaviour of new to-be-printed objects.

1.2 APPROACH

Through materials research, new and improved materials are constantly being invented/created as superior alternatives for existing materials, leading to new and improved products. However, the adoption of a new material typically takes a relatively long time, with often 20 or more years between technical innovation to the widespread uptake. (Bengisu & Ferrara, 2018). When a material is launched commercially, its performance and utilitarian advantage should be clear and make sense. However, a material should also be socially and culturally accepted or acceptable for widespread use.

The Material Driven Design (MDD) method was created to facilitate designers with the means to design innovative product solutions with a novel material as a starting point, incorporating both technical and experiential aspects in the design process. Through a 4-step process, the method helps designers characterise a material on both a technical and experiential level, which serves as input for the actual design phase. The MDD method is explained on the next page.

In this project, the MDD method serves as a starting point, with different elements being taken from the MDD method, and applied to suit the goal of this project. Similar to the MDD method, a material group, shape memory polymers, was determined to be the starting point of this project. However, unlike with the MDD method, a production process, FDM 3D-printing, was chosen as an ʻʻadditionalʼʼ starting point.

The focus of this project will be on the technical aspects of shape memory polymers and 3D-printed shape memory objects. Therefore, the 4-step MDD process, as described on the next page, will be altered to not feature step 2 and step 3. Furthermore, the experiential characterization in step 1 will also be left out of the project. Instead, there will be more focus on the technical characterization of the material. This focus on the technical aspects at the expense of experiential aspects has been chosen due to the fact that the 3D-printing of shape memory objects still needs substantial research in order to be applied to the design of shape memory objects. Therefore, to be able to achieve substantial results within the duration of the project, the experiential aspects of the MDD method will be left out. However, these aspects will be kept in mind during the project, and will be included at the end of the project in the form of recommendations for further research.

As applying the MDD method in the way described in this chapter has not been documented yet, this raises the question on how the design process exactly takes shape and how this influences the eventual outcome of the project. Therefore, at the end of the project, an evaluation will be done to determine the impact and effectiveness of using this altered method.

The project starts with a parallel study of SMP's and 3D-printing technology. Findings from this phase will form the basis for technical characterization (first step of the MDD method). The concepts developed in the final step of the process be used as a base for the final demonstrator and guidelines. The demonstrator will be designed to show the possibilities of 3d-printing with SMP's. Based on the research on 3D-printing and SMP's, as well as the results of the MDD process, guidelines for designing 3d-printed SMP objects will be set up, to help other designers in designing these kinds of objects.

The four MDD steps:

1. Understanding the material: technical & experiential characterization
In this step, a deep understanding about the technical and experiential qualities of the material is formed.

2. Creating materials experience vision
The second step involves reflecting on the material characterisation done in the previous step, and a material experience vision is created, Defining the envisioned user-material interaction, utilizing the technical properties of the material to the fullest. Furthermore, the materials role in a broader context is defined.

3. Manifesting Materials Experience Patterns
In this step, a link is made between the material experience vision and formal qualities of materials and products, to understand how to achieve the envisioned interactions. This results in material experience patterns.

4. Creating Material/Product Concepts
All findings from previous steps are integrated and used for the final step of the process: the design phase. Here, a product idea can be worked out, or product concepts can be created. (Karana et al., 2015)

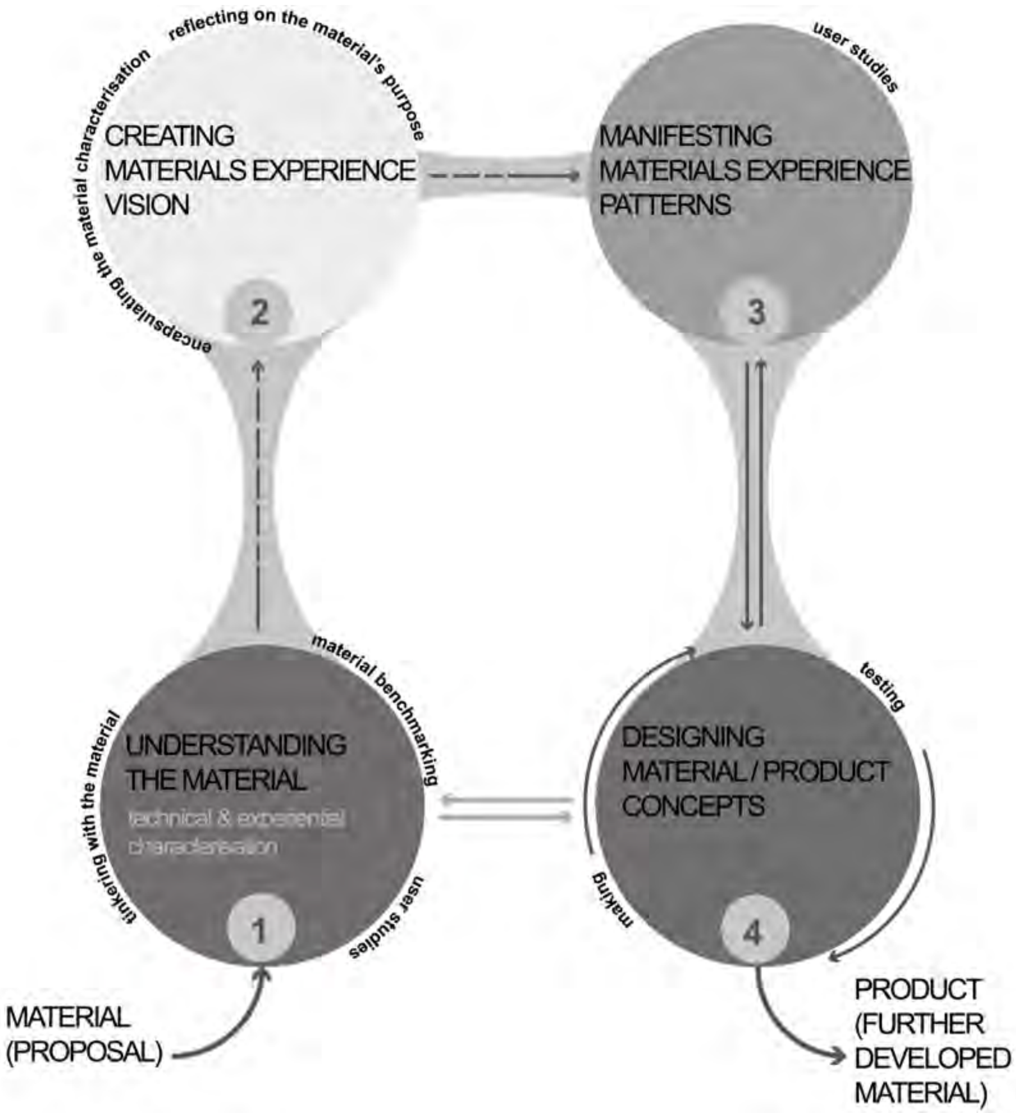
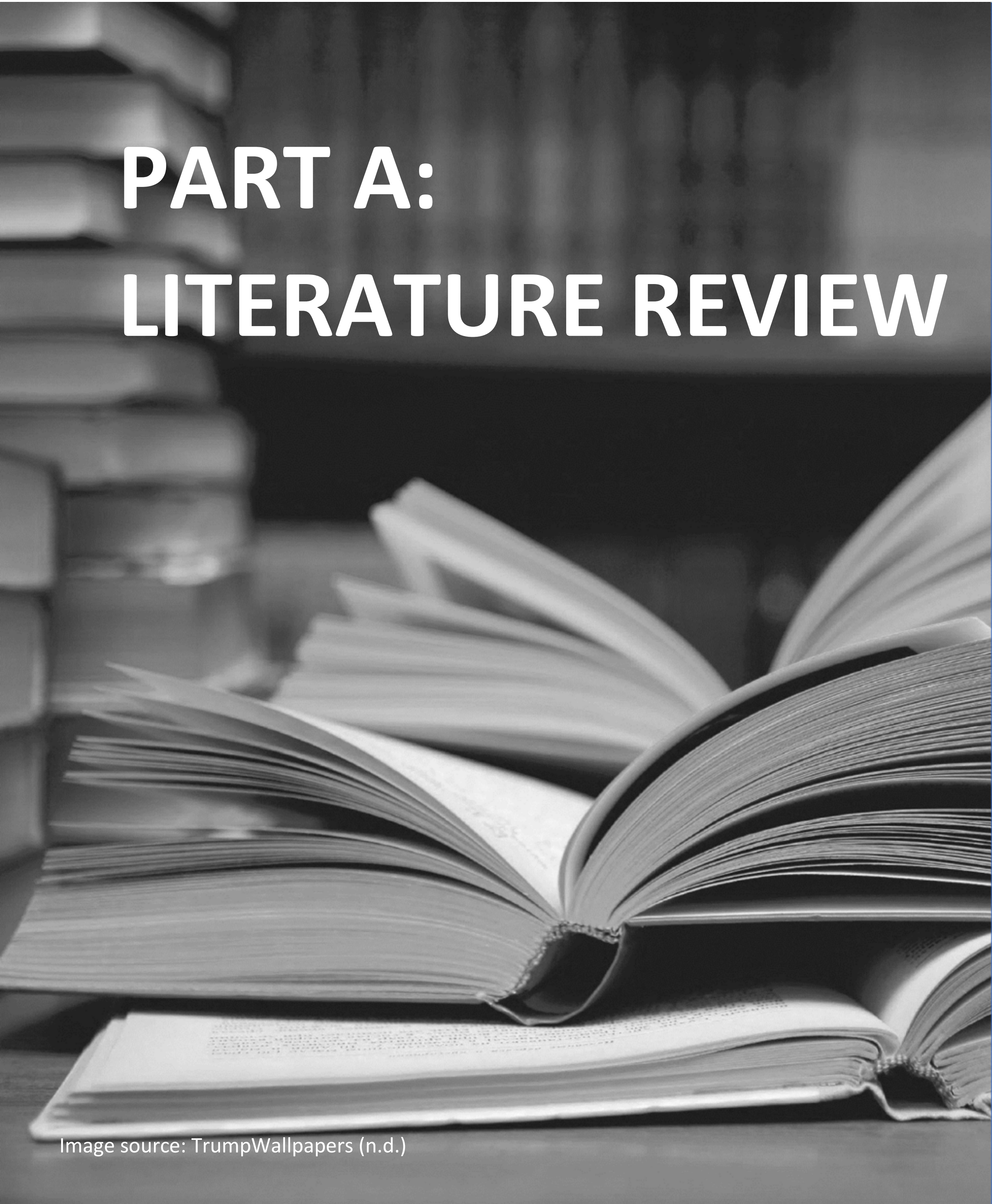


Figure 2 Material driven design method overview (source: Karana et al., 2015)

PART A: LITERATURE REVIEW



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In this part, the literature research done is described. The chapter is divided into 3 chapters: material, manufacturing and design.

The material part starts with an introduction on smart materials, followed by a more focused introduction on shape memory material, from which the shape memory polymers (SMP's) will be the focus on the remainder of the literature review. The mechanisms behind the shape memory effect (SME) in SMP's, different stimuli and different forms of shape memory in SMP's are discussed.

The manufacturing part of this chapter shortly discusses conventional manufacturing techniques for SMP's, but the focus will be on 3d-printing of SMP's. Different 3d-printing techniques are shortly explained. Later on, FDM printing will be explained in detail, as this process will also be used during the project for testing and designing.

In the last part of the literature review, designing with shape memory polymers will be addressed, and examples of interesting/inspiring projects focusing on SMP's will be discussed (benchmarking)

2 MATERIAL

This chapter discusses the material part of the literature review. In this chapter, different topics will be addressed, starting with an introduction on smart materials and shape memory materials, followed by an in depth description of shape memory in polymers.

The questions that will be addressed in this chapter are:

- what material properties does a polymer have to have to display shape memory behaviour?
- How can a polymer be activated to initiate shape recovery?
- What different types of shape memory can be achieved in polymers?

2.1 SMART MATERIALS

Smart materials are a group of emerging materials which can both sense their environment and autonomously perform actuating functions based on environmental stimuli. These materials have many advantages over ‘’traditional’’ materials, like reduced dimensions, lightness and generally no need for an energy source to function. Apart from functioning autonomously, these materials can be controlled and programmed to perform a specific kind of interaction. The ability to both sense and actuate autonomously makes them inherently interactive, and provides many opportunities for designing new and improved products providing new experiences and solutions.

An example of a smart materials are piezoelectric materials, which produce an electric charge when stress is applied, or the other way around (APC, 2019). Other examples include self-healing materials (figure 3), chromogenic systems, which change colour in response to changing light, temperature, or electricity (figure 4), and electroluminescent materials (figure 5). Another example of smart materials are shape memory materials, which will be the focus for this project.

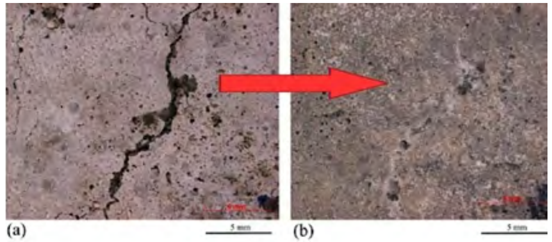


Figure 3 self-healing concrete (Waikoto, 2018)

Figure 4 glasses changing colour in response to light (photochromism) (sixty-minute spectacles, 2018)

Figure 5 electroluminescent display on a watch (multicherry, 2020)

2.2 SHAPE MEMORY MATERIALS

Shape memory materials (SMMs) are part of a larger group of Stimulus Responsive Materials (SRM), meaning that they have the ability to change as a reaction to external stimuli (figure 6). These materials are capable of remembering a specific shape they were trained to adopt, and can retrieve this shape when being exposed to an external stimulus after deformation. Different kinds of stimuli can cause this reaction, with the most common being temperature. Apart from this, other stimuli like light, magnetic field, electricity and pH can cause shape change depending on the kind of shape memory material that is used. SMMs can be classified in the conventional material groups, e.g. metals, polymers etc. The different groups of SMMs are described below (Bengisu & Ferrara, 2018):

- **Shape memory polymers (SMP's)**
  The shape memory effect in polymers is mainly based on a change of state of the material. Netpoints act as molecular switches, allowing shape remembrance. Shape memory can be achieved in most polymers through a process called crosslinking, or can be an intrinsic property.
- **Shape memory elastomers (SMEs)**
  A subgroup of SMP's, which can undergo great amounts of elastic deformation when put under stress, and recover their original shapes when unloaded
- **Shape memory ceramics**
  Like with SMAs, shape memory in ceramics is based on a martensitic transformation. These materials are inherently brittle, meaning they are only able to recover relatively small strains (2%)
- **Shape memory alloys (SMAs)**
  Alloys like Cu-Zn and Ni-Ti, which possess shape recovery properties, based on austenite- martensite phase transformation.
- **Shape memory composites (SMCs)**
  Composed of two or more materials, of which at least one shape memory material must be involved. SMCs are usually designed with the aim to create a shape memory material with increased strength and stiffness, or add new functionalities.
- **Shape memory gels (SMGs)**
  Hydrogels with shape recovery capabilities

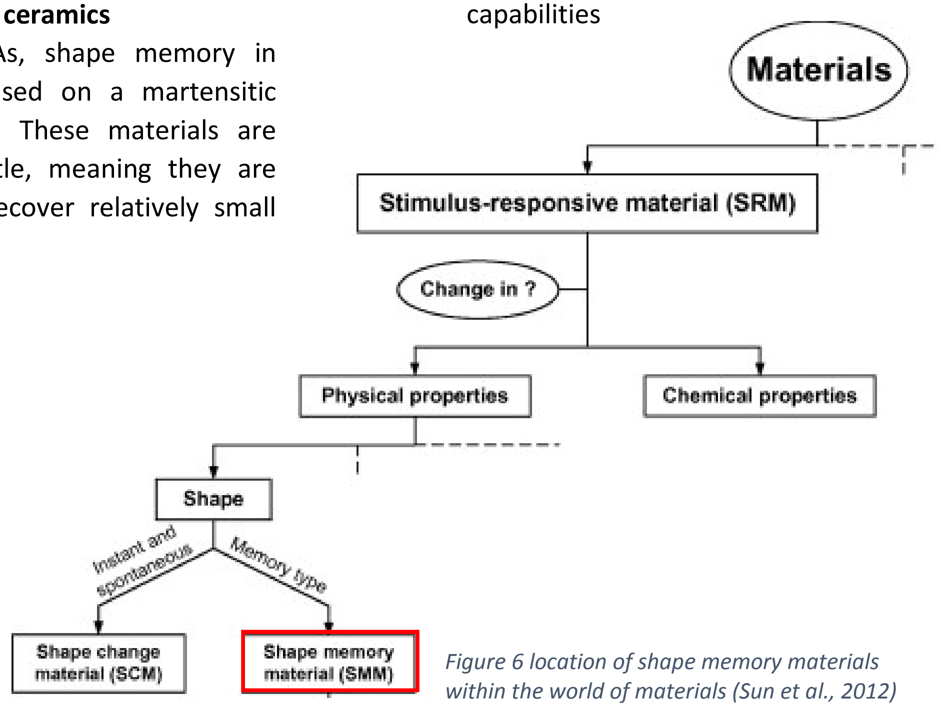


Figure 6 location of shape memory materials within the world of materials (Sun et al., 2012)

2.3 SHAPE MEMORY POLYMERS

The shape memory effect in polymers was first discovered in 1941 by Vernon et al. Since then, SMP's have slowly gained attention from researchers and they have been applied in different fields. Compared to SMAs, which are more commonly applied and available, SMP's offer several advantages in terms of mechanical properties and possible applications. SMP's have lower densities, larger strains (800% for SMP's compared to 8% for SMAs), are easier to process due to lower temperatures and pressures needed, and offer easier shape programming with tuneable stiffnesses and application temperatures. Therefore, they offer more flexibility in design, and are potentially cheaper to apply than SMAs. On the other hand, SMAs are superior to SMP's in terms of strength, stiffness, application temperatures, cycle time and actuation force.

Table 1 Comparison between SMP and SMA properties ("Shape-Memory Polymer", 2020)

	SMP's	SMA's
Density (g/cm³)	0.9-1.2	6-8
Extent of deformation	Up to 800%	<8%
Required stress for deformation (MPa)	1-3	50-200
Stress generated upon recovery (MPa)	1-3	150-300
Transition temperatures (°C)	-10...100	-10...100
Recovery speed	1s- minutes	<1s
Processing conditions	<200°C, low pressure	>1000°C, high pressure

2.3.1 MATERIAL PROPERTIES

In this part of the literature review, the material properties of shape memory polymers are discussed. The two main topics are the molecular structure of these materials, and the different stimuli which can be used to activate these materials.

2.3.1.1 MOLECULAR STRUCTURE

The shape memory effect in polymers is mainly based on entropy; the ability of the atoms or molecules of a material to move freely within a closed system. When an SMP object is in its permanent shape, the molecular chains of the material adopt conformations with the highest entropy. This means that the chains are in a thermodynamically stable state. When the material is heated above the glass transition temperature (T_{trans}), it gets soft and the chains are able to move around. In this state, when the object is deformed under influence of an external force, the chain conformations change, leading to a state of lower entropy. Once cooled below T_{trans}, the chains are unable to move and are trapped in this lower entropy state. When the object is then again heated above T_{trans}, the molecule chains regain their ability to move. If no external forces are applied, the chains will go back to the state of highest entropy, which is the permanent shape of the object. Meaning that the object recovers its permanent shape.

There are two structural requirements for a polymer in order for it to display dual-shape memory behaviour. The first requirement being a **reversible thermal phase transition**, either a glass transition point or melting point. Apart from a few exceptions where a polymer decomposes before it reaches this transition point, all polymers have either one of these transition points. Therefore, polymers have both a glassy and a rubbery state. In the glassy state the mobility of the molecular chains, also referred to as switch segments, is suppressed, therefore the shape of the SMP is fixed. Once heated above the transition temperature, the molecular mobility is activated; the molecule chains are able to move and the material gets rubbery. In this state, the material can recover its permanent shape (or be deformed by an external force)

The second requirement is a **crosslinking network**. Crosslinking points, also called netpoints, are the points where two molecule chains are connected together. The network of these points is responsible for setting the permanent shape. When the material is deformed above its thermal transition, the netpoints restrict chain movement, causing internal stresses. If the material remains in the deformed state when the material is cooled below its thermal transition, these stresses remain and energy is stored within the material. Once heated again, these stresses cause the material to recover its permanent shape. Without the crosslinking network, long-range chain slippage would occur, preventing internal stresses, thus preventing energy storage, in which case the material does not possess shape memory capabilities. The extent to which long-range chain slippage is prevented determines the effectiveness of shape memory behaviour in SMP's. (Xie, 2011)

There are two forms of crosslinking: physical and chemical. Physical crosslinking is based on intermolecular interactions, which occurs in polymers consisting of at least two segregated segments, for example block copolymers. Chemical crosslinking is based on covalent bonds, and can generally be introduced into any polymer, using methods like e-beam radiation. The latter type often resulting in complete prohibition of long-range chain slippage. (Behl & Lendlein, 2007; Xie, 2011)

Figure 7 polymeric network of netpoints and molecular switches (Bengisu & Ferrara, 2018)

2.3.1.2 STIMULI

The most common types of stimuli for triggering a shape change in SMP's are heat and light. Apart from directly heating the material, it is also possible to do this indirectly with for example IR-light, magnetism or electricity. There are also SMP's that respond to pH (Bengisu & Ferrara, 2018). Below, the different stimuli are described.

Thermally responsive SMP's

Heat is the most common stimulus for SMP's. As explained earlier, thermally responsive SMP's depend on netpoints and molecular switches for the shape memory effect. By heating the material above its transition point, it becomes plastically deformable. Deforming causes internal stresses within the material, which are trapped once the material is cooled down while the new shape is maintained by an external force (low entropy state). When reheated, the internal stresses cause shape recovery of the permanent shape, and the material reaches the state of highest entropy.

Photo responsive SMP's

Photo responsive SMP's react to light stimuli by undergoing reversible changes in their properties. This is either caused by photochemical reactions or particles that convert light to heat. In photochemical reactions, reversible photoreactive molecular switches are incorporated in the material, which alter the structure of the crosslinked polymer network when exposed to light of a specific wavelength. These structural alterations change the overall polymer network in a way that macroscopic deformation occurs, meaning that a photo responsive SMP can recover its original shape when exposed to light of a specific wavelength.

Another photosensitive mechanism is the use of molecular switches that convert light to heat in thermally responsive SMP's Radiant thermal energy of infrared light possessing a wide range of spectra (500~4000 cm^{-1}) can in this case be used as a heat source.

Electrically Responsive SMP’s

Electricity can also be used to enable shape memory in thermally responsive SMP’s. Most SMP’s have high thermal and electrical resistance. To increase electrical conductivity in the material, electrically conductive elements are added. This enables the material to be heated using a method called internal resistive joule heating, in which the material is heated by a current passing through the conductive element network. This method has certain advantages compared to external heating, such as convenience, more uniform heating and remote controllability.

Magnetically responsive SMP’s

Like electrically responsive SMP’s, magnetically responsive SMP’s are created by adding magnetic particles to a thermally active SMP. The material can then be heated using an alternating magnetic field, which causes inductive heating. This method enables the material to be rapidly heated as the heat is generated into the polymer itself.

Solution responsive SMP’s

The main mechanism behind shape recovery in solution-responsive SMP’s is the interaction between polymeric macromolecules and the micromolecules of a solution. When an SMP is introduced to a solution (water or a solvent), molecules from the solution are able to infiltrate and bond with the SMP. The formed hydrogen bonds have a plasticizing effect on the SMP, and increase the flexibility of the macromolecules. The interaction between the solution and the SMP also causes an increase in volume of the SMP, which largely decreases the elasticity modulus of the material, as explained by the continuum theories of rubber elasticity, the Mooney-Rivlin equation and volume change refinement theory (Lv et al., 2008). This actually causes the T_{trans} of the SMP to decrease until it is the same as the temperature of the solution/environment. Until T_{trans} reaches this level, the solution softens the material. The factors combined can trigger the actuation of an SMP.

pH-responsive SMP’s

In pH-responsive SMP’s, shape memory is triggered by a change in pH, independent from temperature. These SMP’s are created by adding certain chemical components to the polymer, which can form atomic bonds. By changing the pH-value of the materials environment, this atomic bonding can be disrupted or enabled, triggering shape recovery. (Li et al., 2018)

2.3.2 ASSESSING SHAPE MEMORY PROPERTIES

When assessing the shape memory abilities of a shape memory polymer, there are several parameters which are important to consider:

- **Cycle life**
  Number of shape memory cycles a component can experience without failing

- **Shape/strain fixity**
  The ability of the material to retain its shape in the deformed state. In SMP's, this can be calculated using the following equation:

$$R_f(N) = \frac{\varepsilon_u(N)}{\varepsilon_m} \times 100$$

  Where N represents the number of cycles, E_u the fixed temporary strain after the external load is removed, and E_m the initial strain caused by the external load.

- **Cycle time**
  The time it takes to complete a shape memory cycle, from start of the deformation to end of recovering

- **Shape/strain recovery**
  The ability of the material to regain its permanent shape. In SMP's, this can be calculated using the following equation:

$$R_r(N) = \frac{\varepsilon_m - \varepsilon_p(N)}{\varepsilon_m - \varepsilon_p(N-1)}$$

  Where E_p represents the permanent strain, and (N-1) represents the previous cycle. (Bengisu & Ferrara, 2018)

2.3.3 ONE-WAY SHAPE MEMORY EFFECT

2.3.3.1 DUAL-SHAPE MEMORY

The most common type of shape memory in SMP's is the so called ''dual-shape memory effect''. As the name implies, these SMP's have two states, namely a permanent and temporary shape. The permanent shape is the shape which the material remembers and returns to under the right conditions, with the right conditions usually being a temperature above the materials transition temperature (T_{trans}) and no external forces being applied to the SMP object. The temporary shape is a deformation of the permanent shape caused by an external force. Dual-shape memory includes both the so-called one-way shape memory effect, where shape recovery only occurs from the temporary shape to the permanent shape, as well as the two-way shape memory effect, in which case a material can switch between two shapes based on the external stimuli. Both types of shape memory are displayed in figure 8. Later in the report, two-way shape memory will be further explained.

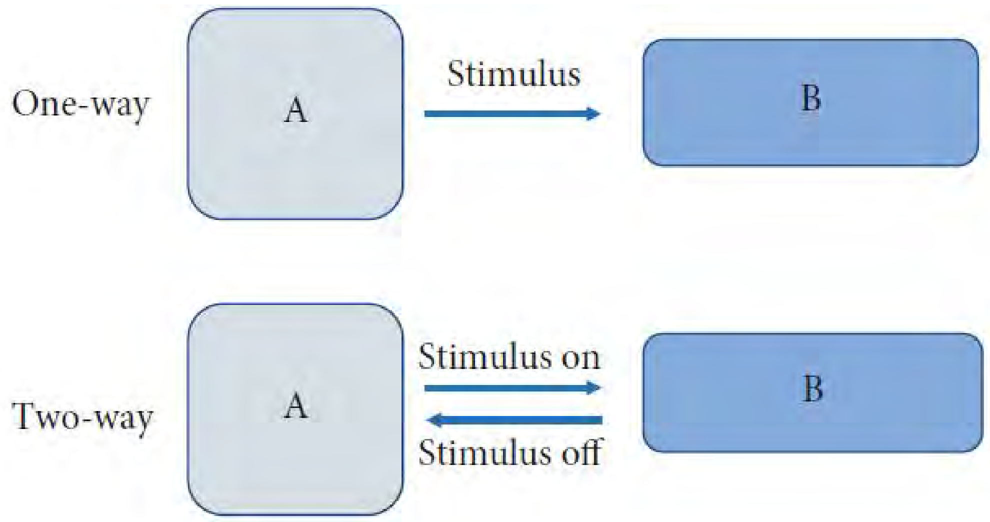


Figure 8 one-way and two-way shape memory (Li et al., 2018)

2.3.3.1.1 MECHANISMS

There are different mechanisms which can be responsible for the shape memory effect in polymers. Two of the leading mechanisms are dual-state and dual-component shape memory (Wu et al., 2013) For the dual state mechanism, a SMP needs to be heated above its transition point, which can be either the glass transition point or melting point, depending on the specific polymer. Above T_{trans}, the material gets soft and can be plastically deformed. If the new shape is maintained by an external force when the material is cooled below T_{trans} and returns to its glass state, this shape will be frozen. The external force can be removed and the part will stay in its new, temporary shape. As mentioned earlier, the temporary state possesses lower entropy than the permanent shape, caused by the crosslinking network. Once the part is reheated above T_{trans}, the internal stresses in the material cause the part to recover its permanent shape, which is the state of highest entropy (as long as there are no external forces preventing recovery) (Bengisu & Ferrara, 2018; Xie 2011)

The dual component mechanism involves a copolymer consisting of two or more segments. The segment with the highest transition temperature (T_{perm}), often referred to as the hard segment or matrix, serves as the netpoints of the material, and is responsible for setting the permanent shape. The molecule chains of the other segment, the soft/inclusion segment, act as molecular switches, allowing recovery and temporary shape fixing. The lower transition temperature of the soft segment allows for a phase transition of only this segment of the material when the material is heated above T_{trans}. When this happens, the part can be plastically deformed. This causes internal stresses in the hard segment. When cooled, the soft segment returns to its glassy state, freezing the temporary shape. Once heated above T_{trans} again, the soft segment gets soft, and the internal stresses in the hard segment cause shape recovery. (Bengisu & Ferrara, 2018; Wu et al., 2013).

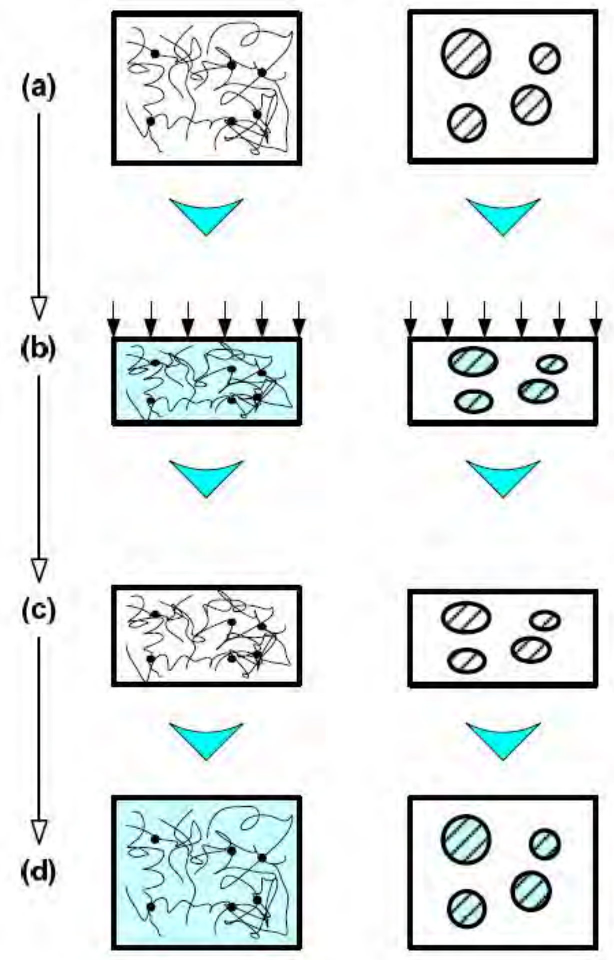


Figure 9 Dual-state (left) and Dual-component (right) shape memory. A: initial shape. B: shape deformation. C: temporary shape fixation. D: Shape recovery. (Wu et al., 2013)

2.3.3.2 TRIPLE-SHAPE MEMORY EFFECT

As discussed earlier, the dual-shape memory effect enables a SMP to switch between two shapes: a permanent shape (remembered shape) and a temporary shape which can be different for each recovery cycle, depending on the external load. However, it is also possible to achieve a shape memory cycle in which the SMP is able to fix and recover more temporary shapes. With the triple-shape memory effect (triple-SME), there is one permanent shape, and two temporary shapes which can be fixed and recovered. Thus, a total of three shapes involved. Triple-SME relies on two distinct thermal transitions in a crosslinked network, which can each be used for fixing a temporary shape.

Triple-SME is practically an extension to dual-shape memory, as the principle of shape fixation and recovery by utilizing the thermal (glass) transition of the material is also used here, only extended with an extra step enabled by another thermal transition.

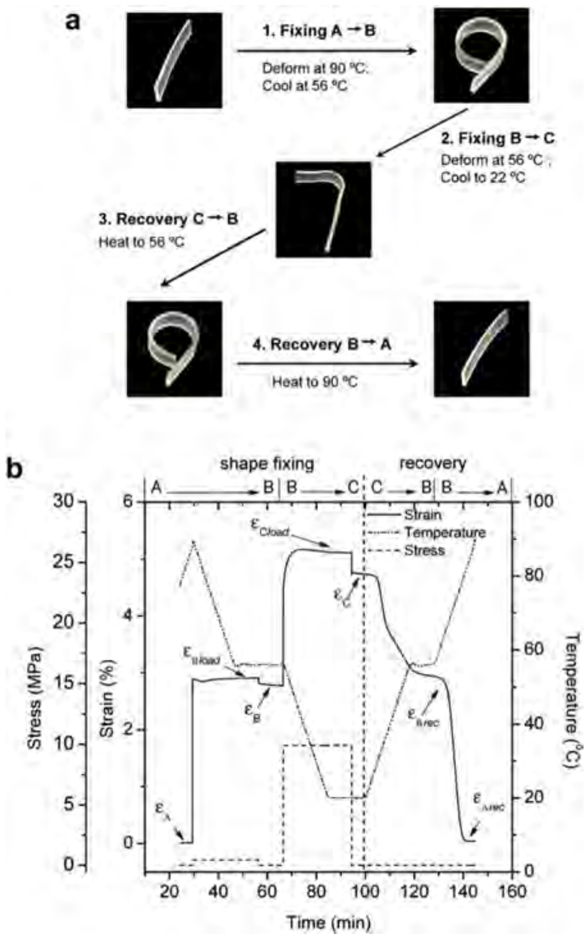


Figure 10 triple shape memory cycle (Xie et al., 2009)

In figure 10, a triple-shape memory cycle of a bilayer polymer consisting of two epoxy dual-shape memory polymers, is illustrated (Xie et al., 2009). This bilayer polymer has two distinctive glass transition temperatures, due to being composed of layers made of different materials, namely 38°C and 75°C. In the two-step shape fixing process displayed in the figure, shape A was heated to 90°C (above both T_gs) and deformed to temporary shape B, after which it was cooled to 56°C (between the two T_gs) and the deformation force was released. For the second shape fixation step, the material was deformed again at 56°C, after which it was cooled below the lowest T_g to room temperature (20°C). After removing the deformation force, the sample was fixed to temporary shape C. Recovery took place without an external load. The sample was heated to 56°C again, which made it recover to temporary shape B. After recovery, the sample was then heated to 90°C, which led to recovery of permanent shape A.

Based on the data shown in figure 10, the following equations can be used to determine shape fixity and shape recovery:

$$R_f(X \rightarrow Y) = (\varepsilon_y - \varepsilon_x)/(\varepsilon_{y\ \mathrm{load}} - \varepsilon_x)$$

$$R_r(Y \rightarrow X) = (\varepsilon_y - \varepsilon_{x\ \mathrm{rec}})/(\varepsilon_y - \varepsilon_x)$$

The R_f equation can be used to determine the shape fixity when deforming from a shape X to a shape Y, with E_y and E_x resembling the fixed strains after cooling and load removal for shape Y and X respectively, and $E_{y\ load}$ resembling the maximum strain under load. The R_r equation can be used to determine the shape recovery from a shape Y back to a shape X, with $E_{x\ rec}$ resembling the strain after recovery.

Other ways to achieve triple-SME have also been reported. One alternative does not follow the two-step shape fixing as described earlier, but instead achieves triple-SME through one-step shape fixing, as explored by. Although this method is not suitable for programming two independent strains into the SMP, and it only yields an overall shape fixity, SMP's programmed with this method show two distinct steps during the recovery process, making them triple-SMP's. Shape recovery for this method is done by gradually heating the material instead of two-step heating as with two-step shape fixing. However, this method of heating is also suitable for two-step shape fixing, although both heating methods lead to different results.

It is also possible for a single polymer to possess two thermal transitions. Semicrystalline polymers for example usually have an amorphous phase (thus a glass transition) as well as a crystalline phase. By crosslinking these materials, it is possible to achieve triple-SME. As an example, Qin and Mather (2009) were able to achieve triple shape behaviour based on two transitions in a liquid crystalline homopolymer. However, the two transitions were difficult to tune in this material. Tunability of the triple-shape functions is important for application of the triple-SME. This is for example easily achievable with bilayer polymers. Tuning can be done by changing the ratio between the components of the bilayer, or by changing (the chemical composition of) the components to change thermal transition temperatures. These types of triple-SMP's are also relatively easy to make, as the chemistry of the epoxy which bilayer polymers are composed of is relatively simple, making it an accessible method for non-chemists to produce triple-SMP objects. A crucial requirement for achieving proper triple-SME in layered polymers is a strong interfacial bond between layers. Otherwise, the stresses caused by shape deformation and recovery may lead to chain slippage and delamination.

Luo and Mather (2010) created a triple-SMP composite by embedding thermoplastic nanofibers with a transition temperature of 55°C into a crosslinked SMP matrix with a glass transition between 20°C and 45°C. Although there was no strong cohesion between the matrix and the fibres, triple-shape memory was achieved, believed to be caused by a different stress transfer mechanism due to the robust physical confinement of the fibres. Because the two components of the composite are decoupled, this approach is quite attractive, and could also be applied to different material combinations. (Xie, 2011)

2.3.3.3 TUNEABLE MULTI SHAPE MEMORY

The introduction an extra transition is what allowed for the discovery and development of triple-shape memory. However, it is possible to introduce more transitions enabling a material to switch between more than three predefined shapes. An example is the indication of quadruple-SME for a multi-phase polyolefin system, reported by Kolesov and Radusch (2008). One of the main focus points in the development of SMP's has been the tailoring of transition temperatures. Traditionally, this is achieved by altering a materials chemical composition. However, this becomes increasingly difficult the more discrete transitions are needed for a multi-SME.

A phenomenon which can be used to achieve multi-SME without altering the chemical composition of the material is called tuneable-SME. This phenomenon relies on a broad thermal transition, during which the material can change shape multiple times. The theory behind this is that ''*a single broad thermal transition can be viewed as the continuous distribution of an infinite number of infinitely sharp transitions. Each of these sharp transitions can be further regarded as an elemental memory unit (EMU) with a corresponding* T_{trans}'' (Xie, 2011). This means that only EMUs that have a transition temperature below the deformation temperature are activated for shape recovery. As the temperature of the material changes (within the broad transition), different EMUs get activated, enabling the material to recover deformations performed at that temperature.

Using this phenomenon, triple shape memory can be achieved, by deforming a material at two different temperatures (the deformation temperatures) within the transition range. With different groups of EMUs being activated at the two deformation temperatures T_{d1} and T_{d2}. Thus, the triple-SME is tuneable by choosing at which temperature to deform the material. This is different from ''traditional'' triple-SMP's, where T_{d1} and T_{d2} need to be between and above the two transition points of the material respectively. Therefore, the EMUs will activate as long as the material is above a transition temperature, regardless of the exact deformation temperature (it makes no difference if the material is deformed just above or further above the transition temperature). Nafion (tetrafluoroethylene-based fluoropolymer-copolymer) is an example of a material which exhibits multi-SME while having a single (broad) transition.

2.3.3.4 TEMPERATURE MEMORY EFFECT

The concept of EMUs can also be used to explain the so-called temperature memory effect. Just like multi-SME, this phenomenon relies on a broad thermal transition. Temperature memory effect refers to the ability of a SMP to memorize a temperature. More specifically, this means that when shape recovery is triggered in a pre-deformed sample under constraint, the temperature at which maximum recovery stress occurs is close to the temperature at which the pre-deformation was caused. This happens because only once the deformation temperature is reached, all EMUs previously activated for shape fixing are re-activated for recovery, leading to a peak in recovery stress. However, the same principle can also be applied to strain recovery (strain-based temperature recovery). As opposed to stress-based temperature recovery, strain is recovered under stress free conditions. When continuously heating the SMP, the highest recovery rate can be observed around the deformation temperature. Figure 11 shows the strain recovery behaviour for Nafion deformed at different temperatures, as published by Xie et al. (2011). Here it shows that recovery rate is at its maximum around the corresponding deformation temperature. With the temperature memory effect, it is possible to tune the stress or strain recovery of a single polymer in a wide range a quantitatively predictive way.

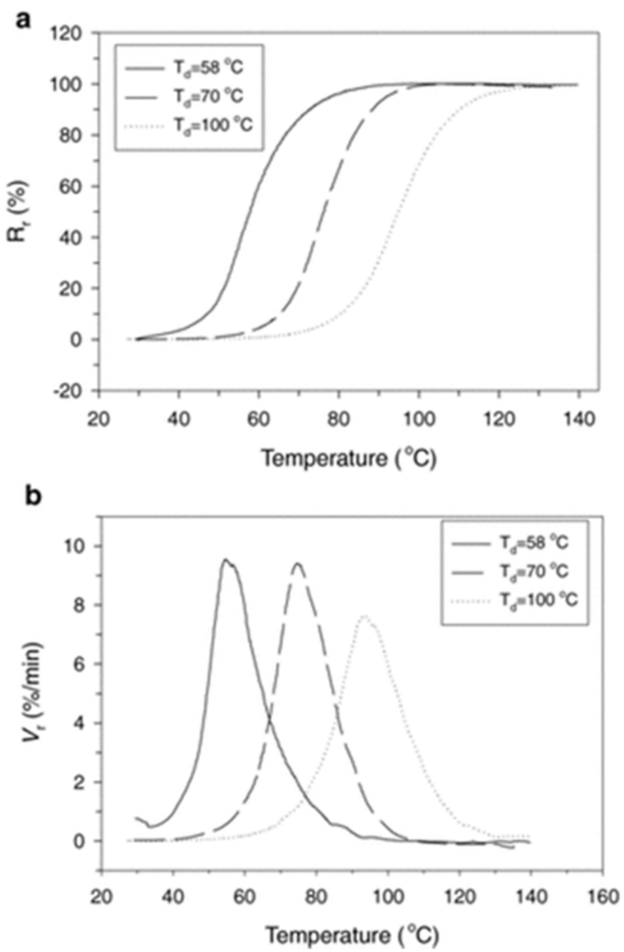


Figure 11 Strain recovery behaviour for Nafion. a: Change of strain recovery. b: change of instantaneous strain recovery rate (Xie et al., 2011)

2.3.4 TWO-WAY SHAPE MEMORY EFFECT

As mentioned before, the two-way shape memory effect allows for an object to switch between two predefined shapes under the influence of an external stimuli (see figure 8). The advantage of two-way shape memory as compared to one-way shape memory is that no direct input is needed from the user to deform the object so that shape recovery can take place. This allows for different kinds of applications. There are different approaches to attain two-way shape memory in polymers, explained below. These approaches are also displayed in figure 12.

<u>Liquid crystalline elastomers (LCE)</u>

LCEs combine the elastic properties of an elastomer with the self-organization of the liquid crystalline phase. A liquid crystalline polymer consists of domains, in which the mesogens (molecule groups) are ordered in the same direction. These domains can be disorderly oriented with respect to each other, in which case the material is referred to as a polydomain material. However, these domains can be aligned (thus also aligning the mesogens) by either physical or chemical means, resulting in a monodomain material. The easiest way to achieve this is by stretching the material. By crosslinking the material in the monodomain/stretched state, a two-way SMP can be created.

When this material is heated, melting induced contraction occurs. The melted domains return to the preferred, more disorderly state, which causes the material to contract. When cooling the material, the crosslinks cause the domains to align again, leading to crystallization-induced elongation, thus returning the material to its other shape. This mechanism allows for elongation up to 500% (Warner & Terentjev, 2007). Among other things, the elongation of these materials allows for a wide range of applications. However, utilization is limited due to the high costs of the complex procedure of creating these materials.

<u>Semi-crystalline networks</u>

It is also possible to achieve two-way shape memory with semicrystalline polymers. However, these SMP's have to be under constant stress in order to yield two-way shape memory. This constant stress enables the material to be elongated when cooling due to creep strain. Once the SMP is heated again, the restoring force of the material is able to overcome the constant load (if the constant load applied does not exceed the recovery force in the first place), thus recovering its original shape. This is due to the fact that an SMP recovers its contraction force when heated above its transition temperature, while it loses this force below the transition temperature. This method of attaining two-way shape memory has gained attention as the process and tailoring of the transformation temperatures is relatively easy compared to other ways of achieving this effect. However, application is still limited due to the need for a constant external force.

<u>Composites</u>

A polymer based two-way shape memory composite (2W-SMC) are usually made of two different polymers, which are either both one-way SMP's or a one-way SMP combined with a non-shape memory elastomer. In case of the latter, the first step is to heat the SMP above its transition temperature and bent it, after which it is cooled to fix the shape. Then, using an adhesive, the elastomer is laminated onto the deformed SMP. Once this composite is heated again, the SMP part will try to recover its original/permanent shape, and create recovery force. This will cause the composite to deform, and puts a strain on the elastomer. When the composite is then cooled again, the SMP will lose its recovery tension, and the stress in the elastomer will cause the composite to go back to its other shape. Although polymer composites provide the easiest way of creating a two-way shape memory polymer, it has limited deformability and slow shape-changing speed which limit the application of these materials.

<u>Interpenetrating network (IPN)</u>

Interpenetrating networks combine two or more polymers into an intertwined network. Shape memory is achieved through a switch-spring mechanism, as displayed in figure 13, with the elastomeric part of the network serving as the spring and the crystalline part as the switch. When the material is heated, the switch part opens, leading to shrinkage in the material, compressing the elastomeric spring part. Once the material cools down again, the elastic recovery of the spring enables recovery of the previous shape, with crystallization occurring in the direction of the spring (Zare et al., 2019)

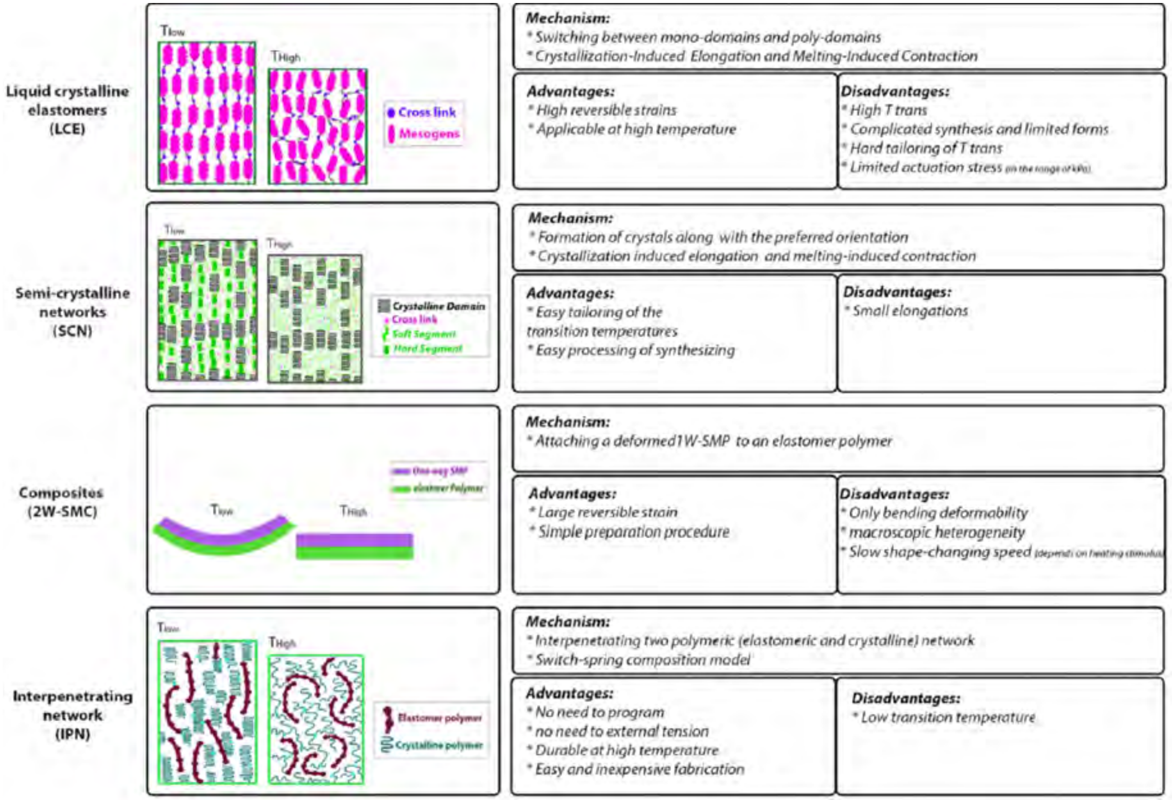


Figure 12 Different methods to achieve two-way shape memory (Zara et al., 2019)

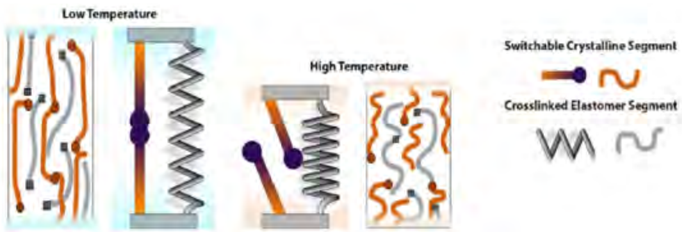


Figure 13 Switch spring mechanism of an interpenetrating network (Zara et al., 2019)

2.4 CONCLUSIONS

In this Chapter, the shape memory effect in polymers has been addressed. The material properties allowing for shape memory, as well as the different types of shape memory have been described. In general, shape memory in polymers relies on two material requirements: the presence of a (thermal) transition point, and a crosslinking network (netpoints). Through different types of stimuli, like temperature, light or electricity, an SMP can switch between a glassy and rubbery state. In the rubbery state, the material can be deformed. When the material goes back to its glassy state, and the deformation is maintained, the material becomes fixed in a temporary shape. By exposing the material to the stimulus again, it can return to its rubbery state, and if no external forces are applied, the material recovers its permanent shape. This can either be direct (dual-shape memory), with an intermediate step/shape (triple-shape memory) or with multiple intermediate steps/shapes (multi-shape memory). Certain materials / material compositions can display two-way shape memory, in which case the material can switch between two predefined shapes without the need for an external force to deform the material, as opposed to one-way shape memory, in which the material

3 MANUFACTURING

This chapter discusses the manufacturing part of the literature review. In this chapter, different topics will be addressed, starting with an introduction on conventional production processes for SMP’s, followed by a description of 3D-printing technology, and how this can be used for printing SMP’s

The questions that will be addressed in this chapter are:

- what are the characteristics of different 3D-printing technologies?
- How can 3D-printing be used to make shape memory objects, and what factors influence the shape memory properties of a 3D-printed object?
- Which shape memory materials are currently available?

3.1 CONVENTIONAL PRODUCTION PROCESSES

In general, manufacturing methods used for regular polymers are also suitable for shape memory polymers. The difference between regular and shape memory polymers production lies in their molecular designs (see ‘’molecular structure’’). Depending on the exact type of polymer, different manufacturing methods might be available. Conventional machining processes like CNC-milling can be used for preformed SMP blocks or sheets. Thin SMP sheets can also be laser cut to create the desired object shape.

Casting is another alternative. Epoxy-based SMP’s for example, can be cast using a suitable mould, which can be either a flexible material like silicone or a rigid material like Teflon. To improve casting quality, it is recommended to use a vacuum to remove air bubbles. After casting, the casted object needs to be hardened through curing. This can be achieved by adding a hardener to the cast material, UV-light or other means.

Injection and extrusion moulding are also possibilities for manufacturing SMP objects, using commercially available SMP’s. Although these are not widespread so far, different materials are available, like Tecoflex and Diaplex, produced by Lubrizol and Mitsubishi respectively. Diaplex is a semi-crystalline thermoplastic polyurethane, which glass transition temperature can be adjusted from -40 to 90°C. This material is available as pellets, solutions, foam, fibre and microbeads, and can be used for injection and extrusion moulding, as well as for other forming processes. As is also the case for regular polymers, when moulding SMP’s, problems such as volumetric contraption, bubble formation and void formation can occur. Correct design of both the mould and part, and dehumidification of the resin generally solves these issues (Bengisu & Ferrara, 2018).

3.2 3D-PRINTING

3D-printing, or additive manufacturing, is the process of constructing a three-dimensional object from a digital file. The principle of 3D-printing was already imagined as early as the 1970's, but the first publication of 3D-printing experiments dates back to early 1980's. in 1981, Dr Hideo Kodama described a layer by layer approach of creating a 3D-object, using a photosensitive resin that was polymerized using UV-light, similar to modern-day stereolithography (SLA). In the years after, 3D-printing technology was further developed and more different 3D-printing methods emerged (*The History of 3D Printing: From the 80s to Today*, 2020). In recent years, additive manufacturing has gained the attention of the general public, with a great deal of hobbyist printers being available for use at home, and high-end printers being used in industry to produce products ranging from consumer goods to prosthetics, tools, and parts used in the automotive industry. Where 3D-printing was first only used for prototyping and one-off manufacturing in early stages of the process, it is rapidly developing to become a proper production method.

The general principle of 3d printing is the build-up of an object from successive layers of material. A digital 3D-model forms the basis of the process. 3D-models are often created using CAD (computer-aided design) software, or from 3d-scans. Either way, to print a physical representation of the digital model, it needs to be sliced. Using slicer software, the 3d-model is sliced into thin horizontal layers. These layers will then be consecutively printed on top of each other to create the 3D object.

3.2.1 TYPES OF 3D-PRINTING

There are different 3D printing processes, each suitable for specific purposes and materials, which can be categorized in seven categories:

Vat Photopolymerization

Printers based on this method use photopolymer resin, which is hardened or ''cured'' using a UV light source. There are three processes which are classified as Vat Photopolymerization, which mainly differ in the way the material is cured (type of light source):

- Stereolithography (SLA)
- Digital Light Processing (DLP)
- Continuous Liquid Interface Production (CLIP)

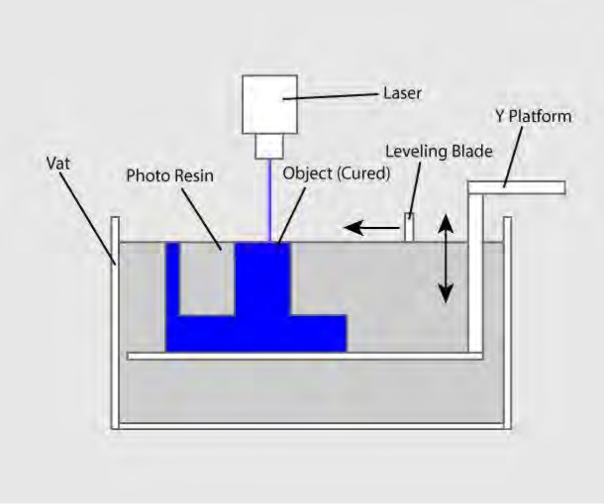


Figure 14 VAT photopolymerization (3DPrinting.com, 2020)

Material Jetting

This process is similar to the way an inkjet printer works, as material is applied in droplets through a small nozzle. The material is applied layer by layer to a build platform, after which it is cured using UV light

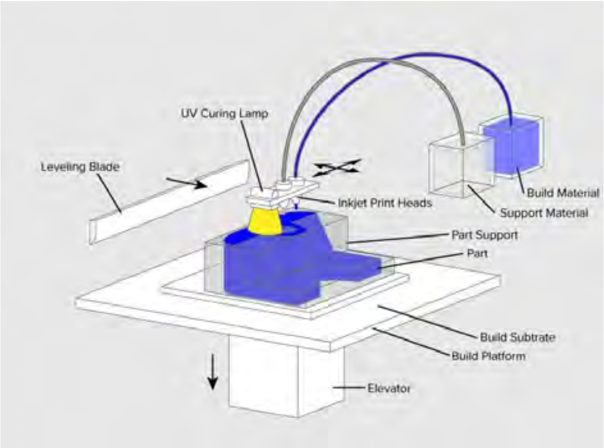


Figure 15 Material Jetting (3DPrinting.com, 2020)

Binder Jetting

In binder jetting, the print is built up of equal layers of a powder material. This powder is bound together by a second component, a liquid binder, which only binds the powder that is necessary to create the model. Once the print is finished, all remaining powder can be cleaned off and often re-used for a next print.

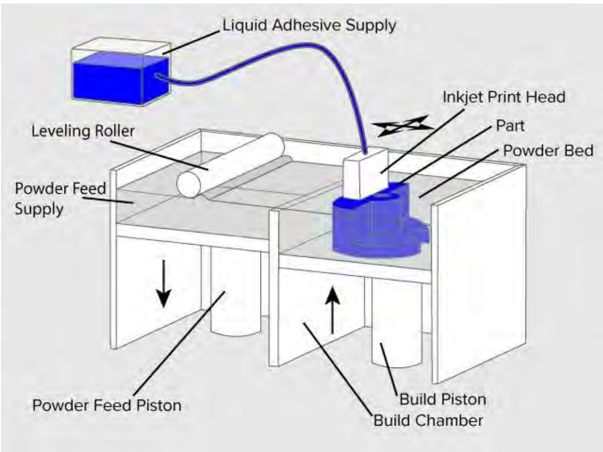


Figure 16 Binder Jetting (3DPrinting.com, 2020)

Material Extrusion

The most common type of additive manufacturing, material extrusion uses a spool of filament which is supplied to an extrusion nozzle where it is heated and extruded. The nozzle (or the print bed) can move in the X and Y direction the material is extruded through a nozzle to create a layer, after which it moves upwards to print consecutive layer on top of this.

The process is usually referred to as Fused Deposition modelling (FDM) or Fused Filament Fabrication (FFF).

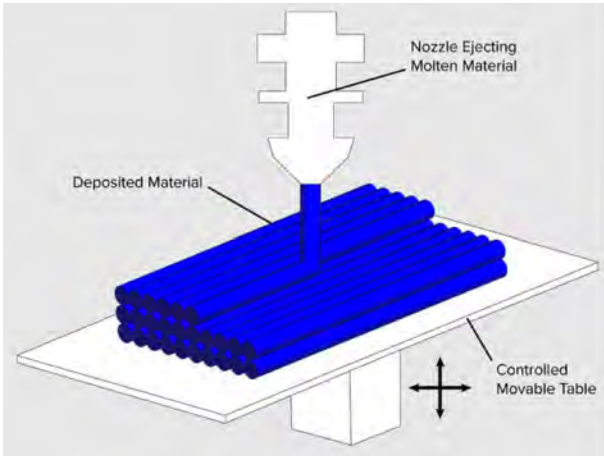


Figure 17 Material extrusion (3DPrinting.com, 2020)

Powder Bed Fusion

Powder bed fusion uses powder as the main material for building up the 3d-object, which is fused together using thermal energy. There are three processes within this category:

- Multi Jet Fusion (MJF)
- Selective Laser Sintering (SLS)
- Direct Metal Laser Sintering (DMLS)

In all three processes, just as with binder jetting, the powder is distributed in equal layers, and only selectively bonded together. Unbonded powder can often be re-used.

In MJF, an additional binder agent is added which is selectively applied to create the desired shape. Using thermal energy, the powder and binder react and create the printed object.

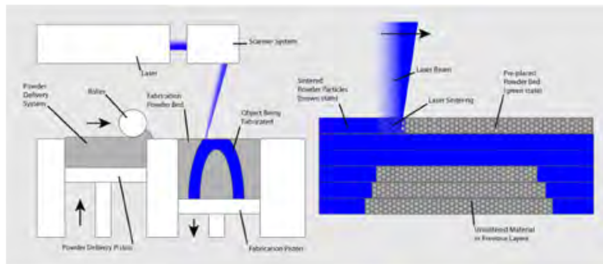


Figure 18 Powder bed fusion (3DPrinting.com, 2020)

Sheet Lamination

This process involves sheet material which is bound together using external force, after which they are formed (cut or milled) into the desired shape. The sheets can be metal, paper or some kind of polymer.

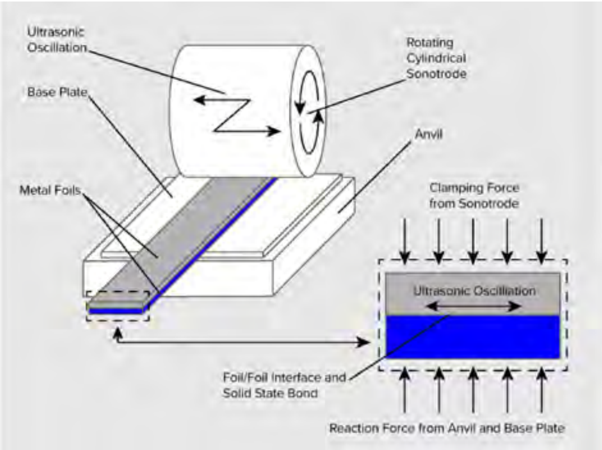


Figure 19 Sheet lamination (3DPrinting.com, 2020)

Directed Energy Deposition

Mostly used in the metal industry, directed energy deposition refers to the method of depositing metal powder or wire on a surface through a nozzle, after which an energy source, for example a laser, melts it to form a solid object. These elements are usually attached to a multi-axis robotic arm for moving the 3D printing apparatus. (3DPrinting.com, 2020)

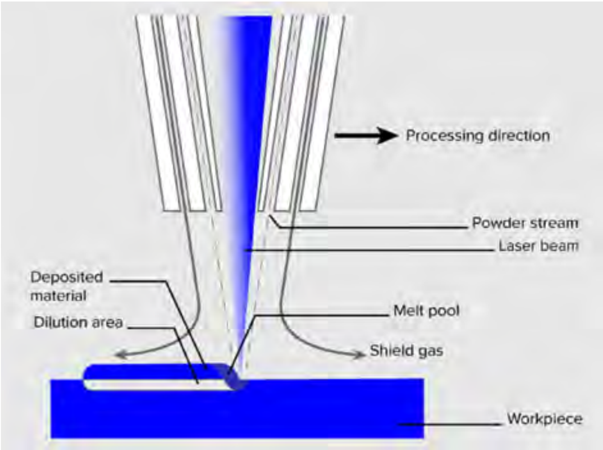


Figure 20 Directed energy deposition (3DPrinting.com, 2020)

On the next page, in table 2, an overview of the described 3D-printing processes is given, comparing the characteristics of each process. This table shows how different printing processes are used for different purposes and materials. Each of these processes has their own strengths and weaknesses, which makes them suited for different applications. This table also shows that certain processes are not suited for printing SMP objects, mainly due to the materials which are used in these processes.

*Table 2 comparison between different 3d-printing processes (*The Types of 3D Printing Technology*, 2020 /* Metal 3D Printing: What is Direct Energy Deposition? *2018 /* Sheet Lamination | Additive Manufacturing Research Group | Loughborough University*, n.d.)*

	VAT photo-polymerization	Material jetting	Binder jetting	Material extrusion	Powder bed fusion	Sheet lamination	Direct energy deposition
Material	Photopolymer resin (Standard, Castable, Transparent, High Temperature).	Photopolymer resin (Standard, Castable, Transparent, High Temperature).	Sand or metal powder: Stainless / Bronze, Full-colour sand, Silica (sand casting).	Thermoplastic filament (PLA, ABS, PET etc.).	Polymers: Thermoplastic powder (Nylon 6, Nylon 11, Nylon 12) Metals: Metal Powder: Aluminium, Stainless Steel, Titanium.	Sheet material: paper (most common) plastic and metal.	Metal powder or wire: including titanium alloys, stainless steel, tool steels, aluminium alloys etc.
Dimensional accuracy	±0.5% (lower limit ±0.15 mm)	±0.1 mm	±0.2 mm (metal) or ±0.3 mm (sand)	±0.5% (lower limit ±0.5 mm)	Polymers: ±0.3% (lower limit ±0.3 mm) Metals: ±0.1 mm	0.1-0.19 mm (layer thickness)	0.5-3.0 mm
Common applications	Injection mould-like polymer prototypes; Jewellery (investment casting); Dental applications; Hearing aids.	Full-colour product prototypes; Injection mould-like prototypes; Low run injection moulds; Medical models.	functional metal parts; Full-colour models; Sand casting.	Electrical housings; Form and fit testings Jigs and fixtures; Investment casting patterns.	Polymers: Functional parts; Complex ducting (hollow designs); Low run part production Metals: Functional metal parts (aerospace and automotive); Medical; Dental.	Aesthetic and visual models.	Functional parts; structural parts in satellites aircraft and architecture; repair of parts; modification of parts.
Strengths	Smooth surface finish; Fine feature details.	Best surface finish; Full colour and multi-material available.	Low-cost; Large build volumes; Functional metal parts.	Best surface finish; Full colour and multi-material available.	Polymers: Functional parts, excellent mechanical properties; Complex geometries Metals: Strongest, functional parts; Complex geometries.	High speed, low cost, easy material handling, full colour.	Repair of functional parts, large sizes possible, high printing speed, multi-material capabilities, limited material waste.
Weaknesses	Brittle, not suitable for mechanical parts.	Brittle, not suitable for mechanical parts; Higher cost than SLA/DLP for visual purposes.	Mechanical properties not as good as metal powder bed fusion.	Brittle, not sustainable for mechanical parts; Higher cost than SLA/DLP for visual purposes.	Polymers: Longer lead times; Higher cost than FFF for functional applications Metals: Small build sizes; Highest price point of all technologies	May require post-processing, limited material use, fusion processes not optimal (yet), not suited for functional uses.	Low resolution and poor surface quality, high costs, not possible to make parts that need support structures (for overhangs etc.).

3.2.2 MULTI MATERIAL PRINTING

Multi material printing is a form of additive manufacturing where two or more materials are used at the same time to print a single object. This vastly expands the possibilities in design, allowing for variations in colour or technical properties within one object/part. This technology has the potential to reduce time and costs for both manufacturing and assembly, and reduce the need for post-processing (e.g. colouring), creating an advantage on several aspects over other manufacturing methods. (Pires, 2020)

Several types of 3d-printing are capable of multi material printing. In stereolithography, multiple reservoirs can be used to supply different photopolymers, between which can be switched during printing to create sections (layers) with different properties. Material jetting makes use of multiple nozzles to print droplets of photopolymers. These nozzles can each extrude a different photopolymer, thus allowing for multi material printing. In binder jetting, it is not possible to print with multiple materials. However, there exist machines which have an extra nozzle next to the binder supplying nozzle, which can apply pigment to the layer after the binder to create full-colour prints. (“Multi-Material 3D Printing”, 2020)

FDM printing also allows for multi material printing, which can be achieved in different ways. Even with a ‘’normal’’ FDM printer, not equipped with any features aimed at multi material printing, this is possible. By pausing the print at any point, it is possible to manually change the filament, leading to the rest of the object to be printed with the second material. Although a relatively easy method for multi material printing, it is difficult to place the material in specific regions of a layer. A printer with two extruders allows for better material control. Generally referred to as dual extrusion, it is possible to either print an object out of two materials, or use the second nozzle to print dissolvable supports. Another option is to use printer attachments which manage filament switching operations. An example is the Mosaic Palette 2, produced by Mosaic productions (figure 21). This device can manage four different types of filament. By splicing and fusing different parts of filament based on when different materials are needed during the printing process, specific types of filament can be applied to specific locations in the printed object. (Pires, 2020)

Figure 21 Mosaic Palette 2. Four different types of filament enter the device (bottom), which are then spliced and fused to create one filament wire with different properties for different sections (top) (Pires, 2020)

With multi material 3d-printing, it is possible to create shape memory objects with localised shape memory effect. For example, an object containing a hinge part can be printed from a non-shape memory material, while only the hinge part is made of an SMP. Thus, by exposing the object to the SMP’s activation stimulus, the hinge can deform, changing the shape of the object.

3.2.3 FDM PRINTING OF SMP'S

3D-printing is a promising production technique for SMP objects. 3D printing of shape memory materials introduces an extra dimension, which is why it is often referred to as 4D printing (see figure 22). This extra dimension refers to the ability of the material to transform over time. 4D printing makes it possible to print objects that would normally be too large or too time consuming to print due to additional support material. By printing a shape in a folded state, objects that would otherwise have to be printed as several separate components can now be printed in one piece (see figure 23). The other way around is also possible: by printing a specific object which can then be compressed or folded for easy transportation, after which it can be brought back to its intended shape. This technique, combined with the characteristics of SMP's, gives SMP's great potential for a wide variety of applications.

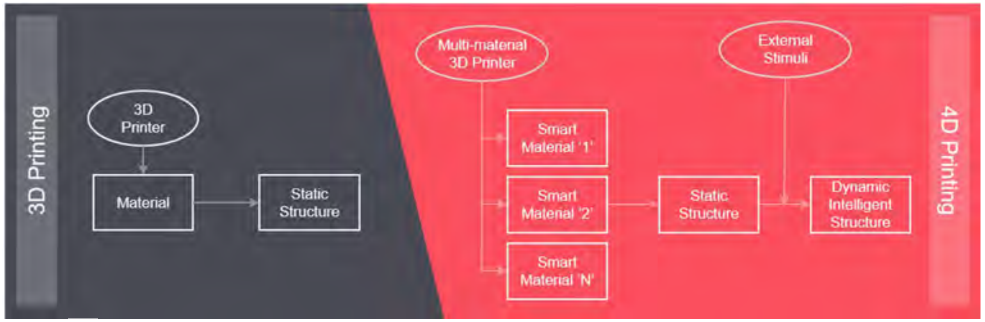


Figure 22 3d-printing and (multi-material) 4d-printing processes compared ((4D Printing – The Technology of the Future, 2020)

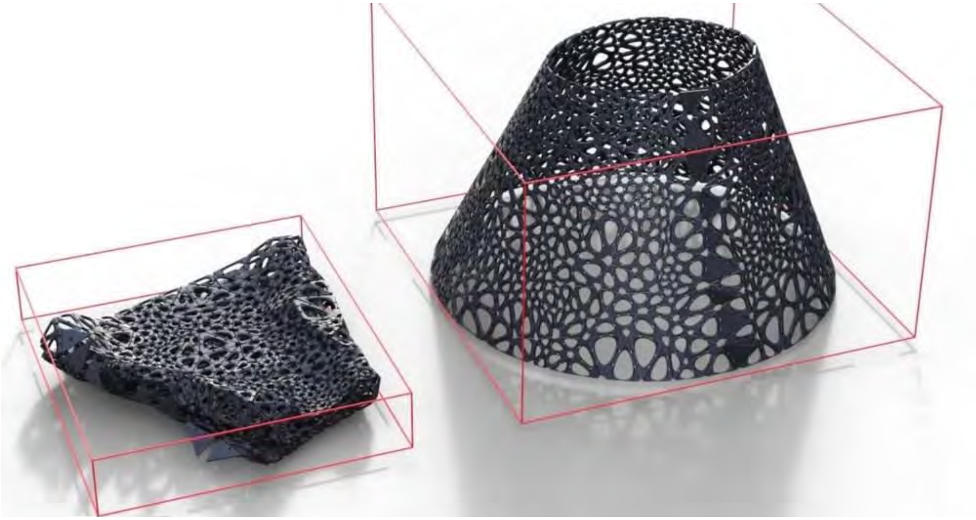


Figure 23 printing of a folded shape, which is deformed to the intended shape after printing, leading to an 87% decrease in print volume (4D Printing: A technology coming from the future, 2020)

3.2.3.1 PRINTING PARAMETERS

Apart from the design of an object and the material used to print this object, the properties of the 3D-printer and the changeable parameters need to be considered when creating shape memory objects using additive manufacturing. Printer settings can significantly affect the mechanical properties of a print, influencing the shape memory capabilities of the printed object. Knowledge about how different parameters concerning for example accuracy and reliability affect shape memory capabilities is still lacking. However, in recent years, with the growing interest and application of additive manufacturing, there have been studies investigating the effect of printing properties on shape memory.

Mehrpouya et al. (2020) tested the influence of different parameters on the shape memory capabilities of an FDM-printed unfolded pyramid made of PLA. The design of the test sample can be seen in figure 24. While keeping all other parameters constant, four parameters were selected and changed for different samples: Activation temperature (temperature of the water the sample was put in for shape recovery), Layer height, Printing temperature and Sample thickness. During the experiments, the samples were put in 65°C water for 60 seconds, deformed and cooled to room temperature. Afterwards, the samples were submerged in hot water again (either 65,70 or 75°C) for 30 seconds to recover their original shapes. The shape recovery/unfolding process was recorded with a digital camera. Using tracking software, the video footage was analysed to evaluate the unbending of the samples.

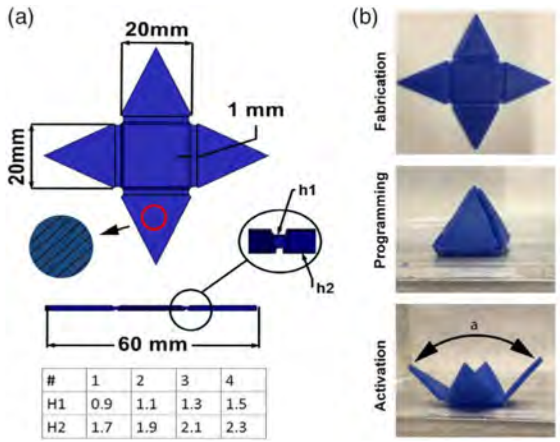


Figure 24 (a) design of the test sample (b) different steps of the testing process (Mehrpouya et al., 2020)

From the data, it was concluded that **activation temperature** has a superior role in shape recovery, with higher activation temperatures resulting in a higher recovery rate (complete recovery at 75°C, while only 75% recovery at 65°C). It did not have a significant influence on activation time. From this, it can be concluded that initial heat penetration depends on model structure, while amount of heat influences shape recovery. **Sample thickness** was the second most influential parameter tested. This parameter does influence activation time significantly, with thickest samples having a 7 second longer response time than the thinnest samples. However, maximum recovery was still reached around a similar time for all samples, despite differences in activation time. **Layer height** also influences activation time to some extent, with a smaller layer height leading to longer activation times. This is thought to be caused by the amount of air gaps between print lines. With a smaller layer height, there are less air gaps, making it more difficult for heat to penetrate the print, thus increasing activation time. It was also found that by increasing the layer height, The speed of unbending and recovery rate increase (Increasing layer height from 0.15 to 0.3mm increased recovery from 77% to 88%). Lastly, **printing temperature** had little effect on shape memory capabilities, with only slight changes in activation time (samples printed with a higher nozzle temperature react later). However, this can significantly affect mechanical properties of the print.

3.2.3.2 SELF-BENDING

A common occurrence in 3d-printed SMP's is self-bending. This refers to the phenomenon of a printed SMP object deforming when exposed to an external stimulus (heat) without an external force acting on it. This is caused by internal stresses that get trapped in the material when the material cools down during printing. Printing parameters (as well as design and material parameters) can have a significant influence on the degree that self-bending occurs. A study by van Manen et al. (2017) focused on **layer orientation** for making use of the self-bending phenomenon to design flat objects which could fold themselves into the intended shape without external forces. In this study, different objects made of PLA were printed using a hobbyist FDM-printer. It is described how printed lines of filament expand in the width direction, while they shrink in the length direction when heated above glass transition temperature (figure 25). Using this phenomenon, structures with hinge parts were designed where, by combining layers printed in different directions, self-bending was utilized for controlled deformation (figure 26).

Apart from the influence of line orientation on self-bending/twisting, the literature also describes the effect of some other parameters. A higher **nozzle temperature** and **layer height** lead to less strain, while a higher **activation temperature** leads to more strain. This is in line with research presented by Esfahani (2021). This research focused on the effect of printing parameters on self-bending. Concluding from this research, parameters related to temperature have the biggest influence on self-bending. As also described by van Manen et al. (2017), increasing the nozzle temperature and layer height decreases self-bending. Furthermore, increasing **build plate temperature** increases self-bending, just as increasing **fan speed** and **printing speed** increase this. Increasing **sample thickness** however results in less bending.

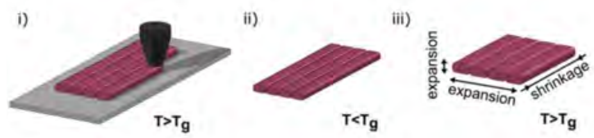


Figure 25 expansion and shrinkage of printed lines (van Manen et al., 2017)

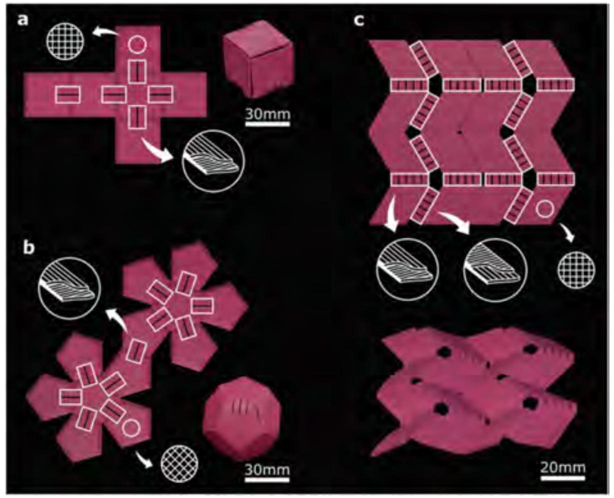


Figure 26 self-foldable structures with hinge parts achieved by utilizing the shrinkage and expansion of the printed lines (van Manen et al., 2017)

3.2.3.3 SEQUENTIAL SHAPE CHANGE

As described earlier, layer height and sample thickness have an influence on activation time of shape recovery/ self-bending, with an increase in layer height and decrease in sample thickness lowering the time needed for the material to heat up above the transition temperature. This can be used to create so-called sequential shape change, since an SMP only starts deforming when all material has reached a temperature above the glass transition. Van Manen et al. (2017) designed different objects using sequential shape change, by altering sample thickness and adding **grooves** in the active areas. The grooves allowed for faster heating, since heat could more easily reach the innermost material. In figure 27, the two nature inspired designs by van Manen et al. are shown. The sequential shape change is displayed, as well as the specific dimensions and groove structure used in the active sections.

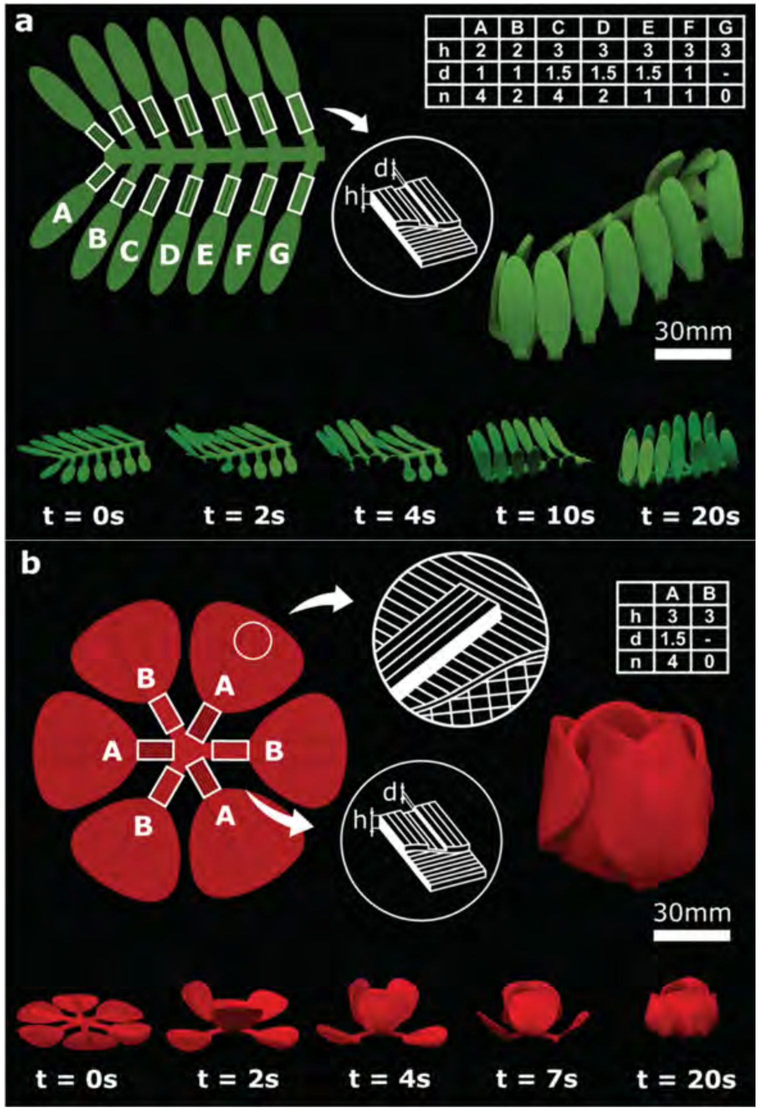


Figure 27 Sequential shape changing objects, using thickness variations and grooves in the active sections to achieve sequential shape change

Without relying on self-bending, sequential shape recovery can also be achieved. Using material jetting, Yu et al. (2015) created a spiral-like object with multiple hinges. Prior to printing, seven material compositions were created by mixing two liquid monomers in specific ratios. This resulted in material compositions with different glass transition temperatures. The composition with the lowest T_g was assigned to the inner two hinges (1 and 2 in figure 28), while the composition with the highest T_g was assigned to the two outermost hinges (8 and 9 in figure 28). The other compositions were assigned to the remaining hinges in between, in order of ascending T_g (3-7 in figure 28).

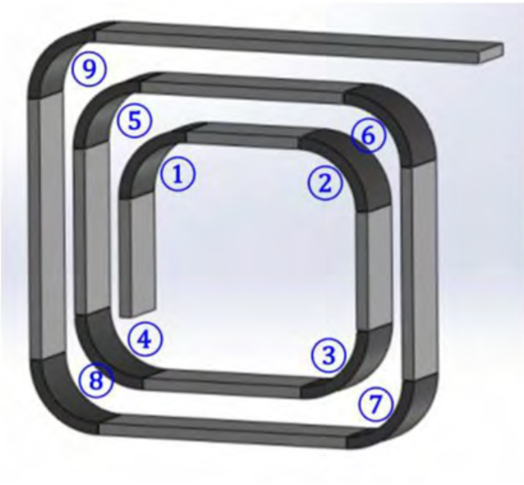


Figure 28 design of the spiral shape sample (Yu et al., 2015)

After printing the spiral shape, it was straightened in water of 100ºC and cooled afterwards. To initiate shape recovery, the sample was put in hot water again. This resulted in sequential shape recovery, as displayed in figure 29.

A control test was performed using the same spiral shape where all hinges were printed using the same material composition (figure 30). This resulted in a non-sequential shape recovery.

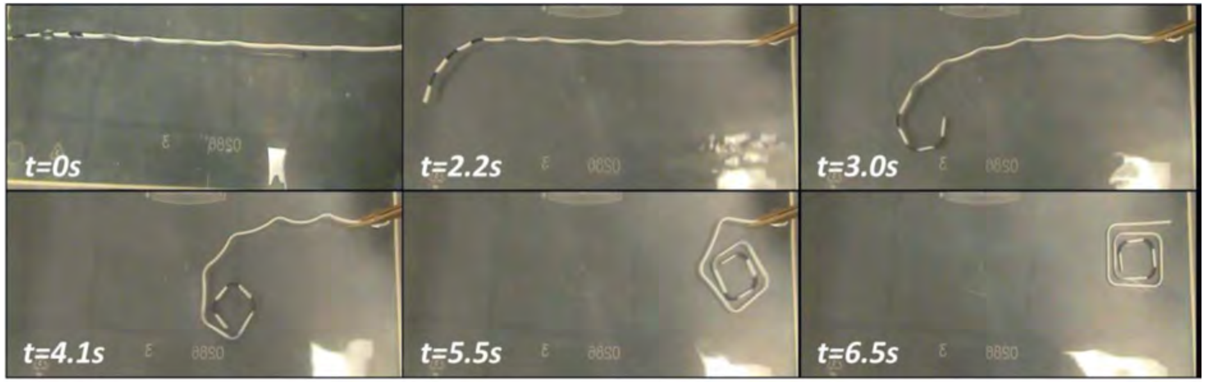


Figure 29 sequential shape recovery of the straightened spiral shape, using different material compositions for different hinge parts (Yu et al., 2015)

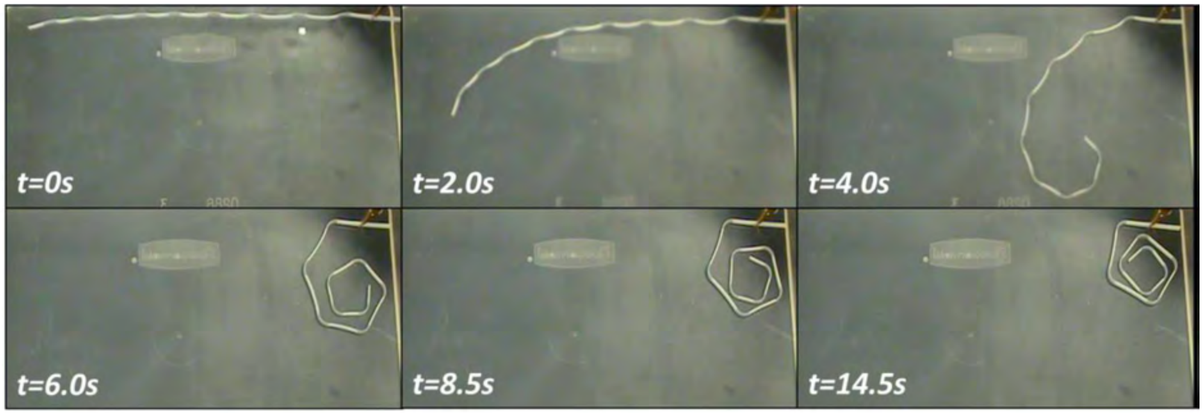


Figure 30 non-sequential shape recovery using the same material composition for different hinge parts (Yu et al. 2015)

3.2.3.4 MATERIAL AVAILABILITY

The availability of SMP's specifically for 3d-printing is limited. Looking at FDM printing, there are commercially available filaments, although the composition of these materials is proprietary. (SMP Technologies 2016). However, as previously discussed, most polymers possess shape memory properties to a certain extent. That is why PLA, a commercially available filament which is widely used but generally not marketed as an SMP, has been used in multiple instances for (research on) 3d-printed SMP objects. Another alternative applied by researchers is the use of in-house made SMP filaments. Yang et al. (2016) made filament from Diaplex pellets, by heating and extruding the material to form thin filament. An overview of commercially available SMP's is shown in table 3

SLA printing is also suited for printing thermosets. Zarek et al. (2016) used a PCL (polycaprolactone) based resin to print various forms and test the shape memory abilities, with the aim to fabricate SMP components for flexible and responsive electrical circuits. This could be applied in soft robotics, wearable materials and medical devices (Bengisu & Ferrara, 2018).

Table 3 Overview of commercially available SMP's (Sun et al., 2019)

Polymer	Activation temperature	Main-features
ABS	T_g: 105°C	Thermo-plastic Excellent heating-responsive SME
EVA	T_g: 60°C	Thermo-plastic Excellent heating/chloroform-responsive SME
PC	T_g: 142°C	Thermo-plastic Excellent heating-responsive SME
PCL	T_m: 55°C	Thermo-plastic Bio-degradable Excellent heating-responsive SME Programmed at low temperatures
PEEK	T_g: 155°C	Thermo-plastic Excellent heating-responsive SME
PLA	T_g: 65°C	Thermo-plastic Bio-degradable Good heating-responsive SME
PMMA	T_g: 115°C	Thermo-plastic Good heating/ethanol-responsive SME
PS	T_g: 65°C	Thermo-set Good heating/acetone-responsive SME
PTFE	T_g: 65°C T_m: 325°C	Thermo-plastic Excellent heating-responsive SME Two-step recovery upon heating
PU	T_g: 35-65°C	Thermo-plastic/thermo-set Bio-compatible Excellent heating/ethanol/water-responsive SME
PVA	T_g: 30°C	Thermo-plastic Excellent heating-responsive SME Water-responsive SME
TPU	T_m: 55°C	Thermo-plastic/vitrimer Excellent heating responsive SME

3.3 CONCLUSIONS

SMP's can usually be manufactured using conventional production techniques like injection moulding, CNC milling and casting. Additive manufacturing, or 3D-printing, is a promising technique for producing SMP objects, which has become widely accepted as a proper production technique in recent years. With the development of multi material printing, the technique offers unique advantages in terms of cost and labour reduction, and creating object with non-uniform properties. The most well-known and widely used type of additive manufacturing is FDM-printing, in which filament is heated and extruded in lines, creating layers of material. These layers are stacked to create 3d objects. 3D-printing of shape memory materials is often referred to as 4D-printing, as shape memory materials introduce the dimension of time (shape change). By varying the printing parameters used, the shape memory properties of a material can be controlled. By combining this with smart design, objects can be created which can deform through self-bending, which can allow for sequential shape change. However, SMP materials are generally not commercially available for 3d printing, although regular used materials in FDM printing, like PLA, possess shape memory capabilities, and can be used to design shape memory objects. In table 4, the effect of the different parameters on shape memory behaviour and self-bending, as discussed in this chapter, is displayed. The identified parameters and their effects will form the basis of the guidelines and further testing during this project.

Table 4 Effect of different parameters on the shape memory behaviour of a SMP

Parameter	effect
Activation temperature	Large influence: higher activation temperature leads to a higher recovery ratio, and more self-bending.
Layer height	Increasing layer height reduces activation time somewhat and increases recovery rate and speed. It also decreases self-bending.
Sample thickness	Influence on activation time: increasing sample thickness increases activation time, and reduces self-bending.
Printing temperature	Printing at a higher temperature slightly increases activation time and reduces self-bending.
Layer orientation	Influences the degree and direction of self-bending/twisting.
Build-plate temperature	A higher build plate temperature increases self-bending.
Printing speed	Higher printing speed increases self-bending.
Fan speed	Higher fan speed (cooling) increases self-bending.
grooves	By adding grooves in an active area, surface area increases and heat can penetrate the material easier, leading to shorter activation times.
Material (composition)	Different materials have different properties, influencing shape memory behaviour.

4 DESIGN

This chapter discusses the design part of the literature review. In this chapter, a design methodology aimed at designing with shape memory polymers will be described, followed by a benchmark of projects and products utilizing the shape memory effect in polymers. The described methodology can be used by designers as a basis for designing with shape memory materials, and certain elements of this method will be used for designing concepts and the demonstrator further in the project.

The questions that will be addressed in this chapter are:

- How does the use of SMP's in design influence the design process?
- What is the current state of research on and application of SMP's?

4.1 METHODOLOGY

Designing shape memory objects requires an approach which befits the unique properties of shape memory materials. In a more traditional design process, the materials that will be used are expected to behave in a certain way, while a shape memory material can behave differently over time depending on external factors like temperature, moisture etc. So, when designing with these materials, a design approach is needed which accounts for the changing properties of the material, and allows for optimal use of these properties. In the book '' Shape-Memory Polymer Device Design'' by Safrinski and Griffis (2017), a design method is presented which was created for designing with shape memory polymers. An overview of this method is shown in figure 31. In its core, it is comparable to more traditional design processes, in the sense that the main ''stages'' are similar. However, the exact steps to be taken within each stage are aimed specifically at designing with SMP's.

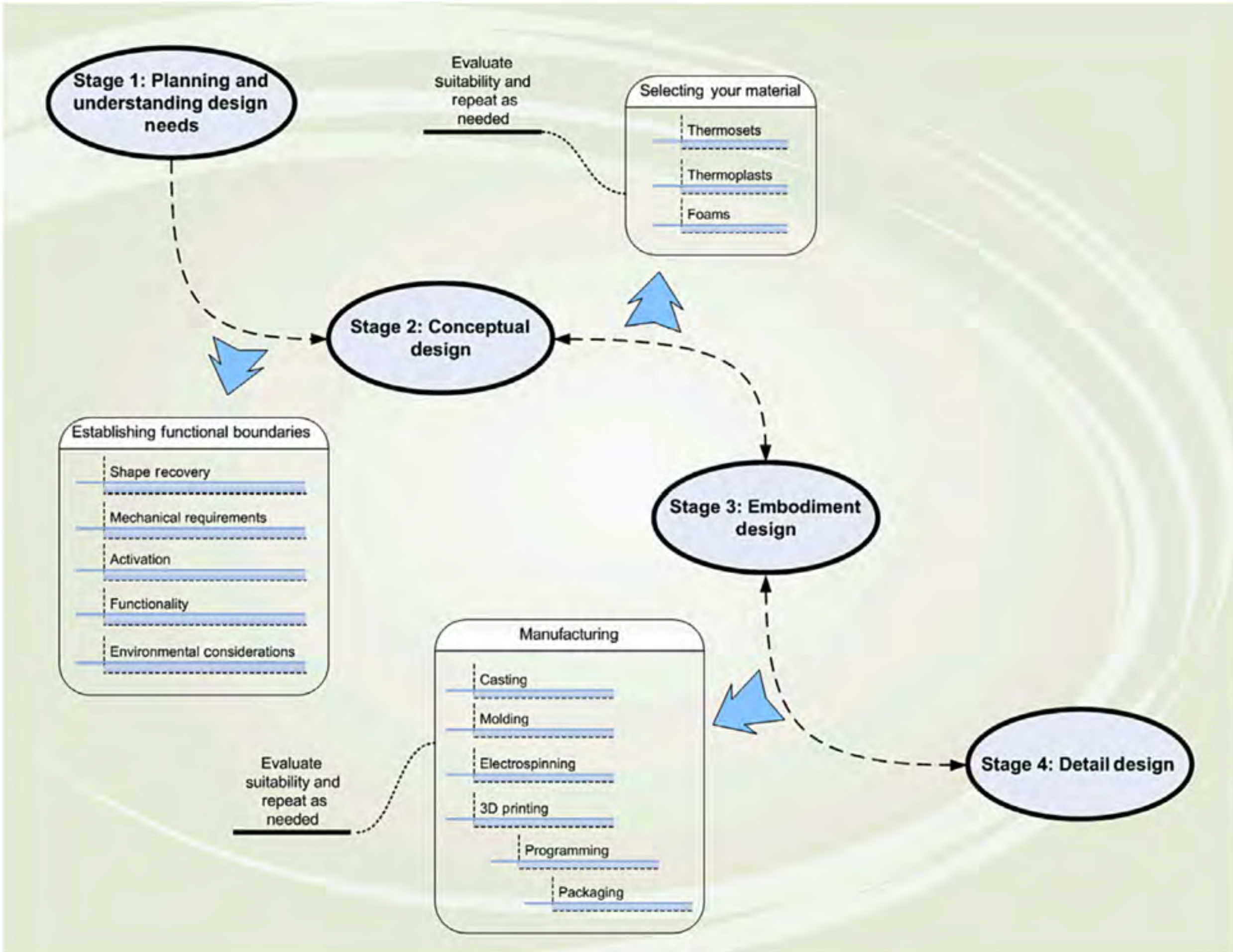


Figure 31 Overview of a design process for designing with SMP's (Safranski & Griffis, 2017)

4.1.1 STAGE 1: PLANNING AND UNDERSTANDING DESIGN NEEDS

The first step of the process involves specifying the design task and the aim the design needs to achieve. For this, requirements and needs need to be identified and qualified. These might not be entirely clear from the start, and might need additional development and clarification throughout the design process. Due to the active nature of SMP's, a common pitfall for designers is to be overly ambitious in defining the intended use of the material. Therefore, it is important to have well-defined expectations and preferences for the materials functioning. This includes understanding the limitations of the material, to be able to design around these limitations successfully. There are several different aspects which need to be considered during the design process. Figure 32 shows an overview of these different aspects and choices that need to be made by the designer, such as the functioning of the shape memory material (e.g. activation, type of shape memory, shape recovery), how it will be manufactured and how the product will be used. Identifying and specifying all important aspects and choices is important to end up with a well-rounded design/solution.

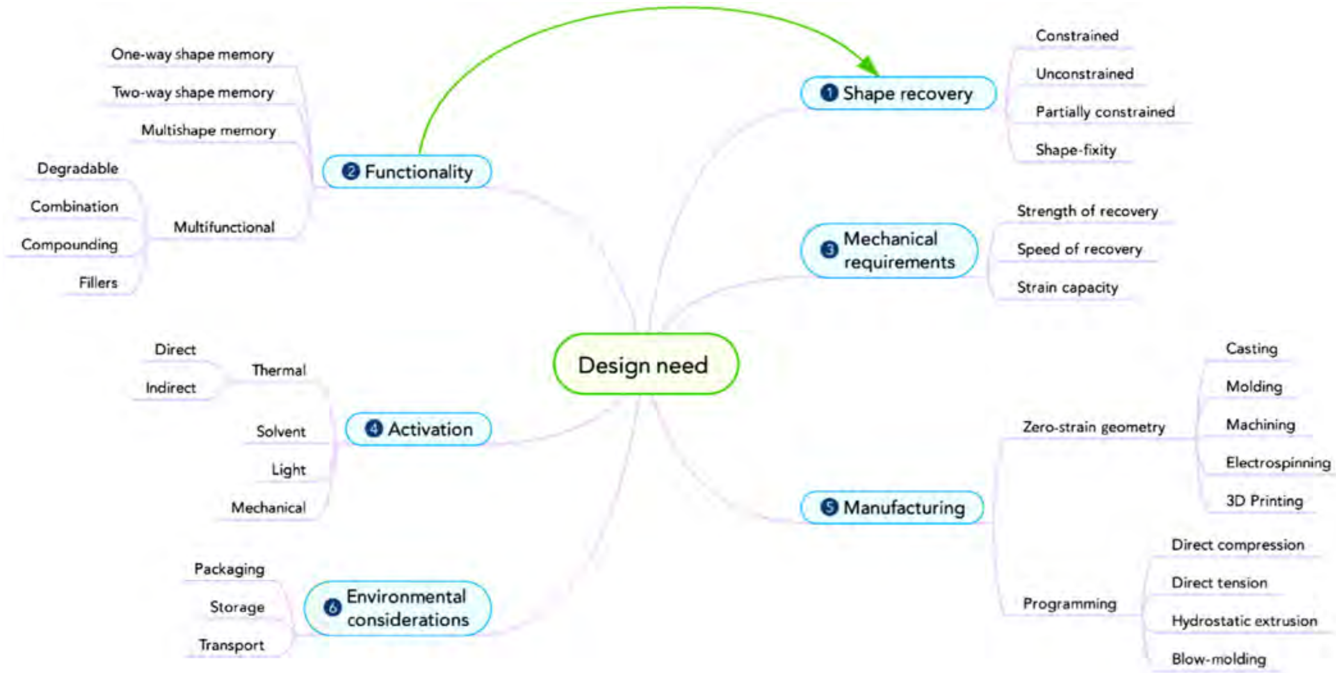


Figure 32 Different aspects in the design process when designing with SMP's (Safranski & Griffis, 2017)

4.1.2 STAGE 2: CONCEPTUAL DESIGN

Similar to designing with traditional materials, conceptual design or ''ideation'', starts with defining the design goal. Having a design goal which clearly states the intent of the final product regardless of shape memory capabilities prevents the designer from focusing on how to use SMP's to improve the design, which could lead to a design driven by a particular material. A three step process is described to create concepts to fulfil the design goal.

ESTABLISHING FUNCTIONAL BOUNDARIES

At the first step, the functional boundaries are established. For SMP's, the functionality usually takes the shape of a transformation of the material (bending, stretching etc.). Therefore, it is important to determine and describe the desired result for the ''starting'' state, and the desired result(s) for the ''ending'' state of the design. Different factors are considered when specifying the functioning of an SMP (component):

<u>Actuation</u>

Actuation force is an important aspect to define, as SMP components can vary significantly in the amount of recovery force they produce. When the maximum actuation force needed and the movement required during deployment are known, the SMP actuator can be designed accordingly.

<u>Method of activation</u>

As described in chapter 2, there are different methods to activate SMP's, with the most common being thermal activation. It is important to know the activation requirements for a material to select the right material and design the SMP components in such a way these requirements can be met.

<u>Speed and strength of recovery</u>

Speed and strength of recovery can be defined for unconstrained, partially constrained and constrained scenarios, with partially constrained and constrained recovery requiring a force working on the recovering material. The maximum speed of recovery is generally achieved close to the programming temperature of the material.

<u>Strain capacity</u>

Strain capacity refers to the magnitude to which the material can deform. For some materials, this can be influenced by changing the programming temperature. Due to variability in batch processing of polymers in general, the programmed strain should not exceed 80% of the failure strain, to ensure proper shape recovery.

<u>Shape memory effect and multifunctionality</u>

As discussed in chapter 2, SMP's generally display one way shape-memory behaviour. However, two-way shape memory can also be achieved in certain cases. Furthermore, different variants of one-way shape memory have also been achieved in recent years, like triple and multi shape-memory. These different options can be considered when designing SMP components. However, as mentioned earlier in this chapter, it is important not to over functionalize SMP's, as this can affect the materials properties and compromise its ability to operate successfully.

ESTABLISHING MECHANICAL REQUIREMENTS

The next step is to establish the mechanical requirements of the design. In this step, the functional attributes of other, non-shape-memory parts of the design are considered and the interaction between SMP and non-SMP parts is specified. Based on this, different material and product solutions can be explored. It is worth noting that limiting the complexity of the geometry of the active parts improves the chance of a successful design.

ESTABLISHING ENVIRONMENTAL CONSIDERATIONS

The third step of conceptual design is environmental considerations. In this step, the designer thinks about environmental exposure (heat, light etc.), as this can impact the shape memory properties of the SMP. Both for the use environment and for the time the product spends in shipping and storage, environmental conditions must be identified, so proper protections can be implemented to ensure that the product will function as intended for the intended lifespan. The protections can be implemented in the product itself, in packaging or by including storage instructions.

Throughout the process, solutions are thought up to deal with or fulfil the points addressed in each step. This way, a wide range of solutions to functions or subfunctions is created, both in terms of product designs and materials to be used, which are then assessed on evaluation criteria set up by the designer for each of the aspects of the overall function. The most promising material and product (sub)solutions are chosen and combined into concepts fulfilling the design goal. The chosen concept(s) will be taken to the next stage.

4.1.3 STAGE 3: EMBODIMENT DESIGN

In the embodiment stage, the created concepts are further developed. With the general concept being the input for this stage, the focus is on developing the details. It might be that in this stage the concept turns out to not be suitable to achieve the design goal, in which case the conceptual design stage must be repeated. If the concept is still viable, it needs to be developed and prototyped to such an extent that it can be tested on functional, mechanical and environmental levels. This way, it can be ensured the design meets the requirements. Once the embodiment of the product suffices, material characterization can be performed as a preparation for stage 4, to discover potential challenges with using the selected SMP in terms of manufacturing, assembly and packaging, and potentially change the material if needed.

4.1.4 STAGE 4: DETAIL DESIGN

In the final design stage, the selected solution is developed into a product which is production ready. This includes the development of manufacturing, assembly, packaging and storage aspects. In terms of manufacturing SMP components, there are different methods available, as discussed in the chapter 3, with casting and moulding being the most often used, depending on the design and specific material selected. 3D-printing has significant potential for creating SMP objects, as it is possible to design complex geometries with highly variable strain requirements during programming.

For assembly of products containing shape memory parts, it can occur that programming of the material is needed for assembly. Correct programming is crucial for ensuring good shape memory behaviour. Depending on the material, different stimuli can be used to activate the material, as discussed in chapter 2. Different means can be used for deformation, of which compression and tension are the most common to compress or stretch the material respectively. Other options include bending, torsion, or even extrusion of the material above in its active state.

Packaging and storage are also important aspects to consider for shape memory objects. In both scenarios, the SMP objects must be protected from unintended activation caused by environmental activation conditions. Failing to do this might lead to unintended activation under constrained conditions, which can affect long-term shape-fixity and cause stress and creep relaxation. Also, for packaging, potential spring-back needs to be considered. The packaging must be designed to account for this. This might prove challenging if the SMP for example has a broad activation temperature. In this case a possible solution is to design packaging in a way that the material can partially recover into a partially constrained state.

Over time, SMP's can degrade under certain environmental conditions. Therefore, it is important to store these objects in a way that environmental conditions can't affect them, meaning for example that for certain materials it is important that they are not exposed to moisture or high temperatures for prolonged storage.

4.2 BENCHMARKING

To get a good overview of existing applications of SMP's, benchmarking was performed. Different examples were found that show the possibilities of SMP application in different fields, and different techniques which can be used to manufacture these SMP objects. The benchmarking includes both existing applications as well as concept applications and explorative models resulting from research projects. As the material used in this project (PLA) is a temperature-activated SMP, the benchmark lists different examples of temperature-activated SMP applications, with the heat source and exact material composition differing for the different examples. All found examples are categorized based on application type and manufacturing method. More details about each of the examples can be found in appendix A.

Three main categories were identified for application type: functional, aesthetic and research, with the last category containing examples that don't have a specific purpose other than researching the material and its behaviour. Most of the examples fit in the ''functional'' category however, as is shown on the next page in figure 33. Within this category, there are three main application areas: medical, soft robotics and active (dis)assembly. In the medical area, most examples are activated by body heat, thus enabling these products to be rather simple in their construction, as no extra external or internal heating components are needed for activation. In the active (dis) assembly area however, all examples are activated by an external heat source. The activation temperature of the materials used here is higher than what the materials are exposed to in normal use situations, ensuring the material will only be activated when this is desired. Lastly, the soft robotics area contains examples of grippers reacting to an external heat source to contract and grab small items, showing that the recovery force of these materials is high enough to lift small objects.

In figure 34, the same examples are recategorized based on manufacturing method. Since this project focuses on (FDM) 3D-printing, the three identified manufacturing categories are 3D-printing (FDM), 3D-printing (other), and other for non 3D-printed examples. The FDM 3D-printing category mainly contains fairly simple structures that are not bound by low tolerance, made of one or two materials. The examples in the ''3D-printing (other)'' category are more complicated in terms of material composition, with several examples being composed of multiple materials to achieve specific results. Lastly, the ''other'' category contains non 3D-printed examples. Most medical examples belong in this category, which can be explained by the specific requirements medical products generally need to meet. Apart from medical examples, this category contains several examples which are not suited for 3D-printing due to the materials used or the envisioned functioning of the object.

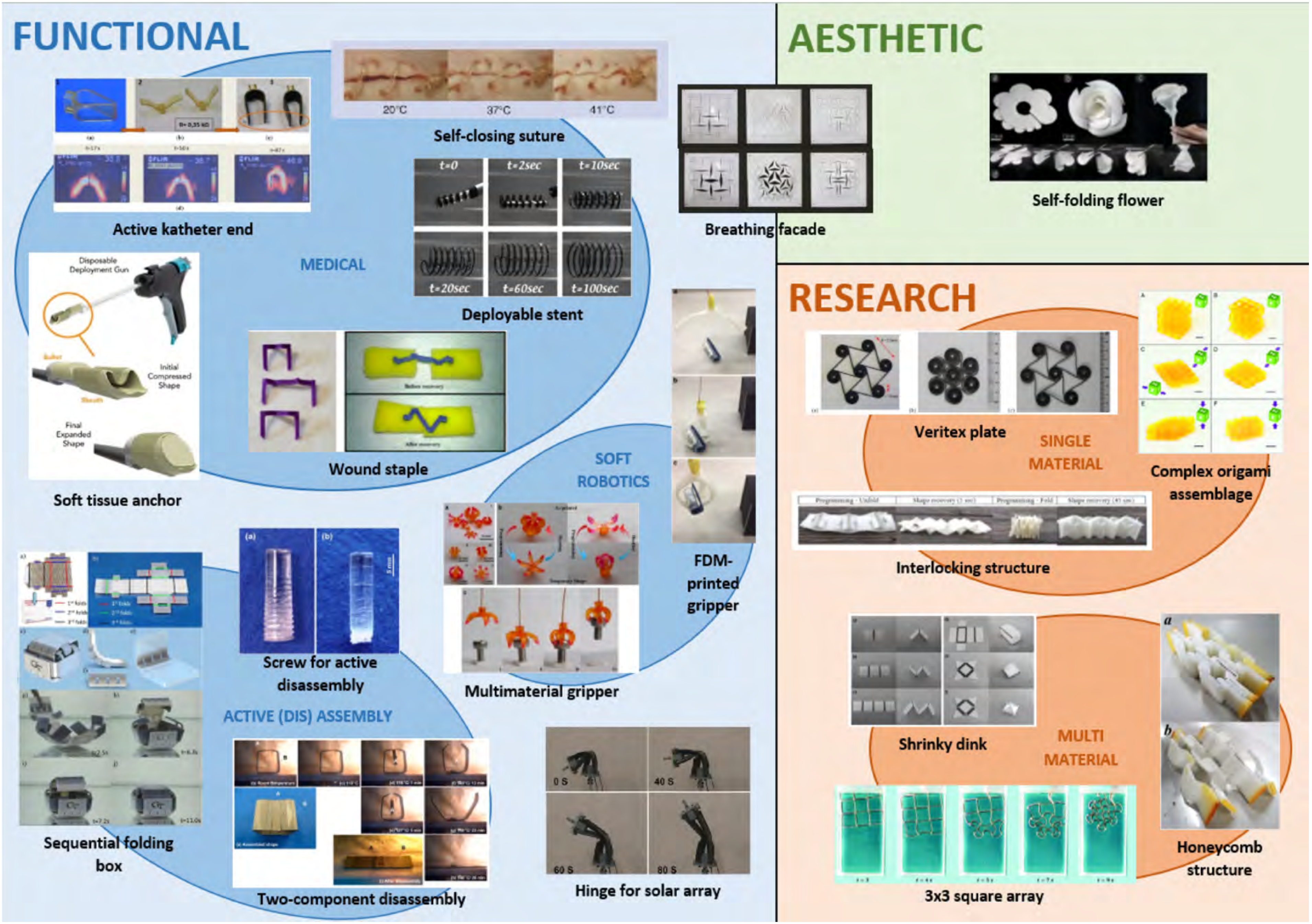


Figure 33 Categorization of the found examples based on application

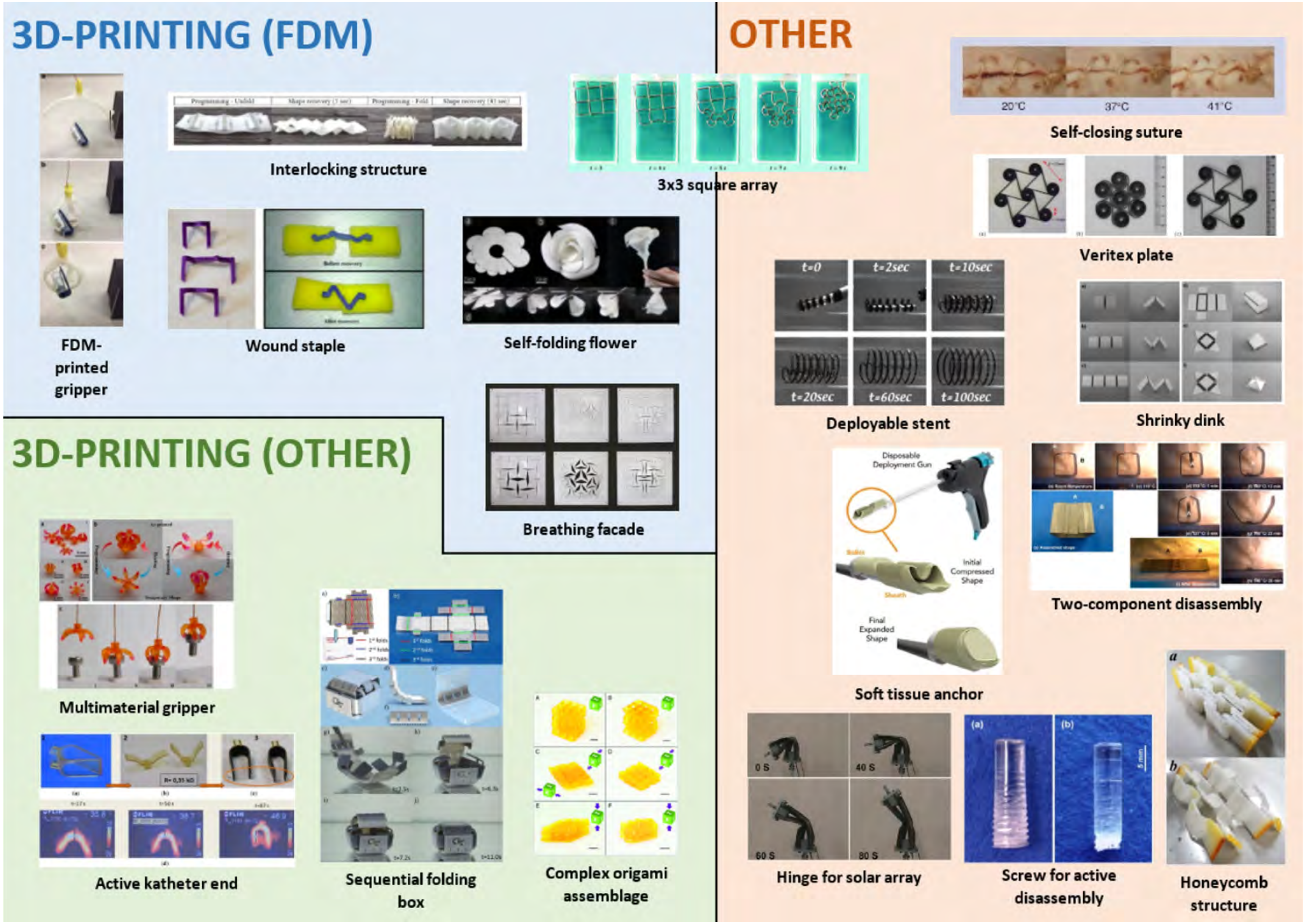


Figure 34 Categorization of the found examples based on manufacturing technique

4.3 CONCLUSIONS

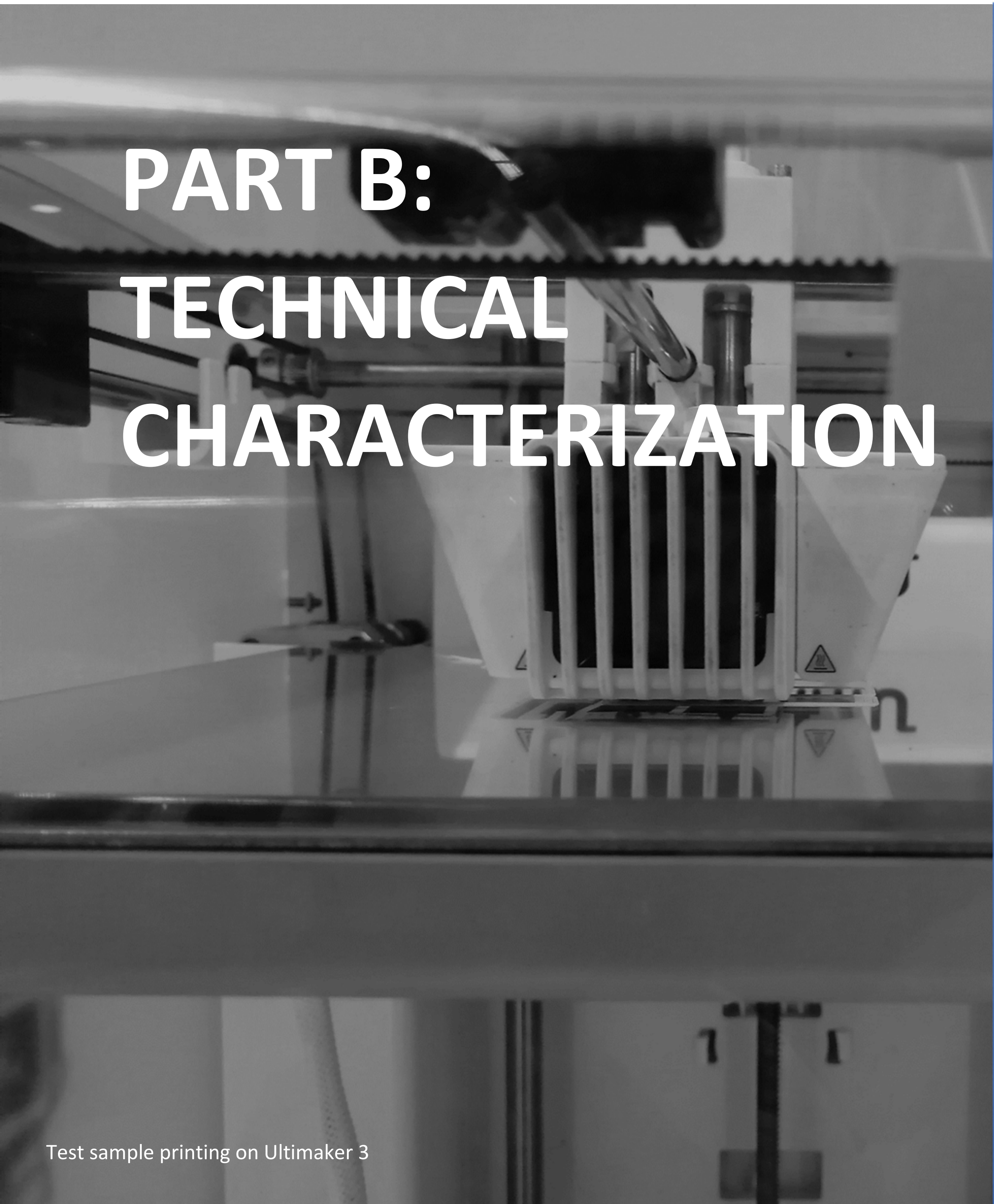
This part of the literature review focused on the design aspects of shape memory polymers. A four-stage design method for designing with these kinds of materials was presented. This method resembles a more traditional method in the stages it goes through, but differs in the specific steps and things to consider within each step. The focus of this method is on the shape memory material use, which introduces new elements to consider which are not or in less extent present in more traditional design methods.

In the first stage ''planning and understanding design needs'', the process is started by creating an overview of what the aim is and how to reach this. In Stage 2, ''conceptual design'', solutions are thought up through a 3 step process of establishing the functional boundaries in terms of shape memory properties, establishing mechanical requirements for the product overall and establishing environmental considerations which focus on the use scenario and different aspects which can affect the shape memory material. The (sub) solutions are combined and formed into concepts, which are further developed and tested in stage 3: Embodiment design. At the end of this stage, a selection is made of which material and concept combination to continue with. In the final stage: detail design, manufacturing, assembly, packaging and storage aspects are worked out.

As mentioned earlier, the described method focuses on the implementation of shape memory materials in the design. This is done using a systematic approach which tries to ensure that the use of shape memory materials in the final design is logical and justified. However, while aspects related to material use are well-described, other aspects related to designing in a more general sense (e.g. aesthetics, the user/ general usage etc.) get less attention. To get a well-rounded design method, which can guide designers through the process of designing with shape memory materials, the described method needs to be expanded to include these kinds of aspects. However, when looking at it from a different angle; seeing the described method as an extension of a traditional design approach, the emphasis on material use makes sense. Further in this project, the method as described in this chapter will be applied like this, meaning that certain elements of this method will be implemented to account for the use of shape memory materials.

A benchmark was done to get inspiration and assess the current state of research and application of SMP's. The benchmark consisted of examples from different fields and in different stages of development. Overall, the examples found were either related to the medical field, soft robotics, active (dis)assembly, or were research projects exploring and developing new materials. Based on these examples, the conclusion can be drawn that use of these materials in production-ready concepts is still limited, and before widespread application, more research is still needed.

PART B: TECHNICAL CHARACTERIZATION



Test sample printing on Ultimaker 3

In this chapter, the testing of 3d-printed shape memory polymers is described. To get a clear picture of the strengths and weaknesses of the material, different PLA structures have been printed and tested to see what the shape memory capabilities of this material are, and how different parameters related to the material itself, the design of an object and the printing process influence these capabilities.

This chapter starts with an introduction on the material that will be the focus of this project: PLA. Next some explorative prints done to get acquainted with the shape memory effect are described, followed by a series of simple tests meant as a way to, through an iterative design process, design a test sample which would be used for comparative testing of the influence of different parameters on shape memory capabilities of PLA prints. Next follows a series of studies where the influence of different parameters is tested. The results of these tests will be used as input for setting up the design guidelines for designing 3D-printed shape memory objects, which is described at the end of this part of the report.

5 MATERIAL INTRODUCTION AND PRELIMINARY TESTING

In this chapter, the material which is used for testing the influence of different parameters on shape memory behaviour in polymers is introduced. Furthermore, preliminary testing done to get acquainted with the shape memory effect in polymers, as well as the process of designing a test sample which can be used for parameter testing are discussed.

5.1 MATERIAL INTRODUCTION

The material that will be the focus of testing and concept development later on in the project is PLA. As mentioned earlier, in chapter 3, this is one of the most commonly used materials for FDM 3D-printing. In this chapter, a short introduction will be given on the characteristics of the material.

Polylactic acid, or PLA for short, is a thermoplastic polyester which is made of lactic acid. These materials are biodegradable and biocompatible, and are made of renewable sources. The lactic acid monomers are typically made of fermented plant starch from corn, sugarcane or sugar beet pulp. These materials range from amorphous glassy polymers to semi-crystalline and highly crystalline polymers. The glass transition temperature for these materials usually ranges from 60-65°C, with a melting temperature of 130-180°C. However, by adding different chemical components, it is possible to create PLA materials with a better thermal resistance. The basic mechanical properties of these materials are between those of polystyrene and PET. (Rogers, 2015 & “Polylactic Acid”, 2021)

The material has become popular because of its economic and environmental benefits. However, widespread application is hindered by physical and processing shortcomings. In appendix B, a SWOT analysis of the material can be found, explaining in further detail the strengths and weaknesses of the material. Nonetheless, the material is one of the most widely used bioplastics, and the main filament material for FDM 3D-printing.

Apart from 3D-printing, there consists a wide range of applications for PLA materials, with its biodegradability and biocompatibility being the main drivers behind this. In the medical field, PLA is for example used in parts meant for bone reconstruction in the form of screws, rods, plates etc. Other applications include disposable (food) packaging, food service wear like plates, cups and cutlery, agricultural equipment like plant pots, mulch film, waste bags and tomato clips. However, PLA can also be applied in products which have an extended lifespan, like housing for electronics and appliances, flooring and wall coverings, and toys. (Ingeo In Use, n.d.)

In terms of shape memory capabilities, PLA is generally not classified as a shape memory material. However, as mentioned in chapter 2, shape memory is an inherent quality of most polymers, and PLA is oftentimes used in studies for creating shape memory objects and testing its properties.

Figure 35 Examples of PLA products: disposable cups, mulch film, flooring and toys (Ingeo In Use, n.d.)

5.2 FIRST EXPLORATION

To get acquainted with the shape memory effect, two objects were designed to be printed. A short description of this process is given in this chapter. For further elaboration, see appendix C.

Simple origami structure

The first printed object was a simple origami structure. The object was designed to be printed as a flat sheet, and be deformed by hand into a 3D-structure. the general thickness of the sheet was 3 mm, with 0.5mm grooves modelled in the places were folds would be made. Figure 36 shows the initial object and the shape memory cycle. The printed object was heated by submerging it in 65°C water, which made it deformable. After cooling, the deformed object was put in the hot water again to initiate shape recovery. As can be seen in the figure, it didn't completely recover to its initial shape. However, this test was an informative way to get acquainted with the shape memory effect in polymers.

Christmas tree

For a second explorative experiment, a new shape was designed based on an origami Christmas tree. In this experiment, the shape was printed in 3D-configuration, and deformed to a 2D-configuration, as shown in figure 37. The method of heating, deforming and recovering was the same as for the origami structure. Similar to the origami structure, the shape didn't fully recover, which might be due to object design or environmental factors like the water cooling down. Also, the inactive sections (parts which weren't supposed to deform) can also been seen to have deformed to some degree. This also needs to be taken into consideration when designing SMP objects.

Figure 36 origami structure after printing (left) after deformation (middle) and after recovery (right)

Figure 37 Christmas tree after printing (left) after deformation (middle) and after recovery (right)

5.3 SAMPLE DESIGN

For testing the influence of different parameters on the shape memory behaviour of 3d-printed PLA objects, a full factorial experiment was designed. For this experiment, a test sample was designed through an iterative design process. A total of 3 different (consecutive) versions was designed and tested to see if it would suffice for the factorial experiment. Each version was tested, and based on the results, an improved version was designed. This sub chapter shortly describes the simple tests done to evaluate the sample designs. For further elaboration on the samples and tests, see appendix D.

The main objective of the preliminary testing was to design a test sample which would be suitable for testing the influence of different parameters on the shape memory behaviour of 3D-printed objects. For this, it is desirable that the amount of self-bending of the samples is limited. Self-bending in this case refers to the deformation that occurs when the material is exposed to the activation stimulus without an external force acting on it to deform it. This is related to the internal stresses present in the sample after printing, with a high degree of self-bending meaning there are a significant amount of internal stresses present in the material.

Self-bending of the samples was tested by putting the samples in hot water (+/- 65°C) to see how they would deform. Afterwards, the degree of self-bending was evaluated, and changes were made to the design.

5.3.1 SAMPLE DESIGN V1

The first sample design featured two hinge parts connecting three inactive parts, and was printed with all infill lines in the longitudinal direction. This design and the measurements are shown in figure 38. After emersion in hot water, the sample showed very noticeable self-bending. Based on the literature research, it can be reasoned that this is caused by a limited material thickness and the direction of the infill lines. Other factors might also have an influence, but based on this test, this can't be said for sure.

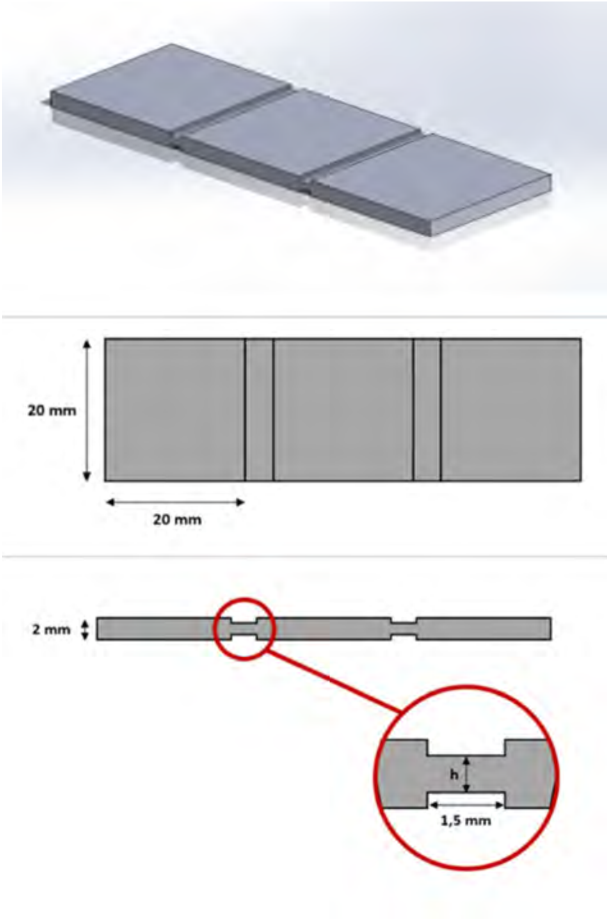


Figure 38 Sample design V1

5.3.2 SAMPLE DESIGN V2

Based on the findings of testing sample V1, a new sample was designed with the aim to reduce self-bending. Sample V2 has increased thickness in the inactive parts, and reduced complexity with only one hinge and two inactive parts, as shown in figure 39. Layer height was also increased from 0.15 to 0.2 mm, the printing speed lowered from 50 to 40 mm/s and the travel speed reduced from 150 to 100 mm/s, since these parameter settings were found to lead to less self-bending in the literature (Esfahani, 2021). Different infill line directions were tested to see which infill direction would lead to the least self-bending. Three infill directions were tested by submerging them in the same manner as with sample V1. Afterwards, self-bending was measured. Compared to sample V1, self-bending was reduced, and it was found that a diagonal, alternating infill led to the least amount of self-bending. However, self-bending was still observed, also in the width direction of the sample.

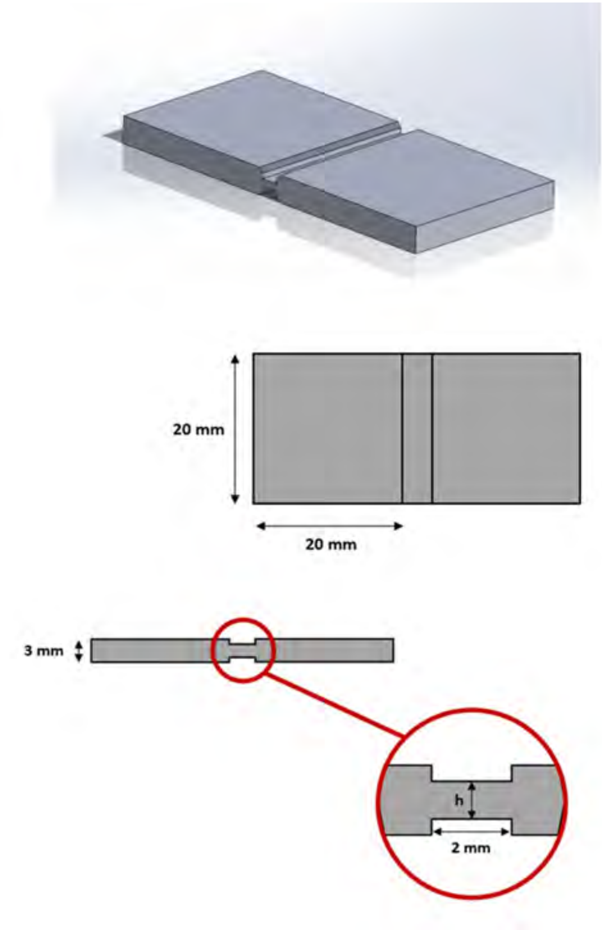


Figure 39 Sample design V2

5.3.3 SAMPLE DESIGN V3

As sample V2 already showed quite good results, only one design change was made for sample V3, namely that the width of the sample was halved. Also, it was chosen to continue with the diagonal alternating infill pattern, as this showed the best results for sample V2. This resulted in the sample design as shown in figure 40. Using this sample design, the influence of build-plate temperature and fan speed (the speed at which the fans which cool the printed material spin) was tested. For both parameters, two values were chosen (30°C and 50°C for build plate temperature, and 50% and 100% for fan speed). Using the same submersion method as used for the previous sample designs, 12 samples were tested (four different samples, each printed in threefold). Overall, sample V3 showed better results for self-bending that previous sample designs, and it was found that a lower fan speed leads to less self-bending. For build-plate temperature however, no clear influence was found. However, because a higher build plate temperature led to better build plate adhesion during printing, the high value was chosen to be most suited for printing the samples for the parameter testing.

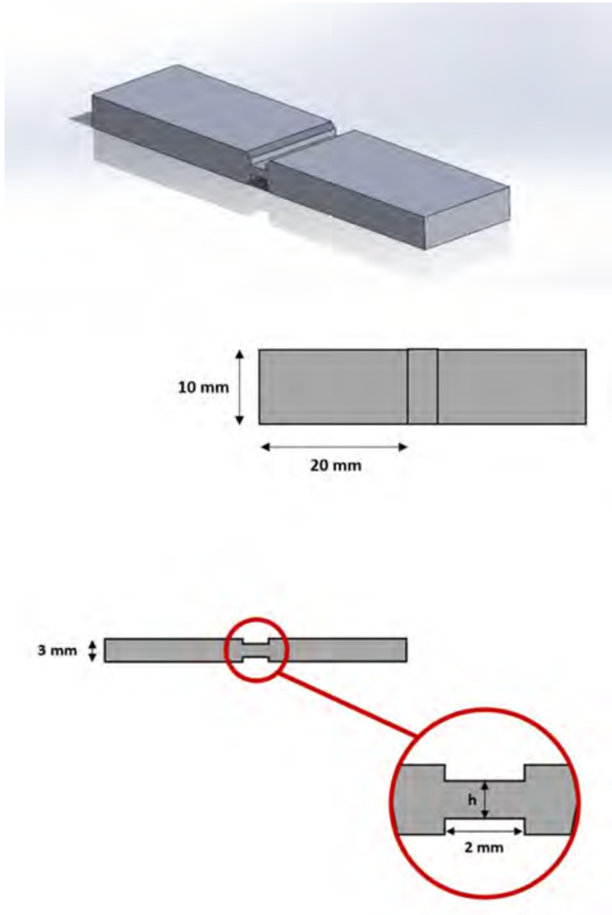


Figure 40 Sample design V3

6 PARAMETER TESTING

In this chapter, the parameter testing that was done is described. The parameter testing was performed in four parts, with each part addressing different parameters. For each part, the method, results and conclusions are described, and at the end of the chapter, an overall conclusion is drawn, and an overview of the important insights is given.

6.1 SINGLE HINGE TESTING

As described at the start of the ''preliminary testing'' section of this chapter, the influence of different parameters on the shape memory behaviour of PLA-printed samples is tested with a full factorial experiment. A detailed description of the test setup and results can be found in the appendix E.

The preliminary tests function as the basis for this experiment. The final test sample design and parameter settings leading to the least self-bending from these preliminary tests will be used for the factorial experiment:

- Sample design: V3
- Build plate temperature: 50°C
- Infill: diagonal alternating

In this test, the influence of four parameters will be tested.

- Material
- Hinge height
- Nozzle temperature
- Fan speed

For each of these parameters, a high and low value was determined, with an exception for material. For this parameter, two similar materials from different suppliers were chosen as the two values. 4 parameters with each two values leads to a total of 16 different samples. All different samples are shown in table 5. For significant results, each sample was printed three times, leading to a total of 48 printed samples.

All samples were printed on the same Ultimaker 3, with a controlled climate to minimize changes in humidity and temperature, as these factors can have an influence on print quality. The printed samples are displayed in figure 41.

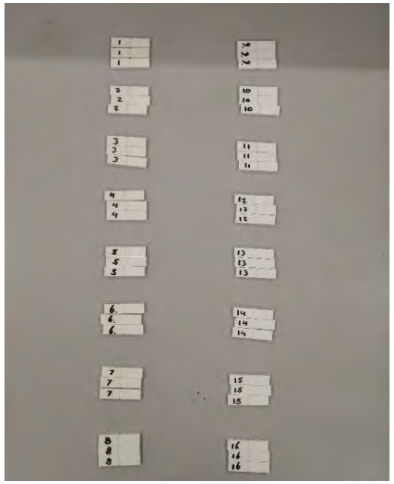


Figure 41 printed samples

Table 5 Overview of the different samples and their parameter values

Sample	Material	Hinge height (mm)	Nozzle temperature (°C)	Fan speed (%)
1	Ultimaker	0.8	195	50
2				100
3			210	50
4				100
5		1.4	195	50
6				100
7			210	50
8				100
9	Makerpoint	0.8	195	50
10				100
11			210	50
12				100
13		1.4	195	50
14				100
15			210	50
16				100

6.1.1 METHOD

The first step of testing was putting the samples in 65°C water for 60 seconds. A water bath was used to ensure a constant water temperature. After 60 seconds, the samples were taken from the water and deformed over a 90-degree angle, as shown in figure 42. To ensure that every samples would be deformed in the same way, two pieces of angle profile were used as a mould. The samples were taped to one of the angle profiles using double sided tape with eight at a time (figure 43). For deforming, the second piece of angle profile was pressed over the samples, and kept in place during cooling to ensure the fixation of the deformation (figure 44).

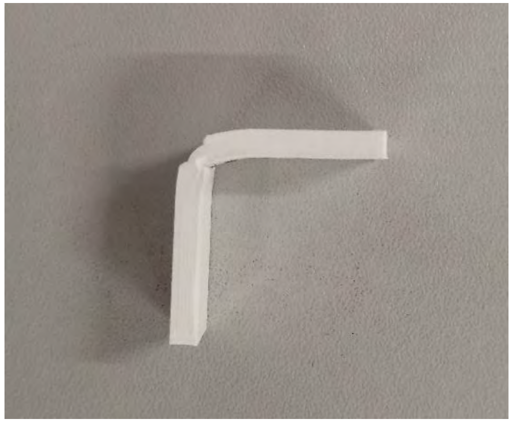


Figure 42 deformed sample

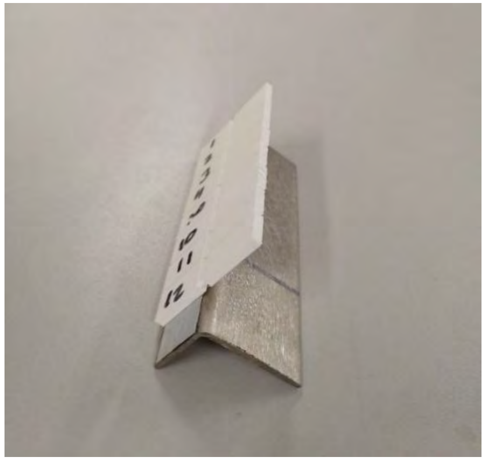


Figure 43 samples taped to an angle profile with eight at a time to ensure similar submersion time and deformation

Figure 44 Samples pressed between two angle profiles to ensure similar deformation

Once the samples were cooled down, they were put in the water bath again for 30 seconds for shape recovery (submerging time). Using a tool made to hold the samples in place (figure 45), they were submerged in the water once again with two at a time (figure 46).

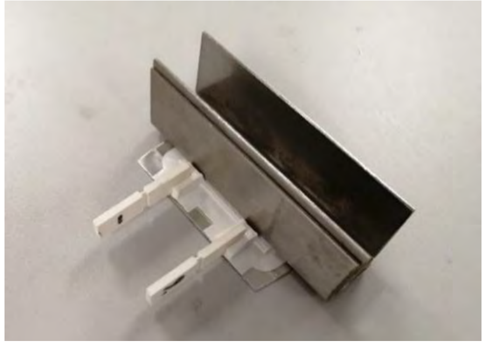


Figure 45 tool to keep the samples in place, with two samples already placed in the clamps

Figure 46 two samples clamped in the tool submerged in the water bath during shape recovery

The influence of the four parameters was assessed on two levels:

- **Recovery ratio**
  The percentage of the deformation angle that has been recovered in the 30 second submersion time (for successive studies, as described in chapter 6.2 to 6.4, this was changed to 60 seconds). This was derived from the remaining deformation that was measured using digital callipers as shown in figure 47.

- **Activation time**
  The time it takes for a sample to start the shape recovery process after being put in hot water. Video footage was made of the recovery process, which was analysed to determine the time between the samples being submerged in water and the start of the recovery process.

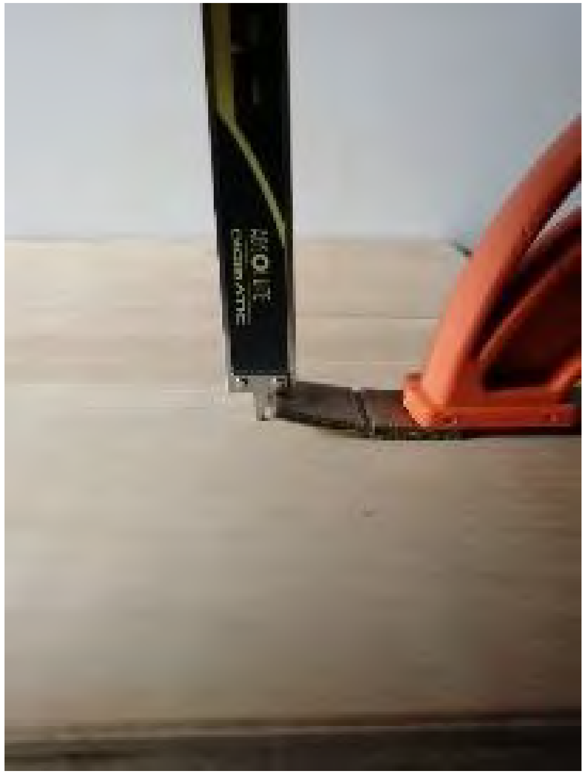


Figure 47 measuring the deformation of the samples using digital callipers

The results from the test were analysed with ANOVA using JMP analysing software (JMP, n.d.). The analysis was performed to the second degree, meaning that all individual parameters were analysed, as well as all parameter pairs. The influence of a parameter on either recovery ratio or activation time was considered to be significant if the analysis resulted in a P-value lower than 0.05 for that parameter. The P-value is a statistical parameter that gives the probability of obtaining results that are equal or more extreme than the results actually observed. In the case of the parameters tested, this means that the lower the P-value of a specific parameter, the higher the probability of that parameter having a significant influence on activation time or recovery ratio. For this study, a P-value smaller than 0.05% was chosen as significant, meaning that the chance of this parameter not affecting recovery ratio or activation time is less than 5%

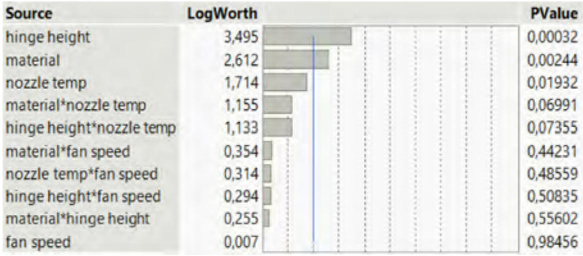
6.1.2 RESULTS

<u>Recovery ratio</u>

Analysing the effect of the four parameters on recovery ratio led to the results shown in figure 48. Assuming parameters with P<0.05 as significant, results in three parameters that have a significant influence on recovery ratio: hinge height, material and nozzle temperature. These parameters are listed in table 6, together with the influence they have on recovery ratio.

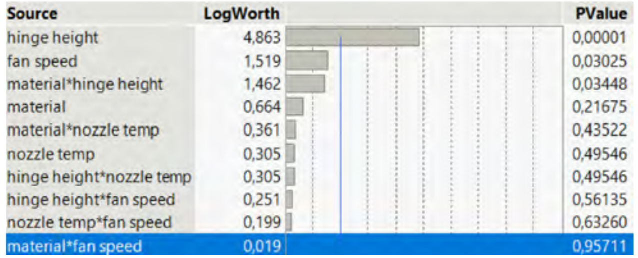
<u>Activation time</u>

Analysing the effect of the four parameters on activation time led to the results shown in figure 49. Assuming parameters with P<0.05 as significant, results in two parameters, hinge height and fan speed, and one parameter couple, material*hinge height, that have a significant influence on activation time. The two individual parameters are listed in table 7, together with the influence they have on activation time. The third significant influencer on activation time is the Material-Hinge height parameter combination. The effect of material*hinge height is shown in figure 50.



Source	LogWorth	PValue
hinge height	3,495	0,00032
material	2,612	0,00244
nozzle temp	1,714	0,01932
material*nozzle temp	1,155	0,06991
hinge height*nozzle temp	1,133	0,07355
material*fan speed	0,354	0,44231
nozzle temp*fan speed	0,314	0,48559
hinge height*fan speed	0,294	0,50835
material*hinge height	0,255	0,55602
fan speed	0,007	0,98456

Figure 48 analysis results showing the significance of the different parameters on recovery ratio



Source	LogWorth	PValue
hinge height	4,863	0,00001
fan speed	1,519	0,03025
material*hinge height	1,462	0,03448
material	0,664	0,21675
material*nozzle temp	0,361	0,43522
nozzle temp	0,305	0,49546
hinge height*nozzle temp	0,305	0,49546
hinge height*fan speed	0,251	0,56135
nozzle temp*fan speed	0,199	0,63260
material*fan speed	0,019	0,95711

Figure 49 analysis results showing the significance of the different parameters on activation time

Table 6 Recovery ratios for the significant parameters and the difference between recovery ratios for the high and low value of the parameters

Parameter	Average recovery at low value (%)	Average recovery at high value (%)	Difference (percentage-point)
Hinge height	97,1	91,7	-5,4
Material	96,1 (Ultimaker)	92,6 (Makerpoint)	-3,5
Nozzle temperature	95,4	93,3	-2,1

Table 7 Activation time for the significant parameters and the difference between recovery ratios for the high and low value of the parameters

Parameter	Average activation time at low value (s)	Average activation time at high value (s)	Difference (s)
Hinge height	6,8	10,5	3,7
Fan speed	9,1	8,3	-0,8

As can be seen in the figure, the difference in hinge height has a larger effect on samples printed with Ultimaker material. Also, on average, Ultimaker material performs better with a lower hinge height (6.6s) compared to Makerpoint (6.9s), while Makerpoint performs better with a higher hinge height (10.0s) compared to Ultimaker (11.0s).

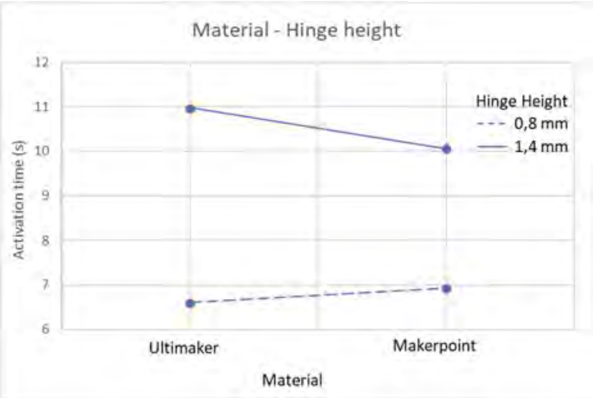


Figure 50 Graph showing the influence of material combined with the influence of hinge height on activation time

6.1.3 CONCLUSIONS

Based on the analysis of the results, conclusions can be drawn for each of the parameters on shape memory behaviour of the samples.

<u>Material</u>

The analysis shows that material has a significant effect on recovery ratio. According to the data, the average recovery ratio for the Ultimaker samples is higher than that of the Makerpoint samples. Furthermore, the choice of material, in combination with the hinge height has a significant effect on activation time. However, this influence is more complicated, as Ultimaker has shorter activation times than Makerpoint for the low hinge height, while the opposite is true for the high hinge height.

Although both materials are PLA with the same thickness and in the same colour, there are significant differences in performance. Apart from their shape memory behaviour, Ultimaker appears more brittle and consistent in printing quality than Makerpoint. When looking at the data sheets for both materials, there are significant differences between mechanical properties, as shown in table 8. Which of these properties cause/causes the difference in shape memory behaviour is not known, but this test shows that material choice does have an influence on shape memory behaviour, and should be considered when designing shape memory products.

Table 8 Differences in material properties for the two filament materials used

	Unit	Ultimaker	Makerpoint
Printing temperature	**(°C)**	200 – 210*	205 +/- 10
Melting temperature	**(°C)**	145 - 160	115 +/- 35
Glass transition temperature	**(°C)**	~ 60	57
Melt mass-flow rate	**(gr/10 min)**	6.09	9.56
Tensile stress at yield	**(Mpa)**	49.5	70
Elongation at yield	**(%)**	3.3	5
Elongation at break	**(%)**	5.2	20
E-modulus	**(Mpa)**	2346.5	3120
Impact strenght	**(KJ/m²)**	5.1	3.4

Hinge Height

Of the four parameters tested, Hinge height has the largest influence on both recovery ratio and activation time, with a thicker hinge leading to a lower recovery ratio and a higher activation time.

The higher activation time can be explained by the fact that the material needs to heat up beyond its glass transition point in order to initiate shape recovery. With a thicker hinge, more material needs to be heated, which takes a longer time leading to longer activation times. This also makes it possible to achieve sequential shape change by altering the hinge height/thickness of the material.

The reason behind the lower recovery ratio however, is less easily explained. A possible explanation would be that the shape recovery process was not finished after the 30 second submersion time. The thicker hinge samples have a longer activation time, meaning that there is less time in which these samples are actually recovering. So, it is logical to assume that these samples did not have enough time to complete the shape recovery process. With more time, the samples with a thicker hinge might be able to recover to the same extent as the samples with a thinner hinge, or even further.

Nozzle temperature

A higher nozzle temperature (210°C compared to 195°C) leads to a lower recovery ratio, although the effect of this parameter is smaller than that of material choice and hinge height. A possible explanation for this is that the higher printing temperature leads to a higher crystallization rate in the printed material, which makes it less elastic, thus decreasing the materials ability to store internal stresses.

Fan speed

Fan speed was found to have an influence on activation time, with a higher fan speed leading to lower activation times. Why this is the case is not clear. A possible explanation might be that a higher fan speed limits material flow after extrusion, causing bigger air gaps between material lines, which result in easier heat penetration leading to shorter activation times. However, it is not known if this is actually the case, and is outside of the scope of this project to further examine.

6.2 DOUBLE HINGE TESTING

For the next step of characterising the shape memory behaviour of PLA, a new type of sample was designed and tested. This sample design, shown in figure 51, is similar to the sample used in single hinge testing in terms of the dimensions of the different sections, but for the new, double hinge sample, an additional hinge and inactive part is added. This was done to test if increased shape complexity influences shape memory behaviour.

In this test, the following parameters will be tested:

- Hinge Height
- Bending direction
- Shape complexity

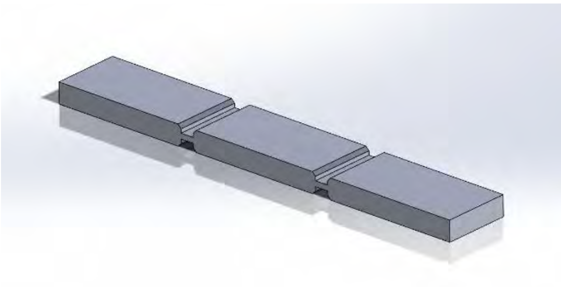


Figure 51 double hinge sample design

Based on the results of the single hinge tests, values for the parameters tested with the single hinge samples were chosen:

- **Material**
  Ultimaker material was chosen, as this material led to better shape recovery and more consistent results than the Makerpoint material that was tested
- **Nozzle temperature**
  A 195°C nozzle temperature was chosen over a 210°C nozzle temperature, as the lower nozzle temperature lead to a higher shape recovery ratio
- **Fan speed**
  Fan speed was chosen to be 50%. Based on the test results, 100% fan speed has slightly shorter activation times, but earlier tests and literature show that lowering the fan speed decreases self-bending, which was determined more important for these tests.

In the single hinge tests, a significant difference was found between samples with a 0.8 and a 1.4 mm hinge height. Increasing the hinge height significantly increased the activation time and decreased the recovery ratio. A possible explanation for this was that the 30 second submersion time that was set was too short for the samples to fully recover. It is expected that the samples with a thicker hinge will recover more when giving sufficient time to recover. To find out if this is the case, the effect of hinge height will again be tested, but now the submersion time will be extended to 60 seconds.

In previous tests it was observed that the samples would bent without an external force when heated. This phenomenon of self-bending was limited through iterative sample design, but not eliminated. Samples would bend upwards, as displayed in figure 52. This raises the question how bending direction influences shape recovery. To test this, the printed samples will be bend in different ways, as displayed in figure 53.

Figure 52 self-bending of the printed samples. The line beneath the sample represents the build plate. Printed samples curve upwards

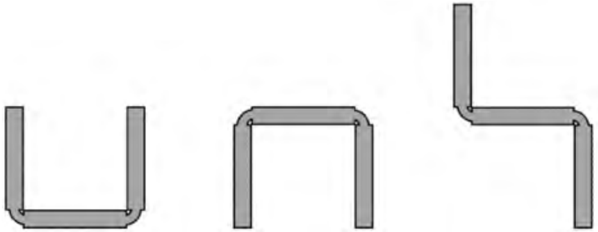


Figure 53 different shapes in which the double hinge samples can be deformed, with the left sample showing both hinges bended upwards (positive/ U shape), the middle sample showing both hinges bend downward (negative/ N shape) and the right sample showing one hinge bend upwards and one downwards (S shape)

Shape complexity refers (for this experiment) to the number of hinges and size of the samples. The new double hinge sample design will be compared to the single hinge design for the previous tests. Since the submersion time for the samples in this experiment is different than that of the previous experiment, new single hinge samples will be printed and tested.

With two values for hinge height and shape complexity, two values for bending direction for the single hinge samples and three for the double hinge samples, there are 10 different sample types, as shown in table 9. With each sample printed in threefold to achieve significant results, the number of samples that is printed is 30 (18 double hinge, 12 single hinge)

Table 9 Different sample types and their parameter values

Sample	Hinge height (mm)	Bending direction	Amount of hinges
1	0.8	Negative	2 (double)
2			1 (single)
3		Positive	2 (double)
4			1 (single)
5		Positive/negative	2 (double)
6	1.4	Negative	2 (double)
7			1 (single)
8		Positive	2 (double)
9			1 (single)
10		Positive/negative	2 (double)

6.2.1 METHOD

The method applied for these tests was for the most part identical to the single hinge experiments. The samples were put in a 65°C water bath for 60 seconds, attached to a part of a mould as displayed in figure 54. Then, a second mould part was used to deform all samples to the same degree. The mould parts were clamped together during cooling, and removed afterwards. This resulted in the deformed samples as shown in figure 55. The additional single hinge samples were deformed as described in the ‘’single hinge testing’’ chapter.

To initiate recovery, the samples were submerged in the 65°C water bath again for 60 seconds, using a similar tool used in the single hinge tests. Figure 57 shows an S-shape sample in the middle of recovery.

Video footage of the recovery process was made to determine the activation time for the different samples. Deformation was measured in a similar way as in the single hinge tests. However, the double hinge samples were clamped in the middle as to be able to measure the remaining deformation of both hinges independently (figure 58).

Figure 54 Samples attached to a part of the deformation mould (left: U and N samples. right: S samples)

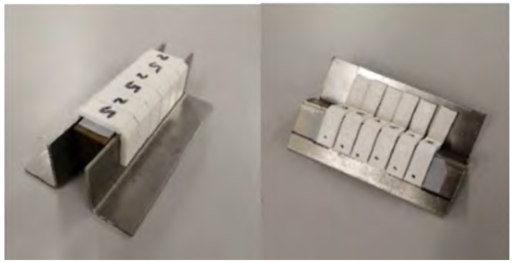


Figure 55 Deformed samples (left: U and N samples, right: S samples)

Figure 56 all deformed samples

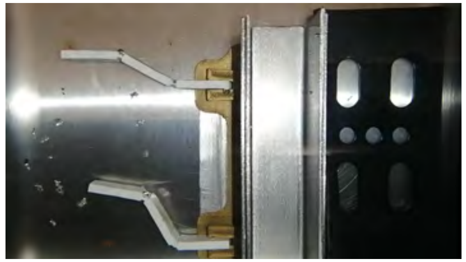


Figure 57 S shape sample recovery

Figure 58 clamping method for measuring deformation after recovery

6.2.2 RESULTS

Similar to the single hinge tests, the influence of the parameters was assessed on recovery ratio and activation time, using JMP analysing software to analyse the results.

<u>Recovery ratio</u>

Analysing the effect of the three parameters on recovery ratio led to the results shown in figure 59. Assuming parameters with P<0.05 as significant, two individual parameters, bending direction and amount of hinges, and two parameter couples, ''bending direction*hinge height'' and ''bending direction*amount of hinges'' were found to have a significant effect on recovery ratio. The values for the individual parameters with a significant influence, bending direction and amount of hinges are displayed in table 10.

For the significant parameter couples, ''bending direction*hinge height'' and ''bending direction*amount of hinges'', the results are displayed in table 11. The table shows the difference in % point between positive and negative bending for the low and high value of the coupled parameters. Figures 60 and 61 show the difference between recovery ratios for the coupled parameters.

Source	LogWorth	PValue
bending direction	2,470	0,00339
bending direction*hinge height	2,002	0,00995
Amount of hinges*bending direction	1,688	0,02053
Amount of hinges	1,401	0,03974
Amount of hinges*hinge height	1,101	0,07917
hinge height	0,901	0,12567

Figure 59 analysis results showing the significance of the different parameters on recovery ratio

Table 10 Recovery ratios for the significant parameters and the difference between recovery ratios for the high and low value of the parameters

	Average recovery for the low value (%)	Average Recovery for the high value (%)	Difference (% point)
Bending direction	101,2 (negative	91,8 (positive)	-9,4
Amount of hinges	96,9	96,1	-0,8

Table 11 difference between the recovery ratio for samples for the high and low values of the significant parameters combined with bending direction

	Difference between negative and positive bending for the low value of the other parameter (% point)	Difference between negative and positive bending for the high value of the other parameter (% point)	Difference (% point)
Bending direction* hinge height	12,7	6,2	-6,5
Bending direction* amount of hinges	11,0	7,8	-3,2

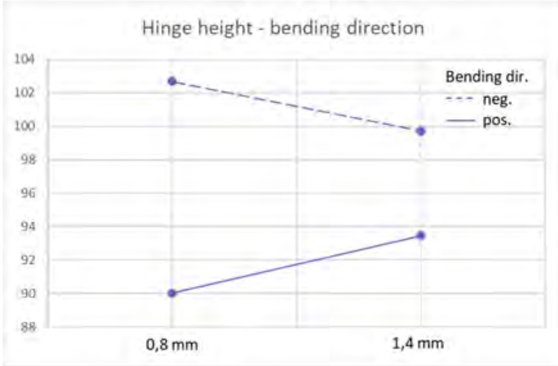


Figure 60 Graph showing the influence of hinge height combined with the influence of bending direction on recovery ratio

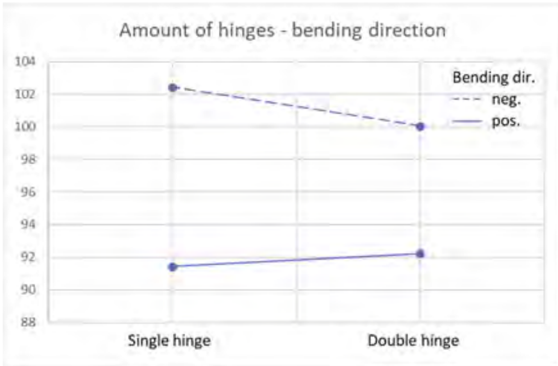


Figure 61 Graph showing the influence of amount of hinges combined with the influence of bending direction on recovery ratio

Activation time

Analysing the effect of the three parameters on activation time led to the results shown in figure 62. Assuming parameters with P<0.05 as significant, there are no parameters that significantly influence activation time. However, when comparing the activation times based on the low and high values of the parameters, substantial differences were found, as shown in table 12.

Source	LogWorth	PValue
hinge height	1,279	0,05259
bending direction	1,129	0,07422
Amount of hinges	1,089	0,08149
bending direction*hinge height	0,515	0,30527
Amount of hinges*hinge height	0,452	0,35288
Amount of hinges*bending direction	0,164	0,68555

Figure 62 analysis results showing the significance of the different parameters on activation time

Table 12 Recovery ratios for the significant parameters and the difference between activation times for the high and low value of the parameters

	Average activation time for the low value (s)	Average activation time for the high value (s)	Difference (s)
Hinge height	5,2	9,4	4,2
Bending direction	8,8	5,9	-2,9
Amount of hinges	5,5	8,0	2,5

6.2.3 CONCLUSIONS

Based on the analysis of the results, conclusions can be drawn for each of the parameters on shape memory behaviour of the samples.

Hinge height

The inclusion of hinge height as one of the parameters to be tested was based on the results of the single hinge testing. In these tests, it was found that hinge height had a significant effect on recovery ratio, with a larger value for hinge height leading to lower recovery ratio. However, this was thought to be caused by the limited submersion time, from which the thicker hinge samples with their longer activation times suffered the most. Therefore, for the double hinge testing, the submersion time was extended to 60 seconds, and new, single hinge samples were printed to see how these samples would recover when given more time to recover. A comparison was made between the negatively bended single hinge samples printed for these tests, and the single hinge samples which were printed with the same settings for the previous test (single hinge testing). The results of this comparison are displayed in table 13.

Table 13 comparison between 30 second and 60 second submersion time for two sample types

	0.8 mm hinge recovery ratio (%)	1.4 mm hinge recovery ratio (%)	Difference (% point)
30 second recovery	99,9	95,3	-4,6
60 second recovery	103,6	101,1	-2,5

Judging from this comparison, it can be concluded that the extended submersion time does indeed lead to a higher recovery ratio for the 1.4 mm hinge samples, but also for the 0.8 mm samples. This means that both sample types are not fully recovered after 30 seconds. it is assumed that after the 60 second submersion time, the samples did recover to their full extent.

The second thing that stands out is the difference between recovery ratio for the two different hinge heights. With a 30 second submersion time, this difference is more prominent than with a 60 second submersion time (4,6 compared to 2,5 % point). Although the difference is smaller with a sufficient submersion time, there is still a noticeable difference. This remaining difference is believed to be caused by remaining internal stresses in the material, which is further discussed under the ‘’bending direction’’ part of the conclusion.

As mentioned in ‘’6.2.2 Results’’, the hinge height parameter didn’t have a significant influence on recovery ratio by itself. When comparing the recovery ratio for all 0.8mm samples to all 1.4 mm samples (double and single), the average recovery ratio is identical for both hinge heights (96,3%). However, in combination with the bending direction, hinge height does have a significant influence. Based on the measurements, the thicker hinge samples appear to be less influenced by bending direction than the thinner hinge samples, with the differences between recovery ratios for negative and positive bending for the 1.4 mm hinge samples being smaller than for the 0.8 mm hinge samples (3,2 % point compared to 6,5 % point difference). The differences between 1.4 mm hinges samples and 0.8 mm hinge samples are expected to be caused by remaining internal stresses in the printed samples, which cause self-bending. Literature (Esfahani, 2021) and earlier tests show that an increased sample thickness reduces self-bending, which is expected to be the reason why the differences for between negative and positive bending are less when the hinge part is thicker. This is further explained in the next part (bending direction) of the conclusion.

For activation time, it was found that hinge height did not have a significant effect ($P=0.05259$) all be it close to being significant ($P<0.05$). Which seems odd considering the level of significance found for this parameter in the single hinge testing ($P=0.00001$). A possible reason for the lack of significance found in these tests is because all parameters show considerable influence on activation time, which makes the activation time appear like a more random phenomenon when analysing it the way it was done. Although no significance was found during the double hinge tests, the parameter is still considered to be of important to consider for activation time based on previous testing, literature (Mehrpouya et al., 2020) and the considerable differences between activation times for the two values of this parameter as found in the double hinge testing.

Bending direction

Bending direction was found to have the biggest influence on recovery ratio from the three tested parameters. On itself, it was responsible for a 9.4 % point difference in recovery ratio when comparing samples that were bended negatively (101,2% recovery ratio) or positively (91,8% recovery ratio). As mentioned earlier, self-bending is expected to be the cause of the differences between bending direction for the different hinge heights, and it is also expected to be the cause of the differences between bending directions as an independent variable.

As discussed in the introduction of this test series, when printing the samples, internal stresses are stored which cause the samples to deform when heated above T_g. This self-bending behaviour differs in magnitude based on various parameters, but is always in the same direction. It bends in the upwards direction, as displayed in figure 52. Hinges bended positively are bended in the same direction, while negatively bended hinges are bended in the opposite direction. When the deformed samples recover, they move towards the shape they achieved after self-bending, which explains why negatively bended samples recover more than 100%, while positively bended samples recover less than 100% (around 92% for this study) on average. This difference between positive and negative bending introduces an extra challenge when designing 3D-printed shape memory parts/products. To get properly predictable and uniform shape memory behaviour, independent of bending direction, self-bending needs to be eliminated. Otherwise, it is expected that bending direction will affect recovery.

Another interesting observation is how close the values for average recovery are together. Table 14 displays the average recovery for the different positively and negatively bended samples, and the average when combining both.

Table 14 average recovery ratio for different samples types either bended negatively or positively, and the average recovery for each sample type when combining the averages of negative and positive bending

Shape complexity/ hinge height (mm)	Positive bending average (%)	Negative bending average (%)	Overall average (%)
Single/ 0.8	89,5	103,3	96,1
Single/ 1.4	93,3	101,1	97,2
Double/ 0.8	90,6	101,7	96,2
Double/ 1.4	93,7	98,3	96,0

Even though the averages for positive and negative bending differ quite a bit, the combined average seems to always be around 96-97%. With the limited number of different samples tested it might be too early to draw any conclusions from this, but it might be that this number indicates the average shape recovery if no internal stresses would be present in the material after printing, thus no self-bending would occur. This might be interesting to consider for further testing.

Concerning activation time, bending direction was found not to have a significant effect (P=0.07422). However, as was the case with hinge height, noticeable differences were found in activation time for the two bending directions, with negatively bended hinges having an activation time which was on average 49% higher than that of positively bended hinges (8,8 seconds compared to 5,9 seconds). So even though no significance was found in this study, it is wise to consider this parameter when designing shape memory objects.

<u>Amount of hinges</u>

In this study, it was found that the amount of hinges or sample complexity has a significant influence on recovery ratio (P=0.03974). However, the difference between the single hinge and double hinge samples in terms of recovery ratio is limited, with a difference of 0.8% point found between the average recovery of the two sample types. (96,9 for single hinge compared to 96,1% for double hinge samples). The reason why sample complexity has a significant effect is not entirely clear. It is possible that this is not caused by actual differences in shape memory behaviour, but by imperfections in the testing and measurement method. However, since the differences are so small, it is up for debate if this parameter should be considered when designing shape memory objects. It could be that when making more complicated shapes and different configurations as were tested during this study, the effect of this parameter might be more significant

In combination with bending direction, amount of hinges has a larger significant effect similar to hinge height. With the added hinge part, the recovery ratio for negatively bended samples slightly drops, while the recovery ratio for positively bended samples slightly increases. The reason why this is the case is not entirely clear. A possible explanation is the increased time it takes to print the double hinge samples, which leads to each layer having more time to slowly cool down.

Concerning the activation time, the amount of hinges were found not to have a significant influence (P=0.08149). However, as was also the case for hinge height and bending direction, when comparing the activation time for the single hinge samples with that of the double hinge samples, a considerable difference was found. The single hinge samples had an average activation time of 5.5 seconds, while this was 8 seconds for the double hinge samples, which is an increase of 45%. Again, the reason for this difference is not known at the moment.

6.3 ORIENTATION TESTING

With an eye on the implementation of 3d printed shape memory polymers in design, the influence of print orientation on shape memory behaviour was tested. Up until this point, all tested samples had been printed flat on the build plate, meaning the cross section of the hinges and inactive parts were identical for each sample type. However, it is highly unlikely this will always be the case in real-world applications of shape memory in 3d-printed objects. Therefore, different printing orientations for the single hinge sample type used in the earlier studies (single hinge and double hinge testing) were identified and the shape memory behaviour of samples printed in these different orientations was studied.

For this study, 4 different printing orientations were identified:

- Side
- Upright
- 45-degree flat
- 45-degree side

In figure 63, the single hinge sample which will be used in this study is displayed in the different orientations. In terms of print settings, the settings used in the double hinge testing are also used in this study. For hinge height, a 1.4mm hinge height was chosen. To improve printing quality, support is used for the samples that need this to print properly.

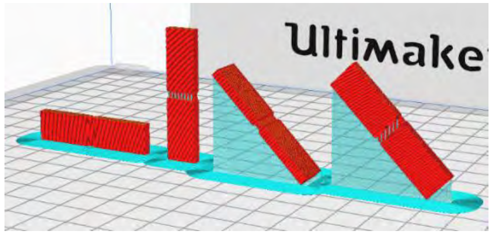


Figure 63 printing orientations. From left to right: side, upright, 45-degree flat, 45-degree side

3 identical samples will be printed for each orientation, meaning that initially, 12 samples are printed. However, in the ‘’double hinge testing’’ study, bending direction showed to be of a significant parameter influencing shape memory behaviour. Reason for this are the internal stresses in the printed samples. With the samples wanting to recover to the self-bended shape instead of the printed shape, this led to different results depending on the bending direction. It is not known how printing orientation affects these internal stresses, so the first step of this study is to measure self-bending after exposing the samples to heat. Based on the results of this part of the study, additional samples might be printed if significant self-bending occurs. Then, an additional set of the concerned samples will be printed, so both ‘’negative’’ and ‘’positive’’ bending can be tested.

6.3.1 METHOD

As mentioned, the first step of this study is to measure the degree of self-bending for the different orientations. For this, the samples are submerged in a water bath of 65°C for 60 seconds. The samples are attached to a piece of metal using double-sided tape, as shown in figure 64 to ensure all samples are emerged for the same amount of time and have the same degrees of freedom to bend. After 60 seconds, the samples are taken out of the water and measured. If significant self-bending is measured in the samples printed in a particular orientation, a second set of these samples is printed, so both negative and positive bending can be tested.

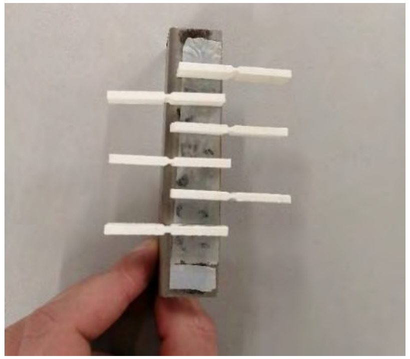


Figure 64 samples attached to a metal part for emersion for self-bending

After assessing the self-bending of the samples, the procedure for testing shape memory behaviour follows the same method as the ''double hinge testing''. The samples are again submerged for 60 seconds in the 65°C water bath, after which they are deformed between two pieces of angle profile. Once cooled down, the angle profiles are removed, and the deformed samples are put in the water bath again, two at a time, for 60 seconds, to initiate shape recovery. After this period, the samples are removed from the bath and left to cool, after which the remaining deformation of the samples is measured, from which the recovery ratio is derived. Also, video footage is made of the recovery process to determine the activation time for each sample.

6.3.2 RESULTS

First, the self-bending of the samples was assessed. After, the recovery ratio and activation time for all samples was measured/determined.

Self-bending

The results of the self-bending measurements are shown in figure 65. The self-bending of the ''upright'' and ''45-degree side'' samples is considered limited (<1,0mm), and no extra samples were printed in these orientations. The self-bending of the ''Side'' and ''45-degree flat'' samples, was considered significant, so an extra set of 3 samples in these two orientations was printed. These were also submerged for 60 seconds in 65°C water to initiate self-bending. The results from this step were not recorded.

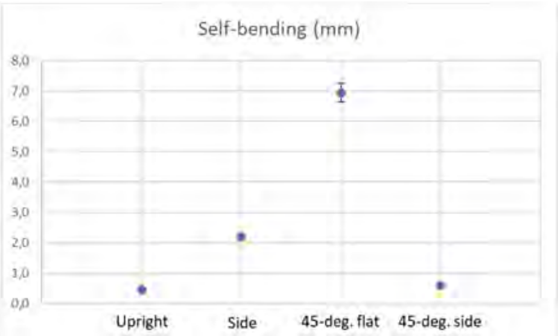


Figure 65 Graph showing the measured self-bending for each sample type

Recovery ratio

From the measured remaining deformation after shape recovery, the recovery ratio for each sample was derived. In figure 66, the resulting recovery ratios are displayed per sample type. In the figure, the different bending directions for the ''side'' and ''45-degree flat'' are considered as different samples.

Activation time

The activation time of each sample was derived from the video footage made during the recovery process. The results of this are displayed in figure 67.

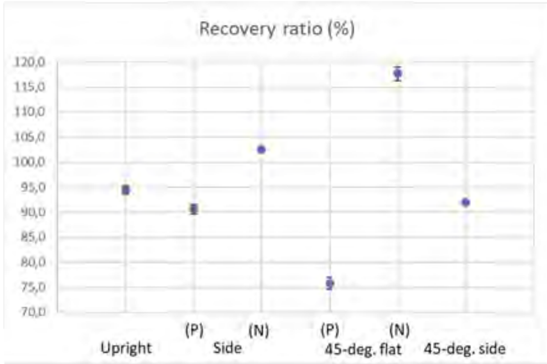


Figure 66 Graph showing the average recovery ratio for each sample type, with "P" and "N" resembling positive and negative bending respectively

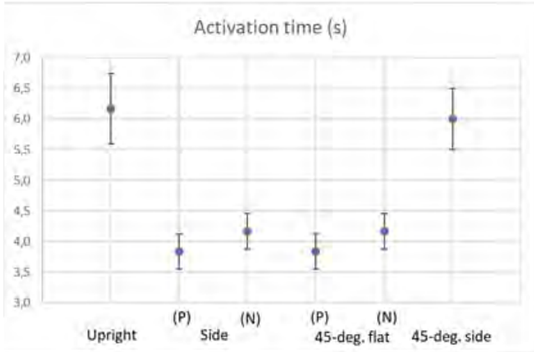


Figure 67 Graph showing the average activation time for each sample type, with "P" and "N" resembling positive and negative bending respectively

6.3.3 CONCLUSIONS

Based on the analysis of the results, conclusions can be drawn on the influence of printing orientation on shape memory behaviour.

Self-bending

The first step of the study was to assess the self-bending of the different samples. Next, the samples were deformed, after which shape recovery was initiated. In figure 68, the measured self-bending and remaining (absolute) deformation after recovery is shown for each of the sample types. As was also concluded from the ''double hinge testing'' study, is that self-bending has a noticeable influence on shape recovery. The figure shows the remaining deformation for both positively and negatively bended samples (in the case of the ''side'' and ''45-degree flat'' samples). From this figure, it can be concluded that the remaining deformation after recovery is influenced by the degree of self-bending. Which is logical when thinking about the mechanism behind self-bending: internal stresses. In the self-bended state, the material is in the state with the highest entropy. When recovering from a deformation, the material tries to return to this state. The rate in which the material is able to do so depends on different factors, like the recovery temperature and material (switching segments and crosslinking points), with insufficient heating leading to incomplete recovery. The same goes for a weak crosslinking network, which causes chain slippage, meaning the material can't fully store the internal stresses, which causes incomplete recovery.

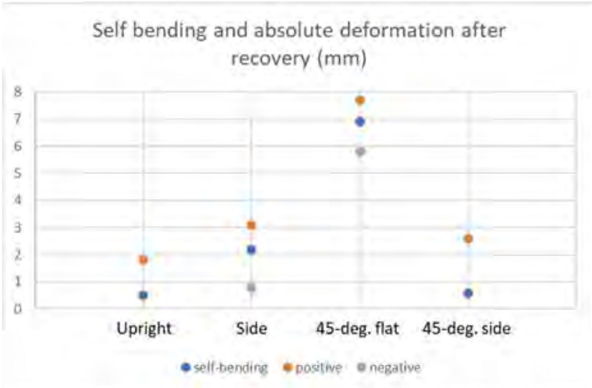


Figure 68 comparison between the measured self-bending and recovery ratio for each sample type, for both positive and negative bended samples

Recovery ratio

The most noticeable thing about the results is the difference between the negatively and positively bended ''45-degree flat'' samples, with a recovery ratio of 117,6% and 75,9% respectively. However, when looking at the high degree of self-bending of these samples, these values appear quite logical. A more important question to answer is *why* the degree of self-bending of these samples is so high. When looking at the printed samples and the specific orientation, multiple possible explanations arise.

One of the reasons might be the printing quality of the samples. For these samples, a support structure was needed to allow for printing the samples in the desired orientations. However, even with support, the surface quality of these samples was inferior to that of the samples printed in any of the other directions (figure 69). A possible explanation for this might be that the combination of printing speed, orientation, fan speed and support structure caused the model to slightly deform during printing, leading to inaccurate disposition of the extruded material on the previous layer.

Figure 69 bottom side of a 45-degree flat sample, showing low printing quality

The ''45-degree side'' sample, which needs to same kind of support structure to print, displayed proper quality (all be it still a slightly lower quality than the upright or side samples). Therefore, the reason why self-bending (and thus remaining deformation) is present to such an extent in these samples might be more related to printing quality achieved and not necessarily by the printing orientation. Or put differently: the orientation caused the low quality of the samples, which affected shape memory behaviour, but this does not indefinitely mean that all samples printed in this orientation will display this kind of behaviour. If, for example, with different settings a printing quality comparable to the samples printed in other orientations is achieved, it might be that the self-bending and recovery behaviour of samples printed in the ''45-degree flat'' orientation is also comparable to the other orientations. However, this will not be further studied in this project, so for now this topic remains undecided. But this could be a good starting point for sequential studies.

Apart from the ''45-degree flat'' sample, the results for shape recovery are not that far apart. Overall, the conclusion of the study in terms of recovery ratio is that a high degree of self-bending leads to a low recovery ratio (high degree of remaining deformation after recovery). Based on the test results, this means that ''upright'' printed samples have the best recovery to the original shape, followed by the ''45-degree side'' and ''side'' samples, and the ''45-degree flat'' sample with the worst recovery to the printed shape. Comparing the results of this test with that of the flat-printed single-hinge samples of the ''double hinge testing'' study, the ''upright'' samples still display the best recovery ratio (94,4%), with the flat printed samples from the double hinge testing as second (93,3%), followed by the other orientations tested in this study.

In the double hinge testing, it was observed that when comparing the negatively and positively bended versions of a sample type (same number of hinges, same hinge height), the average recovery was between 96 and 97,2%. In this study, two sample types were also deformed in the two different directions. In table 15, the averages for positively and negatively bending these samples, as well as the combined average are shown.

Table 15 average recovery ratio for different samples types either bended negatively or positively, and the average recovery for each sample type when combining the averages of negative and positive bending

Orientation	Positive bending average (%)	Negative bending average (%)	Overall average (%)
Side	90,6	102,5	96,6
45-degree flat	75,9	117,6	96,8

This table shows that overall averages of the different sample types are within the same range which was found in the ''double hinge testing'', strengthening the theory that no matter how big the internal stresses and thus the self-bending of the material is, the average recovery when considering both bending directions is the same. Meaning that when no self-bending occurs, the recovery to the original printed shape will be around 96/97%. However, as mentioned in the ‘’double hinge testing, it might be too early to draw a conclusion like this. It might also be that for bending angles other than 90 degrees or with a redesigned hinge, this percentage is different. This would have to be tested by changing these aspects.

Activation time

Regarding the activation time, ‘’upright’’ and ‘’45-degree side’’ samples gave comparative results, with the average activation being 6.2 and 6.0 seconds respectively. These values are in line with the activation time found for the flat single hinge samples of the ‘’double hinge testing’’ study, which was 6.0 seconds. The activation times for the ‘’side’’ and ‘’45-degree flat’’ samples were slightly lower, but identical to each other at 4.0 seconds average both (3.8 seconds for the positive and 4.2 seconds for the negative samples for both). The reason why the activation times were different from each other is not exactly known. The most obvious parameters influencing activation time are material thickness and porosity. With the low print quality of the ‘’45-degree flat’’ sample, the thickness of the material is slightly less than what is should be in some areas, and the samples might also be more porous due to this lower quality. However, this does not explain why the ‘’side’’ samples have a lower activation time than the ‘’45-degree side’’ samples, since the latter of these two has a lower surface quality, but a longer activation time. So,

concluding from this study, activation time can be influenced by changing printing orientation, but the extent to which this changes and what is exactly behind this change is not known.

6.4 3D TO 2D TESTING

In the tests done so far, the test samples were printed in a flat/ 2D-configuration and deformed over a 90 degree angle to create a 3d-configuration. As a last step, the 2D-configuration was recovered. However, depending on the eventual application, it might be that an object needs to be printed in a 3D-configuration, to be deformed to a 2D-configuration, and when exposed to heat, recover its original 3D-shape. This could for example mean that the hinge sections which in previous tests were printed in a flat configuration need to be printed under an angle. The aim of this study is to see if the shape memory behaviour from a hinge printed in a 3D-configuration is comparable to that of a hinge printed in a 2D-configuration, and how different printing orientations influence this behaviour.

For this study, the single hinge sample with a 1.4mm hinge height used in previous tests was redesigned to feature a hinge under a 90-degree angle, as displayed in figure 70. The dimensions of the sample were kept the same as for the 2D-samples, with only the hinge being altered to print the sample in a 3d-configuration.

Different printing orientations were identified, in which the samples will be printed:

- flat
- side
- upright
- 45-degree

For each orientation, 3 samples will be printed, leading to a total of 12 samples. The different orientations are displayed in figure 71. To improve printing quality, support is used for the samples that need this to print properly.

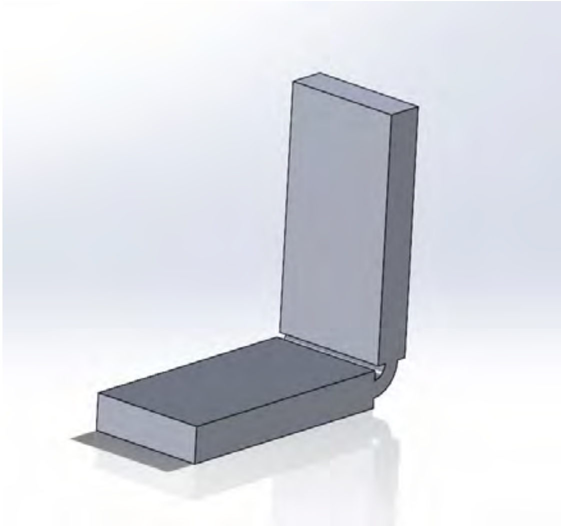


Figure 70 3D-configuration sample design

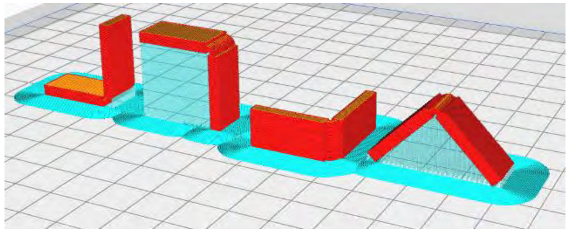


Figure 71 printing orientations. From left to right: flat, upright, side, 45-degree

6.4.1 METHOD

The method used in this study is identical to that of the ‘’double hinge testing’’, although the exact way in which the samples are deformed and remaining deformation is measured differs.

First, the samples are attached to a flat piece of metal using double-sided tape, as shown in figure 72. The samples were then submerged in a water bath of 65°C for 60 seconds, after which they were taken out of the water and deformed to a flat configuration by pressing the metal piece together with a flat surface (table) with the samples in between. Force was applied to the metal piece to maintain the deformation while the samples cooled down. Once the samples were cooled enough, the force was released and the samples removed from the metal piece, resulting in flat/2D samples.

For recovery, the same tool that was also used in earlier tests was used to submerge the deformed samples two at a time for 60 seconds to initiate shape recovery. After this time period, the samples were taken out of the 65°C water and left to cool. Once cooled, the remaining deformation was measured. Since the recovered shape for these samples was the 3D-configuration, a different method of measuring was needed compared to earlier tests. Figure 73 shows how the remaining deformation was measured. For samples which recovered more than 100%, the measuring method as shown in figure 73 was used. In both situations, the distance between the highest part of the sample to the flat surface underneath was measured, after which these measurements were compensated for the thickness of the sample. Afterwards, the recovery ratio was derived from these measurements using the same formula as used in earlier tests (see appendix E: single hinge testing). Activation time was derived from the video footage made during the recovery process.

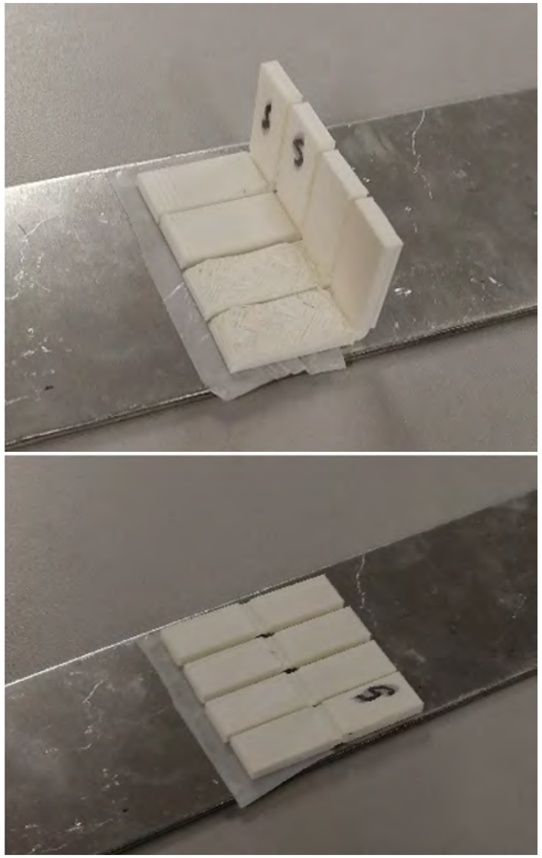


Figure 72 samples attached to a metal plate for deformation. Top: before deformation Bottom: after deformation

6.4.2 RESULTS

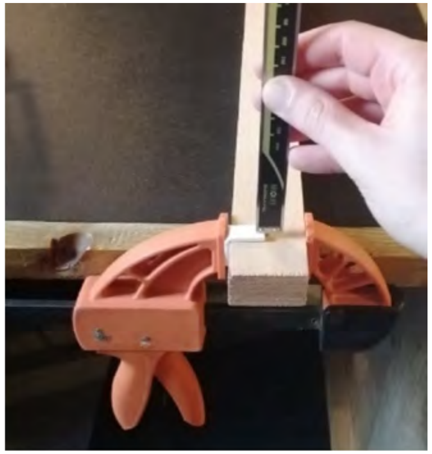


Figure 73 clamping of the samples and measuring of the remaining deformation

Figure 74 clamping of the samples that recovered more than 100% and measuring of the remaining deformation

The samples were assessed on activation time and recovery ratio after the recovery process.

<u>Recovery ratio</u>

In figure 75, the resulting recovery ratios are displayed per sample type.

<u>Activation time</u>

The activation time of each sample was derived from the video footage made during the recovery process. The results of this are displayed in figure 76.

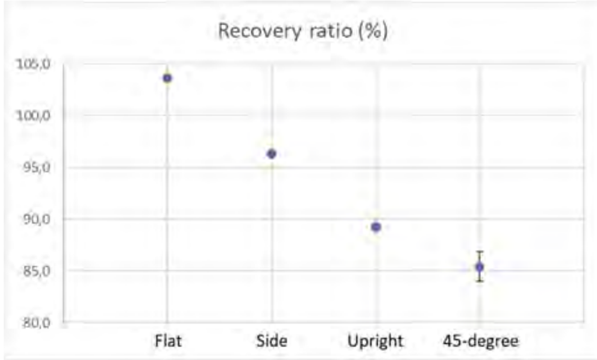


Figure 75 Graph showing the average recovery ratio for each sample type

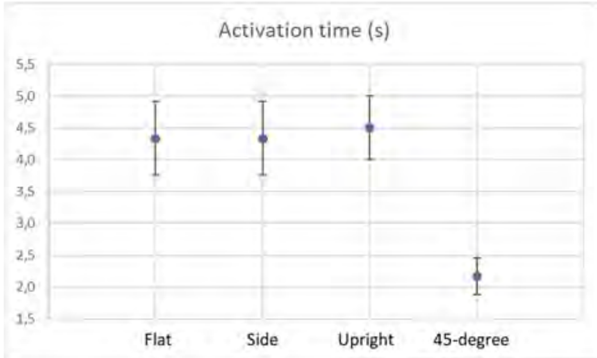


Figure 76 Graph showing the average activation time for each sample type

6.4.3 CONCLUSIONS

The aim of this study was to get an idea of the shape memory behaviour of printed objects when changing the process from a printed 2D configuration which gets deformed into a 3D-configuration to a process where an object is printed in a 3D-configuration and deformed to a 2D-configuration. For this, single hinge samples with a hinge part in 90-degree bended configuration were printed in different orientations. Based on the analysis of the results, conclusions can be drawn about the shape memory behaviour of these samples compared to flat/2D printed samples.

Recovery ratio

The recovery ratio differs quite substantial for the different orientations. The ''flat'' samples had an average recovery ratio of 103,6%, which indicates that internal stresses are present in the printed sample, which caused self-bending in the opposite direction in which the sample was deformed. This was not measured during the study, so the exact degree of self-bending is not known. What was also observed during measuring was that the part of the samples which was printed flat on the build plate was slightly bended after recovery, while the part printed upright was perfectly straight. This indicates that all/most of the internal stresses after printing were located in the flat printed part of the samples. This is in line with results from earlier tests (upright samples from the ''orientation testing'' and flat samples from the ''double hinge testing'').

The ''upright'' samples show limited recovery with an average recovery ratio of 89,3%. However, the orientation of this sample type can be seen as the opposite of the ''flat'' sample type, which, based on the recovery ratio, was bended in the negative direction. With the ''upright'' sample being printed exactly the other way around, and deformed to a 2D-configuration, this can be seen as bending in the positive direction. As seen in the previous tests, the results of negative and positive bending taken together leads to an average recovery ratio of 96-97%. When combining the average recovery for the ''flat'' samples (negative bending) with that of the ''upright'' samples (positive bending), the overall average is 96,5%, which is in line with previous tests, and supports the theory of the 96-97% average recovery regardless of internal stresses.

The ''side'' samples show an 96,4% average recovery. When considering the results from earlier tests, this recovery ratio is the assumed recovery ratio that is achieved when no internal stresses are present after printing. If this is actually the case is not known, because the self-bending of the samples was not recorded. However, based on previous results, it was expected that this sample would have the least internal stresses after printing, so it is not too farfetched to assume the internal stresses were very limited in this sample type.

The ''45-degree'' sample suffered from similar issues as the ''45-degree flat'' sample from the ''orientation testing'' study, in that the surfaces that needed to be printed were under a 45 degree angle for both samples. This resulted in lower surface quality on the bottom side of the printed sample. In the orientation tests, this led to a high rate of self-bending, and a low (or high, when considering negative bending) recovery ratio. In this study, the average recovery ratio for the ''45-degree'' sample was 85,4%, which is the lowest recovery ratio of this study, but substantially higher than the 75,9% recovery ratio for the positively bended ''45-degree flat'' sample from orientation. When comparing printing quality of the two samples, it shows that the 45-degree samples of this study have a better surface quality than the 45-degree flat samples of the orientation testing, which can explain the difference in recovery ratio between the two sample types.

Activation time

The average activation times of the ''flat'', ''side'' and ''upright'' samples are very similar, with the averages being only 0.2 seconds apart (4.3 seconds for the flat and side samples, 4.5 seconds for the upright samples). The 45-degree samples however, have a much shorter activation time at 2.2 seconds on average. This shorter activation time can be explained by the quality and orientation of the samples. As mentioned earlier, the 45-degree samples have a quality comparable to that of the ''45-degree flat'' samples of the ''orientation testing''. This manifests itself in samples which are thinner as intended on some points, and also more porous, meaning the polymer structure of these samples is less homogeneous. This can also be seen when looking at the hinge from the top, as shown in figure 77. The infill of the hinge part looks rather coarse, and with no walls encapsulating this part of the hinge, heat can penetrate more easily. This leads to shorter activation times.

Although the activation times for the other sample types are similar, they are still lower than generally found in the earlier tests with similar samples (but then the 2D versions). The ''side'' sample can be compared to the ''side'' sample from the ''orientation testing''. When comparing activation times for these samples, there is only a slight difference: 4.0 seconds on average for the 2D samples, and 4.3 seconds average for the 3D samples. For the other two sample types, there is no 2D sample which they can directly be compared to. However, for both these sample types, porosity is a possible explanation for the lower activation time. Since the wall lines are not printed directly on top of each other but with a slight offset for each consecutive layer in order to create a curved surface, it is possible that heat can penetrate more easily, leading to shorter activation times.

Figure 77 top view of the 45-degree sample, showing the porosity of the hinge part

6.5 OVERALL CONCLUSION

The tests done in this project were meant to get a good understanding of the shape memory capabilities of a material widely used for 3D-printing: PLA. The results from these tests are also meant to serve as input for the guidelines which will be set up to help designers in designing 3D-printed SMP objects. Through different tests, the effect of numeral parameters on the shape memory behaviour of the material were investigated. These parameters, related to designing and printing shape memory objects, were tested using small samples, which were designed through an iterative process, and modified for each test to fit the specific parameters which would be tested. All parameters tested, and their influence on self-bending, recovery ratio and activation time are shortly described in table 19. The findings from the testing process will be used to further develop the guidelines for 3D-printing shape memory objects.

As already mentioned in the conclusions of the different studies, an interesting observation was made when comparing average recovery ratios of the samples from different tests. It was found that, when combining the average recovery ratios of the negatively and positively bended versions of a specific sample type, the average recovery ratio is 96-97%. This is shown in tables 16 to 18, where the recovery ratios for all sample types throughout the different tests for which both negatively and positively bended versions were tested are displayed. As shown, the average when combining negatively and positively bended versions is between 96,0 and 97,2%. Based on this, the conclusion was drawn that this is the actual recovery rate of the 3D-printed material, if internal stresses are absent. Meaning that, if a sample can be printed without remaining internal stresses, recovery after deformation would lead to a 96-97% recovery ratio. With this theory, the degree of internal stresses can be derived from the recovery ratio of a printed object: the farther the recovery ratio of a recovered object deviates from 96-97%, the more internal stresses are present after printing. However, it should be said that this conclusion is only drawn based on the recovery under the conditions defined for testing (60 second submersion time to initiate recovery in 65°C water). If this theory applies for other recovery conditions cannot be said with certainty.

Table 16 Results of double hinge testing

Shape complexity/ hinge height (mm)	Positive bending average (%)	Negative bending average (%)	Overall average (%)
Single/ 0.8	89,5	103,3	96,1
Single/ 1.4	93,3	101,1	97,2
Double/ 0.8	90,6	101,7	96,2
Double/ 1.4	93,7	98,3	96,0

Table 17 results of orientation testing

Orientation	Positive bending average (%)	Negative bending average (%)	Overall average (%)
Side	90,6	102,5	96,6
45-degree flat	75,9	117,6	96,8

Table 18 results of 3D to 2D testing

Upright samples average (%)	Flat samples average (%)	Overall average (%)
89,3	103,6	96,5

Table 19 the tested parameters and their influence on self-bending, recovery ratio and activation time (the effects which were not tested are indicated with "-")

	Self-bending	Recovery ratio	Activation time
Material thickness/ hinge height	Self-bending decreases if the material thickness/ hinge height increases.	Increasing the material thickness/hinge height causes the recovery ratio of the object to deviate less from the optimal recovery.	Becomes longer when the material thickness/ hinge height increases, due to more material needing to heat up.
Build plate temperature	No clear influence was found.	-	-
Infill pattern	Infill pattern can affect this. The effect depends on the specific infill pattern. Self-bending occurs in the longitudinal direction of the infill lines, meaning that when all infill lines are printed in the same direction, there is more self-bending than when the direction of the infill lines is altered between the layers.	-	-
Material	Material choice affects this. The effect depends on material choice.	Material choice affects this. The effect depends on material choice.	Material choice affects this. The effect depends on material choice.
Fan speed	Lower fan speed leads to slightly less self-bending.	No clear influence was found.	A higher fan speed leads to slightly lower activation times.
Nozzle temperature	Based on recovery ratio, the assumption was made that a higher nozzle temperature leads to more self-bending.	A higher nozzle temperature leads to a larger deviation from optimal recovery.	No significant influence was found.
Shape complexity	Based on recovery ratio, the assumption was made that double hinge samples have more self-bending compared to single hinge samples.	Increasing shape complexity was found to cause slightly larger deviations from optimal recovery.	No significant influence was found. However, there was an observable difference in activation time for single and double hinge samples, with double hinge samples having a longer activation time.
Bending direction	No effect	Bending in negative direction (opposite direction from self-bending) leads to a higher recovery ratio than bending in positive direction (same direction as self-bending). However, the average recovery when combining negatively and positively bended versions of a sample type lead during testing always to an overall average recovery of 96-97%.	
Print orientation	Self-bending is affected by this parameter, with the effect depending on the specific orientation.	Recovery ratio is affected by this parameter, with the effect depending on the specific orientation.	Activation time is affected by this parameter, with the effect depending on the specific orientation.
Print configuration (3D/2D)	Based on recovery ratio, the assumption was made that print configuration has no significant influence on self-bending. However, results can vary depending on orientation	Print configuration has no significant influence on recovery ratio. However, results can vary depending on orientation.	Print configuration has no significant influence on activation time. However, results can vary depending on orientation.

6.5.1 EVALUATION ON PARAMETER TESTING

While the results from the technical characterization already give quite some information about how to print shape memory objects, there is still a considerable number of parameters and scenarios to be tested to be able to completely understand and predict the shape memory behaviour of printed objects. For example, in the tests, a limited range of different values for the parameters was tested (e.g. two values for hinge height, while in practice, hinge height can vary much more, depending on the designed object). Predictions can be made how changing parameters to values not tested in this project will influence shape memory behaviour, but the exact effect on the behaviour can only be known for certain after further testing. Also, this test series didn’t touch upon the subjects of different deformation angles, higher environment temperature for recovery, infill density, other materials, effect of cyclic behaviour on shape recovery etc. In short, the parametric study done in this project provides a clear basis for designing shape memory objects, while also being a starting point for further testing and understanding the behaviour of 3D-printing shape memory materials.

7 GUIDELINES

By combining the knowledge gained through literature research and parameter testing, the final guidelines are set up. As defined at the start of this project, the guidelines are meant as a tool to help other designers in designing 3D-printed shape memory objects. In this chapter, the setup of the guidelines is discussed.

7.1 GUIDELINE DOCUMENT

Through testing and literature research, information about the influence of fourteen different parameters on the shape memory behaviour of 3D-printed structures has been gathered. To make all this information easily accessible and usable for designers, a separate document has been created in which this information is distilled into guidelines. Next to the guidelines, an introduction is given on the topics of shape memory polymers and 3D-printing, so the document could be used by designers, without them needing to consult this report to understand the content of the guidelines. However, the guideline document does reference to this report and the corresponding literature, should the designer ever need further elaboration or background information on the parameters.

7.2 GUIDELINE EXAMPLE

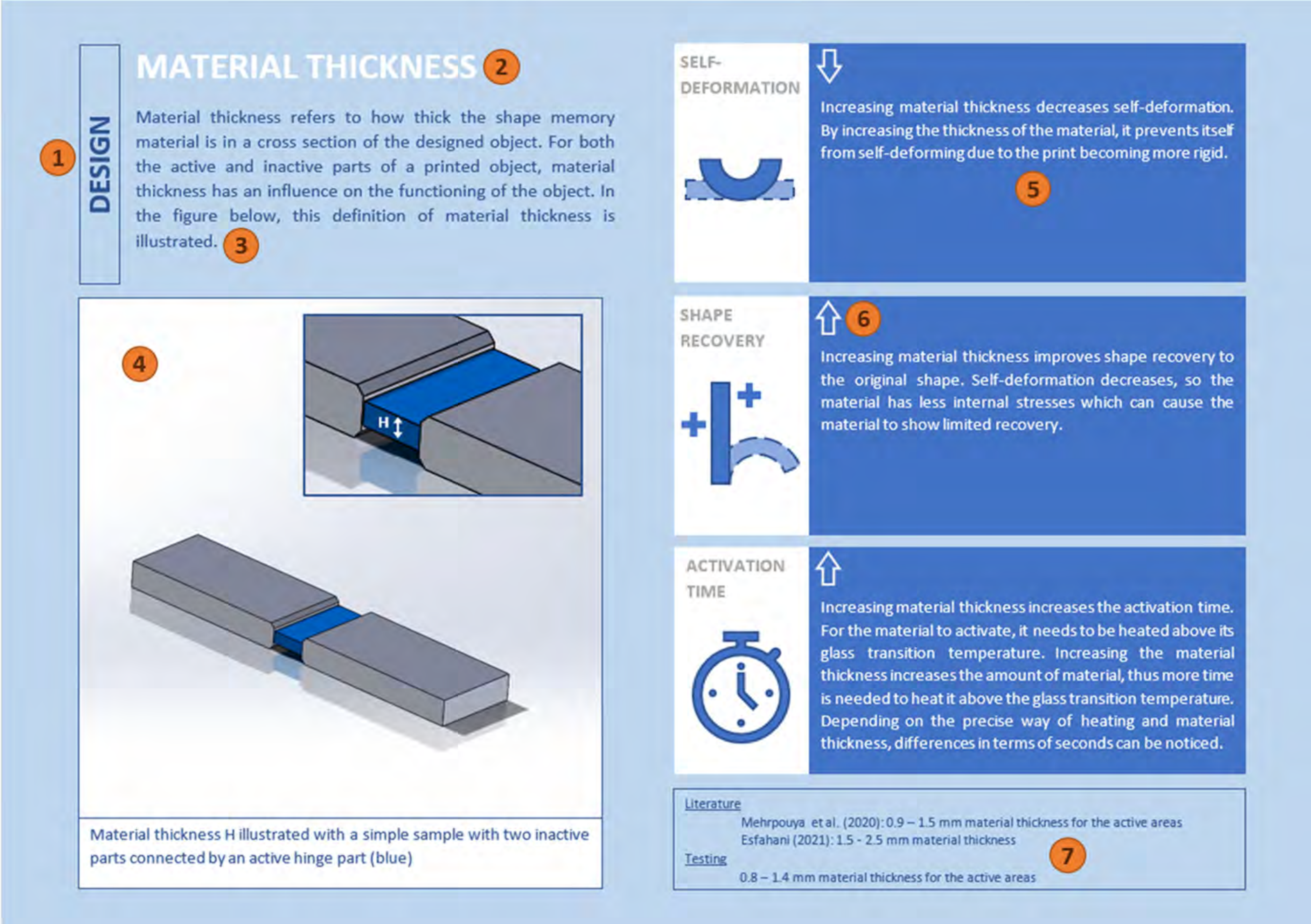
In figure 78, an example of one of the guidelines is given. Each guideline has the same lay out, and takes up one whole page. In the figure, all different elements are indicated with an orange number and in table 20, an explanation is given for each element.

The guidelines are set up to convey information on 3D-printing shape memory objects in a comprehensive and clear manner, while also being easily approachable due to the visual design of the document. Length of the text is limited, and information is conveyed visually where possible. Information on the origin of the guideline is provided in the bottom right corner of each page to create some context for the user of the document, with the aim to make the guidelines easier to apply to new design challenges.

However, the guideline document is only a first setup of. There are still a significant number of parameters and shape memory aspects which are not addressed in the guidelines. Furthermore, some parameters have not been researched to the full extent, due to the timeframe of the project. This means there is still a significant amount of follow up research to be done in order to create a complete guide for creating 3D-printed shape memory objects. This will be further discussed in chapter 14: recommendations.

Table 20 Explanation of the different elements in the guideline example

Element	Explanation
1	The category to which this guideline belongs (either Design, Material, Manufacturing or Use).
2	Guideline title/ parameter name
3	Introduction/explanation of the parameter discussed in this guideline.
4	Image providing extra information on the definition of the parameter.
5	Description of the effect the parameter has on one of three shape memory aspects: self-deformation, shape recovery and activation time.
6	Icon serving as a visual representation of the effect the parameter has on this shape memory aspect.
7	The sources used to write this guideline, also showing the values of the parameter that were tested either in other projects (''literature'') or in this project (''testing'').


1 DESIGN

MATERIAL THICKNESS 2

Material thickness refers to how thick the shape memory material is in a cross section of the designed object. For both the active and inactive parts of a printed object, material thickness has an influence on the functioning of the object. In the figure below, this definition of material thickness is illustrated. 3

4

Material thickness H illustrated with a simple sample with two inactive parts connected by an active hinge part (blue)

SELF-DEFORMATION

Increasing material thickness decreases self-deformation. By increasing the thickness of the material, it prevents itself from self-deforming due to the print becoming more rigid. 5

SHAPE RECOVERY 6

Increasing material thickness improves shape recovery to the original shape. Self-deformation decreases, so the material has less internal stresses which can cause the material to show limited recovery.

ACTIVATION TIME

Increasing material thickness increases the activation time. For the material to activate, it needs to be heated above its glass transition temperature. Increasing the material thickness increases the amount of material, thus more time is needed to heat it above the glass transition temperature. Depending on the precise way of heating and material thickness, differences in terms of seconds can be noticed.

Literature

Mehrpouya et al. (2020): 0.9 – 1.5 mm material thickness for the active areas

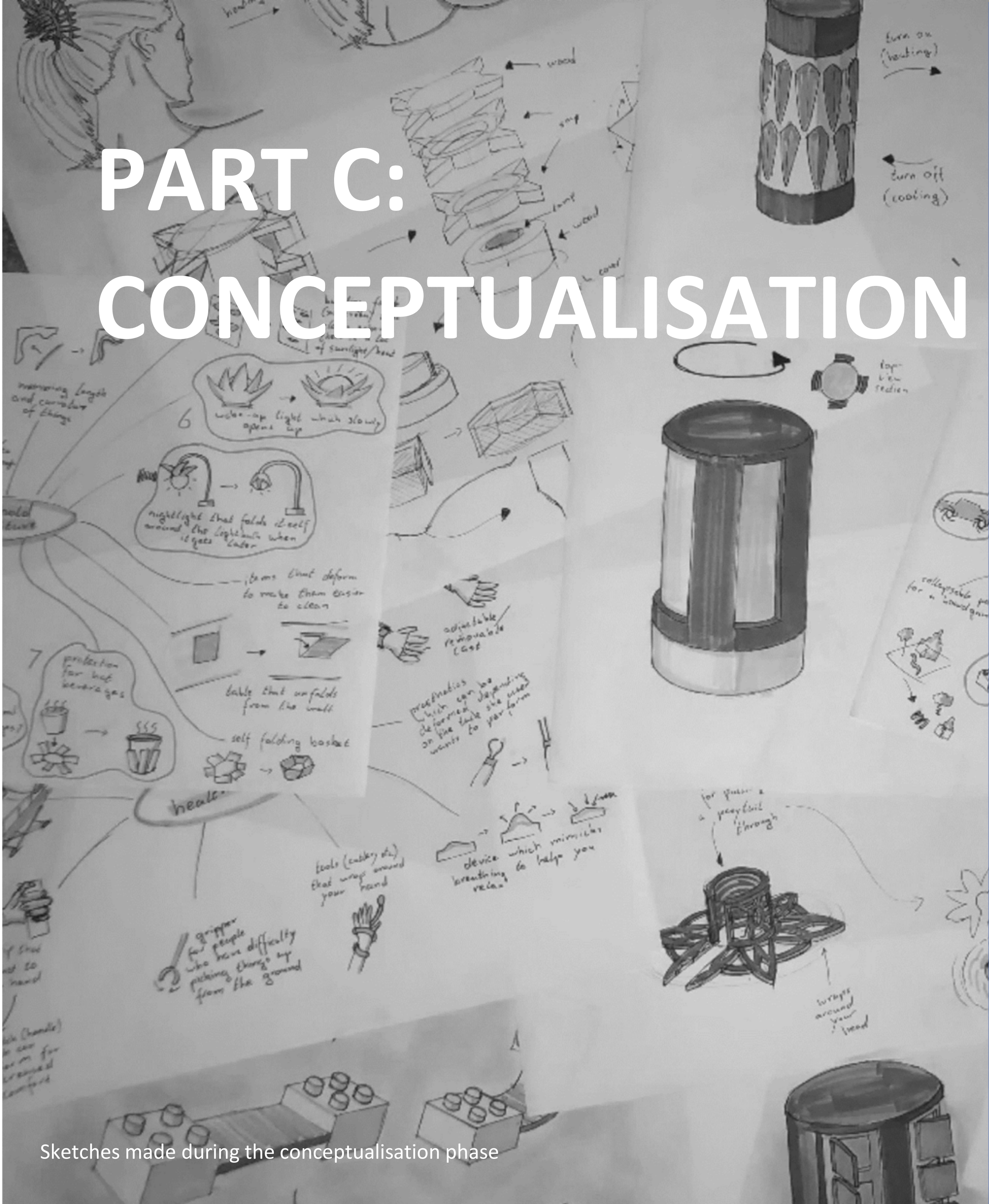
Esfahani (2021): 1.5 - 2.5 mm material thickness

Testing 7

0.8 – 1.4 mm material thickness for the active areas

Figure 78 Guideline example

PART C: CONCEPTUALISATION



Sketches made during the conceptualisation phase

Combining the knowledge gained through literature research and testing, this chapter describes the development of a concept/demonstrator model showing the capabilities of 3D-printed shape memory materials. Based on the initial aim of the project, and knowledge gained through literature research and testing, a vision and list of requirements and wishes are developed. Using these elements as a starting point, ideation is done to come up with product ideas using shape memory polymers. A small number of ideas is then selected and developed into concepts, of which one is eventually chosen to become the demonstrator product. The chosen concept is further developed, and a physical prototype is printed and tested. This part is concluded with the final design of the concept/demonstrator.

8 IDEATION

In this chapter, the ideation phase of the project is discussed. This phase started with the creation of a vision, which specified the design goal, and was used to assess how the later generated ideas fit the goal of the project. Next, the established requirements and wishes are discussed, which are used to assess the generated ideas on equal terms. This is followed by two inspirational collages, which serve as inspiration for the ideation and later concept development. A creative session was organised to kickstart idea generation, which is discussed next. The last part of this chapter describes the idea generation and eventual choice of ideas to be further developed into concepts.

8.1 VISION

At the start of this project, the aim of the project was defined: develop a deployable structure which will serve as a demonstrator showing the capabilities of SMP's, as well as a set of design guidelines for designing 3D-printed SMP structures, with the aim to inspire designers to work with these kinds of materials and manufacturing technique. Based on this aim/goal, a vision was created to serve as the starting point of inspiration for the ideation and conceptualisation phase of this project. The vision, shown below, with which this phase is to:

Several terms mentioned in the vision are further explained:

Real-world application: the aim is for the demonstrator to also serve a purpose in the sense that it is an actual product (concept) with a function, for example a lamp, piece of furniture, clothing or some kind of tool.

Inspire designers: To serve as inspiration for a wide range of designers, the eventual product/concept should both be functional and have aesthetic value (e.g. not be a product where the aesthetic design has little to no value, for example internal parts for machines, medical equipment like stents and catheters etc.)

Engaging and inspiring way: shape memory should be a core functionality/ play a core role in the functioning of the product, and be visible for the user.

Based on the established guidelines: The guidelines that were derived from the tests and literature research done in this project shall serve as the basis for designing the functionality of the product. Designing the product like this will also be a test for the guidelines, to see how well they can be applied in a design context.

*Create a concept with a **real-world application**, with the purpose to **inspire designers** to implement SMP's and utilize 3d-printing technology in their designs and production of these designs. The concept should communicate the technical capabilities of the SMP material combined with FDM 3D-printing technology in an **engaging and inspiring way**. Functional application of the shape memory effect shall be done **based on the established guidelines**.*

8.2 REQUIREMENTS & WISHES

To be able to assess the ideas and concepts that are created, and determine which are/is suitable for further development, a set of requirements was created. Using these requirements, the different ideas and concepts can be rated in an equal manner, ensuring the selection of the ideas/concepts which are most in line with the envisioned goal, as described in the vision.

Based on knowledge gained in this project, and the specified design goal/vision, the following requirements were formulated:

- The product should fulfil a specific purpose apart from demonstrating the capabilities of the material.
- The product should have aesthetical value.
- Shape memory should play a core function in the functioning of the product.
- The product (shape memory parts) should be produced using FMD 3D-printing.
- The product (shape memory parts) should be produced based on the established design guidelines
- Both temporary and permanent shapes should have a clear function
- The material should be able to be activated using a heat source, in a safe and practical way
- The shape memory capabilities should create added value for the product
- The active parts of the product/ the shape change caused by shape memory should be visible for the user

Next to the requirements, a number of wishes were formulated:

- The product should be something that is or can be used daily
- The user should actively interact with the product to increase awareness and appreciation for the functioning of the product

8.3 INSPIRATIONAL COLLAGES

As a way to inspire and visualize the envisioned design direction, two collages were created. These collages communicate two themes which are closely related to shape memory capabilities which are the main focus of this project. As described in the vision, the aim is to create a concept which shows the shape memory functionality and aesthetic value which can be created using SMP's in combination with 3D-printing. The collages focus mainly on the aesthetic part, while the functional part was also taken into consideration when choosing the themes for the collages. The keywords used to find the images composing the collages are shown in figure 78, with the adjectives shown in blue and the nouns in orange, and the size of the words resembling their importance in the collages.

The first collage, shown in figure 80, visualizes the theme of Origami in design. From the start of this project, this Japanese art form of creating structures and shapes by folding sheets of paper has been involved, either through found literature or designing of test objects to be printed. The samples used in testing show similarities to origami in the way the samples are ''folded'' on the hinge part, albeit less sharp. The principles of Origami are a valuable source of inspiration for 3D-printed SMP objects, as these can be applied on both the aesthetical and functional aspects of the design. The collage shows examples of origami-inspired structures and products.

Figure 79 adjectives and nouns used to find the images composing the collages

The second collage, shown in figure 81, combines the themes of dynamic and organic. It shows examples of objects and products that have a sense of dynamics to them: it feels like these objects can move. Even though this is not necessarily the case, the design of the objects creates a sense of natural movement or flow. The way that shape memory objects deform and recover their shape can evoke this same feeling. Just like with the origami theme, the themes shown in this collage can be applied to both the functional and aesthetical parts of design. In the aesthetic design, the expectation that a product can change shape/move can, like with the examples shown in the collage, be achieved through a certain form language. However, it can also be the case that the design requires this expectation to not arise, to create a surprise effect. Either way, this collage serves as a visual representation of this expectation.

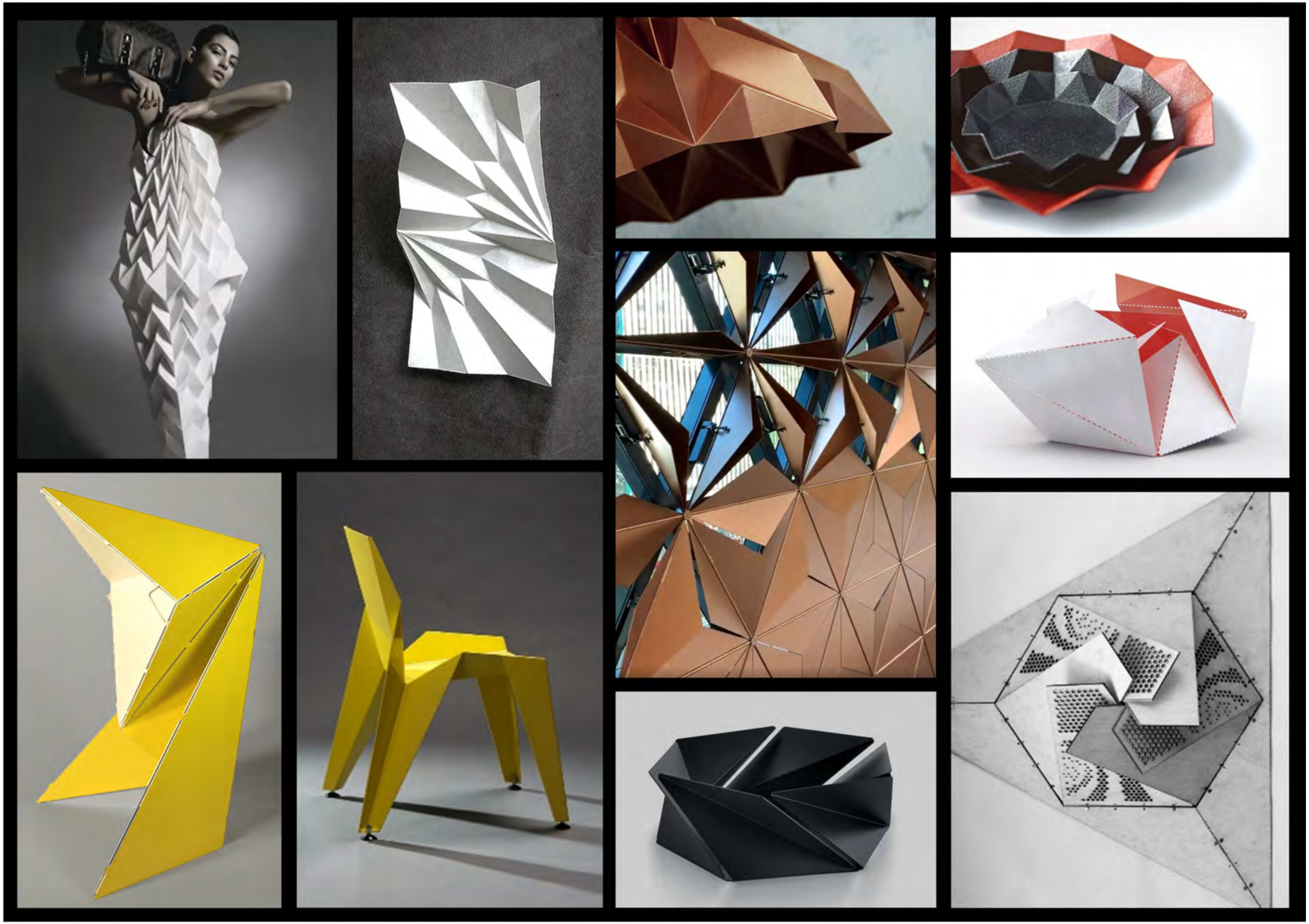


Figure 80 Origami collage

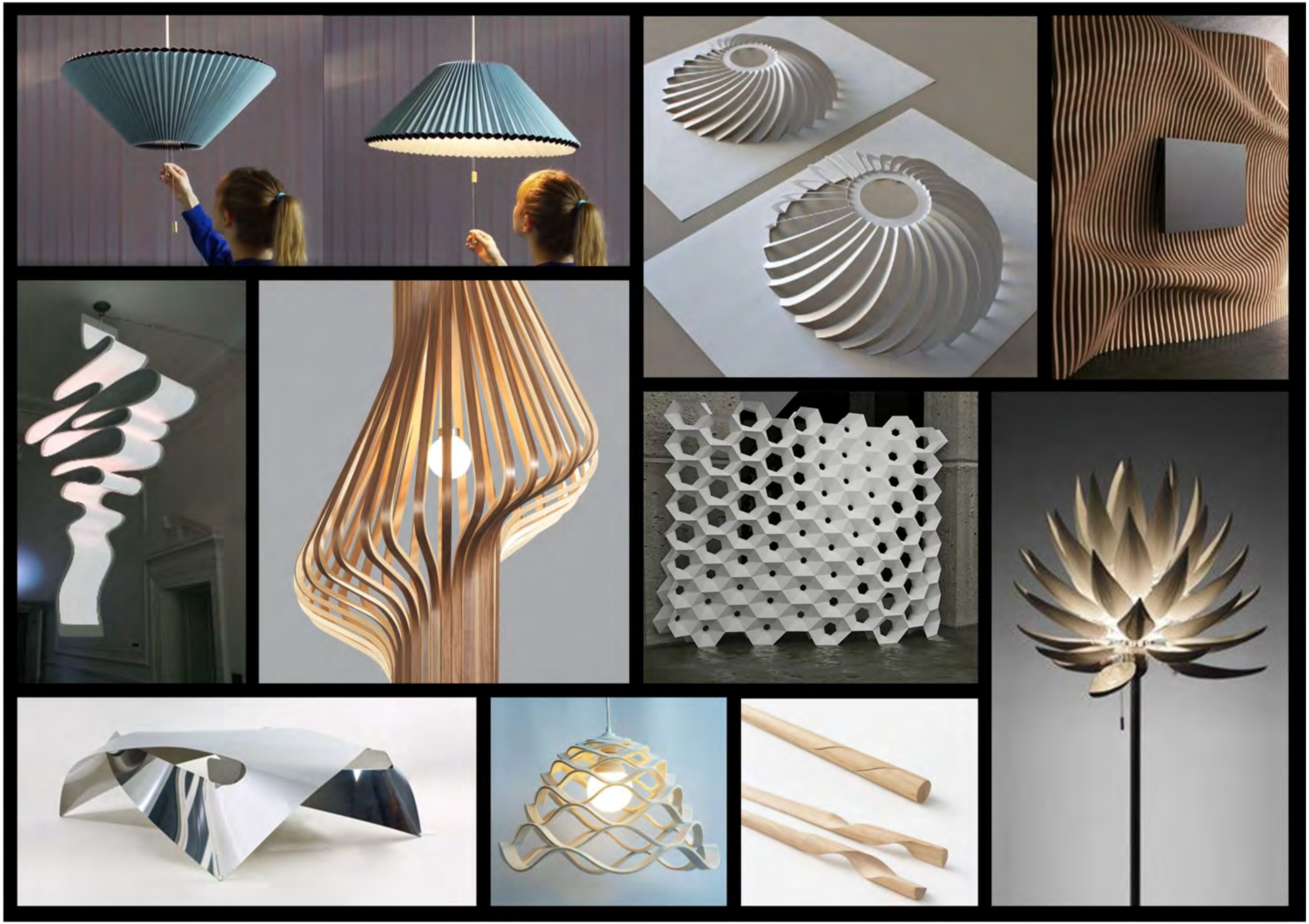


Figure 81 Dynamic organic collage

8.4 CREATIVE SESSION

To get inspiration on how to apply the shape memory properties of PLA in a real-world application/product, an online creative session was organised. In this session, a group of people was asked to brainstorm about possible applications and products where the shape memory capabilities of PLA could be used. The complete setup and transcription of the results can be found in appendix H.

The creative session was set up based on the creative problem solving process (CPS) as created by Buijs and Tassoul (2005). 6 people were present during the session: 1 facilitator (me), 4 industrial design students and one participant without a background in design, to get different insights from different viewpoints. The first part of the session was short introduction in which the shape memory effect, the material (PLA), and Miro, the online whiteboard tool which we would be using for the session, were explained. Prior to the meeting, a Miro board was set up for the session. Also introduced in the introduction was the problem statement which would form the basis of the creative session:

How can you apply this material and its shape memory capabilities in a product?

After the introduction followed a warm up exercise where participants were asked to come up with products/things related to the words ‘’flexible’’ and ‘’surprising’’. The warm up exercise served as a way of familiarizing the participants with Miro, and to get them in the right mindset for the rest of the session.

After the warm up exercise followed 3 brainstorm rounds. In the first round, the participants were asked to come up with verbs related to the word ‘’movement’’. At the end of the round, 3 of these verbs were chosen to expand the problem statement into questions:

How can you apply this material and its shape memory capabilities in a product to make it:

- *Walk/crawl?*
- *Wiggle?*
- *Unfold?*

These 3 questions formed the basis for the second brainstorm round, in which participants were asked to generate product ideas for these 3 questions. This resulted in a vast amount of different ideas, which, at the end of the round, were clustered into different product categories.

The third brainstorm round was an individual exercise in which participants had two minutes per cluster to come up with more ideas related to this cluster. After two minutes, the facilitator would ask the participants to move on to the next cluster. This was repeated until each participant had worked on each cluster.

Next, each participant chose 3 ideas which he/she thought were interesting or had potential. After this, the group was divided into groups of 2, and each duo had to choose one of the ideas to develop into a concept, which they had to present afterwards. This led to four concepts being developed (there were 3 duos, but one duo developed two ideas).

Adjustable mannequin

The adjustable mannequin is meant for people working in fashion, especially tailors who need to make suits and costumes made for one specific individual. It works by first making a mould of the body of the person for who the garments need to be made. This mould can then be heated and used to form a mannequin made out of shape memory material, resulting in a mannequin with the exact bodily dimensions as the customer. Tailored clothes can then be made using this mannequin. Figure 82 shows the process of mould making and deforming the mannequin. Once the clothes are done, the mannequin can be heated again, returning to its original shape. Then the mannequin can be used again for the next customer.

Closing night light / Overcooking prevention

(This duo developed two ideas together)

The closing night light was envisioned to help people fall asleep by slowly covering the light source over time. Once you would lie in bed and turn the light on, it would give of a certain amount of light, and as time goes by and it gets later, the light bulb slowly gets covered by the external parts of the lamp, actuated by one or more shape memory materials.

The overcooking prevention was envisioned to ensure that things in pans would not overcook because the lid is closed. This special lid/ add-on device for a lid lifts the lid once the water inside is close to overcooking. It would lift the lid using small shape memory polymer tubes that deform once the water starts rising.

Wake up light

The wake up light is a lamp which slowly opens up to let more light through. The idea is that this is used as a lamp to help you gradually wake up in the morning. The wake up light is shaped as a flower, with the petals being actuated by the shape memory material. In its initial state, the petals cover the light source. But once the lamp is turned on, the petals heat up and slowly unfold over time. Once the light is turned off, either some sort of weight or a spring forces the petals to form around the lightbulb again when the shape memory polymer loses its recovery force.

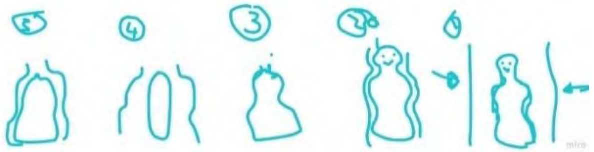


Figure 82 Adjustable mannequin sketches

Figure 83 Closing night light & overcooking prevention sketches

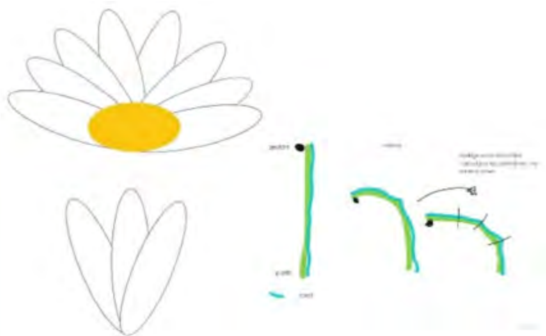


Figure 84 wake up light sketches

8.5 IDEA GENERATION

With the vision as a starting point, and taking inspiration from the collages and creative session, idea generation was done in order to come up with a wide range of product ideas in which 3D-printed SMP's could be applied. The first step was to see what elements of the creative session could be included for the ideation and possibly further steps. Therefore, all ideas from the creative session were evaluated based on viability, feasibility and personal preference. A range of ideas was selected, which collectively could be categorised in four of the (slightly altered) product categories created during the creative session:

- Clothing & accessories
- Medical/healthcare
- Household & furniture
- Leisure & entertainment

8.5.1 IDEA GENERATION RESULTS

The next step was the actual ideation process. For all four product categories, product ideas were thought up. In figures 85 to 88, the results of this process are shown.

Clothing & accessories

3D-printing allows for the creation of shapes and structures which are difficult or sometimes even impossible to create using other production techniques. This, combined with shape memory capabilities of polymers, can be used to create unique accessories ranging from bracelets and rings which can adjust to the wearer to bags which could be adjusted in shape to what needs to be carried in it. The ability to switch between a glassy and rubbery state also creates opportunities for securing items you take with you, for example in the form of a bag (compartment) which can be opened by heating it, or a modern take on a classic locket necklace, with a photo only accessible when heating the locket. Apart from this, there are opportunities to create products not necessarily for consumers, but for dressmakers and tailors, like for example a mannequin which can be shaped to exactly resemble the measurements of a customer in need of a tailored suit or costume. These and other ideas related to this product category are shown in figure 85.

Figure 85 Ideation on clothing & accesories

Medical/Healthcare

Concepts and products using shape memory materials already exist in the medical industry. Things like stents, sutures and catheters are already making use of the qualities of shape memory materials. However, it could be wider applied in different products. It could be used for products supporting the autonomy of disabled and elderly people, like SMP grippers to grab things from places which are hard to reach for them, or knee supports to help them stand up. Or it could be used for products related to injuries like a cast which can be removed or adjusted to make showering easier and to make the overall process of healing more comfortable. Applying SMP's for grips and handles could also increase the comfort and ease of use on for example crutches and cups. These and more ideas related to medical and healthcare can be found in figure 86.

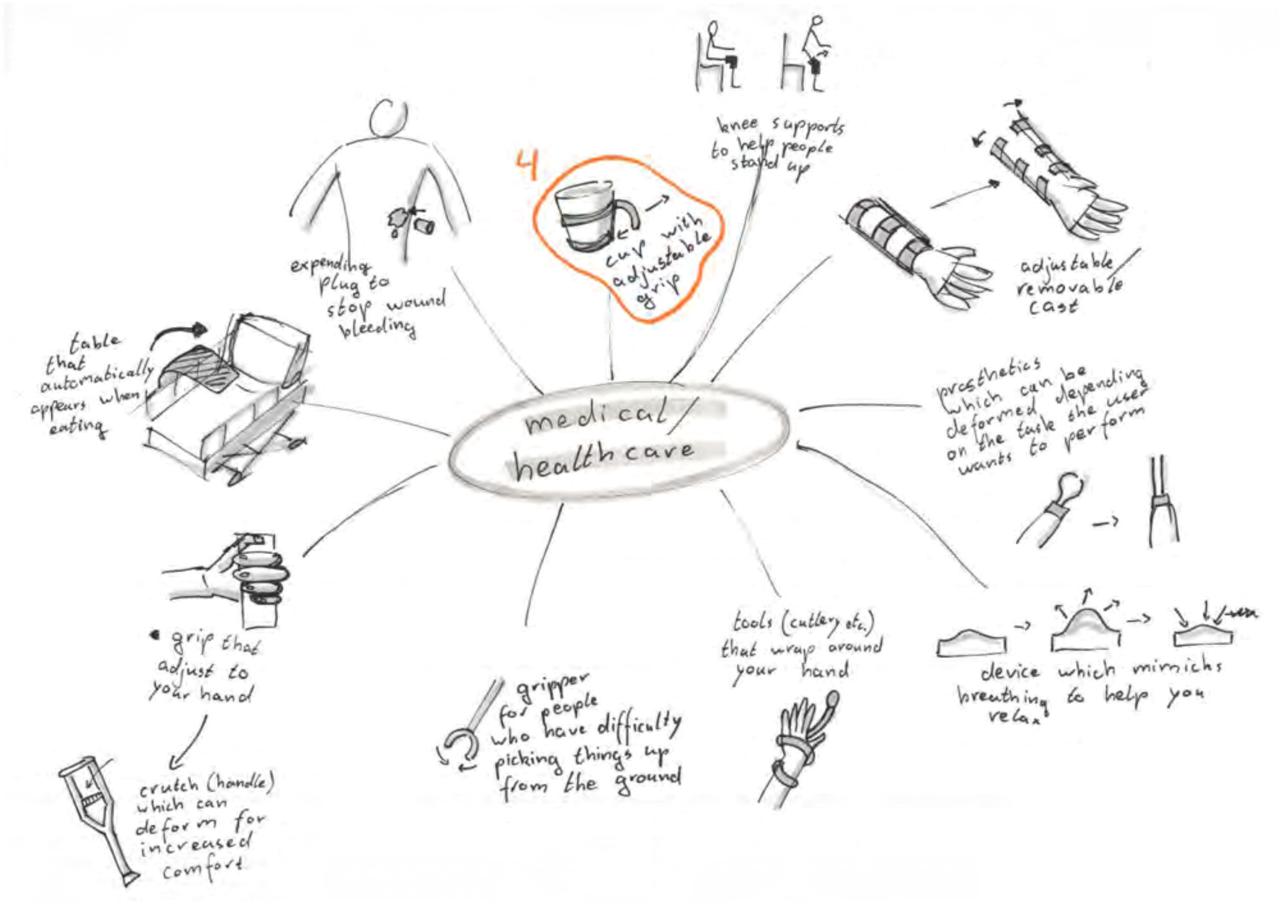


Figure 86 Ideation on medical/healthcare

Household & furniture

In this category, shown in figure 87, there is a wide range of different possibilities for applying SMP's. The foldability of these materials can be used for storage purposes, for example in foldable furniture or utensils. It can also be used for climate control, to either block heat or light from entering. Another possible application relates to lighting. Apart from a possible aesthetic application, it could be used to create nightlights or wake up lights which can change the amount of light over time.

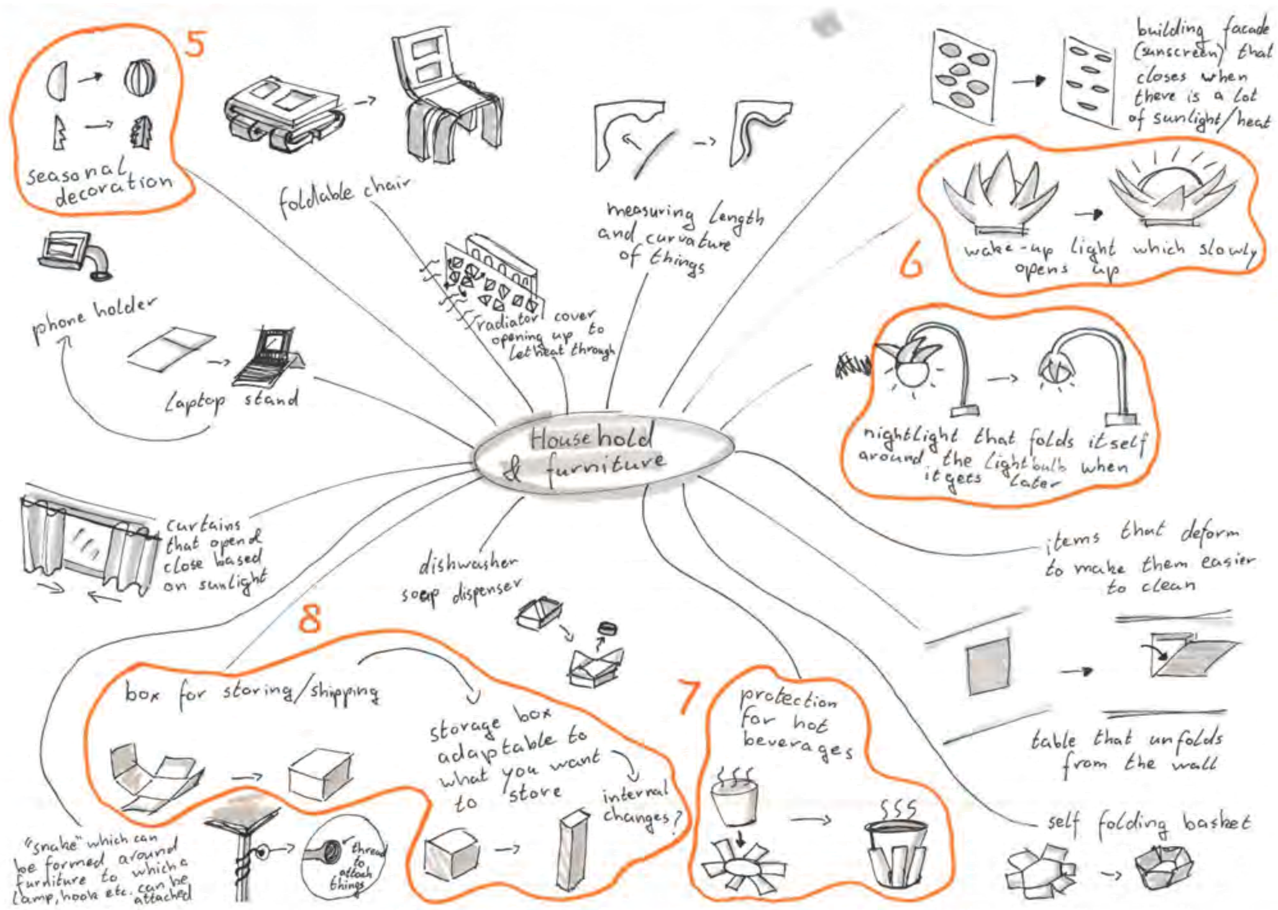


Figure 87 Ideation on household & furniture

Leisure & entertainment

The leisure & entertainment category, shown in figure 88, contains ideas ranging from toys to flower pots. While the ideas in this category are quite broad, the common theme most, if not all ideas share is that they use SMP's to enrich an experience, be it for example adding an extra dimension to construction toys, or providing a surprising way to wrap gifts.

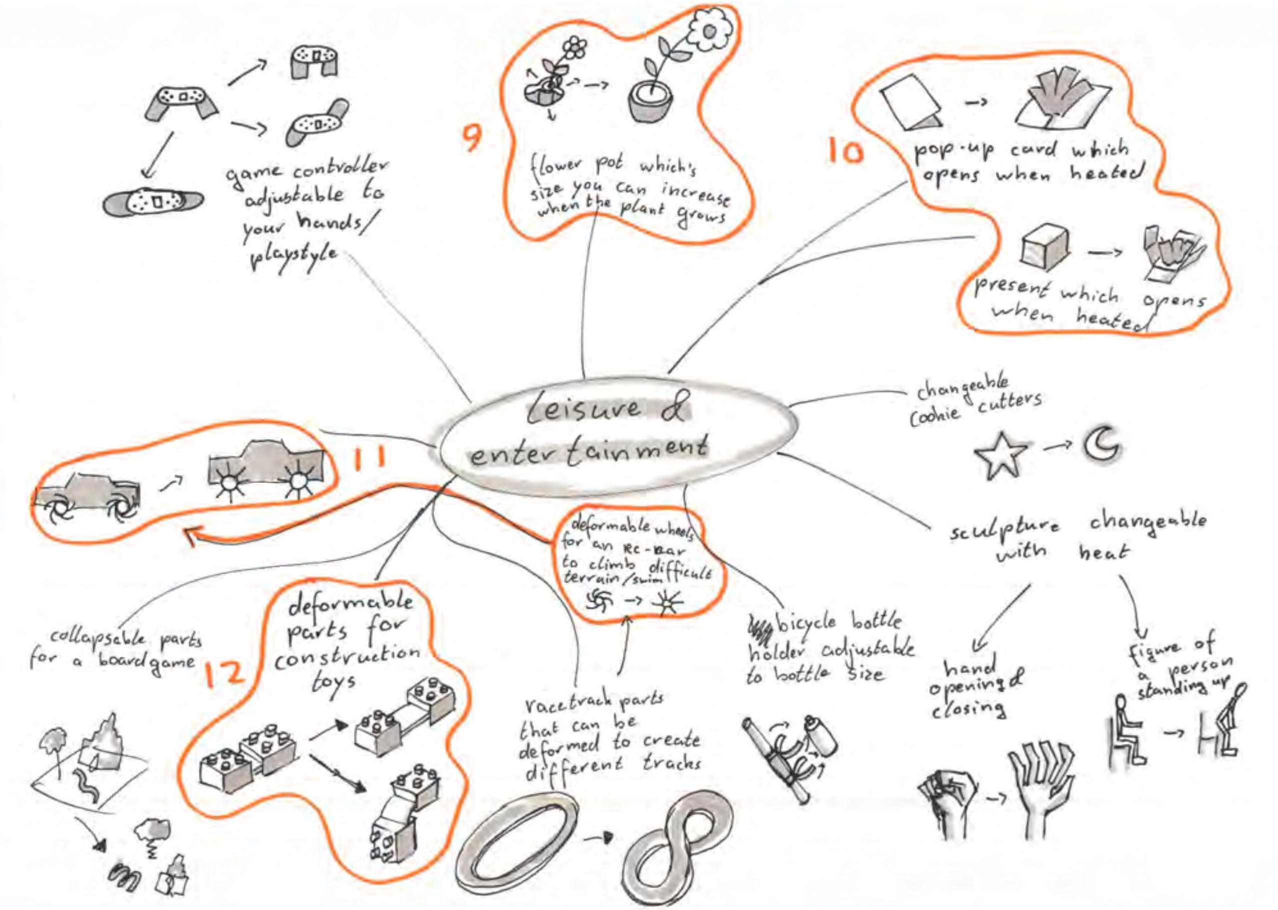


Figure 88 Ideation on leisure & entertainment

8.5.2 IDEA ASSESSMENT

After ideation, a selection was made of the most promising, interesting and viable ideas, which are encircled with orange in the figures (89 to 92). These selected ideas were then assessed on four aspects related to the requirements and wishes: the purpose of the permanent shape, the purpose of the temporary shape, the added value of shape memory and if the material can be heated in a practical and safe manner. In appendix I, this assessment is shown.

Also taken into consideration was the vision, in which inspiring designers is an important aspect. Based on the assessment, and what was thought to suit the vision best, four ideas were selected, to be developed into concepts. The following ideas were chosen:

Figure 89 Hair ornament

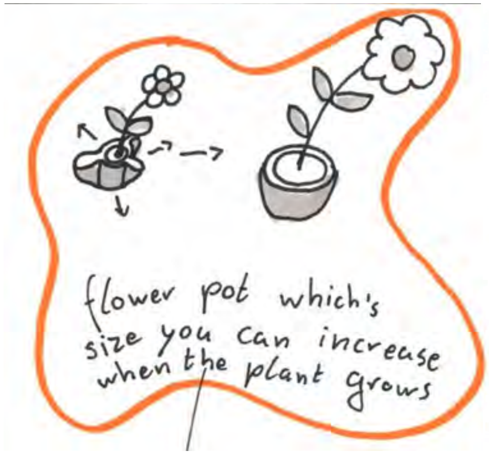


Figure 90 Flower pot

Figure 91 Wake up/ night light

Figure 92 Construction toy

9 CONCEPT DEVELOPMENT

This chapter marks the start of the fourth step of the MDD method, in which the four ideas chosen at the end of the ideation phase will be further developed into concepts. For each idea, the functioning is thought out, as well as the strong and weak points of each idea in relation to the earlier defined requirements. Also, a first version of the physical design is drawn out, to get an idea how these concepts could look and how the active SMP components could work. During concept development, elements from the design methodology described in the literature review will be considered, to create well-rounded concepts which can be compared in an objective manner. Based on the concepts as they are developed in this step, a choice will be made which concept will be developed further into a physical model/demonstrator.

9.1 CONSTRUCTION TOY

This concept revolves around the customisability that shape memory can provide. In its core, the concept can be seen as an extension to regular construction toys like LEGO. The blocks are meant to be compatible with this popular type of construction toys, while bringing the added value of shape memory in the form of deformable parts. As is shown in figure 93, one part consists of one or more ''regular'' blocks, connected with each other through a part with shape memory capabilities. This connecting part can be deformed to create different shapes and orientations, allowing for the creation of new types of structures. There is a multitude of different blocks which can be produced to serve different purposes, of which some are shown in figure 94. Blocks can either serve as real construction parts (walls, bridges, pillars etc.), serve a more aesthetic/sculptural function (sculpture blocks, blocks meant to create a smooth surface etc.) or a combination of both.

In their permanent shapes, the blocks would be flat/compact, allowing for easier shipping/storage, and be directly usable for ''conventional'' building, meaning that the spacing between different parts connected with a shape memory part will be similar to the spacing between regular blocks. When deformed, the shape and orientation of the blocks can be whatever the user wants it to be, to suit their needs and create new and exciting structures. In this lies the added value of the concept: adding a new dimension to a well-established concept.

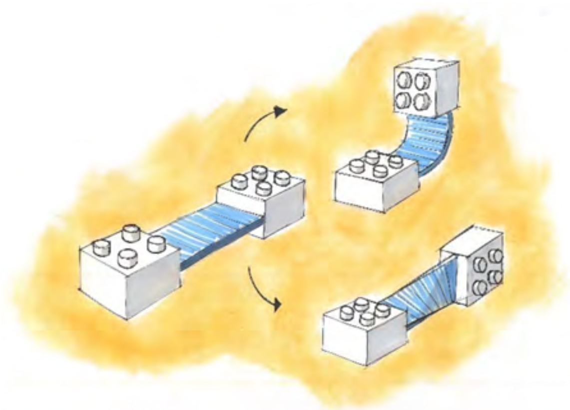


Figure 93 Different deformation options, by deforming the shape memory part (blue)

In essence, the concept is rather straightforward, which can be a good thing, but might limit the inspiring effect it will have on designers. Also, the aesthetic value of the concept on itself is limited. furthermore, it is not necessarily the shape memory that provides the added value, but more the fact that a part of the blocks can become deformable and then rigid again, so the permanent shape has limited value in this concept. This should be considered when considering if this concept would be suitable to be further developed in this project.

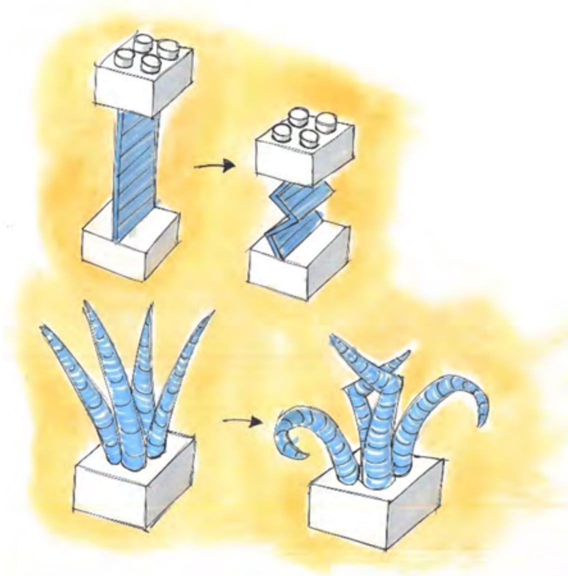


Figure 94 Different types of blocks

9.2 HAIR ORNAMENT

This is a concept based on the ability of shape memory materials to create objects tailored to the user. This already occurs in both clothing and clothing accessories (rings, bracelets etc.), but without making use of shape memory materials (apart from some conceptual examples). However, shape memory is very much suited for this purpose. This is a concept for a hair ornament which uses shape memory to provide a tailored fit to the user. It was designed to be worn on the back of the head, around a ponytail. In its temporary shape, the ornament can be a flat object with an opening at one place, as shown in figure 95 (left), making it easy to position the ornament around a ponytail. The flat shape also makes it easy for storage.

The ornament can then be heated using a hair dryer, which activates shape recovery. The product then starts recovering to its permanent shape: heavily curved and with the opening closed, as shown in figure 95 (right). The ornament will wrap itself around the user's head, taking the shape of the user's head, which also secures it in place using small pins. Once the user wants to take off the ornament, it can be heated again, after which the user can deform it and remove it.

3D-printing is a very suitable production technique for this kind of application, since it allows for custom designs and sizes. The product has a high degree of aesthetic value, while also showing the functioning of the shape memory material. However, it might be difficult for the user to see the shape memory in action, since the ornament is located on the back on the head. Also, in terms of heating, this should be able to be done in a safe manner, but using the hair dryer for too long might damage the user's hair. So, for further development, these things should be considered and the product should be designed accordingly.

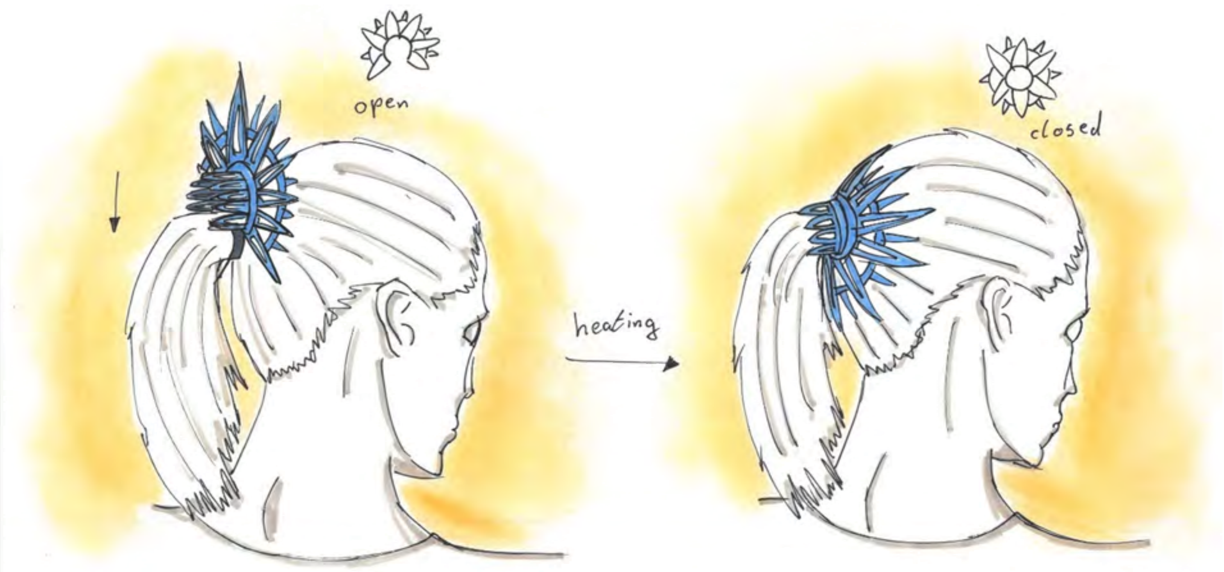


Figure 95 Hair ornament in the deformed state (left) and recovered state (right)

9.3 WAKE-UP LIGHT

This concept uses the idea of a wake-up light, which slowly increases light intensity to provide a natural way of waking up, which helps you to get out of bed and have more energy during the day. In this concept, shape memory is used to simulate this effect by letting the lamp deform to gradually increase the amount of light it gives off. When the lamp is turned off, it is in its closed state, as shown in figure 96 (left). This is the temporary shape of the active parts. When the lamp turns on, the light bulbs inside heat up the shape memory material. Once heated enough, shape recovery will start, which causes the active parts to return to their permanent shape, which is shown in figure 95 (right). With the active parts slowly being heated and slowly recovering their permanent shape, the amount of light the lamp gives off increases.

Once the lamp is turned off, the shape memory material will slowly cool down, and gravity will cause the active sections to be deformed again, ‘’closing’’ the lamp automatically. No user interaction is needed deform the material and activate it for recovery. Instead, the user experiences the shape memory capabilities of the material by the gradual increase in light intensity, and the gradual shape change.

This concept is promising in terms of the ability to show how varying certain parameters cause the material to behave differently. In this case, sequential shape change can fairly easily be implemented, while also serving a purpose in the functioning of the product. Also, by using the radiation heat from the lamps combined with gravity, a two-way shape memory effect can be simulated using a one-way shape memory material. Therefore, this concept is thought to be inspiring to designers. However, purely in terms of the product, it is in a certain way inferior to existing wake up lights, which also can change light temperature. This should be considered when choosing the concept to develop further.

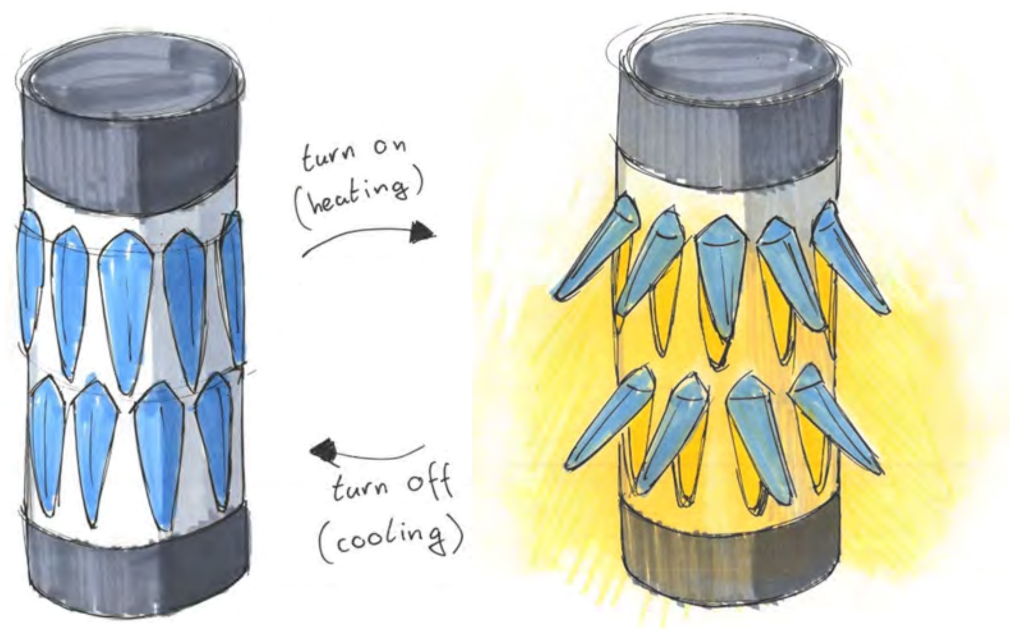


Figure 96 Wake-up light in its closed state(left) and open, recovered state (right)

9.4 FLOWER POT

Growing plants need to be repot to make sure they get the right amount of nutrients and moisture for the stage of the growing process they are in. The size of the pot a plant is placed in can play an important role in keeping these factors balanced. When a plant grows larger, it needs more space and more nutrients and moisture, therefore it needs a bigger pot. This concept was created to account for this. In essence, this is a concept for a plant pot which can be changed in size depending on the plant and how much space and resources it needs. The concept is based on origami, with different sections that can be folded/unfolded to change the size of the pot. In its temporary shape, the pot can be made into its ''small'' configuration, as shown in figure 97. This makes it suitable for plants in the early stages of growing.

As the plant grows bigger, the pot can be changed to its ''large'' configuration through shape memory. The outside of the pot can be heated using a hair dryer, to activate shape recovery. This will cause the pot to go back to its permanent shape, which means that the folded parts will unfold, increasing the size of the pot. After putting in some extra dirt, the plant can grow further without the need of repotting to a different pot. If you want to put a new plant in the pot, it can be heated again using a hair dryer or hot water so it can be deformed back to its small configuration.

This concept deals with a real-world scenario, and reduces the need to repot your plants, which leads to a reduced amount of plant pots needed. The concept has both functional and aesthetic value, while showing in an easy to see manner the shape memory material in action. However, the temperature needed to activate the material should be considered, as this might damage certain types of plants. Therefore, if the concept is developed further, this should be considered. Furthermore, this use of shape memory in this concept is limited in terms of how frequent these capabilities will be utilized. This should also be considered when choosing which concept to develop further.

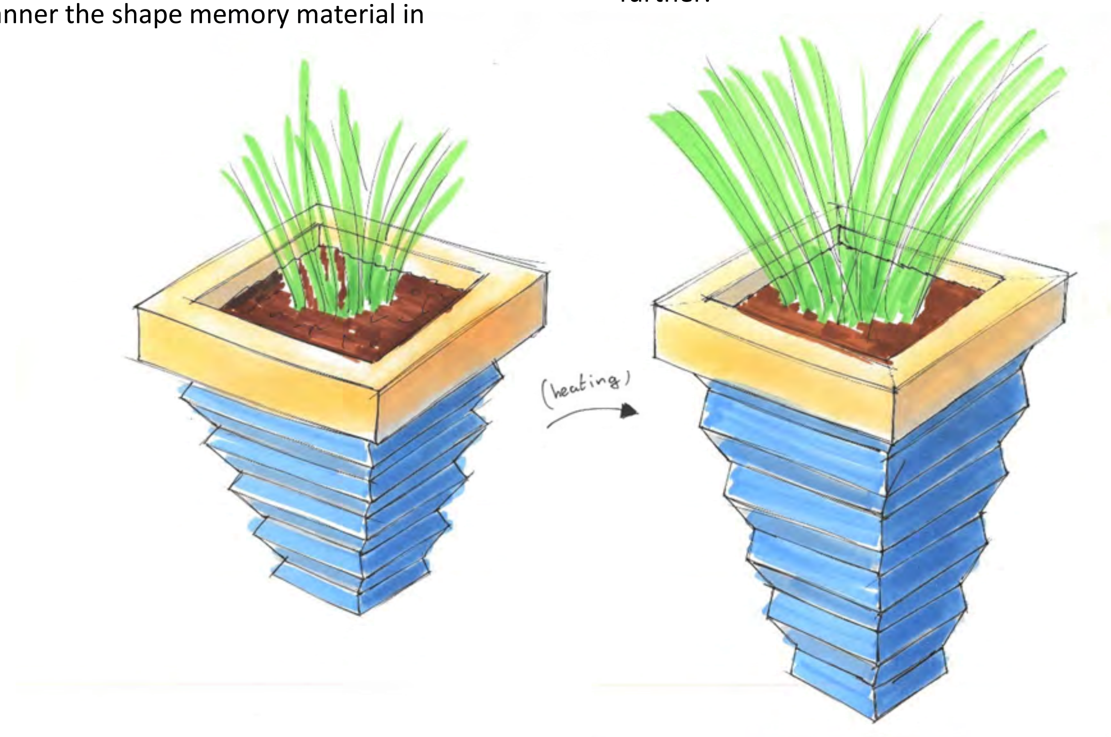


Figure 97 flower pot in small, deformed state (left) and large, recovered state (right)

9.5 CONCEPT CHOICE

When looking at the developed concepts, they all display the potential to communicate the shape memory effect in polymers to designers and other people, while at the same time serving a real-world purpose and displaying aesthetic qualities. However, with the concepts having diverse purposes and designs, each concept has its strong and weak points. In this chapter, these points are evaluated and a choice is made which concept is the most suited to be further developed into a physical model/demonstrator.

9.5.1 CONCEPT EVALUATION

The **construction toy** concept fulfils a specific purpose, in that it is a construction toy which adds an extra dimension to building structures. It shows aesthetic value, although this is not the core of this concept, and therefore limited compared to the other concepts. Shape memory plays an important role in the versatility of the product, although the product can be used without utilizing the shape memory capabilities. The role of the permanent shape is limited, since changing between different temporary shapes is the strength of this concept. Therefore, the added value of shape memory specifically is limited, as it is more shape *change* that is of value here. However, the shape memory is clearly visible for the user, it can be deformed in a safe and practical manner, and because of the relatively easy geometry of the parts, it can be printed fairly easy. Also, since the user would be actively interacting with the parts, awareness and appreciation for the functioning of the product can be created, which is one of the strengths of the concept.

Unlike the construction toy concept, the **hair ornament** concept displays of lot of aesthetic value, and both the permanent and temporary shape play an important role in the use of the product. This concept fulfils the purpose of a hair ornament which, compared to the other concepts, has the least functional value. However, the shape change of the product is clearly visible, although the user might not be able to see it properly as the ornament is placed on the back of the head. But it should give the user feedback on the shape change in the form of the feeling that the ornament forms around the head. In combination with the fact that this concept creates active interaction between the user and the product, it can create awareness and appreciation for the functioning of the shape memory material. In terms of 3D-printing, the permanent, curved shape might prove challenging to be printed, although this might be solved with a design composed of several parts.

The **wake up light** concept shows the most potential for daily use, with the function being to wake up the user in a natural way by giving off more light over time when the SMP deforms. This deformation is caused by heat from the lamp inside, so the user won't have to touch it, creating a safe way of heating. Also, shape deformation to the temporary, closed shape is caused by gravity, simulating a 2-way shape memory effect. This does mean that the user has very little interactivity with the product. However, the way the SMP is used and deformed here has the potential to inspire other designers more than the other concepts do. Also, this concept allows for demonstration of sequential shape change, so in terms of showing the capabilities of the material, this concept has some extra possibilities compared to the other concepts. Furthermore, it has both functional and aesthetic value. Similar to the other concepts, shape change is clearly visible, although the user might notice the shape change primarily based on the amount of light the lamp gives off.

Finally, the **flower pot** concept shows both functional and aesthetic value, and a clear function as a flower pot. The shape memory capabilities of the material are utilized in the form of being able to increase or decrease the size of the pot. While this does provide added value in the form of less need to repot, and therefore less pots that need to be used, it is a functionality which will only be used every so often. Even without utilizing the shape memory capabilities, the flower pot can still be used properly, although without the size change. For activating the material, hot water or a hair dryer can be used, in a safe and practical way for the user. However, this could potentially harm the plant in the pot. If this is the case, the plant needs to be removed before shape change, which compromises part of the functionality of the product. Another point to consider is the need for water tightness, which cannot be ensured for FDM printed parts without a coating. However, the shape change is clearly visible in this concept, and creates active interaction between the user and the product, which is an advantage over the wake up light concept.

9.5.2 FINAL CONCEPT CHOICE

Based on the evaluation of the different concepts in terms of fulfilling the requirements and fitting the established vision, the **wake up light** concept was chosen to be further developed. This concept is believed to have the most potential is showing the capabilities of the SMP and inspiring designers, while both having strong functional and aesthetic value. It's potential for daily use, way of utilizing the heat of the lamp and gravity to recover and deform, and showing sequential shape change are all positive points which contribute to the choice for this concept. However, this concept does provide limited active interaction between user and product concerning the shape memory cycle, which is something to consider for further development, to see if this can still be incorporated.

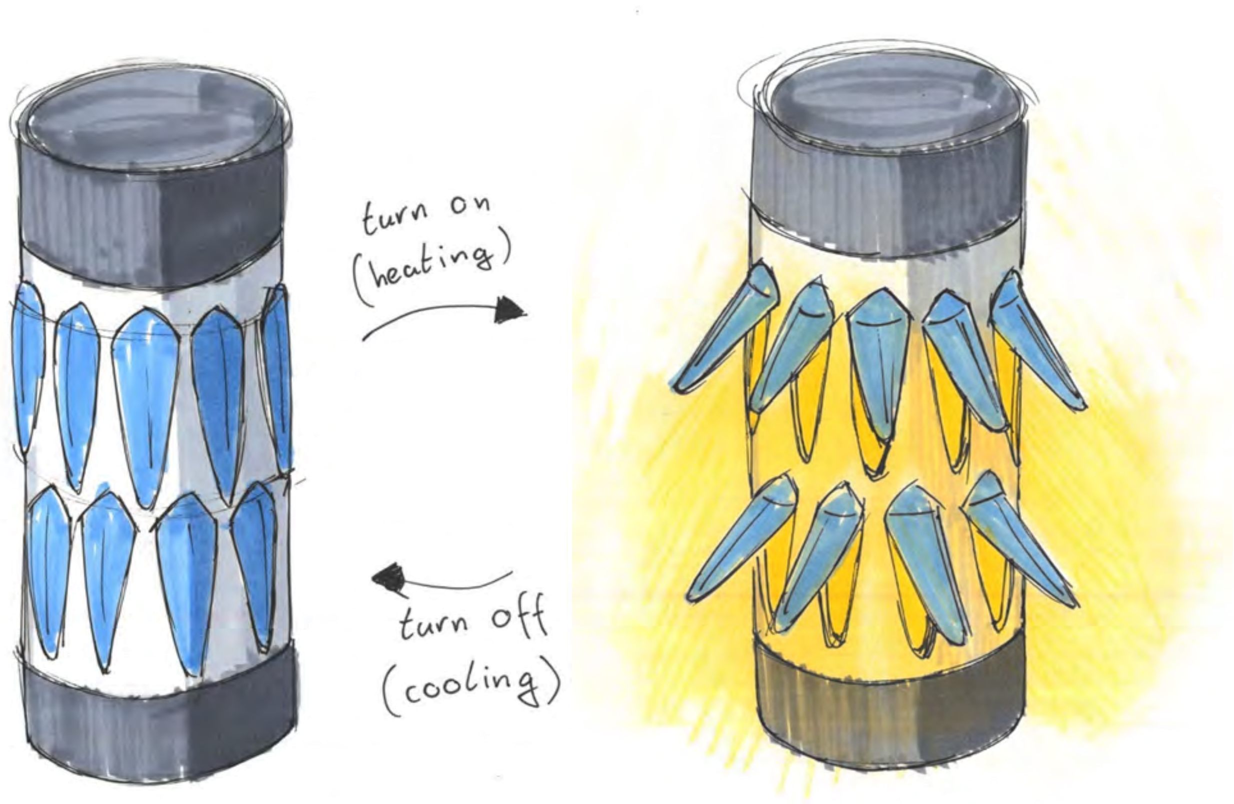


Figure 98 Chosen concept: Wake-up light

10 CONCEPT ELABORATION

The concept chosen after concept development, the wake up light, will be developed further into a demonstrator model. Several development steps need to be made before the first prototypes can be printed and tested. In this chapter, these development steps are described. First, the envisioned working principle will be tested to see if it works as envisioned and if it is feasible to use in this concept. Based on the results of this test, the concept will be further developed in terms of functionality and aesthetics.

10.1 TESTING THE CONCEPT'S WORKING PRINCIPLE

Now the wake up light has been chosen to be developed into a demonstrator, the first step for further development is to test if the principle of deformation and shape recovery works as envisioned for this concept. The functioning of the concept as envisioned relies on the change in recovery force in the material when heated above its glass transition point, and cooled below this point. When heated above T_g, the material transitions from a glassy state to a rubbery state, enabling the molecular chains to move. If the material is then deformed and cooled, this deformation will remain as the material returns to its glassy state, trapping internal stresses in the material. When heated again above T_g, the chains can move again and want to return to their highest entropy configuration, thus the material recovers its original shape. In theory, the recovery force of the material is highest at the temperature at which it was deformed, and becomes lower the more the temperature of the material deviates from this. This principle is used in the concept of the wake up light. In its closed state, the SMP parts are in a deformed configuration, as shown in figure 99. When heated by the heat of the light bulb inside, they want to return to their original shape, which is the open state of the lamp. As shown in the figure, recovery happens against gravity. Once the lamp is turned off, the temperature slowly drops, thus decreasing the recovery force in the material. At a certain point, gravity overcomes the lowering recovery force, causing the SMP parts to deform, returning the lamp to its closed state.

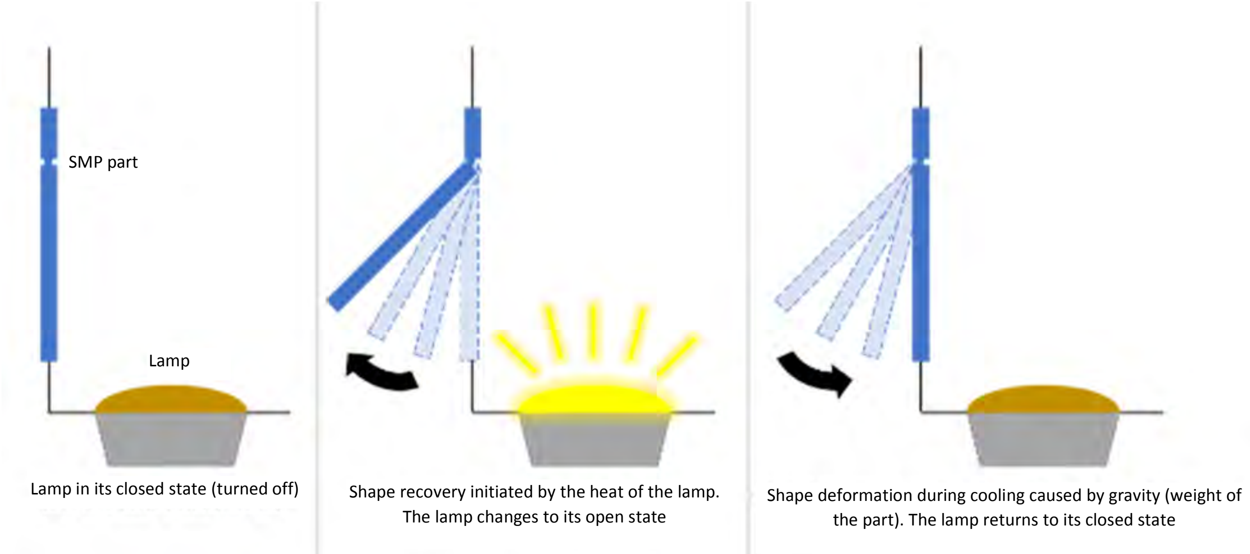


Figure 99 Schematic overview of the working principle of the wake-up light

10.1.1 TEST SETUP

A short test is performed to see if the principle works as envisioned. For this proof of principle, there are two things which need to be tested:

- Can the heat of the lamp be used to heat the SMP material above its T_g?
- Can the change in recovery force be applied to let the sample be deformed by gravity when the material cools down?

To test this, a 230V 50W halogen spotlight, also envisioned to be used in the demonstrator, is used. An unused double hinge sample from the technical characterization phase is used to first determine if the lamp is able to heat the SMP material to a temperature above its T_g. To do this, the lamp is placed in a sideways orientation, and the sample is held in front of it roughly 2 cm away from the lamp, as shown in figure 100. The sample is regularly checked if it is deformable. If this is the case, the sample is deformed and cooled, after which it is put in front of the lamp again to initiate recovery.

If the sample can be heated above T_g properly using the lamp, the next step will be to see if the sample can be deformed by gravity and the original shape can be recovered using the lamp. To test this, a similar test setup as used for the previous test is used. For this test, newly printed samples are used. These samples resemble the single hinge samples used during technical characterization, but one of the inactive parts has a variable length, in order to test how heavy/big the moving inactive part can be to achieve the envisioned result. Figure 101 shows the different test samples. These samples are printed using a differently coloured PLA, since this was the available material. However, since this is a proof on principle, only meant to see if the envisioned principle can be achieved at all, this should not be an issue. In figure 102, the test setup is shown. The samples are first heated above T_g, after which the lamp is turned off. During cooling, it is observed if the material deforms under its own weight while cooling. If this is the case, the lamp is turned on again to see if the sample recovers to its original shape when heated.

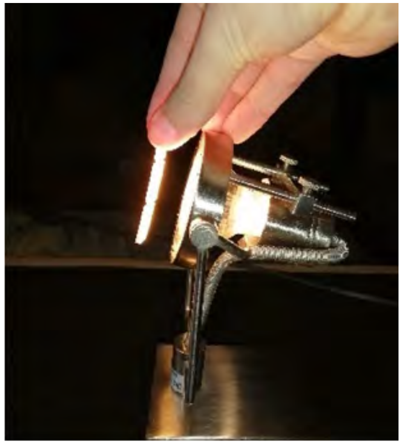


Figure 100 Test setup to test heating with a lamp

Figure 101 Test samples for recovery

Figure 102 Test setup for recovery test

10.1.2 RESULTS & CONCLUSION

The testing led to important insights regarding the feasibility of the envisioned concept. The first step explored the possibility of heating the SMP material using a halogen lamp. During this experiment, the sample was slowly heated in front of the lamp, which eventually led to the material reaching its rubbery state, making it possible to deform the sample. The sample was then deformed to the shape shown in figure 103, after which it was cooled. Then, the sample was heated in front of the lamp again, causing the sample to recover its original shape. The recovered sample is shown in figure 104. In conclusion, the lamp can be used to heat the SMP material properly.

In the second step it was tested if the principle of having the SMP parts deform under their own weight when cooled, and then recover heated shape when heated again is feasible. During testing, the 25, 30, and 35 mm samples would already start deforming under their own weight while heated above T_g. Then, after turning of the lamp, no further deformation was observed, meaning that the difference in recovery force during heating and cooling was limited to such an extent that it did not have an effect on the deformation of the samples. The 20 mm sample did not show noticeable deformation during heating, but also did not show noticeable deformation when the lamp was turned off and the sample was cooled. The samples as they were after this heating and cooling process are displayed in figure 105. Heating all samples again to initiate shape recovery did not result in recovery of the original shape. No changes in the deformed shape were observed. In conclusion, the recovery force of PLA is very small, making it very challenging to have this material recover against gravity. This is in line with the literature review, which showed that the recovery force of SMP's is very limited compared to for example SMA's. Furthermore, the difference in recovery force between when the material is heated and when it is cooled is also limited, which is in line with the limited recovery force in general. Therefore, the application of this principle in the wake up light concept will not work as envisioned, so the concept of the wake up light needs to be redesigned around an alternate working principle.

Figure 103 Deformed sample

Figure 104 recovered sample

Figure 105 Recovery test samples after heating and cooling

10.2 REDESIGNING THE WORKING PRINCIPLE

The testing of the working principle showed that the envisioned functioning of the concept was not feasible. Therefore, this needs to be redesigned. Part of the working principle can be maintained, namely the way the material is heated. Heating using a halogen light proved to be a feasible way to heat the material above its T_g. Therefore, the parts in need of a redesign are the shape memory parts which open and close to expose more or less light respectively. These need to be made in a way that they are not dependent on gravity for deformation or shape recovery. What also should be taken into consideration is the conclusion drawn during concept choice. In this step, it was concluded that there was little active interaction between the user and the lamp (e.g. the user does not play a role in the shape memory cycle, apart from turning the lamp on and off). This was determined to be a negative point about the concept, which, if possible, should be addressed during concept elaboration. Changing the working principle provides the opportunity to incorporate more active interaction in the concept.

Based on these two drivers, the working principle of the concept was redesigned to still fulfil the same function, but in a feasible and interactive way. The redesigned working principle is shown in figure 106. The choice was made to change the orientation of the SMP parts, so that the hinge parts are positioned vertically instead of horizontally, so gravity won't play a role during deformation or shape recovery. However, this does mean a new force needs to be introduced to deform the SMP parts to return the lamp to its closed state. This is where the active interaction between user and lamp can be incorporated. Once the user is awake and the lamp can be turned off, the user can close the small hatches by for example turning a part of the lamp (as shown in the figure), or by putting a cover over the lamp which pushes the hatches back to their closed positions. The exact manner in which this is done depends on the further development and final design of the concept, which is the next step now that the working principle has been redesigned.

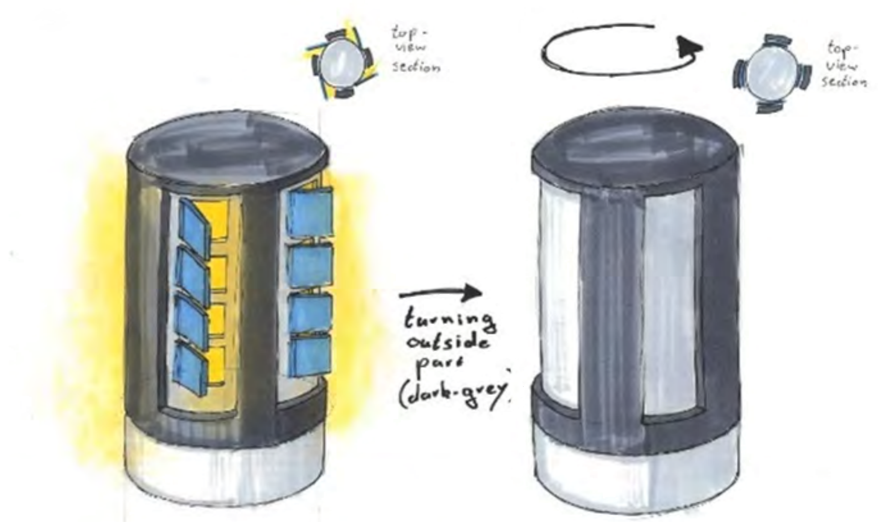


Figure 106 Redesign of the working principle, with the lamp in its open, recovered state (left) and its closed state, where the dark grey part is rotated to close the hatches (right)

10.3 PRELIMINARY DESIGN

With the redesigned working principle, the concept can be further developed. Inspiration is taken from the collages to design the concept in terms of material, overall form language and how the lamp changes shape. Sketches made during the design process can be found in appendix K. The design as presented in this chapter is the preliminary version of the design. Based on testing, which is discussed in chapter 11, final changes are made to the design.

Figure 107 shows the preliminary design of the wake-up light, which has been given the name *DAWN*, due to the lamps functioning bearing resemblance to a sunrise. The lamp is composed of five 3D-printed PLA rings stacked on top of each other. These rings are mounted on a wooden base which houses a 50 watt halogen spotlight, which, apart from light, produces the heat needed to activate the shape memory components. The bottom of the wooden base is partially open, so cool air can enter the lamp from there as the hot air inside the lamp ascends. The upper layer of the lamp is again wood, which closes off the lamp on the top side. Figure 108 shows an exploded view of the lamp, showing all components.

Figure 107 Preliminary design of the wake-up light, in its closed state

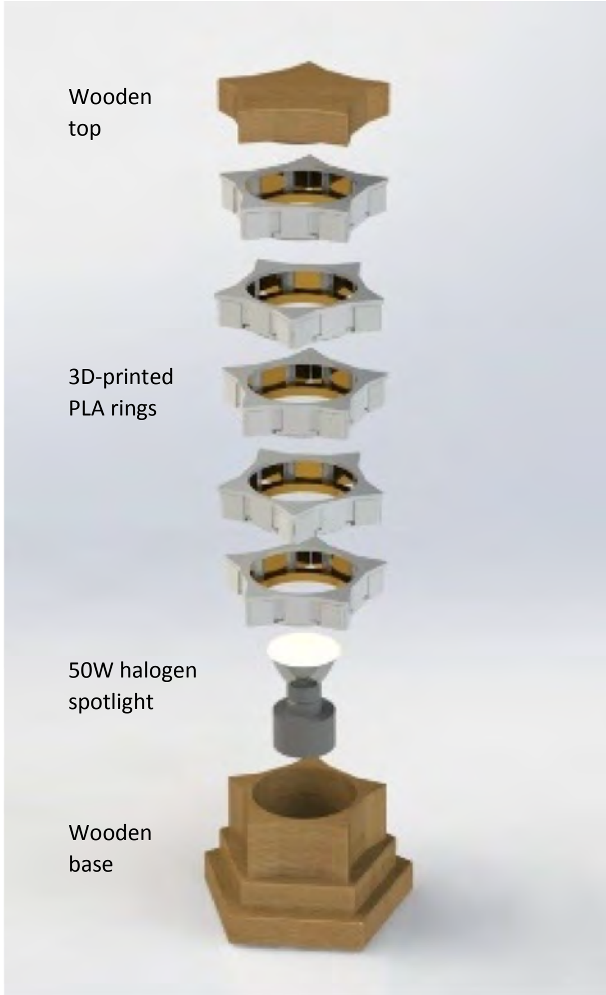


Figure 108 Exploded view, showing the different components.

DAWN was designed to give of a small amount of light when it is turned on, and slowly open up to expose more of the light created by the lightbulb inside, so that the user wakes up in a gradual and natural way. Each 3D-printed layer contains 10 active parts, which serve as hinges to 10 separate hatches, as shown in figure 109. In this figure, the hatches are displayed in their closed state, meaning that little light is led through. This is the so called temporary or deformed shape of the material. When the lamp is turned on, it starts producing heat, which, in the mostly enclosed space, causes the temperature to rise inside the lamp. This causes the PLA to heat up. Once the material is heated enough to be activated, the hinges will slowly start to return to their permanent shape, resulting in the shape shown in figure 110. In this open state, more light will be visible, as the hatches are not blocking the light anymore. An impression of how the lamp will look once all hatches are opened is shown in figure 110. Because of *DAWN*'s cylindrical design, the shape change of the structure can be seen from all directions.

The hinges, hatches and all other parts of each ring are all made of the same material: PLA. However, since only the hinges should deform, and thus receive the most heat, while the rest of the structure should heat up as little as possible, the inside of each ring, apart from the hinges, is covered with heat reflective foil. This protects the structural components from becoming too soft and losing their structural integrity, while focusing the heat on the hinges to activate shape recovery. Apart from a functional purpose, the heat reflective foil serves an aesthetic purpose, as its secondary function is to enhance the aesthetical value of the design, by creating interesting light reflections and by emphasising the difference between the closed and open state of the lamp. The technical details and specific dimension of the PLA rings will be discussed in chapter 11.

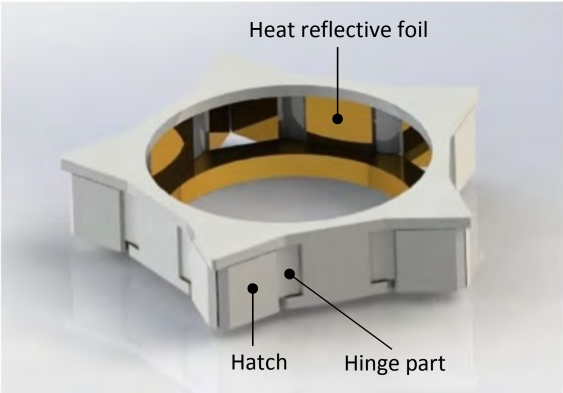


Figure 109 3D-printed ring in closed state

Figure 110 Wake-up light in its open state

Figure 111 3D-printed ring in open state

While gradually opening the lamp to give off more light is an automatic process utilizing the material properties of the SMP material and the heat of the internal lightbulb, the process of closing the lamp is done with the help of the user. The user is expected to have woken up/ get out of bed when the lamp is in its open state, as shown in figure 110. To return the lamp to its closed state, there are two steps which the user needs to do. First, he/she should align all the rings. The second and fourth PLA ring can be turned to align with the other rings, as shown in figure 112. With all the hatches aligned, the next step is to place a cover over the lamp, as shown in figure 113. This metal cover has 3d printed guiding profiles mounted on the inside, which deform the hinges again, to return the lamp to its closed state. Once the cover is placed, the lamp can be turned off, which causes the lamp to cool down. Since the cover is keeping the hinges in their closed state, the lamp is fixed in its closed shape when the PLA cools down below its glass transition point. Once cooled, the cover can be removed, revealing the lamp as shown in figure 114. For the next use, the user can rotate the second and fourth layer again, to return the lamp to its ''starting position'' as was earlier shown in figure 107.

Figure 112 All rings aligned with the lamp in its open state

Figure 113 cover placed over the lamp to deform the hinges and return the lamp to its closed state

Figure 114 Wake-up light after the cover is removed

As mentioned earlier, on the inside of the cover there are guiding profiles which deform the hinges from their open state to their closed state. Figure 115 shows one of the five identical guiding profiles which are attached to the inside of the cover. The shape of this part gradually deforms the hinges of the hatches when the cover is placed over the lamp. At the bottom of the profile, it has a small, triangular shape, which fits in the area between two opened hatches, as shown in figure 116A. As the cover is lowered over the lamp, the hatches are pushed back to their deformed state by the guiding profiles, eventually reaching the closed state, as shown in figure 116C. With all rings aligned, the five guiding profiles, each attached to one of the internal sides of the pentagonal cover, return all hinges and hatches to their deformed/closed state.

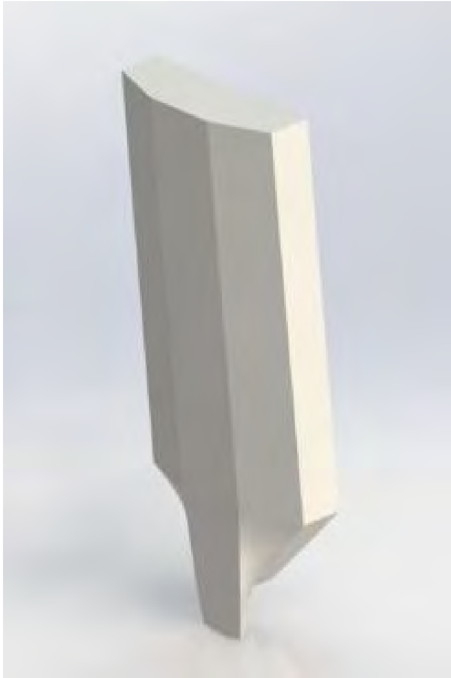


Figure 115 Guiding profile

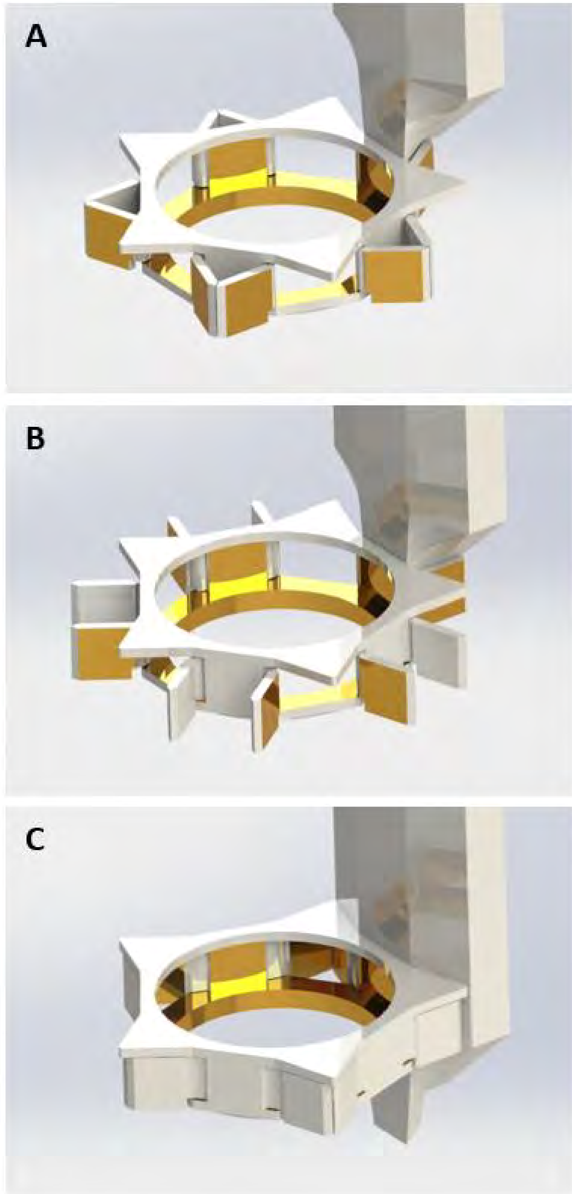


Figure 116 Closing of the hatches (illustrated with the guiding profile on one side)

11 PROTOTYPING AND TESTING

To ensure that the final demonstrator will function as intended, the components of the lamp that are involved in the shape memory process will be tested. These are the PLA rings with the hatches, and the tool used to close the hatches after shape recovery, which are the guiding structures on the inside of the cover. Two rounds of testing will be done, with changes made to the design made in between depending on the test results. Based on the results of the second round of testing, a final design of the components is made. In designing and manufacturing the rings, the established guidelines are used. This is done to evaluate the guidelines and to have a theoretical foundation for (re)designing the parts.

The chapter concludes by describing the final design of the concept, which has been created by applying the findings from the two test rounds described in this chapter to the preliminary design shown in the previous chapter.

11.1 TEST ROUND 1

The first test is performed with the ring design shown in figure 117. The overall height of this ring is 21 mm, with a 55 mm radius as measured from the most outer points to the centre of the ring. The values for the parameters as discussed in the guidelines are described in table 21. The ''use'' parameters mentioned in the guidelines are not applicable to this design (bending direction should in theory make no difference, since the hinges are printed in a vertical orientation, and activation temperature is not fully controlled, since the heat inside the lamp, generated by the lightbulb, is not constant). Also, the infill of the print was chosen to be 100%, since this has also been used in earlier testing.

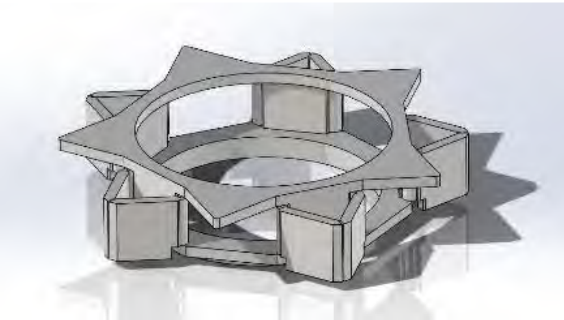


Figure 117 Ring design V1

Using these settings, the designed ring was printed. Once printed, the support material was removed, resulting in the print shown in figure 118. Overall, the ring has been printed properly. However, it was observed that the surface quality of the bottom of overhang structures was inferior to that of all other surfaces. Figure 119 shows the two areas in which this was observed: the top of the hinges, and the top of the lower ring structure (since the ring was printed upside down, the top of these areas is affected, not the bottom).

Table 21 Chosen values for the different parameters, based on the guidelines

	Parameter	value	explanation
Design	material thickness	1.2 mm for the hinges, 3 mm for all other parts	Only the hinges need to be deformed
	Porosity	no grooves in the hinges	fast activation is not desirable
	Print configuration	printed in a 3d configuration, with the hatches opened	shape recovery will cause the hatches to open and expose the light
	Shape complexity	10 simple hinges that are 14 mm wide, all oriented in the same direction	This ensures similar behaviour for all hinges in one ring
Material	Material	Ultimaker white PLA	same as used in testing
Manufacturing	Layer height	0.2mm	to ensure decent surface quality while limiting self-deformation
	Printing speed	40 mm/s	same as used in testing
	Infill line direction:	45/135 degree alternating between layers	to limit internal stresses and self-deformation.
	Fan speed	50%,	to limit self-deformation
	Build plate temp	50°C	to ensure proper build plate adhesion
	Printing temp	195°C	to ensure proper shape recovery
	Orientation	Flat on the build plate, with hinges in vertical direction	to limit self-deformation and ensure good surface quality

Next, the inside surfaces of the structure were covered in heat reflective foil, as shown in figure 120. With the ring ready to be tested, a test setup was built. A cardboard tube was covered with heat reflective foil on the inside to simulate the other rings of the lamp. This tube was placed over the lightbulb, and the ring prototype was placed on top of the tube. Lastly, a piece of carboard, also covered with heat reflective foil, was placed on top of the ring. The complete setup is shown in figure 121.

Figure 118 Printed ring

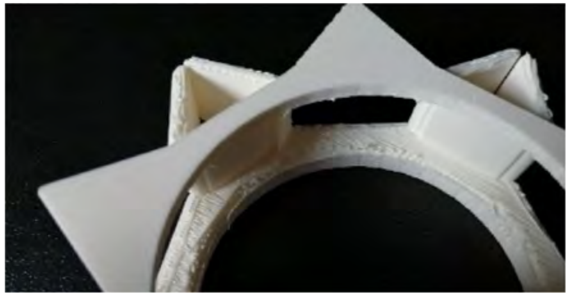


Figure 119 Close up of the areas with low surface quality

Next to the ring, a test piece of the guiding profile was printed. This part, as shown in figure 122, was used to deform the hinge parts of the ring to create the closed configuration of the ring.

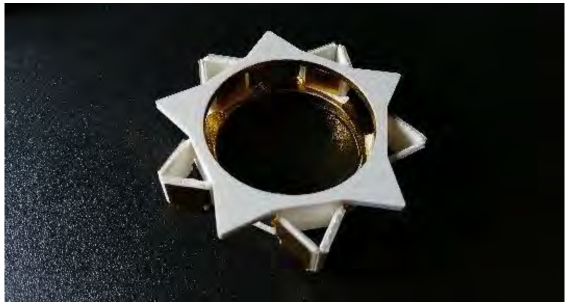


Figure 120 Ring with the inside surfaces covered with heat reflective foil

Figure 121 Test setup: A cardboard tube is placed over the lamp, and the printed ring is placed on top

The test was initiated by turning on the lamp. The heat generated by the lamp slowly heated the ring. Once the hinges were deformable, the guiding profile was used to close two of the hatches, after which the lamp was turned off. After cooling, the guide profile was removed. The hatches closed with the guiding profile are shown in figure 124. The process of closing the hatches went as expected, with the hatches being guided to their closed configuration by sliding the profile past it, and keeping it in place while cooling to fix them in their closed configuration. However, at a certain point during this process there was a significant amount of friction between the guiding profile and the hatches. Because of this, some force was needed to slide it past the hatches and close them. This was expected to be caused by the surface roughness and shape of the guiding profile.

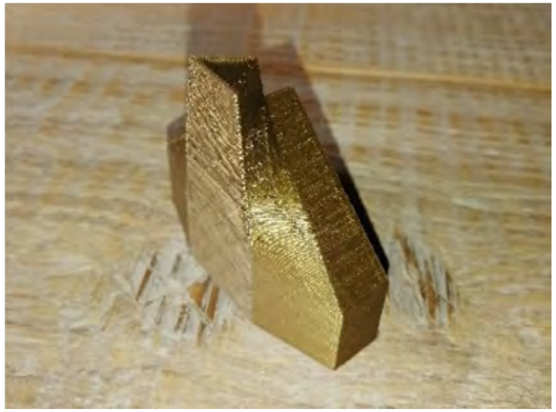


Figure 122 Printed piece of the guiding profile

The next step was to test the shape recovery. For this, all hatches were first closed by heating the ring above its glass transition point, deforming the hinges and cooling the ring. Once cooled, the lamp was turned on again to heat up the ring. The process of heating and shape recovery was observed and recorded. After roughly 8 minutes, the hatches started slowly opening, exposing more light. After 7 more minutes, no further shape recovery was observed, and the lamp was turned off. Figure 125 shows the ring with the recovered hinges. As can be seen, the hinges recovered to a large extent, but not fully. This was also not expected based on the results of the technical characterization. However, the results are deemed quite satisfactory. What was also observed is that the hatches themselves were not deformed during either the hinge deformation process or the shape recovery, which is a nice result. However, the other parts of the ring did heat up quite substantially, causing the structure to become rubbery. This is not desirable, since this compromises the structural integrity of the part. Also, there was quite some light visible through the material, which should be limited to get the envisioned effect of the lamp opening to expose the light.

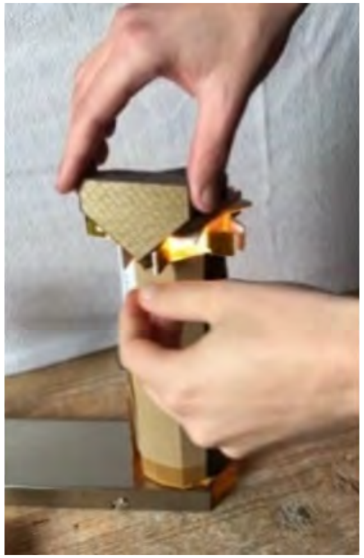


Figure 123 Closing the ring by sliding the guiding profile against the ring

Figure 124 Ring with the hatches closed

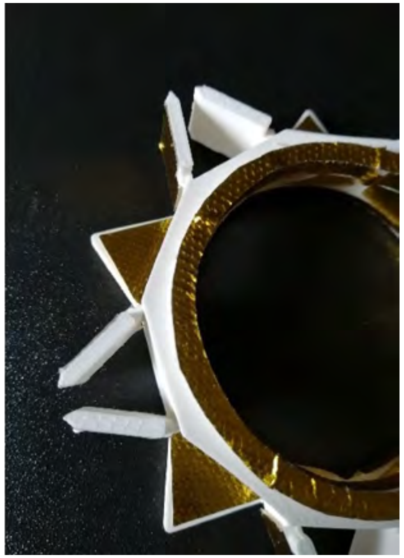


Figure 125 Recovered ring

11.1.1 CONCLUSIONS

Overall, the first test round went quite well. However, there are three main points of improvement for the next version of both the ring and the guiding profile:

- The surface quality of the bottom of overhang structures should be improved, since this is inferior to other surfaces of the printing ring.
- The shape of the guiding profile should be slightly redesigned, and the surface should be made smoother, so there is less friction when closing the hatches.
- The ring should be redesigned to be better suited for the intended use, since the structural parts of the ring became rubbery because of the heat. To maintain the structural integrity of the part, this has to be limited. Also, there was quite some light visible through the material, which should also be limited.

Furthermore, even though within an acceptable range, the shape recovery of the hinges could be improved. This should also be considered for redesigning the ring.

11.2 TEST ROUND 2

For the second test round, both the ring and the guiding profile were redesigned. Overall, the new design of the ring is fairly similar to the first version, with some changes made to tackle to points mentioned in the conclusion of the first test round. The material thickness for all inactive parts, except for the hatches, has been changed from 3 mm to 5 mm, to limit light penetration and create a sturdier structure which is more suited for the high temperatures inside the lamp, therefore maintaining the structural integrity of the part. This increased the overall height of the ring to 25 mm. Furthermore, the hinge thickness has been changed from 1.2 mm for all hinges to 1.5 mm for one half and 0.9 mm for the other half of the hinges. This was done to test the shape recovery of hinges with other thicknesses. The redesign of the ring is shown in figure 126. To improve the surface quality of the bottom of overhang areas, a change was made in the supporting structures used for printing. The supports are now printed with a solid roof (completely filled layers on top of the support structures), to provide better support for the overhang structures printed on top of this, which should result in better surface quality. Furthermore, the printing speed of the bottom overhang layers was reduced to 20 mm/s, in a further effort to improve surface quality. Other printing settings remained the same as for the first version of the ring.

The newly printed ring is shown in figure 127. The changes made to the support structure caused to surface quality of the overhangs to improve to a more acceptable level, although the quality is still lower than for the other surfaces. After printing, heat reflective foil was applied to the inside of the ring, similar to the first version used for the previous test round.

The shape of the guiding profile was also slightly altered, with the aim to reduce the friction and force needed to close the hatches. Also, for this test round, the guiding profile was printed in full, as shown in figure 128. With this, it can be tested if all hatches can be closed at the same time. With the aim to further reduce friction during this process, the surface of the guiding profile was slightly sanded.

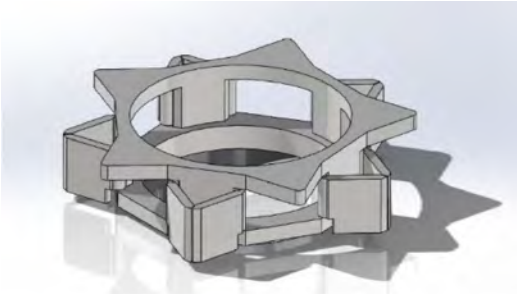


Figure 126 Ring design V2

Figure 127 Printed ring

Figure 128 Printed guiding profile

The overall test procedure was fairly similar to the first test round. The newly printed ring was placed on top of the cardboard tube, after which the lamp was turned on. This caused the material of the ring to heat up, until the point at which the hinges could be deformed. The new guiding profile was then used to close the hatches. Figure 129 shows the guiding profile closing the hatches. Figure 130 shows the result from this process. Overall, the guiding profile worked well to close the hatches. The friction was also less than in the previous test round. However, some force was still needed to close the hatches, so another redesign of the guiding shape should be done for the final demonstrator. Also, since the ring was completely enclosed by the guiding profile, it took a long time for the ring to cool down. This should also be considered for the final demonstrator.

For testing shape recovery, the test setup was slightly altered from the previous test. The cardboard tube was cut in the middle, so the first version of the ring could be placed close to the lamp, while the new ring was placed on top of the cardboard tube again. Furthermore, hatches that could be opened were cut out of the cardboard tube, to more accurately simulate the final demonstrator. This resulted in the test setup shown in figure 131.

Again, the lamp was turned on to heat up the material and initiate shape recovery. Unfortunately, shape recovery was very limited for the new version of the ring. This was expected to be caused by added hatches in the cardboard tube and the addition of the ring in the bottom. This caused the whole structure to be a bit larger, and the inside of the structure to not reach the same temperature as in the previous test, which caused the hinges to barely activate, resulting in very limited shape recovery. Figure 132 shows the limited recovery of the hinges.

Figure 129 Closing the hatches using the guiding profile

Figure 130 Result after closing the hatches

Figure 131 Test setup, with ring V1 at the bottom, and hatches cut out in the cardboard

To test if this was actually the case, the carboard tube in between the two rings was removed, to get the new ring closer to the lamp. After a short time, the ring started recovering further, to the same extent as the previous version of the ring in the previous experiment, thus confirming the theory that too much heat was lost due to the new setup. This should be considered for the final demonstrator. The behaviour of the two different hinges in the new ring was quite similar, with similar shape recovery. However, the activation time for the thicker hinges was longer. Furthermore, the increase of the material thickness for the inactive parts caused the structure to better block the light and maintain its structural integrity, although the material still got rubbery to a certain degree.

Figure 132 Limited recovery of the ring

11.2.1 CONCLUSIONS

The second round of testing provided important insights for the development of the demonstrator product:

- The guiding profile functioned as intended, although there was still some friction, resulting in a certain amount of force needed to close the hatches. A final redesign should be done to limit this.
- Cooling after deformation should be considered for the final demonstrator. Since the rings are enclosed during deformation, cooling down takes a significant amount of time. Ideally, time needed for cooling should be limited in some way.
- The surface quality of the overhangs improved, but is still less than other surfaces. The quality of these surfaces should be improved.
- The inside of the lamp should be sufficiently heated to ensure proper shape recovery. The dimensions and open areas in the housing of the current design are expected to cause problems in terms of heating and shape recovery. For the final design, changes need to be made to ensure the temperature inside of the lamp reaches a sufficient temperature.

11.3 FINAL DESIGN

Based on the two test rounds where both the shape memory rings and the guiding profiles were tested, *DAWN* is redesigned into its final design, which will be made into a demonstrator. Overall, the design has remained the same as described in chapter 10 in terms of overall construction and functioning/use. In this chapter, the changes made based on the test results are discussed. For detailed information on the use of the product, see chapter 10.

The final design is shown in figure 133 and 134. For the final design, a darker coloured wood has been chosen for the base and top of the lamp, to create a larger contrast between the shape memory rings and the other components. From testing it was concluded that the height of the structure in combination with the openings in the rings would cause problems in terms of heating. Too much heat would escape through the openings where the light also comes through, causing limited shape recovery. Two changes to the design were made to ensure proper shape recovery by limiting heat loss and volume that needs to be heated. The preliminary design had five printed rings with shape memory hatches. The final design has four rings. This limits the number of openings, thus limiting heat loss, and it limits the volume that needs to be heated by 20%. The total height of the lamp is now 220 mm.

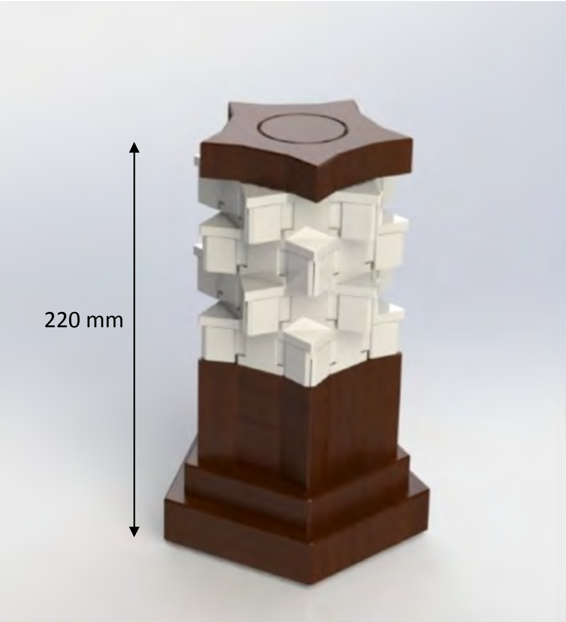


Figure 133 Final design of the lamp in its closed state

Figure 134 Final design of the lamp in its open state

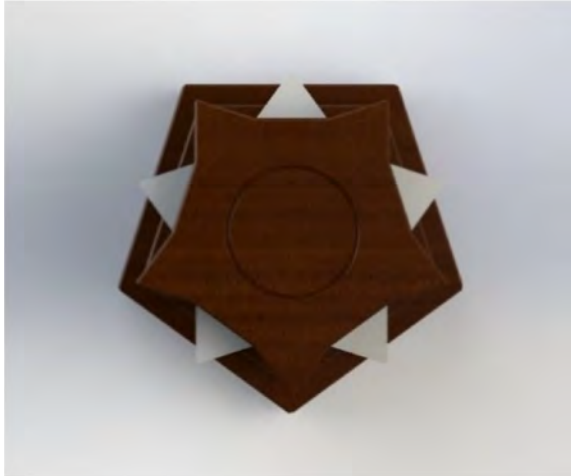


Figure 135 Top view of the lamp

The second change made to the design is the addition of transparent polycarbonate pieces in front of the openings in the 3D-printed rings. This is shown in figure 136. These pieces are meant to contain the heat inside the lamp, to ensure the temperature gets high enough to activate the material and let it recovery properly. To ensure the rings will maintain their structural integrity when heated, the material thickness was chosen to be 5 mm, based on testing. Furthermore, the hinge thickness was chosen to be 1.2 mm, since this hinge thickness showed proper shape recovery during testing, within an acceptable time.

The guiding profile has also been optimised to ensure proper functioning when the lamp needs to be returned to its closed state. During testing it was found that the initial design for this part caused a significant amount of friction, resulting in a significant amount of force being needed to close the hatches. In the final design, shown in figure 137, the part of the guide which is used to deform the hinges has been elongated, to limit friction and reduce the force needed. Furthermore, the final guiding profile has been designed to consist of one piece, instead of five separate pieces which had to be attached to the inside of the cover separately. This was done to make fabrication easier, and to ensure a proper geometry and spacing between all guiding profile sections to improve functionality.

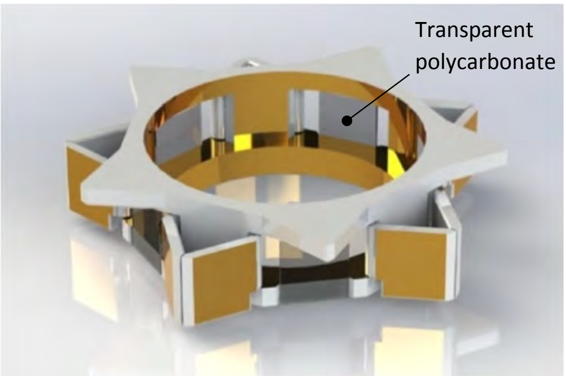


Figure 136 Final ring design, with transparent polycarbonate pieces in front of the openings

Figure 137 Complete guiding profile, with all sides incorporated in one part

Figure 138 One piece of the guiding profile

The final significant change to the design is a removable top insert to allow for faster cooling. Since the final design has been optimised to keep heat inside, and the guiding profile encloses the rings on the side, further reducing heat loss, cooling the lamp takes a significant amount of time. Since it is currently not known if and how prolonged exposure to high temperatures affects the shape memory behaviour of a shape memory object in a deformed state, it is desirable to limit the time needed to cool the material. Therefore, A part of the wooden top can be removed to allow to heat inside the lamp to escape easier, as shown in figure 140. The centre of the top part of the cover was also removed for the same purpose, as shown in figure 141.

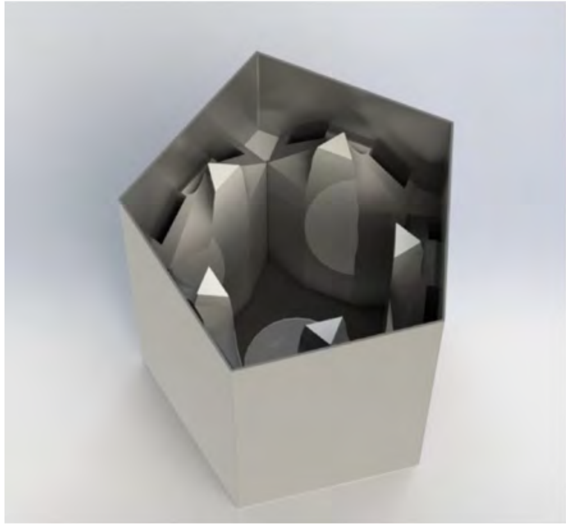


Figure 139 inside of the cover, showing the placement of the guiding profile

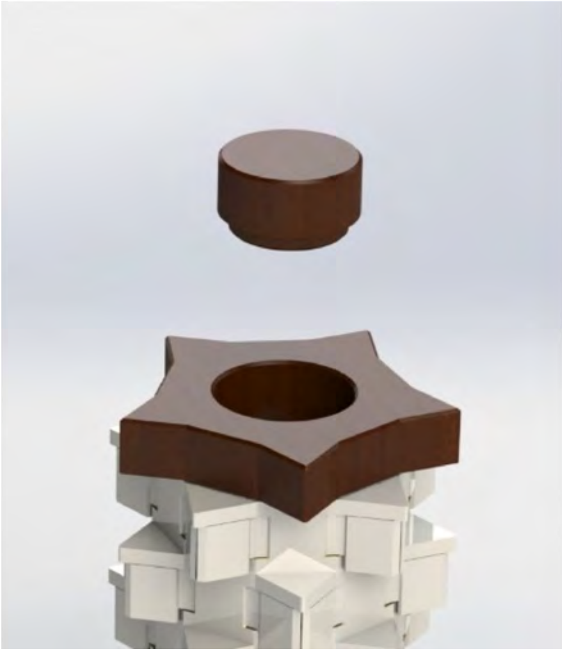


Figure 140 Removal of the top insert, to allow heat to escape

Figure 141 The cover placed over the lamp

12 DEMONSTRATOR

Based on *DAWN*'s final design as described in the previous chapter, the demonstrator was made. In this chapter, the process of making the demonstrator is discussed, as well as the final result and testing of the demonstrator.

12.1 BUILDING THE DEMONSTRATOR

The demonstrator consists of two components: the lamp and the cover which is used to close the lamp. For building these two components, multiple parts needed to be fabricated and assembled, both 3D-printed parts as well as non 3D-printed parts. In this sub-chapter, this process is discussed.

12.1.1 COVER

The process of fabricating and assembling the different parts for the cover is shown in figure 142. This component consists of a metal cover part and the 3D-printed guiding profile. First, the guiding profile was printed in two parts. This was done to limit the chance of the print failing, since the component is relatively large. The printing settings were adjusted to reduce the time needed to print the two parts: a low infill percentage was chosen, as well as a higher layer height than is used for the shape memory rings of the lamp. After printing, the two parts were combined to form the complete guiding profile, after which the inside was sanded to reduce the friction between the guiding profile and the shape memory rings in use.

Secondly, the metal cover was made out of zinc. The printed guiding profile was use as a mould to form the metal around, to ensure the guiding profile would fit perfectly. For the last step, the guiding profile was glued inside the cover, resulting in the assembled cover shown in the figure.

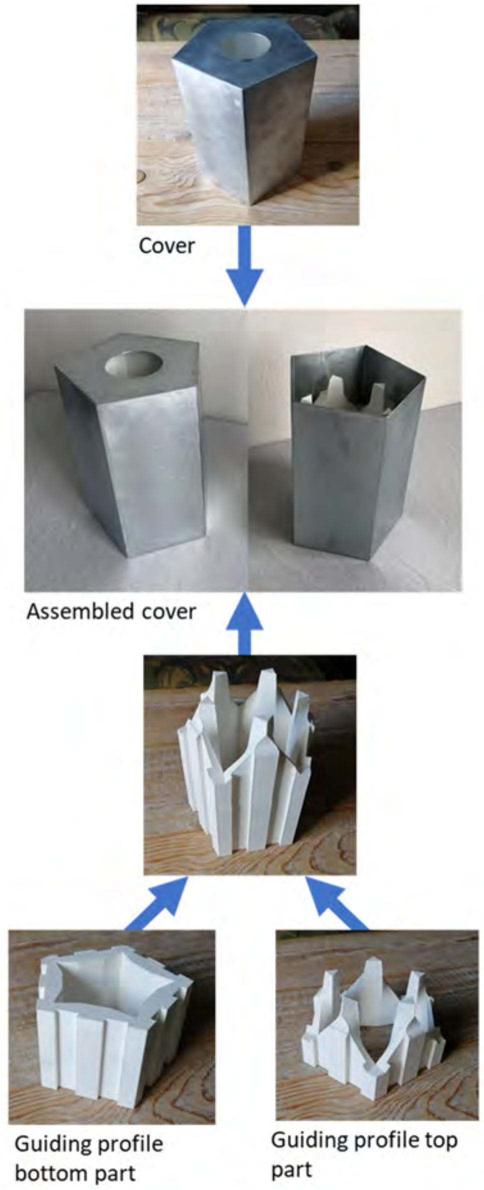


Figure 142 Assembly process of the cover

12.1.2 LAMP

The process of fabricating and assembling the different parts for the lamp is shown in figure 143. First, the shape memory rings were printed. For printing the rings, the same printer settings were used as were used for the earlier versions of the ring, as described in chapter 11. After printing, support material was removed, and the inside of the rings was covered with heat reflective foil. The final assembly step for the rings involved attaching the transparent polycarbonate pieces in front of the openings using an adhesive.

Most of the remaining parts that needed to be created were made of wood, and painted to resemble the dark wood colour envisioned for the final design. This concluded fabrication on the top and top insert. However, the base still needed to be fitted with the power cord and lightbulb. Using two 3D-printed power cord mounting brackets, the power cord and lightbulb were mounted inside the wooden base, resulting in the fully assembled base. For the last step, all components were put together to create the complete lamp.

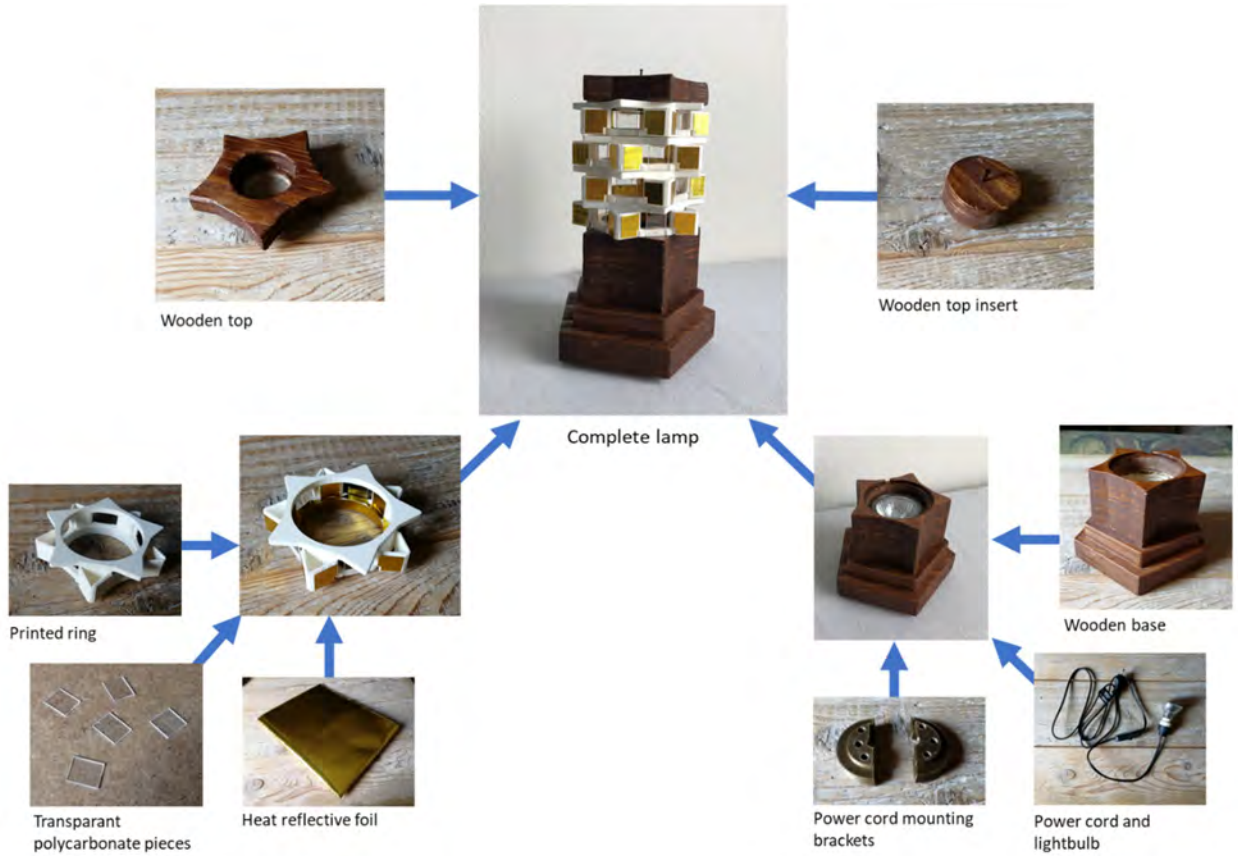


Figure 143 Assembly process of the lamp

12.2 FINISHED DEMONSTRATOR AND TESTING

Figures 144 and 145 on the next pages show the finished demonstrator of the *DAWN* concept in both closed and open state, with the light turned off and on, as well as some details of the lamp and cover. Figure 146 shows the use of the product step by step using photos taken while the functioning of the demonstrator was tested.

For testing the functioning of the demonstrator, the same step by step process as described in figure 146 was followed. Once the lamp was turned on, it took roughly 10 minutes before the hatches started opening up. The second ring (as counted from the bottom) was the first to be activated and start recovering, quickly followed by the bottom and third ring respectively. Last was the top ring. In terms of shape recovery, the third ring from the bottom showed the best results. The hatches in this ring opened up very close to the printed shape. Also, after a slow start, this ring recovered noticeably faster than the other rings, which might have contributed to its great shape recovery. This is expected to be caused by the heat transfer inside the lamp.

The second and top ring showed similar recovery, with an observed recovery ratio around 80%. All be it still reasonable, the recovery was observably less than that of the third ring. The bottom ring showed the least recovery of the four rings, with a recovery ratio around 60%. This low recovery ratio is believed to be caused by the airflow through the lamp. Since heat rises, it is thought that once the bottom ring opens, cold air is pulled in through the openings, which leads to a relatively limited air temperature around the bottom hinges compared to the air temperature around the hinges of the higher rings.

25 minutes after turning on the lamp, the process of closing the lamp was initiated. First, all rings were aligned. This went as expected, with the rings still becoming slightly rubbery, therefore needing to be handled with care. However, the rings didn't feel hot to the touch and could be aligned fairly easily. After alignment, the cover was placed over the lamp. With proper alignment of the rings, this could also be done fairly easily. It was noticed that there were some points at which some force or wobbling with the cover was needed to be able to push it further over the lamp. However, this is not expected to be caused by friction, but rather by play between the rings and wooden parts, which cause certain parts to move around slightly, causing the guiding profile to get stuck on edges at certain points. However, this was manageable, and the cover could be put over the lamp as envisioned.

For cooling, the top insert was removed, and the lamp was left to cool for a few minutes. After this time, the cover was removed and the top insert put back into place. Removing the top unveiled that the hatches had closed as intended, and that there was close to no observable deformation in the non-active parts of the rings. There was only some slight unintended deformation in the outermost points of the top two rings. However, this was only slightly visible up close.

12.2.1 CONCLUSION

In terms of look and feel, the physical prototype of *DAWN* turned out as expected. Overall, the result is quite good. The same can be said about the functioning, although shape recovery could be improved. Improved understanding of the heat transfer and air flow, both during recovery and deformation is needed to fully develop the concept into a prototype which completely functions as intended. Possible further development could involve having varying hinge thicknesses between rings to manipulate the order in which the hatches open, adding internal structures to alter the air flow and heat transfer, or changing the lightbulb/ position of the lightbulb. This could be starting points for further research and development. However, even with the result a presented and discussed in this chapter, the demonstrator is thought to have achieved its goal. In the end, the demonstrator is thought to be an engaging way to inspire designers to incorporate 3D-printed shape memory polymers in their product designs, while at the same time providing more leads for further research and development of the manufacturing and application of these materials in design.

Figure 144 Photos of the finished demonstrator, showing the lamp in both open and closed state, a close up of the polycarbonate pieces (bottom middle) and the inside of the lamp (bottom right)

Figure 145 Photos of the finished demonstrator, showing the cover and the lamp with the light turned on in both closed and open state

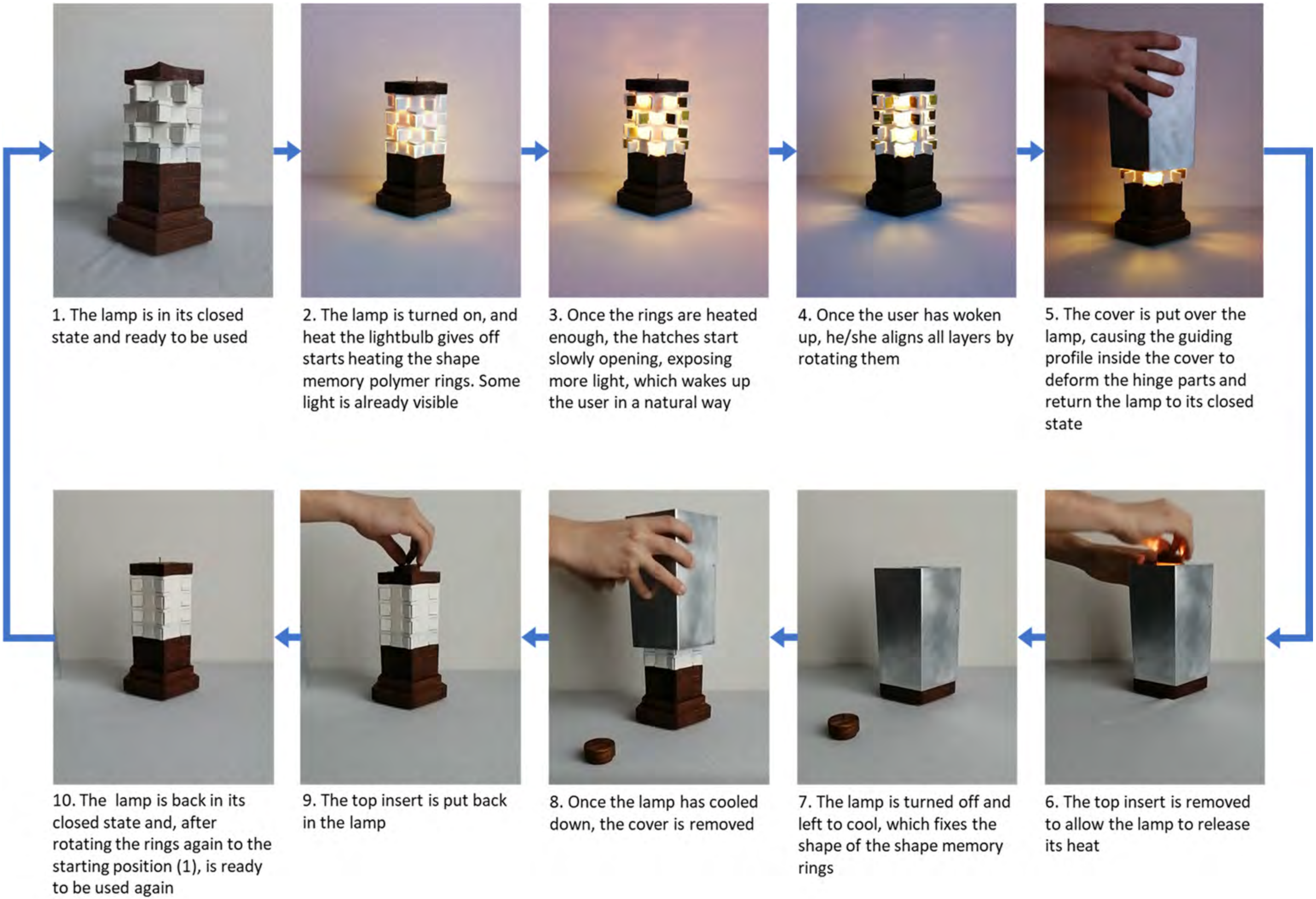
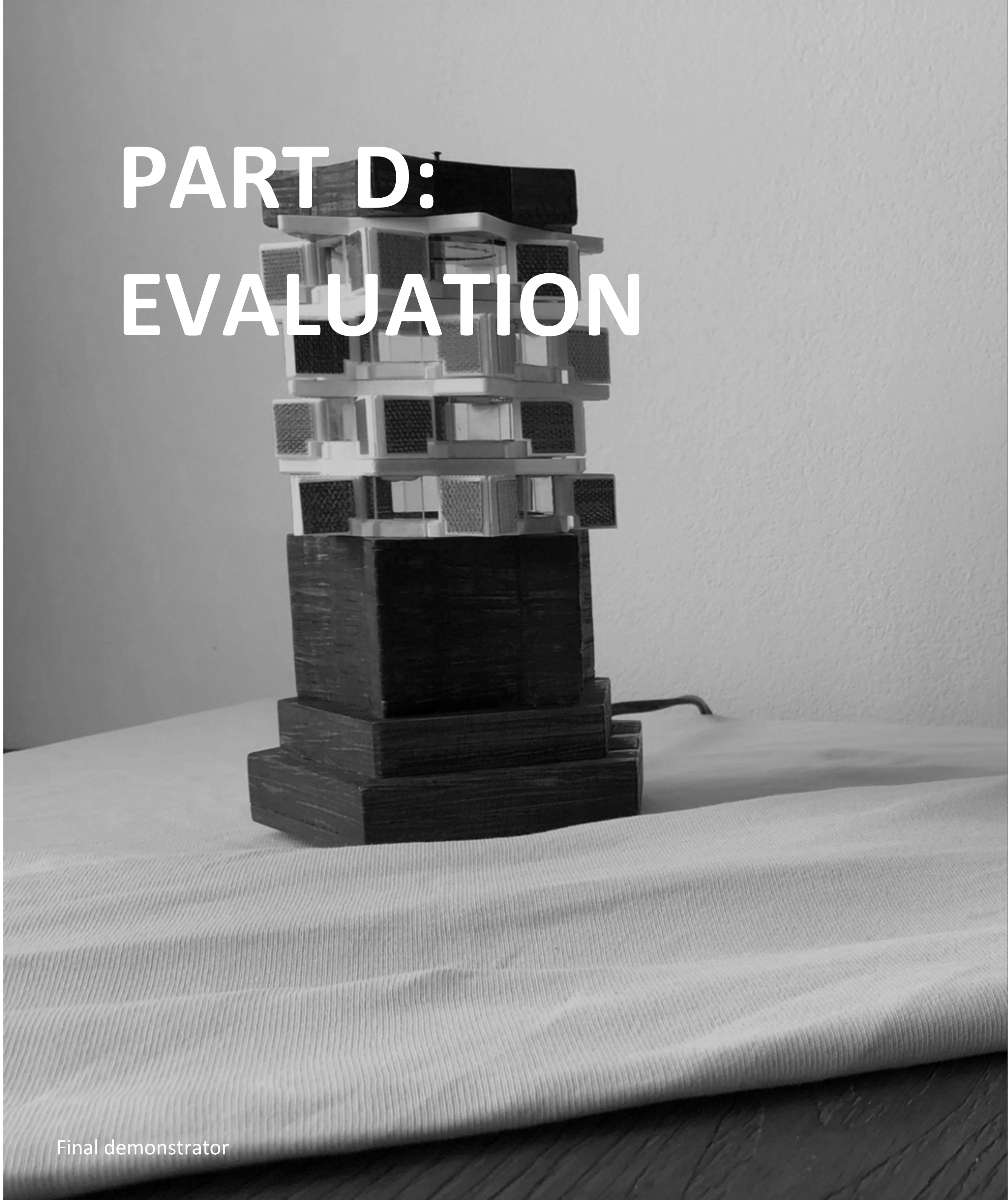


Figure 146 Overview of the different steps in the use of the concept

PART D: EVALUATION



Final demonstrator

In the final part of this report, the process and results from this project are reflected upon and discussed. The learning goals specified at the start of the project are also evaluated, to determine if these goals have been reached. The final chapter of this part discusses several recommendations for further work based on what has been achieved during this project.

13 DISCUSSION AND REFLECTION

The aim of this project was to improve the understanding of the shape memory properties of 3d-printed Shape memory polymers (SMP's), and the parameters that influence these properties. knowledge gained in this project was used to create a set of guidelines for designers on 3D-printing shape memory polymer objects, and a demonstrator showing the capabilities of SMP's, with the aim to inspire and encourage designers to use 3D-printed shape memory polymers in their designs. This was achieved through a process consisting of three main steps: literature research, technical characterization and conceptualisation. In this chapter, this process, as well as the resulting guidelines and demonstrator, will be evaluated. The chapter concludes with a reflection on the learning goals defined at the start of the project.

<u>Literature review</u>

The project started with a literature review on the shape memory effect in polymers, 3D-printing and using SMP's in product design. The purpose of this stage was to get a good understanding of the mechanisms behind shape memory in polymers, and to get an overview of research and other efforts that had already been done to control and apply this. Knowledge gathered in this stage would form the foundation for the technical characterization, and serve as a benchmark for design efforts later in the project. In the literature review, part of the information described had no direct impact on the further course of the project, since certain aspects of the shape memory effect, as well as certain aspects of the 3D-printing described were outside of the scope of the project. However, this information did attribute to the completeness of the information and the context in which this project took place, which is why this information is still regarded as valuable for this project.

<u>Technical characterization</u>

Partly parallel to and after the main part of the literature review was finished, technical characterization was conducted. In this phase, the effect of different parameters related to design, material and manufacturing on the shape memory behaviour of 3D-printed shape memory polymers was researched. Through a series of tests, the effect of nine parameters was investigated. This provided the input for the guidelines which were set up after technical characterization by combining results from this phase with results from the literature review. During testing, the aim was to do this as accurately and reliably as possible, with the same printer used for all test samples, a water bath for constant activation conditions etc. Overall, it is thought this aim was achieved, although there are still some factors which might have had influence on the results. Firstly, for measuring remaining deformation of the used test samples, a glue clamp was used to clamp the samples in place after which the deformation was measured using digital callipers. Because the clamping force was not fully controlled/measured, there might have been differences in clamping force between samples, which could have caused deviations in measuring the deformation. However, the influence is expected to have been limited due to repetition of the experiments (2 repetitions of the same scenario). Secondly, activation time was derived from video footage. This was done by observing the footage. There might have also been deviations in the results because of this way of determining activation time of the samples. However, here the effect on the results is also expected to be limited because of the repetition of the experiments.

Some of the parameters tested had also been addressed in the literature review. Overall, the effects on shape memory behaviour found matched between testing and literature. However, in some cases, results differed. This was expected to be caused by differences in the test setup and defined boundaries between literature and testing in this project. For the guidelines, this meant that a critical assessment needed to be made on the conditions under which the parameters were tested in both cases. While this was an unforeseen task, by critically comparing test setups and consulting extra literature, in the end a final conclusion was reached, so that in the guidelines the effect these parameters have on shape memory behaviour could be clearly described.

Continuing on the topic of the guidelines, it was chosen to put these in a separate document, to make them more accessible to designers. Unfortunately, due to the time span of the project, there was no time to evaluate the guidelines with other designers. However, the guidelines did get used for producing the final demonstrator. Furthermore, there are still knowledge gaps concerning the investigated parameters, which are also mentioned in the guidelines. This is due to the scope of the project. These gaps could provide starting points for future projects. This will be further discussed in chapter 14.

<u>Conceptualisation</u>

The third and final stage of the project, conceptualisation, was started near the end of the technical characterization. The start of this phase was challenging, as the switch from research which focused on technical aspects and limitations to a more open-minded and creative design process proved to be difficult. Therefore, a creative session was organised with peers to kickstart this process. This proved to be quite effective, and a good source of inspiration. With input from the creative session, ideation was done which led to four ideas which were developed into concepts, with eventually a concept for a wake up light, later named *DAWN*, being chosen to be developed. This concept involved a substantial number of unknowns (e.g. heating with the use of a lamp instead of water, the effect of air flow on heat transfer, different temperatures in different areas surrounding the SMP etc.), which required several tests and redesigns to come to the final design which would be made into the demonstrator. In the end the demonstrator was produced and tested. Overall, it functioned as envisioned, although the shape recovery results were mixed, with certain parts showing great shape recovery while other parts showed limited recovery. This was thought to be caused by the air flow through the lamp, which prevented certain areas from maintaining a high temperature for the time this was needed. This shows that for proper application of SMP's in design, environmental conditions are important to consider. In the end, it is thought the concept still fulfils its purpose in that it shows how shape memory polymers could be used in design in an inspiring way. To what extent designers will be inspired by this demonstrator remains to be seen, but the initial reactions have been positive and in line with the reaction that was aimed for. Considering the aim to communicate the guidelines through the demonstrator, this has in my opinion be partially achieved. Initially, the idea was to incorporate sequential shape change in the final demonstrator, but due to the complexity of the concept, this could not be achieved in a controlled way. However, through the different test versions, and the range in shape recovery in the final demonstrator, other important aspects related to shape memory polymers are communicated, which can be argued to be of equal value as the initial aim.

Method

At the start of the project, the MDD method was chosen to be used as the basis for the overall process in this project, combined with FDM 3D-printing as the production method to be used. Throughout the project, the envisioned process has been altered, with the most notable alteration being the choice to remove the experiential characterization and all elements related to this from the project. This was done to focus more on the technical characterisation. Looking back, I think this was the right choice, since this provided the opportunity to produce significant results in terms of understanding the material on a technical level, which resulted in proper guidelines. Had the experiential aspects not been removed from the project, I suspect that both technical and experiential aspects would not have been explored to an extent in which valuable results would have been produced.

What also became clear over the course of the project was that the choice for a particular production method (3D-printing) at the start changed the way the MDD method could be applied, in the sense that there were limitations that influenced the extent to which the SMP could be applied in the end. For these reasons, I cannot claim to have followed the MDD approach, but rather used it as a framework to provide me with a general approach for the project, while using the tools provided by the method in a way that fitted the project. In conclusion, using the MDD method together with a fixed element like a production technique chosen at the start of the project creates new challenges and opportunities for more in depth development, while at the same time narrowing down the possible outcomes of the project.

Personal reflection

At the start of the project I knew very little about the shape memory effect. But through the work and activities I've done in the past months I feel I've learned a lot about the shape memory effect in polymers and how this can be controlled and applied to design. Even though this project was done in challenging times, with Covid influencing our daily lives and with that, the way this project needed to be handled, I learned a lot and was able to finish this project with a good feeling and newly gained experience. At the start of the project, I set up goals of what I wanted to learn. Below, these learning goals are discussed.

Expand my knowledge and experience with 3d printing

From the start of this project up until the end, I have been continuously expanding my knowledge and experience with 3d printing. In the literature review, I learned new things, which I could apply during technical characterisation. During technical characterisation and conceptualisation, I gained hands on experience in using slicer software and 3D-printers, with challenges during the project causing me to learn new learn and try out new things.

Get experienced with designing SMP-based objects

This learning goal has mainly been achieved in the second half of my project, with the technical characterisation providing me with the knowledge I needed to design shape memory polymer objects. During conceptualisation, this knowledge was brought into practice, where I could experience how different parameters influence the behaviour of my designed concept.

Gain experience and knowledge in using the MDD method

I feel I've gained some experience, but since certain elements were removed, I think my use of the method was limited. However, the method did provide a good framework which I based my project around, and tools which were useful in the process, so I think can say I have taking inspiration from it, and applied it as I thought would be beneficial for the project.

Gain experience in working on and documenting of a research-based project, as well as learning and empowering my scientific/technical debate skills.

I can't say I've become an expert on the subjects of shape memory polymers and 3D-printing, but I can say I have gained knowledge which allows me talk about the subjects on a higher, more scientific and technical level. Concerning documentation, I feel I have gained more experience, but not necessarily learned many new things. However, I did learn more about setting up experiments, analysing test results, and documenting these results, which I think is very valuable.

Further develop my prototyping and modelling skills, and possibly develop additional skills related to prototyping and testing

Designing the demonstrator allowed me to polish my modelling skills, as I needed to make computer models which could easily be altered depending on my test results. Therefore, I expanded my knowledge to make this process more efficient. In terms of prototyping, (apart from 3D-printing), the skills I needed to develop to produce the demonstrator were limited, since the production of the parts was not too challenging. However, due to the nature of the project and the use of the product, there were things I needed to consider which I didn't in other projects, for example the behaviour of materials and adhesives at elevated temperatures. This required me to take a systematic approach, which I think enhanced my ability to handle prototyping for projects with specific requirements.

14 RECOMMENDATIONS

Over the course of the project, multiple topics have been extensively addressed. However, due to the scope and timeframe of the project, there were things which could not be addressed. Furthermore, the final results of the project could provide a starting point for further research in future projects. In this chapter, recommendations are given for further research and development in the context of this project.

Research on shape memory behaviour

A potential direction for further research could be to continue with the guidelines and technical characterization as was done in this project. There are different ways to approach this:

New parameters

Apart from the parameters addressed in this project, there are much more parameters which could be investigated. Think for example about the moisture of the material (material), creating curved surfaces (design), infill percentage in the printed structure (manufacturing), and different activation methods (use).

Unknown influences of parameters researched in this project

For the parameters that were researched in this project, further research would provide valuable insights in the behaviour of the material. As mentioned in the reflection, there are parameters of which the effect on specific shape memory aspects is not currently known. An example is the effect of printing speed on the activation time of 3D-printed SMP's. This parameter is discussed in the guidelines, but has not been researched on this specific aspect. There are more examples like this, so investigating these could help in completing the current guidelines.

What has also not been addressed in this project are the cycle life and shape fixity of the material. These are important shape memory aspects which could for what kind of applications a material is suited to be used. Researching these aspects for parameters addressed in the project could further complete the guidelines, and make them more useful for designers.

Quantifying the identified effects

Multiple parameters were researched in this project to the extent that a conclusion could be drawn about the type of effect these parameters have on the shape memory behaviour of a polymer (e.g. increasing material thickness increases activation time). However, the research has not been extensive enough to quantify these effects (e.g. doubling the material thickness leads to a 40% increase in activation time). This could be achieved by testing a wider range of values for a specific parameter, and increasing the amount of repetitions to achieve a clear understanding of the extent of the effect of the involved parameters, which would be valuable for product design.

New materials and material combinations

The shape memory properties of PLA have been researched, and the guidelines have been written based on this. However, from this research it cannot be concluded how other materials would behave when parameters are changes, therefore it is currently unknown if the guidelines can be applied for printing polymers other than PLA. Furthermore, all samples and parts that were printed during this project were entirely made of PLA. However, multi material FMD printing is becoming more common, and the printer used for this project was also capable of multi material printing. This technology is highly valuable for SMP objects, since it allows for the creation of 3D printed objects composed of a SMP for active parts and a non-SMP for inactive parts. However, it is currently unknown if and how multi material printing affects shape memory behaviour, therefore this would also be an interesting direction for a future project.

Experience research

Initially it was planned to also address the experiential aspect of SMP's in this project, but it was decided to put more focus on the technical aspect, so this was removed from the project. However, for successful application of shape memory polymers in design, the experiential side also needs to be considered. This could for example involve user studies on how the shape change of the material is perceived, and what people envision this material to be capable of. Based on this knowledge, products can be designed specifically to evoke the emotions/reactions the designer envisions. In the MDD method, written by Karana et al. (2015), this kind of research is described, so I would like to refer to that for further suggestions on how to approach this.

Application of the guidelines

The deliverables of this project, the guideline document and the demonstrator, are meant to inspire and encourage designers to use 3D-printed SMP's in their designs. Since the guidelines have only been used within this project up until this moment, the guidelines still need to be tested further to determine if they can be of use for designers and inspire them. This could be part future work, in which the guidelines are designed by someone unfamiliar with printing shape memory objects, to see how the guidelines support the designer, and how they could be further improved.

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APPENDICES

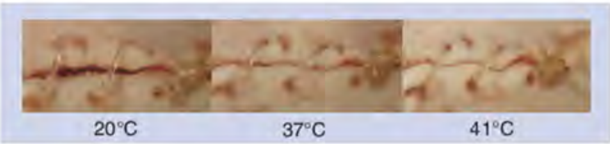
APPENDIX A: BENCHMARKING

SELF-CLOSING SUTURE

Material: oligo(ε-caprolactone)diol (OCL) as switching segments and Crystallizable oligo(*p*-dioxanone)diol (ODX) as the hard segment

Description: A degradable shape memory suture for wound closure. The created material was extruded into monofilaments, and programmed to form the suture. Before suturing, the material was expanded by 200%. The thermo activated material would recover its shape at 41°C, which would close the loosely sutured wound.

(Lendlein, 2002)

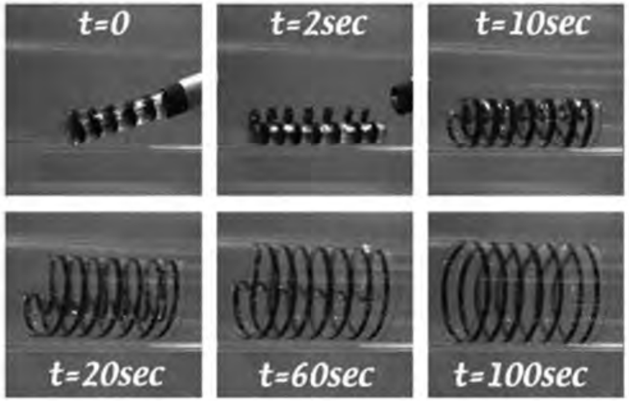


DEPLOYABLE STENT

Material: *Tert*-butyl acrylate (tBA), di(ethylene glycol) dimethacrylate (DEGDMA), poly(ethylene glycol)$_n$ dimethacrylate (PEGDMA)

Description: The materials were mixed with photoinitiator 2,2-dimethoxy-2-phenylacetophenone, and injected in a thin walled tube mould. Using an UV-lamp, the injected materials were photopolymerized, after which they were heat treated at 90°C for one hour. Stents were CNC-milled from these tubes. For testing, these stents were folded and delivered via a 18 Fr. Catheter into a 22mm glass tube filled with 37°C water. The recovery process is shown in the figure (black rings were drawn to visualize the recovery process)

(Yakacki et al., 2007)



SOFT TISSUE ANCHOR

Material: PEEK Altera

Description: This device was created for the fixation of soft tissue to bone in tenodesis, tendon transfer, and ligament reconstruction procedures. The sheath is made of a compressible SMP, which can be expanded once inside the bone by pushing the "bullet" through the sheath, fixing the anchor and the soft tissue in place.

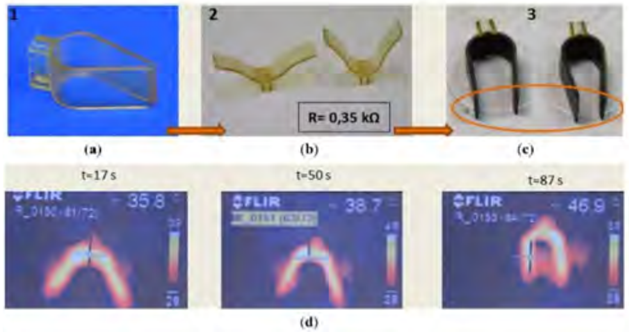
(Medshape, Inc., 2020)

ACTIVE CATHETER END

Material: Accura® 60 epoxy resin

Description: Using stereolithography, shape memory catheter ends/pincers were printed (a), trained (b), and coated with a conductive ink (c). When applying a voltage to this ink, the material would heat up, leading to shape recovery. The conductive ink provides a homogeneous heating process, as can be seen in the figure (d)

(Lantada & Rebollo, 2013)

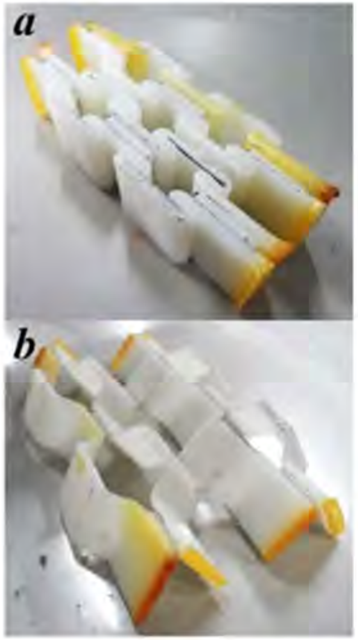


HONEYCOMB STRUCTURE

Material: styrene-based polymer (styrene and butyl acrylate mixed with benzoyl peroxide and cross-linking agent divinylbenzene)

Description: A honeycomb structure designed using kirigami (origami with cutting allowed) techniques. The structure features SMP hinges, enabling the structure to change shape from a closed (a) to an open (b) configuration, with the open/deployed configuration being the materials permanent shape. The concept can be used for larger, deployable structures.

(Neville et al., 2017)

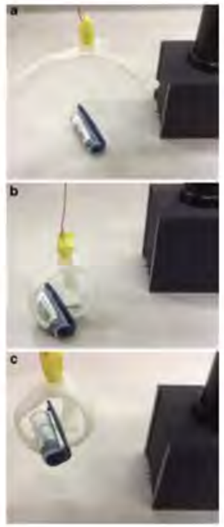


FDM-PRINTED GRIPPER

Material: DIAPLEX MM-4520 (thermoplastic polyurethane)

Description: Using an FDM printer, a claw-like object was printed. The DIAPLEX material was delivered as pellets, so first this needed to be extruded into filament. The printer that was used was a makerbot replicator 2x equipped with an additional cooling system to cool the print. The claw was programmed to an open configuration (a), and used to pick up a pen cap while being heated to initiate shape recovery (b). Once recovered, the material cooled down and was used to lift the pen cap (c)

(Y. Yang et al., 2015)

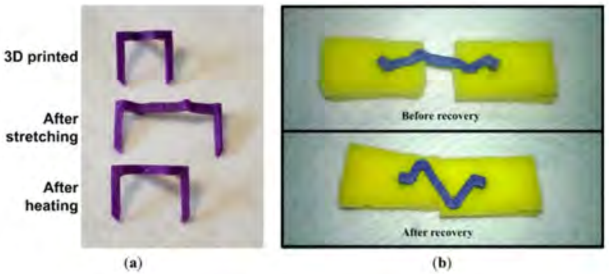


WOUND STAPLE

Material: PLA

Description: PLA biodegradable surgical staples were 3d printed using an FDM printer (Makerbot replicator 2). The staples were stretched and used to connect two pieces of foam, after which the staples were heated to initiate shape recovery. This caused the staple to pull the two pieces of foam together tightly. The demonstrated concept is highly applicable in minimally invasive surgery.

(W. Yang et al., 2014)

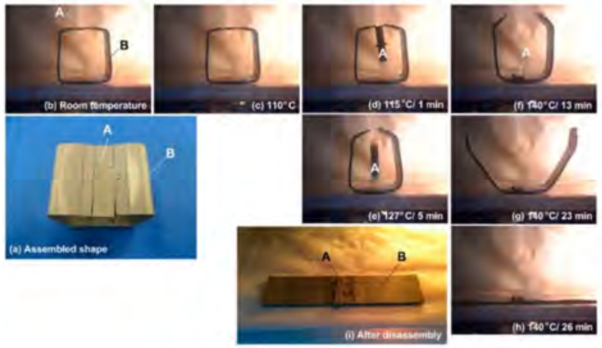


TWO-COMPONENT DISASSEMBLY

Material: ABS/PC blend

Description: An ABS/PC blend was used to demonstrate active disassembly. Here, a box consisting of two components was programmed for disassembly and assembled(a). It was then gradually heated to initiate step-by-step disassembly, until components A and B were fully disassembled. Active disassembly can be an alternative to manual disassembly as recycling of obsolete electrical devices becomes more and more an issue for environment protection.

(W. Yang et al., 2014)

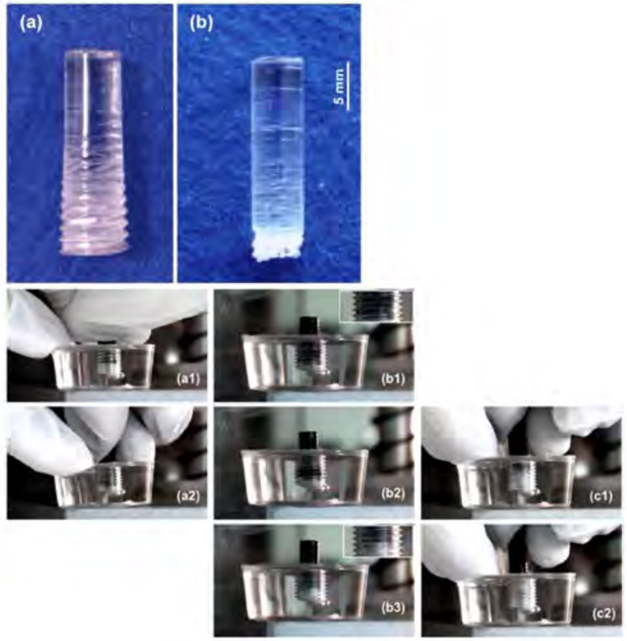


SCREW FOR ACTIVE DISASSEMBLY

Material: PMMA (Poly(methyl methacrylate))

Description: A PMMA rod was formed into a screw (temporary shape) by heating above T_g. The fabricated screw was then tightened in a threaded hole in a transparent silicone mould. By gradually heating the screw and mould at 130°C for 30 minutes, shape recovery was initiated, and the formed thread on the screw disappeared, enabling the screw to be pulled out of the mould easily.

(Purnawali et al., 2012)



VERITEX PLATE

Material: Veritex **(styrene-based composite) plates**

Description: Veritex plates were laser cut into the shape shown in figure a. The structure was heated above T_g (62°C), deformed (compressed) and cooled (b). Then the structure was heated again to initiate shape recovery, resulting in the shape shown in figure c.

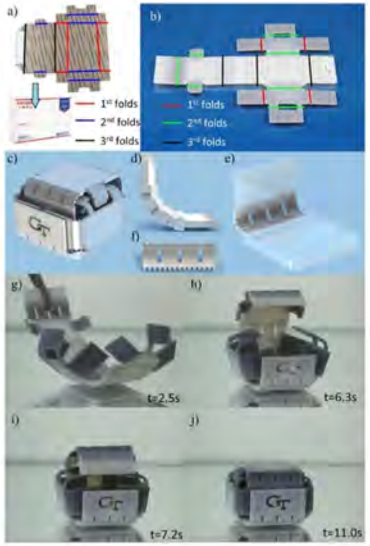
(Rossiter et al., 2012)

SEQUENTIAL FOLDING BOX

Material: two liquid monomers

Description: Two liquid monomers were mixed in different ratios to create materials with different thermomechanical properties. Earlier testing proved that sequential shape change could be achieved using this concept. The same concept was applied to a 3d-printed interpretation of a cardboard box, which has to be assembled following a sequence of folding. The result was a 3d printed box with three different material compositions for the three different fold stages, which could assemble itself when exposed to heat

(Mao et al., 2015)

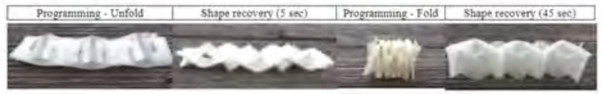


INTERLOCKING STRUCTURE

Material: TPU

Description: In this project, an interlocking folded structure made of TPU was designed and printed using an FDM printer. The structure was deformed to both an unfolded and folded state under the influence of heat. Both temporary shapes were maintained during cooling, after which the deformed structure was heated again to initiate shape recovery.

(Yoon, 2019)

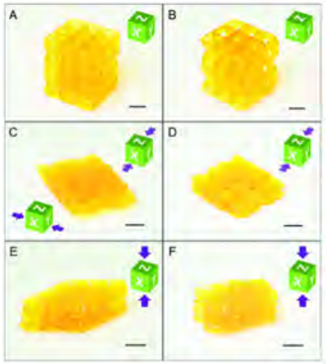


COMPLEX ORIGAMI ASSEMBLAGE

Material: Photocurable resin (50 wt% aliphatic urethane diacrylate Ebecryl 8807, 25 wt% GMA (glycidyl methacrylate) monomer, and 25 wt% IA (isodecyl acrylate) monomer, mixed with **1 wt% Irgacure 819 (phenylbis(2,4,6-trimethylbenzoyl) phosphine oxide) and 0.1 wt% Sudan I as photoinitiator and photoabsorber, respectively)**

Description: Using Digital Light Processing, the newly created photocurable resin was 3d-printed into the origami-like objects shown in the figure, With the left and right displaying two different prints with different configurations for the origami ''tubes'' that form the basis of these structures. Several limitations in 3d-printing of origami structures are overcome with improved material properties and structural design.

(Zhoa et al., 2018)

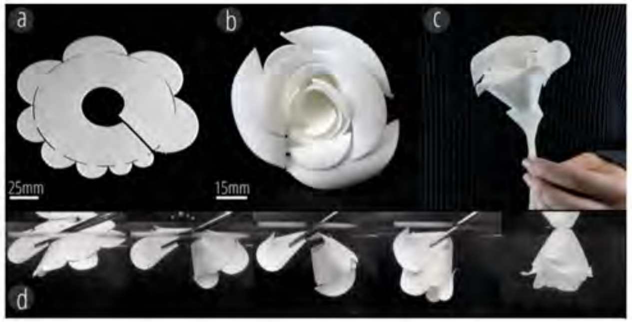


SELF-FOLDING FLOWER

Material: PLA and TPU

Description: By precisely controlling and altering FDM printing parameters like layer height, print nozzle used, printing tool path, printing direction and the speed of printing for the actuator layers, sequential self-folding of complicated shapes was achieved. In the top figure, the final print and shape resulting from heating the print in hot water is displayed. In the bottom figure, setup of the different parameters is displayed.

(An et al., 2018)

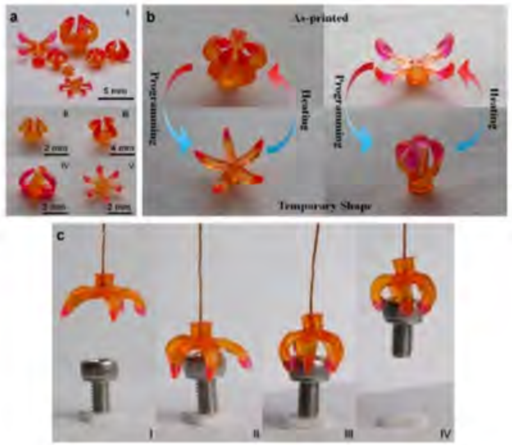


MULTIMATERIAL GRIPPER

Material: Photo-curable methacrylate-based copolymer networks.

Description: In the figure, different multimaterial gripper designs and the process of gripping an object are displayed. These grippers were made using **high resolution projection microstereolithography (PμSL). The material used are photo-curable methacrylate-based copolymer networks, which were composed to have desirable thermomechanical properties. The grippers can potentially be used as micrograppers to grab objects (With a closed configuration as permanent shape), or in drug delivery devices (with an open configuration as permanent shape).**

(Ge et al.,2016)



SHRINKY DINK

Material: Polystyrene

Description: This project demonstrates a simple approach to achieve controlled self-bending in a thin, homogeneous pre-strained polystyrene sheet also known as a shrinky-dink. These sheets shrink in-plane when exposed to heat. Black ink is applied to the sheet in predefined areas, providing localized absorption of light, which heats the polymer directly beneath it above T_g, causing the material to shrink. This concept is displayed in the figure.

(Liu et al., 2012)

BREATHING FACADE

Material: ABS and an undefined SMP

Description: This project aims to create building facades which respond to environmental conditions. The panels shown in the figure are made out of an undefined SMP (T_g around 30°C) with an ABS frame for structural integrity. When the panels are exposed to sunlight with a high enough intensity, the temperature of the panels rises. Once the temperature exceeds T_g, The SMP can be deformed by the wind, causing the panels to open up, as shown in the figure.

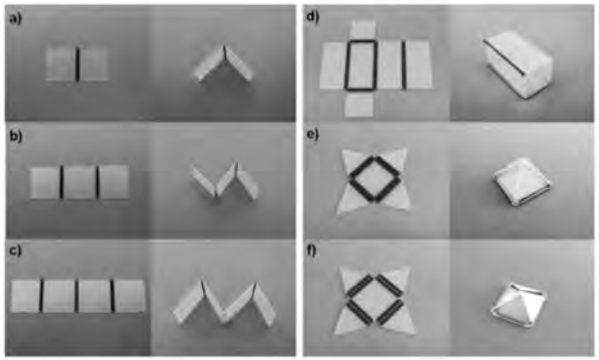
(Tanaka, 2019)

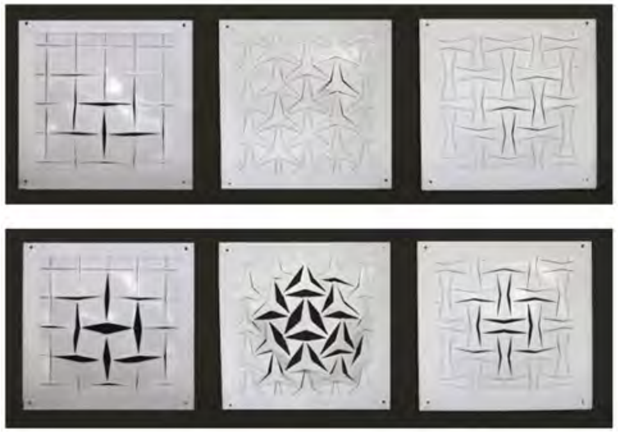
3X3 SQUARE ARRAY

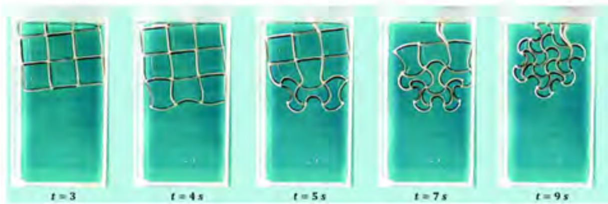
Material: Polyolefin SMPs combined with **PLA**

Description: The figure shows a 3x3 square array which has been FDM-printed from PLA. After printing, SMP layers were then adhesively bonded to the printed structure. When submerged in hot water (90°C), the PLA would soften, and the SMP would be activated, causing it to deform the structure into the shape displayed on the right.

(Janbaz et al., 2016)





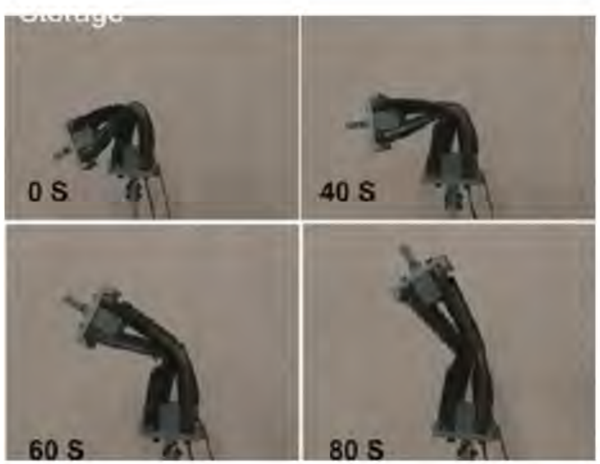


HINGE FOR SOLAR ARRAY

Material: Veriflex (styrene-based SMP composite) reinforced by carbon fiber fabrics

Description: In this project, a SMP composite hinge as a deployable structure was developed. An embedded resistor heater heats the material from the inside when a voltage is applied, surpassing the T_g of the SMP, triggering shape recovery. The figure shows the recovery process of the hinge.

(Lan et al., 2009)



APPENDIX B: PLA SWOT ANALYSIS

STRENGTHS

- Lightweight
- Large strain compared to SMAs
- Biocompatability
- Recyclability (biodegradable)
- Low costs (compared to non-plastics)
- Bio-based (made from renewable resources)
- Non-toxic
- Best option for 3D-printing (easy to print, low melting point, low costs)
- Good moisture barrier compared to pet or ps

WEAKNESSES

- More expensive than other plastics
- Can't be used for high temperature applications
- Brittle (as a pure material)
- Deficient in strength and crystallinity compared to petroleum-based plastics (and SMAs)
- Decomposition over time (under certain environmental conditions)
- Slow recovery compared to SMAs
- Low deformation stress compared to SMAs
- Ethical: corn (food) is used for producing plastic instead of feeding people
- Mixing with other plastics can contaminate the recycling process
- Not food safe when 3D-printed (bacteria can stick in the crevasses)
- Poor oxygen barrier compared to pet and ps
- Although recyclable/compostable, the right conditions are needed, which complicates recycling (needs to be seperated from other plastics)

OPPORTUNITIES

- Applications and use expected to keep growing (PLA in general)
- With the growing need for environmentally friendly materials, bio-based plastics like PLA will start to play a bigger role
- Can be used for medical applications

THREATS

- Without a proper composting environment, the material can create methane when decomposing, which can make it prohibited to use in certain environments/fields

APPENDIX C: FIRST EXPLORATION

Simple origami structure

To get acquainted with the shape memory effect, a simple origami structure was chosen to be printed. After a short search, the deployable origami structure in figure 147 was chosen to form the starting point for this test because of its simplicity. As can be seen in the figure, this structure consists of a series of identical sections. Since this structure is a succession of identical sections, and printing multiple sections would increase printing time, it was chosen to print one section for this test.

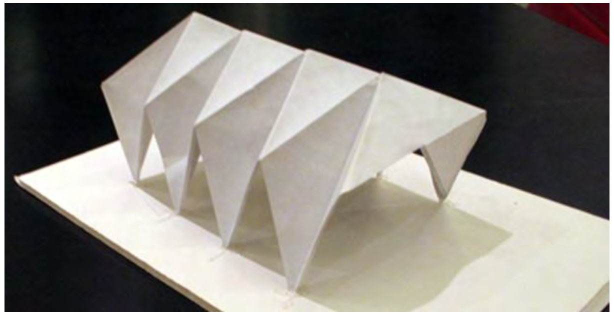


*Figure 147 origami structure used as the inspiration for this test (*Rigid folded structures, *2012)*

The geometry of the structure was analysed to determine what the shape of the sheet should be to make such a structure, and how it should be folded. A paper sheet was cut into the right shape and the fold lines were marked (figure 148). Then, the sheet was folded to form the three-dimensional shape (figure 149).

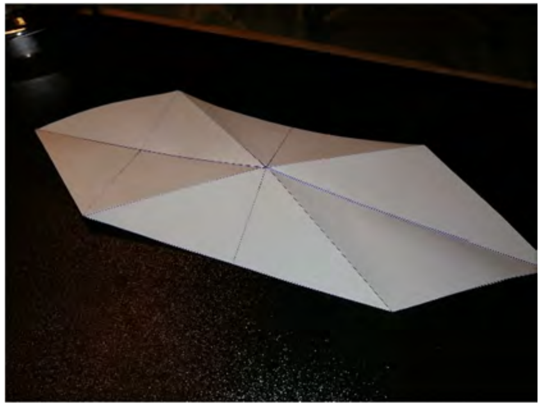


Figure 148 flat paper sheet geometry

Figure 149 folded paper sheet geometry

For 3d-printing, a Solidworks model of the paper sheet was made. The to-be-printed model was made to be 3 mm thick. To account for the material thickness when folding, grooves were modelled in the places were folds would be made. The model was FDM-printed as a flat sheet, as can be seen in figure 150.

Figure 150 flat 3D-printed version of the paper origami model

The sheet was put in hot water around 65°C in order to make it deformable. Once the material was heated enough, it was deformed by hand into the three-dimensional shape displayed in figure 151. To initiate shape recovery, the folded structure was put in the hot water again. This resulted in the recovered shape shown in figure 152. As can be seen, the sheet didn’t completely recover its original shape. This might be due the geometry/design of the object, cooling of the water leading to a temperature too low for shape recovery, the material properties, or a combination of these factors. Although the exact reason for the incomplete shape recovery is not known, this test was an informative way to get acquainted with the shape memory effect in polymers.

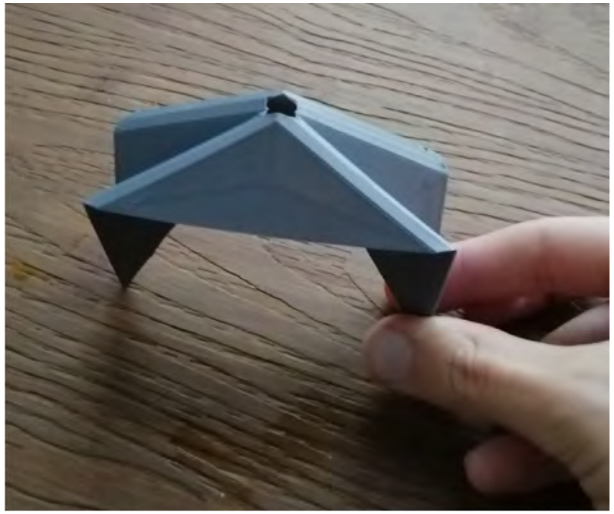


Figure 151 deformed/folded 3d-printed geometry

Figure 152 3d-printed geometry after recovery

Christmas tree

For a second explorative experiment, a new shape was designed based on an origami Christmas tree. In figure 153, the printed object is displayed. The sections of the tree are connected in the centre, as shown in the schematic top view in Figure 154. Two of the sections are not connected together, creating a gap, which allows for the shape to be deformed.

Figure 153 3D-printed object inspired by an origami christmas tree

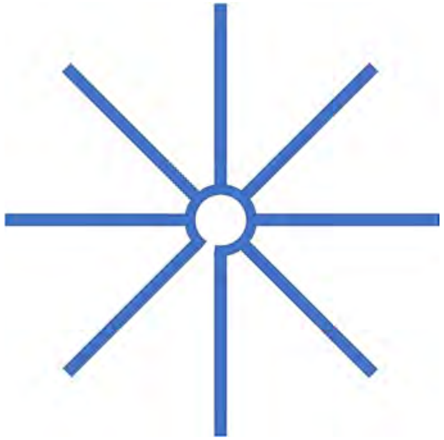


Figure 154 schematic top view of the construction of the tree, with two of the sections not connected to allow for shape deformation

Like in the first explorative test, the 3d-printed tree was submerged in hot water, after which it was deformed to the shape shown in figure 155.

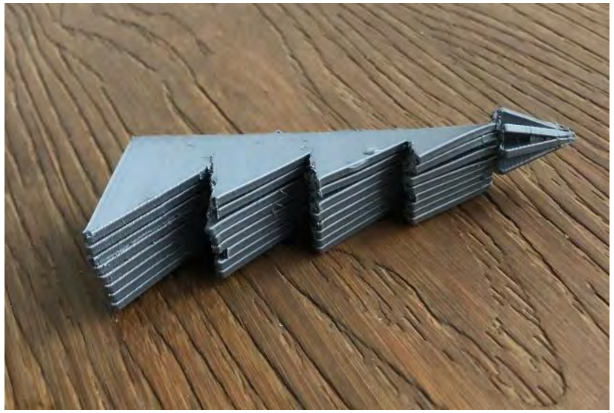


Figure 155 deformed/folded shape

To initiate shape recovery, the tree was then put back in the hot water. After leaving it for several minutes, there was no observable shape recovery happening anymore, and the shape was taken out of the water. Figures 156 and 157 show the recovered shape. The figures show that shape was not recovered completely. Again, this might be due to the design of the object, or the temperature of the water which decreased over the span of the shape recovery. Also, the inactive sections (parts which weren't supposed to deform) can also been seen to have deformed to some degree. This also needs to be taken into consideration when designing SMP objects.

Figure 156 recovered shape (top view) with visible deformation in the inactive sections

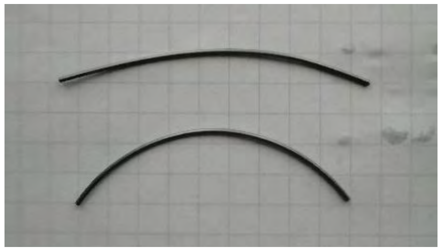
Figure 157 recovered shape showing the distance between the two unconnected sections

APPENDIX D: PRELIMINARY TESTING

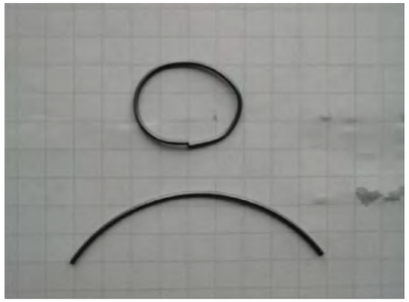
PLA shape memory ability testing

A short test was conducted to see if PLA filament already possesses shape memory capabilities, and to what extent. For this, two 10 cm long pieces of filament (silver, 123-3d) cut from a roll of filament were used (1 square is 1x1cm):

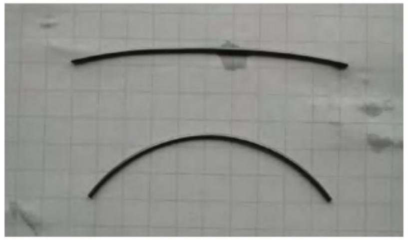
One of these pieces was put in hot water of 65°C for 60 seconds. Then, the sample was taken out of the water and compared to the other sample. As can be seen, the heated sample deformed quite a bit without external forces:



Then, the same sample was heated again, and deformed by hand, after which it was taken out of the water. While cooling, an external force kept the deformation of the sample in place. After cooling, the samples were compared again:



Afterwards, the sample was once again put in the hot water again, without an external force present, causing the sample to recover its original shape:



Testing of sample design V1

The first version of the sample design featured two hinge parts, to bend the two outer parts of the sample either upwards or downwards. Figure 158 and 159 show the sample design and dimensions.

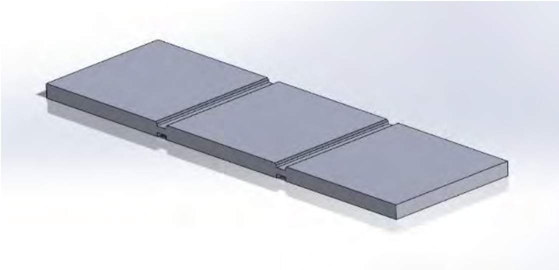


Figure 158 Sample design V1

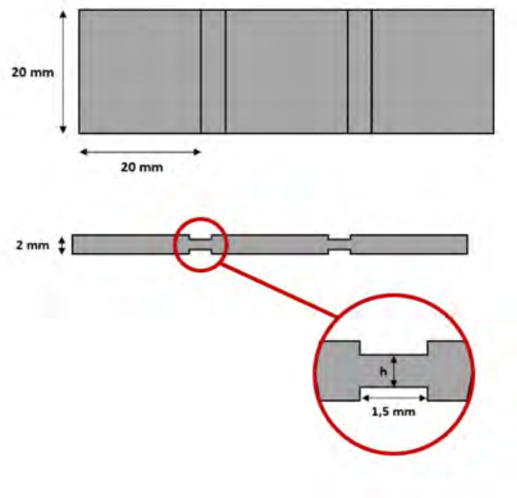


Figure 159 sample design V1 dimensions

This sample was printed with all infill lines printed in the longitudinal direction. Figure 161 shows the printed sample (A) and the different steps of the test process, with each arrow representing a submersion in 65°C water for 60 seconds. The descriptions next to the arrows explain the exact action for each submersion.

As can be seen in the figure, the sample is first put in hot water without an external force acting on it, to see the extent of self-bending in the sample. Self-bending in this case refers to the deformation that occurs when the material is exposed to the activation stimulus without an external force acting on it to deform it. This is related to the internal stresses present in the sample after printing, with a high degree of self-bending meaning there are a significant amount of internal stresses present in the material. Figure 161 B shows the self-bending of the sample, which is very noticeable. Based on the literature research, it can be reasoned that this is caused by a limited material thickness and the direction of the infill lines. Other factors might also have an influence, but based on this test, this can’t be said for sure.

Figure C to F show the deformation by hand, recovery of the original shape, deformation by hand to another shape and again recovery from the deformed shape to the original shape. During these steps, it was observed that the recovered shape of the samples represented the printed shape, not the shape after self-bending. The reason for this might be that the shape memory capabilities decrease for consecutive shape memory cycles, or that the self-bending releases the internal stresses, causing the material to return to the original, printed shape during shape recovery.

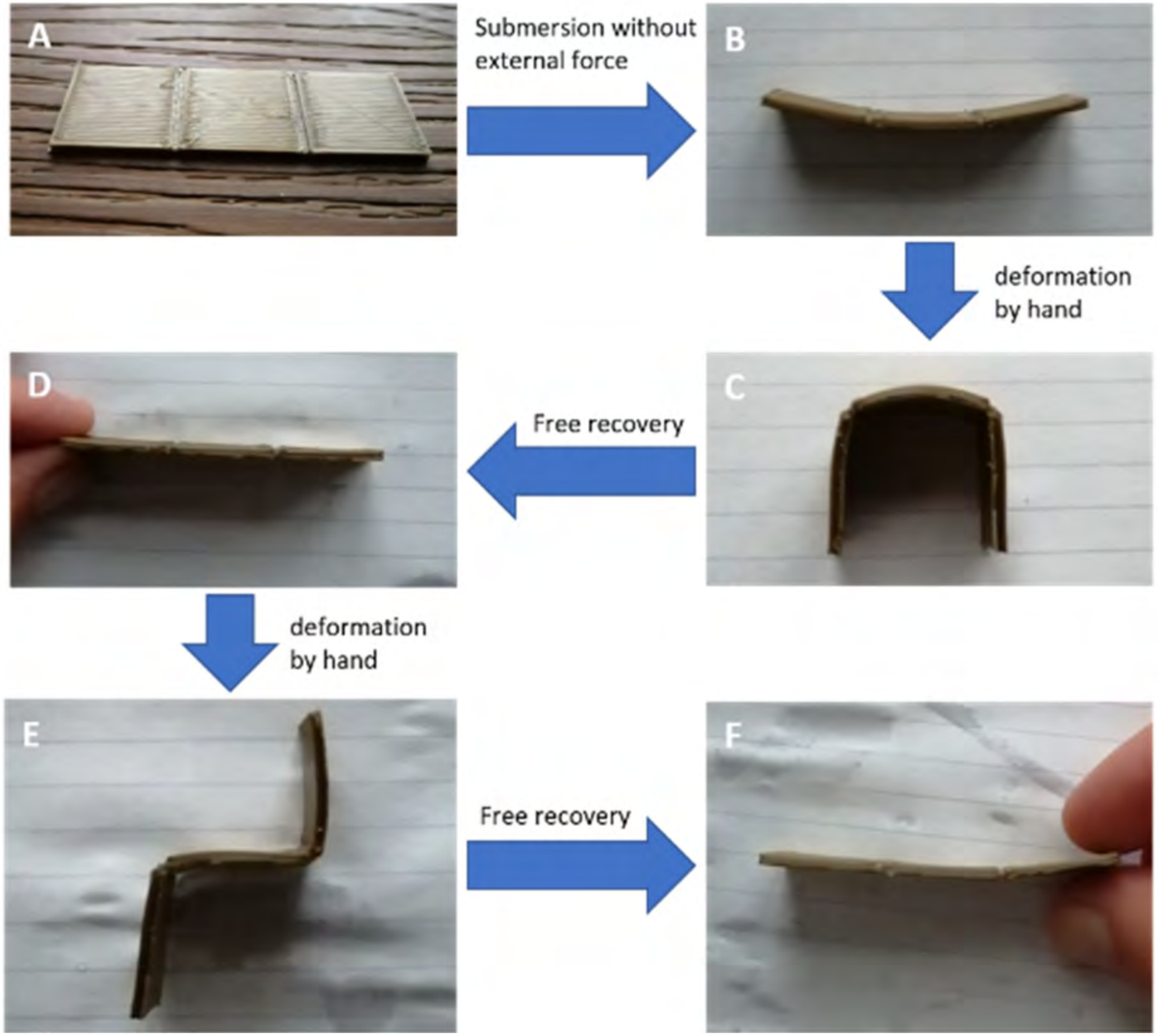

A
Submersion without external force
B
deformation by hand
C
Free recovery
D
deformation by hand
E
Free recovery
F

Figure 161

Testing of sample design V2

Sample design V1 has been redesigned based on the test results. Sample V2 (figures 162 and 163) has been designed to be less complicated to simplify testing, and faster to print. Also, the issue of self-bending that was observed in the previous sample design was addressed. The redesigned version has one hinge part as opposed to two hinge parts in sample V1, and has also been made thicker to reduce self-bending. Layer height was also increased from 0.15 to 0.2 mm, also with the intent to reduce self-bending, but also decrease printing time. The printing speed was lowered from 50 to 40 mm/s and the travel speed reduced from 150 to 100 mm/s to reduce self-bending, since these parameter settings were found to lead to less self-bending in the literature. The previous sample took just over 20 minutes to print, while the new sample can be printed in 15 minutes.

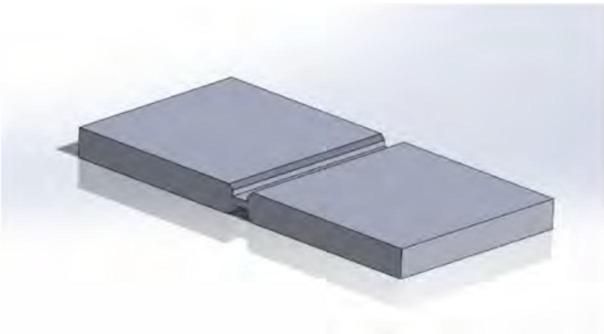


Figure 162 Sample design V2

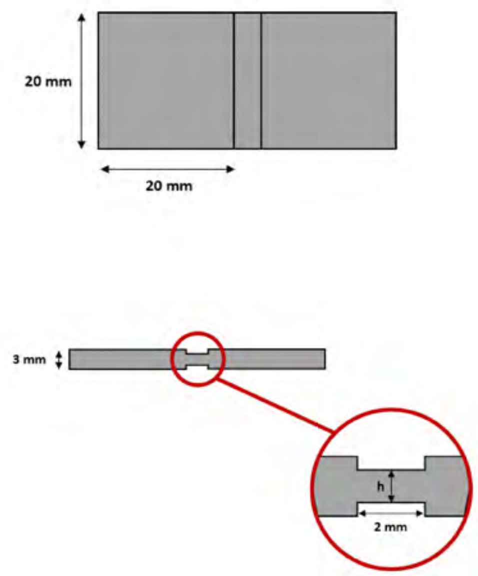


Figure 163 Sample design V2 dimensions

The first step of this test was to compare two different angles of infill lines to see how this affects self-bending. In figure 165, two different samples, one with a diagonal infill (A) and one with an infill in the longitudinal direction, like sample V1 (B). Both samples were submerged in 65°C water for 60 seconds, after which they were taken out and left to cool. C and D in the figure show how the samples deformed. As expected, the sample with an infill in the longitudinal direction shows more self-bending. However, the sample with a diagonal infill shows torsion as displayed in figure 165 E. This shows that the direction of the infill influences the direction of self-bending, as the infill lines shrink in the longitudinal direction.

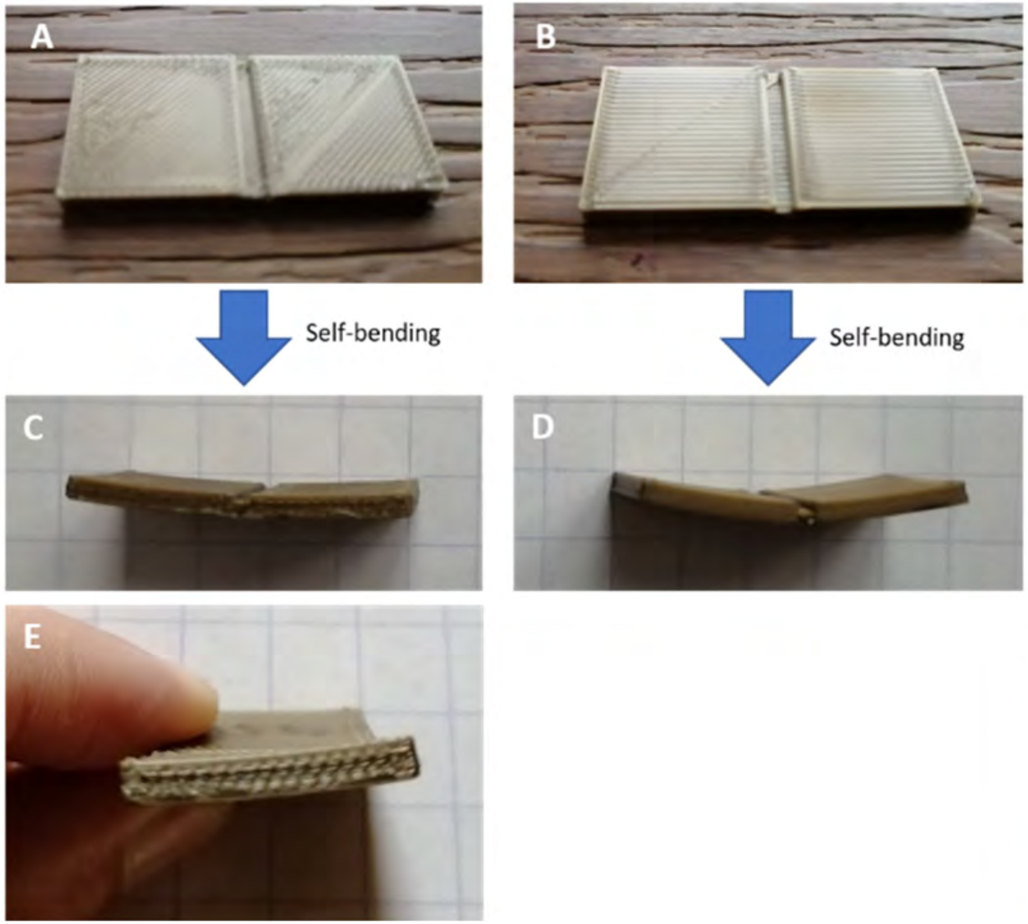


Figure 165

In an effort to decrease self-bending, two more samples were printed, with a diagonal infill were for each consecutive layer, the infill is perpendicular to the infill of the layer below, creating an alternating pattern of two infill directions. While the infill was the same for both samples, the temperature of the printer's build plate was set differently for both samples. One was printed on a 50°C build plate (figure 166 A), while the other was printed on a 30°C build plate (figure 166 B).

The same testing process used for the earlier samples was used. As can be seen in figure 166 C and D, a difference in self-bending is barely noticeable. Both samples also show an equal amount of torsion, which is significantly less than the sample printed with only 45-degree infill lines.

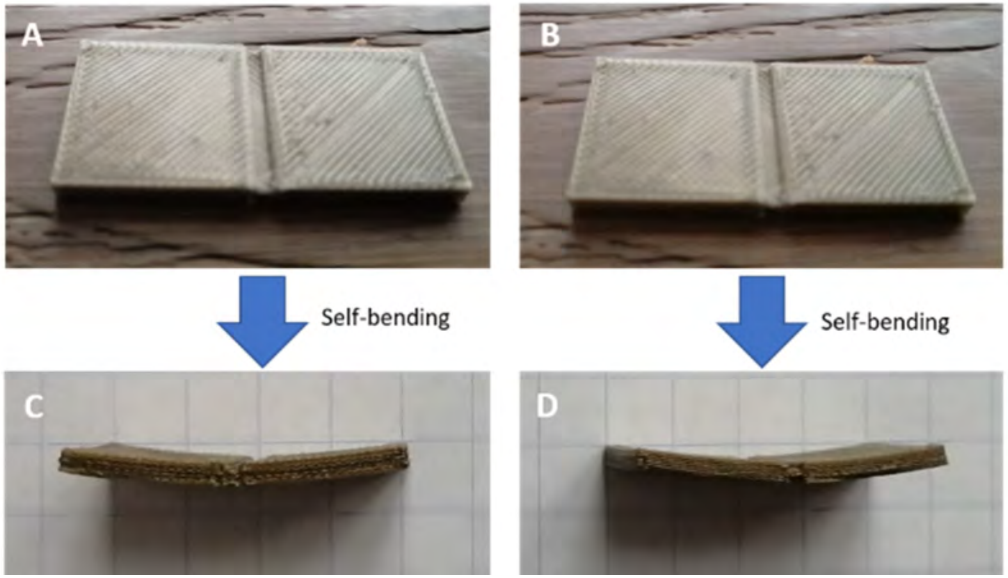


Figure 166 Testing process for sample V2. Both samples have a diagonal alternating infill. Left: printed with a 50°C build plate, Right: printed with a 30°C build plate

To quantify the results from the self-bending tests, the deformation of each sample was measured by clamping in one end and measuring the distance between the other end and a flat surface using digital callipers, as shown in figure 167. After correcting for the thickness of the samples, the results shown in Table 22 were found.

The table shows that the least self-bending occurred for the diagonal infill sample. However, relatively much self-twisting occurred in this sample, which is not desirable. When taking this into account, the diagonal alternating infill samples show more desirable results. Additionally, based on these measurements, the build plate temperature does not seem to have an influence on self-bending. However, with only two samples to compare, no significant conclusions can be drawn from this at the moment.

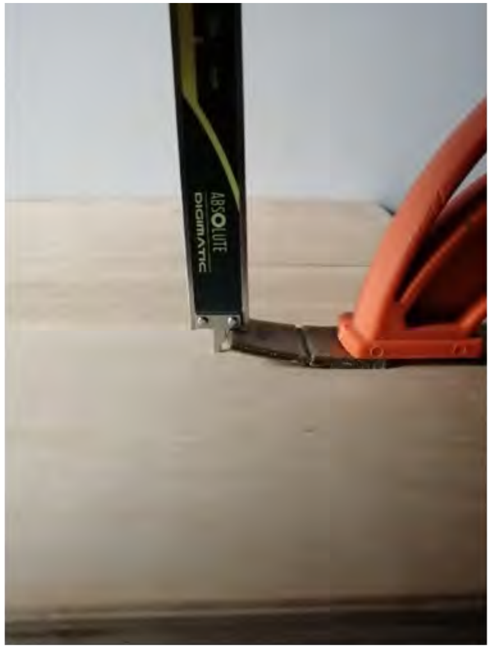


Figure 167 measuring the deformation of the samples

Table 22 results from sample V2 tests, showing the deformation for different samples

Sample	Build plate temperature (°C)	Deformation (mm)
longitudinal infill	50	8.2
diagonal infill	50	5.8
diagonal alternating infill	50	6.8
diagonal alternating infill	30	6.6

Testing of Sample design V3

Based on observations from testing the previous sample designs, a third version of the test sample was designed with the aim to further reduce self-bending and self-twisting. The test samples were made less wide than the second sample version to minimize twisting (figures 168 and 169). Based on the tests done with sample V2, the infill was chosen to be diagonal and alternating between each consecutive layer. Build plate temperature and fan speed (the speed in % at which the fans that cool the printed material spin) were chosen as variable parameters to find out which sample would show the least amount of self-bending. Other parameters were the same for all samples. This resulted in 4 different samples, as shown in table 23. Each version of the sample was printed in threefold to be able to perform the test multiple times to get more significant results. The samples were printed with the same printer and same material as the previous sample versions. One of the printed samples is shown in figure 170.

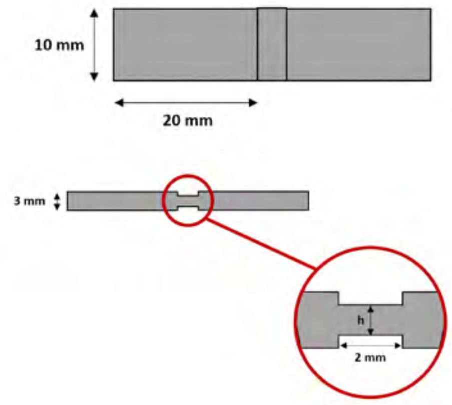


Figure 169 Sample design V3 dimensions

Figure 170 printed sample V3

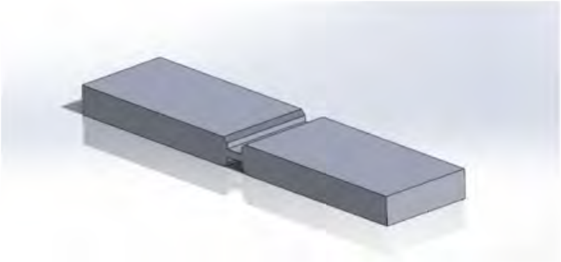


Figure 168 Sample design V3

Table 23 Overview of the different sample types

Sample type	Build plate temperature (°C)	Fan speed (%)
1	30	50
2	30	100
3	50	50
4	50	100

Similar to the previous sample tests, the different samples were submerged simultaneously in 65°C for 60 seconds. After 60 seconds the samples were taken out simultaneously and cooled. This test was repeated two times, each time with a new set of samples.

Afterwards, each sample was measured using digital callipers, the same way as in the test for sample V2. After subtracting the thickness of the samples, this led to the following results shown in table 24. The average for the different sample types was calculated and plotted in a graph, together with the standard deviation (figure 171).

Looking at the results, higher fan speed leads to more bending on average, while the influence of build plate temperature cannot be clearly derived from these measurements. Also, the there was little to no self-twisting within the samples. Based on the results, sample type 3 shows the least self-bending and smallest deviation. As, on average, the samples printed with a higher build plate temperature had less self-bending, and this also makes for better build plate adhesion, the higher build plate temperature will be used for the test samples.

Table 24 Measured deformation for all V3 sample types

	Sample type 1	Sample type 2	Sample type 3	Sample type 4
Deformation test 1 (mm)	3.7	3.3	3.0	3.2
Deformation test 2 (mm)	3.5	3.5	3.2	3.7
Deformation test 3 (mm)	3.3	4.2	3.1	4.4
Average deformation(mm)	3.5	3.7	3.1	3.8

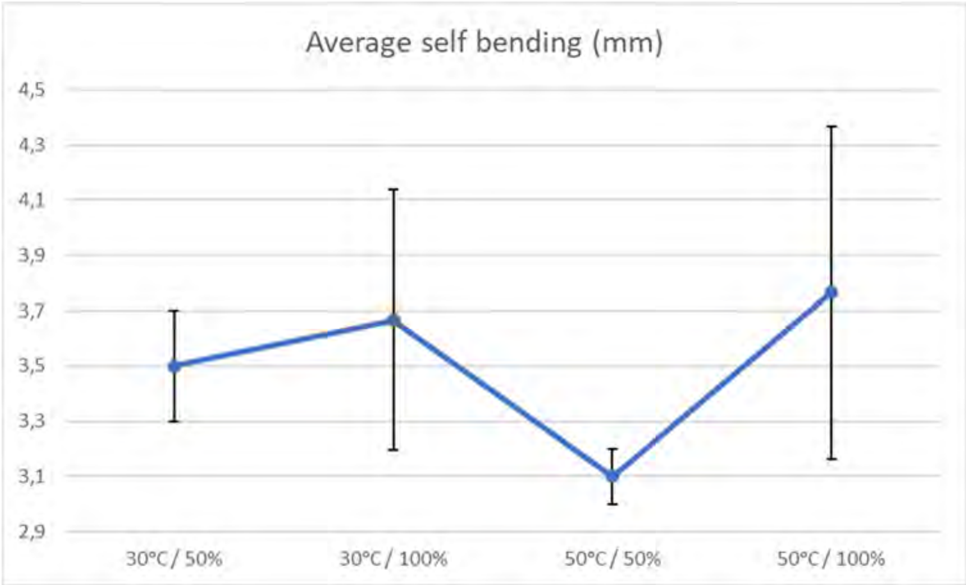


Figure 171 Average self-bending of the different sample types

APPENDIX E: SINGLE HINGE TESTING

TEST PLAN FOR TESTING THE INFLUENCE OF PRINTING PARAMETERS ON THE SHAPE MEMORY ABILITY OF 3D-PRINTED SMP'S

Introduction

When 3D-printing objects, the printer settings and material used have an influence on the mechanical properties and looks of the printed object. When wanting to print an object with shape memory abilities, printer settings, material and object design need to be considered, as all these elements have an influence on the ability of the object to return to its original shape after being deformed. However, research is lacking on which parameters need to be considered when 3D-printing shape memory objects, and the extent to which these different parameters influence the shape memory ability of SMP's.

In this document, a test plan is described for testing the influence of different parameters on the shape memory ability of PLA. The results from the tests will provide insights which will be used as a basis for setting up guidelines for designing shape memory objects and possible further tests.

Method

To test the influence of the different parameters, a systematic and controlled testing approach has been determined, and is described below. For this test, a simple printable geometry with a hinge section was designed.

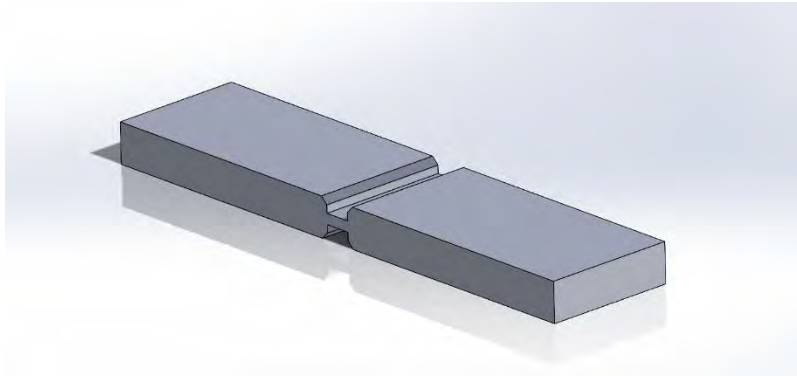


Figure 172 Test sample

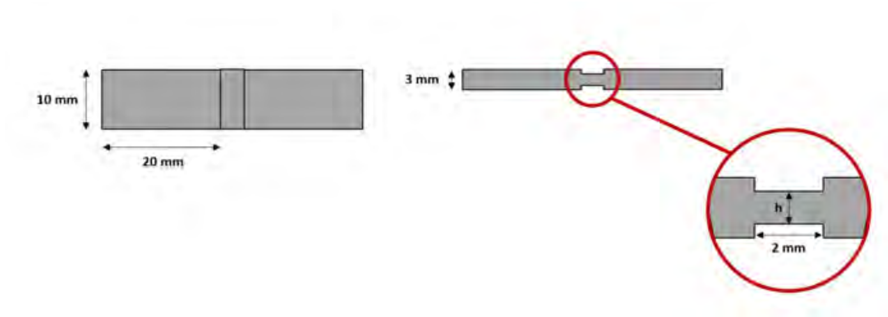


Figure 173 Measurements of the test sample, top view (left) and side view with hinge detail (right)

Figure 1 and 2 show the test sample and its measurements. It contains two hinge parts, of which the height will be varied during the tests (see ''parameters'').

During the test, the sample will be put in water of 65 degrees Celsius (just above the glass transition temperature of PLA, which is 60-65 degrees), for 60 seconds, after which the sample is deformed inside the water to the shape shown in figure 3. The blue part in this figure resembles the bend support used to make sure the samples are deformed as consistent as possible. After deforming, the sample is taken out of the water and cooled to room temperature. Once cooled, the sample is put in the hot water (65°C) again 30 seconds to initiate shape recovery. The process of shape recovery is captured on video. After this, the sample is taken out of the water and cooled again. During and after shape recovery, the following aspects are measured/considered:

- Shape recovery
  After taking the recovered sample out of the water, the recovery is measured as the percentage of deformation angle recovered. This is done using digital callipers.
- Reaction time
  Using the video footage taken during the recovery process, the time it takes for the sample to start recovering after being put in hot water is determined.

Figure 174 Bending of the sample (grey) and the bending support (blue)

The parameters which will be tested for material, manufacturing (3d-printing), and design were identified. For all identified parameters, two values were chosen to be alternated between during the test. The chosen parameters are listed below:

<u>Material</u>

- PLA from different suppliers
  PLA from two different suppliers will be used to see if there are differences between the shape memory capabilities of different PLAs. The specific type of PLA will be the same, with the materials from both suppliers being white PLA filament with a diameter of 2,85mm.
  The chosen suppliers and specific filaments are:
  - Ultimaker: PLA white
  - Makerpoint: PLA signal white

In the table below, the differences between properties for both materials is shown. These values were taken from the technical data sheets provided by the manufacturers.

	Unit	Ultimaker	Makerpoint
Printing temperature	(˚C)	200 - 210*	205 +/- 10
Melting temperature	(˚C)	145 - 160	115 +/- 35
Glass transition temperature	(˚C)	~ 60	57
Melt mass-flow rate	(gr/10 min)	6.09	9,56
Tensile stress at yield	(MPa)	49.5	70
Elongation at yield	(%)	3.3	5
Elongation at break	(%)	5.2	20
E-modulus	(MPa)	2346.5	3120
Impact strength	(kJ/m^2)	5.1	3.4

* This value was taken from the ultimaker website, as it was not in the data sheet

Design

- Height of the hinge
  As shown in figure 2, the height of the hinge *h* is variable. The influence of changing this parameter will be researched during this test, with the two values chosen to be 0.8mm and 1.4mm. Only the hinge part will be varied, the surrounding parts will be kept the same for all samples. This parameter was chosen based on both Esfahani's (2021) research and research done by Azizi et al. (2020)

Manufacturing

- Printing temperature
  Based on research done by Esfahani (2021) , printing or nozzle temperature was chosen as one of the manufacturing parameters. In his study on the self-bending of PLA samples, this parameter was found to be of great importance for the self-bending of the samples. For this test, the values of this parameter were chosen to be 195°C and 210°C, based on the temperature ranges listed by the suppliers of the two materials:
    - Ultimaker (200-210°C)
    - Makerpoint (195-215°C)
- Fan speed
  Another parameter chosen based on the research conducted by Esfahani (2021), cooling rate refers to the fan speed of the fan used for cooling the printed filament. For this research, the chosen fan speeds are 50% and 100%

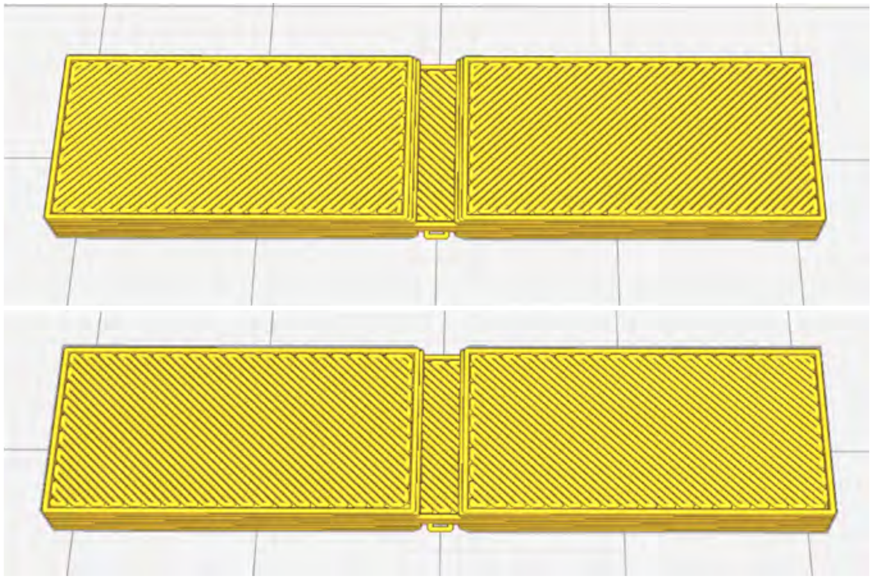
With 4 parameters to be tested, and 2 values for each parameter, this leads to a total of 16 different samples. In the table below, the parameters and values for each of the samples is displayed.

Sample	Material	Hinge height (mm)	Nozzle temperature (°C)	Fan speed (%)
1	Ultimaker	0.8	195	50
2	Ultimaker	0.8	195	100
3	Ultimaker	0.8	210	50
4	Ultimaker	0.8	210	100
5	Ultimaker	1.4	195	50
6	Ultimaker	1.4	195	100
7	Ultimaker	1.4	210	50
8	Ultimaker	1.4	210	100
9	Makerpoint	0.8	195	50
10	Makerpoint	0.8	195	100
11	Makerpoint	0.8	210	50
12	Makerpoint	0.8	210	100
13	Makerpoint	1.4	195	50
14	Makerpoint	1.4	195	100
15	Makerpoint	1.4	210	50
16	Makerpoint	1.4	210	100

Each specific sample will be printed 3 times, in order to make sure the results have significant value. Thus, 48 samples will be printed and tested.

Apart from the variable parameters as described above, there are other parameters which will be kept constant during the research, either because they will not be considered as significant influencers for the shape memory ability of the printed samples, or because the initial research would otherwise become too broad:

- Angle of printing
  The angle of printing refers to the direction of the print lines in relation to the orientation of the printed object. This influences the direction of the bend, not necessarily the degree and speed of bending. The samples will be printed flat on the build plate, with a wall thickness of 1 layer. The infill angle alternates between 45° and 135° for each consecutive angle (e.g. the first layer will be printed with 45° lines, the second with 135° lines, the third 45° etc.) This was done to increase the uniformity of the sample, and minimize self-bending. In the figure below, the pattern used to print the sample is shown.



Infill pattern of the test sample, with a 45° layer (top) and 135° layer (bottom), and one wall line around the sample

- Infill density
  This was chosen to be 100%, based on research by Esfahani (2021). Infill density is a parameter related to the design of the object, and its influence on shape memory ability depends on the specific design of the object.
- Line width
  The line width of the printed lines was chosen to be 0.4 mm
- Layer height
  This was chosen to be 0.15, as this creates uniform layers when printing hinges that are 0.9mm (6 layers) and 1.5 mm (10 layers)
- Printing speed
  This was chosen to be 40 mm/s, travel speed 100mm/s
- Build plate temperature
  This was chosen to be 50°C to ensure good adhesion on the build plate.

Apart from printing parameters, there are other important aspects that are considered to ensure the changes in shape memory behaviour between samples are due to changes in the printing settings:

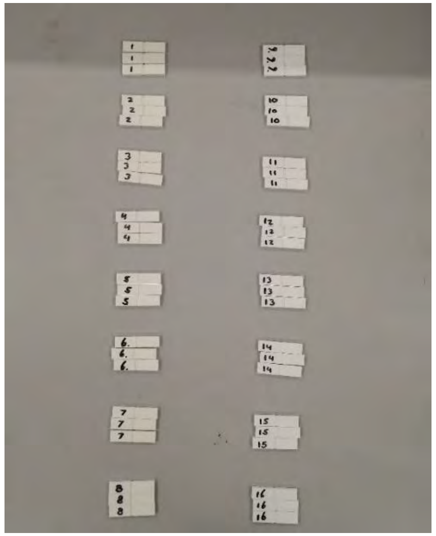
- Room temperature: the aim is to keep this as consistent as possible. The printer used was located in a room with a controlled climate, and placed in a glass cabinet to a constant environment temperature
- The same printer is used for all samples. In this case, an ultimaker 3
- The water temperature will be kept as consistent as possible on 65°C. For this, a water bath is used.

Materials needed:

- 3d printer
- 3d printer filament: Ultimaker and Makerpoint
- Samples (need to be made)
- Stopwatch
- Phone to record
- Water bath
- Heat resistant gloves

Method

The first step was to print all 48 samples. The samples were printed on an ultimaker 3, located in a cabinet in in climate-controlled room, in order to limit environmental influences on the samples during printing.

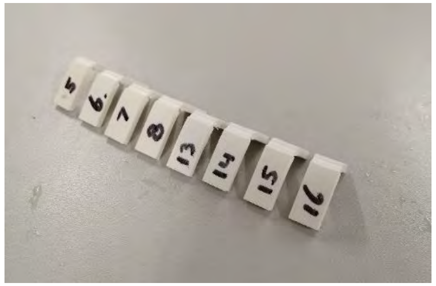


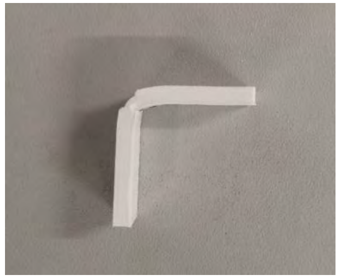
For testing, 8 samples are attached to an angle profile using double sided tape. The 8 samples attached were either the different samples with a hinge thickness of 0.8mm (samples 1,2,3,4,9,10,11,12) or the different samples with a hinge thickness of 1.4mm (samples 5,6,7,8,13,14,15,16) to ensure the samples would each be deformed to the same shape.

The samples were then put in a water bath for 60 seconds to heat.

After this, the samples were deformed using a second piece of angle profile. The samples were clamped between the profile pieces until the samples were cooled down to room temperature.

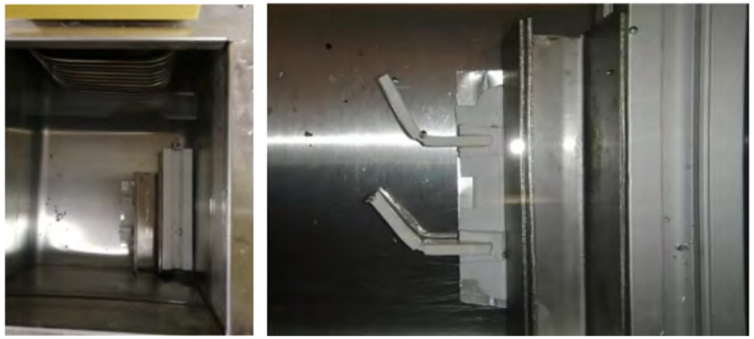
After deforming, the samples were detached from the profiles, and the angle of deformation was measured for a few samples to check if they were deformed equally and to what extent. All samples measured were deformed over an angle of 90 degrees, with some small deformations at the thicker parts near the hinge.





For recovering, the samples were again put in the water bath for 30 seconds. Using a small construction to keep the samples in a fixed orientation while recovering, two samples were put in the water bath at the same time.

Construction to keep the samples in place while recovering



The sample holder (left) with recovering samples (right) in the water bath

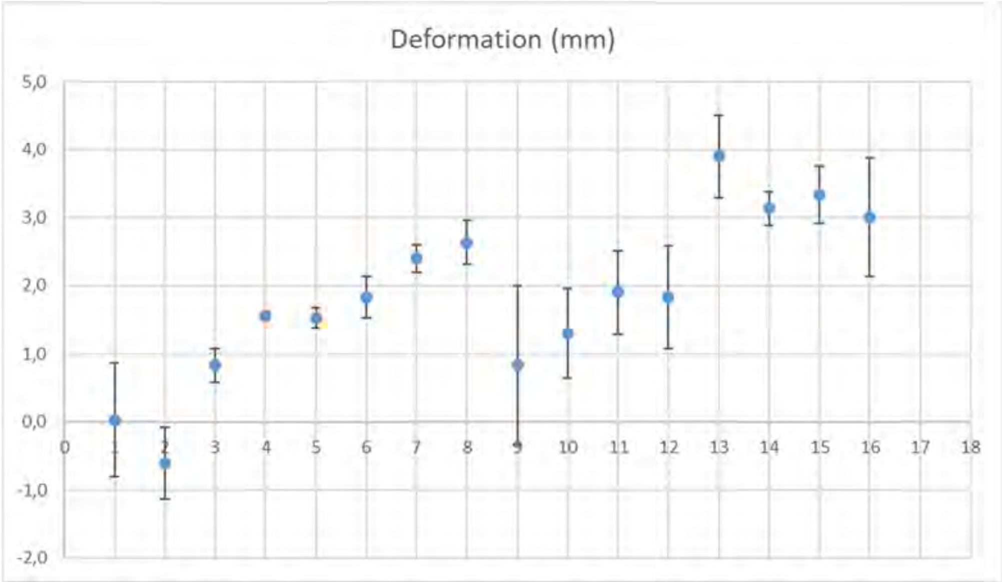
After recovering, the samples were carefully taken out of the water as to not deform them again. Once cooled down, the deformation of the samples was measured using digital callipers. One end of the samples was clamped onto a flat wooden board. Each sample was marked with a stripe at 10 mm from the end of the sample, to ensure all samples were clamped in the same way.

Results

In the table below, the results from the tests, average recovery and average activation time, are displayed per sample type.

Sample	Material	Hinge height (mm)	Nozzle temperature (°C)	Fan speed (%)	Average Recovery (%)	Average Activati (s)
1	Ultimaker	0.8	195	50	99,9 (± 2,5)	6,5 (± 0,9)
2	Ultimaker	0.8	195	100	101,8 (± 1,6)	6,0 (± 0,9)
3	Ultimaker	0.8	210	50	97,5 (± 0,8)	7,0 (± 1,4)
4	Ultimaker	0.8	210	100	95,2 (± 0,2)	7,0 (± 0,5)
5	Ultimaker	1.4	195	50	95,3 (± 0,5)	11,8 (± 0,8)
6	Ultimaker	1.4	195	100	94,4 (±0,9)	10,2 (± 0,8)
7	Ultimaker	1.4	210	50	92,7 (± 0,6)	11,2 (± 0,3)
8	Ultimaker	1.4	210	100	92,0 (± 1,0)	10,7 (± 0,8)
9	Makerpoint	0.8	195	50	97,5 (± 3,6)	7,2 (± 1,0)
10	Makerpoint	0.8	195	100	96,0 (± 2,0)	6,8 (± 1,9)
11	Makerpoint	0.8	210	50	94,2 (± 1,9)	7,5 (± 0,7)
12	Makerpoint	0.8	210	100	94,4 (± 2,3)	6,3 (± 1,6)
13	Makerpoint	1.4	195	50	88,0 (± 1,9)	10,3 (± 0,3)
14	Makerpoint	1.4	195	100	90,4 (± 0,8)	9,7 (± 1,0)
15	Makerpoint	1.4	210	50	89,8 (± 1,3)	10,3 (± 0,3)
16	Makerpoint	1.4	210	100	90,8 (± 2,7)	9,8 (± 0,3)

Based on the measurements, the deformation of the samples after recovering was calculated by subtracting the thickness of the sample from the measured distance between the highest point of the recovered sample and the wooden board. The average and standard deviation of each sample type were calculated, leading to the following results:



Using the measured deformation, the recovery ratio was determined for each sample, using the following formula:

$$R_{recovery} = \left(1 - \left(\frac{D_{recovery}}{D_{deformation}}\right)\right) * 100$$

With $D_{recovery}$ being the remaining deformation angle after recovery, and $D_{deformation}$ being the initial deformation angle.

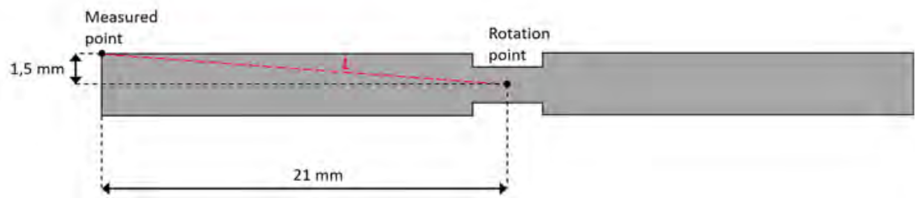
$D_{recovery}$ is calculated using the following formula:

$$D_{recovery} = \sin^{-1}\left(\frac{x + 1{,}5}{L}\right) - \sin^{-1}\left(\frac{1{,}5}{L}\right)$$

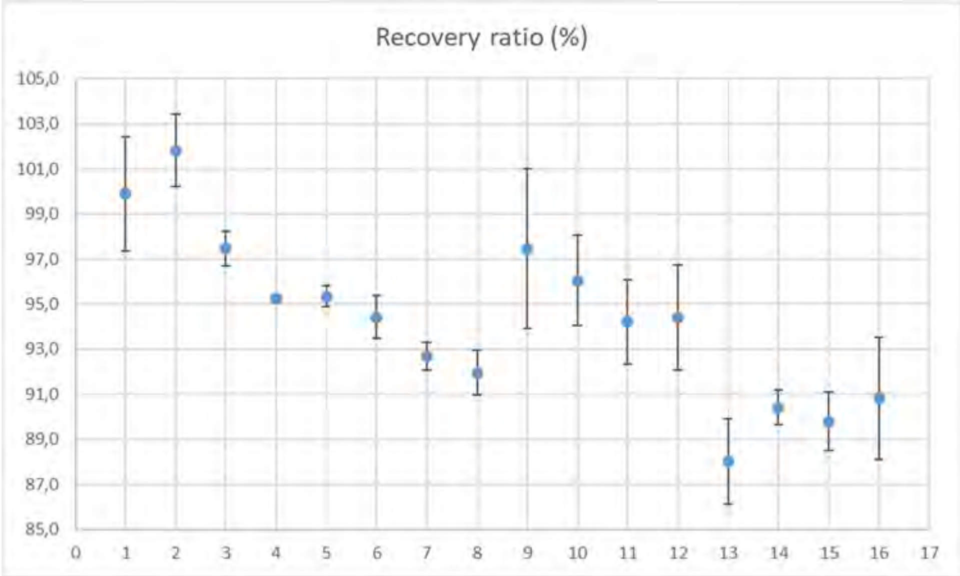
With ''x'' being the measured deformation after recovery, and ''L'' being the distance from the point of rotation to the point which was used for measuring the deformation (see figure below), calculated using the Pythagorean theorem:

$$L = \sqrt{1{,}5^2 + 21^2}$$

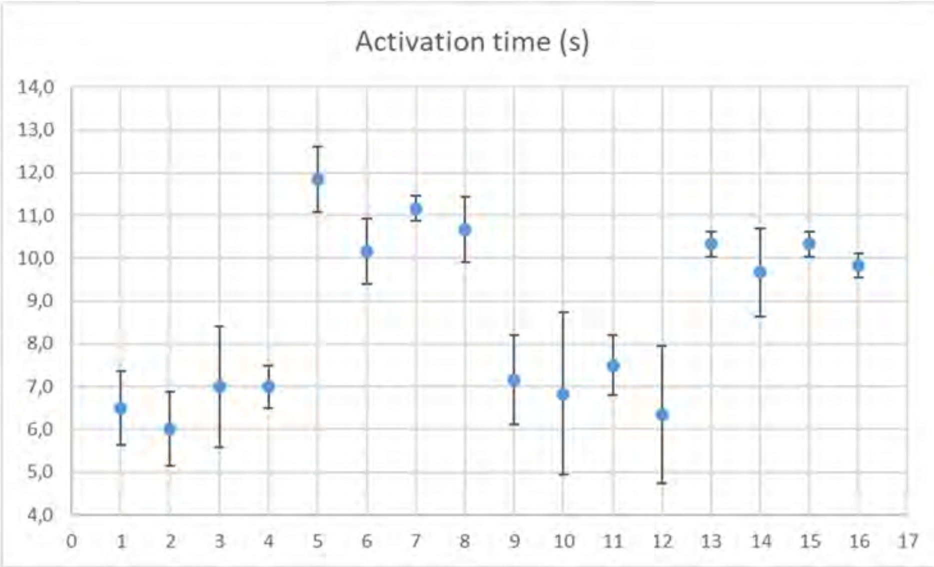
To compensate for the fact that the measured point is not in line with the horizontal plane of the rotation point, the height difference (1.5mm) is added to the measured deformation, and the angle between the horizontal plane and the ''L'' plane (red line in the figure) in undeformed state is subtracted.



Again, from the calculated values, the average and standard deviation were determined, leading to the following results:

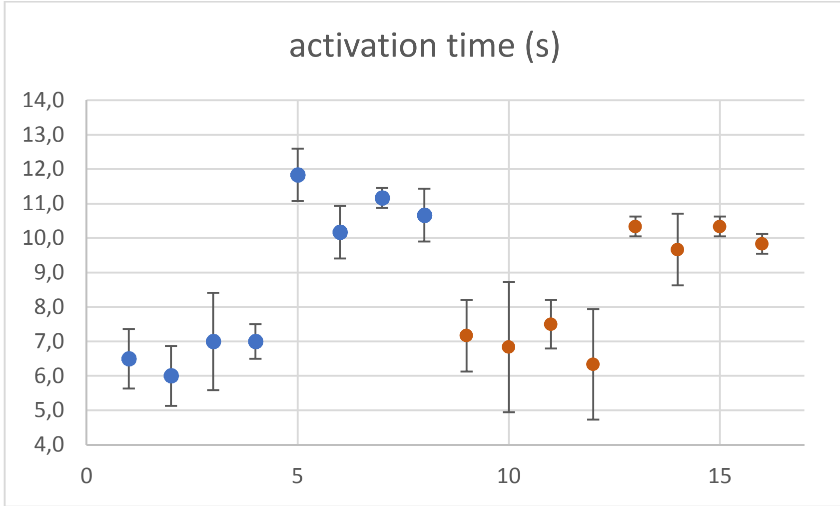


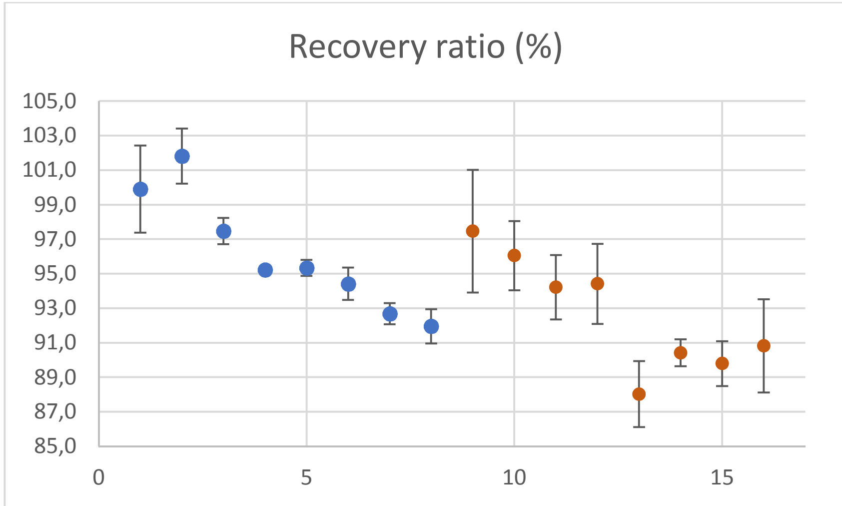
By analysing the video footage taken of the shape recovery of the samples, the activation time for shape recovery was determined for each sample. The moment the samples were put in the water was determined, as well as the moment shape recovery started, to determine how many seconds it took for the samples to start recovering. The average and standard deviation were calculated for each sample type, leading to the following results:



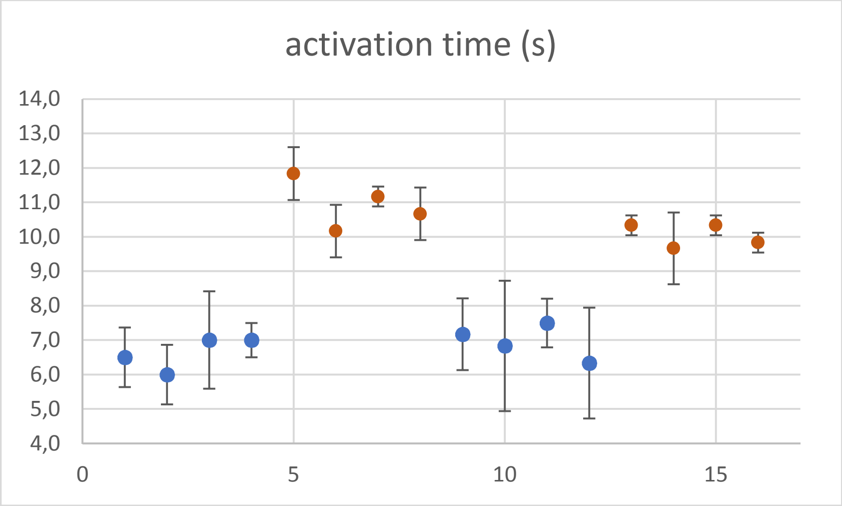
Based on the results shown in the graphs, several things can be concluded:

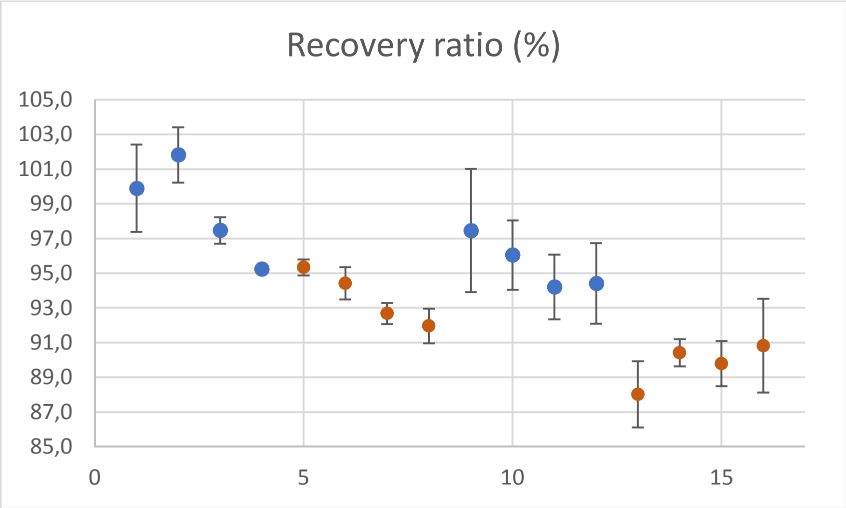
- Material
  In terms of shape recovery, there are differences between the samples printed with ultimaker material (1-8) and the samples printed with makerpoint material (9-16). According to the data, the average recovery ratio for the ultimaker samples is higher than that of the makerpoint samples. However, it also shows that the makerpoint samples are less consistent in their shape recovery, as the standard deviation for these samples is in general higher than that of the ultimaker samples. It is not clear what material properties exactly cause these differences. In terms of activation time, both materials give comparable results, with the ultimaker samples having a slightly lower activation time for the thin hinge samples, while the makerpoint samples had a faster average activation time for the thick hinge samples.



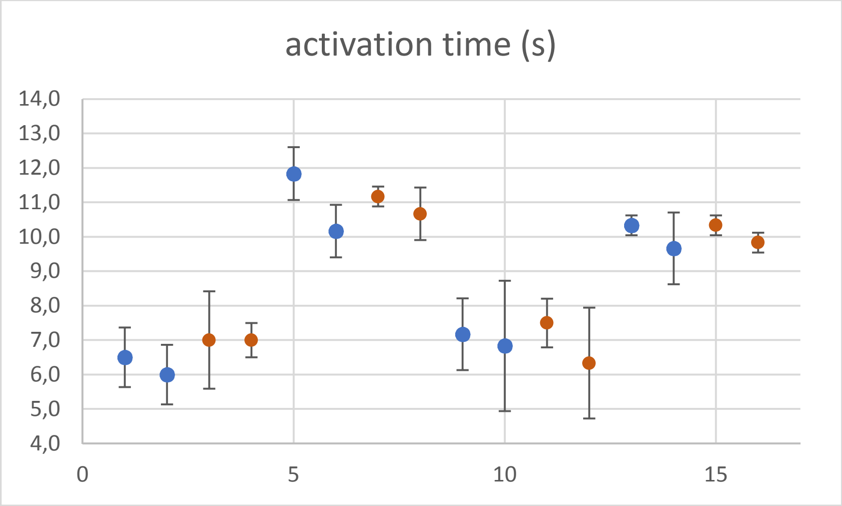


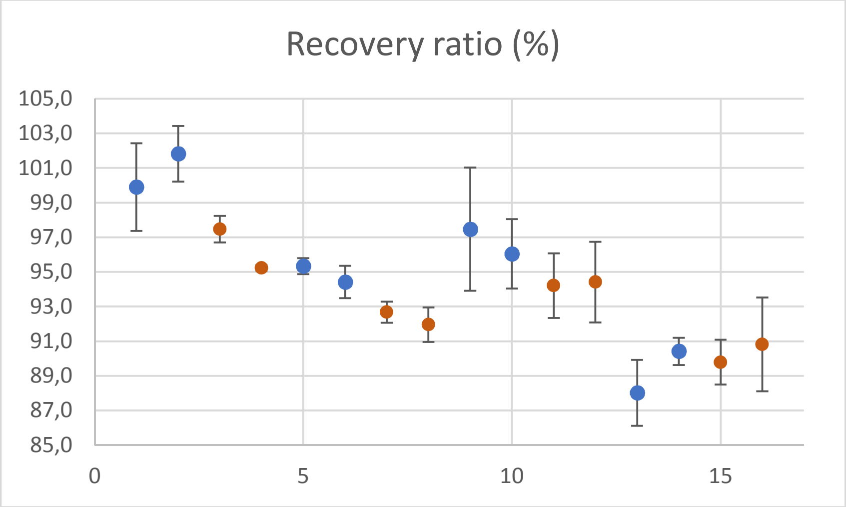
- <u>Hinge Thickness:</u>
  Hinge thickness has a clear influence on the activation time. The samples with a thicker hinge section (orange) were observed to have a longer activation time than the samples with a thinner hinge (blue). Also, the samples with a thicker hinge show less recovery after 30 seconds than the samples with a thin hinge. However, from the performed test it cannot be concluded if the samples had already finished recovering after 30 seconds, which leaves the question if the thicker samples can recover to the same extent as the thinner samples given more time, or not.



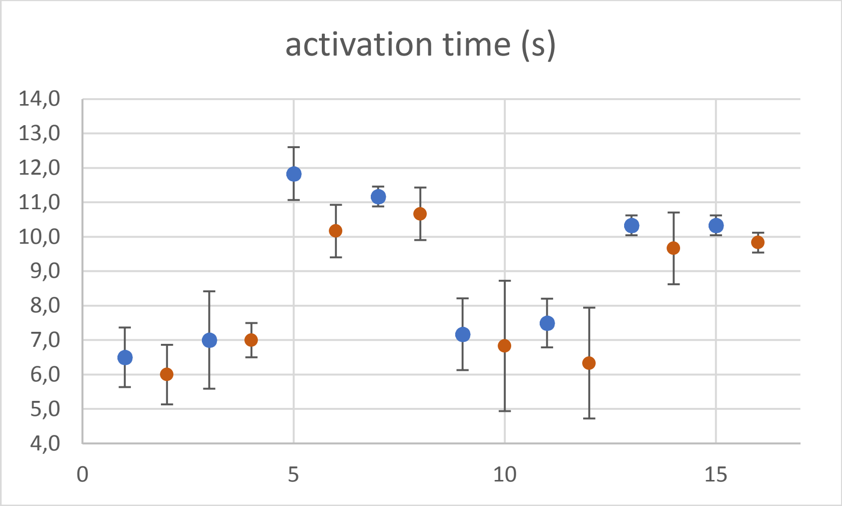


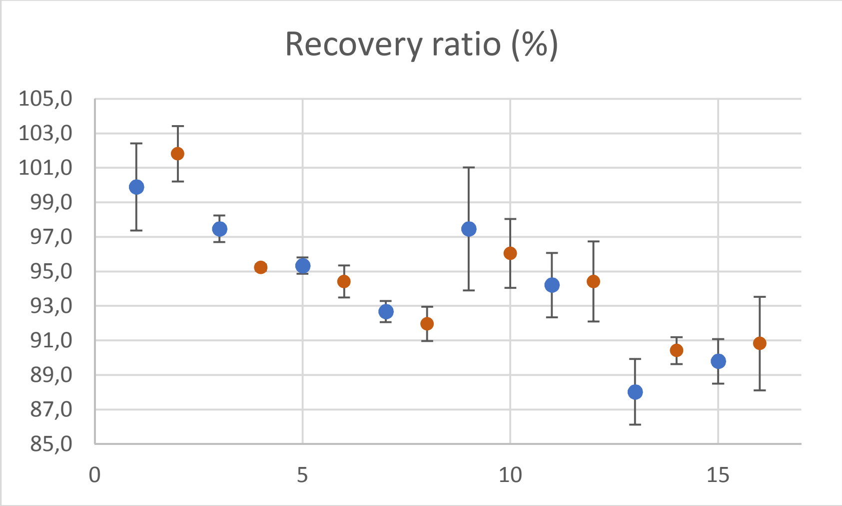
- <u>Nozzle temperature</u>
  Nozzle temperature seems to have no influence on either recovery ratio or activation time. There is no clear distinction between samples printed with a lower printing temperature (blue) and samples printed with a higher temperature (orange).





- Fan speed does not seem to have a clear influence on recovery ratio. In some cases, higher fan speed (2,4,6,8,10,12,14,16) leads to a higher recovery ratio, while in other cases it is the exact opposite. However, from the data it seems that fan speed does influence the activation time, with a higher fan speed leading to shorter activation times on average.





APPENDIX F: DATA SHEET FOR ULTIMAKER PLA

Technical data sheet PLA

Ultimaker

Chemical composition	See PLA safety data sheet, section 3
Description	Ultimaker PLA filament provides a no-hassle 3D printing experience thanks to its reliability and good surface quality. Our PLA is made from organic and renewable sources. It's safe, easy to print with, and it serves a wide range of applications for both novice and advanced users
Key features	Good tensile strength and surface quality, easy to work with at high print speeds, user-friendly for both home and office environments, PLA allows the creation of high-resolution parts. There is a wide range of color options available
Applications	Household tools, toys, educational projects, show objects, prototyping, architectural models, as well as lost casting methods to create metal parts
Non-suitable for	Food contact and *in vivo* applications. Long term outdoor usage or applications where the printed part is exposed to temperatures higher than 50 °C

Filament specifications

	Value	Method
Diameter	2.85 ± 0.10 mm	-
Max roundness deviation	0.10 mm	-
Net filament weight	350 g / 750 g	-
Filament length	~ 44 m / ~ 95 m	-

Color information

Color	Color code
PLA Green	RAL 6018
PLA Black	RAL 9005
PLA Silver Metallic	RAL 9006
PLA White	RAL 9010
PLA Transparant	N/A
PLA Orange	RAL 2008
PLA Blue	RAL 5002
PLA Magenta	RAL 4010
PLA Red	RAL 3020
PLA Yellow	RAL 1003
PLA Pearl White	RAL 1013

Technical data sheet - Ultimaker PLA 1

Mechanical properties*

	Injection molding		3D printing	
	Typical value	Test method	Typical value	Test method
Tensile modulus	-	-	2,346.5 MPa	ISO 527 (1 mm/min)
Tensile stress at yield	-	-	49.5 MPa	ISO 527 (50 mm/min)
Tensile stress at break	-	-	45.6 MPa	ISO 527 (50 mm/min)
Elongation at yield	-	-	3.3%	ISO 527 (50 mm/min)
Elongation at break	-	-	5.2%	ISO 527 (50 mm/min)
Flexural strength	-	-	103 MPa	ISO 178
Flexural modulus	-	-	3,150 MPa	ISO 178
Izod impact strength, notched (at 23 °C)	-	-	5.1 kJ/m²	ISO 180
Charpy impact strength (at 23 °C)	-	-	-	
Hardness	-	-	83 (Shore D)	Durometer

Electrical properties*

	Typical value	Test method	Typical value	Test method
Dissipation factor (at 1 MHz)	-	-	0.008	ASTM D150-11
Dielectric constant (at 1 MHz)	-	-	2.70	ASTM D150-11

Thermal properties

	Typical value	Test method
Melt mass-flow rate (MFR)	6.09 g/10 min	ISO 1133 (210 °C, 2.16 kg)
Heat detection (at 0.455 MPa)	-	-
Heat deflection (at 1.82 MPa)	-	-
Vicat softening temperature	-	-
Glass transition	~ 60 °C	ISO 11357
Coefficient of thermal expansion	-	-
Melting temperature	145 - 160 °C	ISO 11357
Thermal shrinkage	-	-

*See notes

Technical data sheet - Ultimaker PLA 2

Other properties

	Value	Test method
Specific gravity	1.24	ASTM D1505
Flame classification	-	-

Notes

Properties reported here are average of a typical batch. The 3D printed test specimens were printed in the XY plane, using the normal quality profile in Ultimaker Cura 2.1, an Ultimaker 2+, a 0.4 mm nozzle, 90% infill, 210 °C nozzle temperature, and 60 °C. The values are the average of five white and five black specimens for the tensile, flexural, and impact tests. The Shore hardness D was measured in a 7-mm-thick square printed using the normal quality profile in Utlimaker Cura 2.5, an Ultimaker 3, a 0.4 mm print core, and 100% infill. The electrical properties were measured on a 54-mm-diameter disk with 3 mm thickness printed in the XY plane, using the fine quality profile (0.1 mm layer height) in Ultimaker Cura 3.2.1, an Ultimaker 3, a 0.4 mm print core, and 100% infill. Ultimaker is constantly working on extending the TDS data.

Disclaimer

Any technical information or assistance provided herein is given and accepted at your risk, and neither Ultimaker nor its affiliates make any warranty relating to it or because of it. Neither Ultimaker nor its affiliates shall be responsible for the use of this information, or of any product, method or apparatus mentioned, and you must make your own determination of its suitability and completeness for your own use, for the protection of the environment, and for the health and safety of your employees and purchasers of your products. No warranty is made of the merchantability or fitness of any product; and nothing herein waives any of Ultimaker's conditions of sale. Specifications are subject to change without notice.

Version	Version 4.002
Date	November 19, 2018

APPENDIX G: DATA SHEET FOR MAKERPOINT PLA

MakerPoint
digital fabrication solutions

MakerPoint PLA

MakerPoint PLA is a tough, easy to use high grade PLA type of filament, ideal for 3D printing. Slightly modified, the filament retains the typical features of PLA, but makes it tougher and less brittle. Due to a low shrinkage factor PLA will not deform after cooling. Poly Lactic Acid is a biodegradable plastic made from renewable natural resources and one of the most popular materials for 3D printing.

Features:

- Tougher and less brittle compared to regular PLA
- Easy to print at low temperature
- Low warping
- Biodegradable
- Limited smell

Dimensions		
Size	Ø tolerance	Roundness
1,75mm	± 0,05mm	≥ 95%
2,85mm	± 0,10mm	≥ 95%

Colors
MakerPoint PLA is available in a large selection of bright colors. Special colors are available upon request with a minimum order quantity of 40kg.

3D-printing	
Description	Typical value
Printing technology	FFF
Printing temp.	205 ± 10°C
Heated bed temp.	35-60°C (when available)
Cooling fan	100%
Flow Rate	100%

Physical properties		
Description	Test method	Typical value
Specific gravity	ISO 1183	1,24 g/cc
MFR 210°C/2,16 kg	ISO 1133	9,56 gr/10 min
Tensile strength at Yield (MPa)	ISO 527	70 Mpa
Strain at yield	ISO 527	5%
Strain at break	ISO 527	20%
E-Modulus	ISO 527	3120 Mpa
Impact strength - Charpy method 23°C	ISO 179	3,4 KJ/m²
Moisture absorption	ISO 62	1989 ppm
Printing temp	DF 205	205±10°C

Last change: 2019-09-09
The data correspond to our knowledge and experience at the time of publication. They do not on their own represent a sufficient basis for any part design, neither do they provide any agreement about or guarantee the specific properties of a product or part or the suitability of a product or part for a specific application. It is the responsibility of the producer or customer of a part to check its properties as well as its suitability for a particular purpose. This also applies regarding the consideration of possible intellectual property rights as well as laws and regulations. The data are subject to change without notice as part of MakerPoint's continuous development and improvement processes.

MakerPoint
digital fabrication solutions

Thermal properties		
Description	Test method	Typical value
Melting temp.	ISO 11357	115°C ± 35°C
Glass transition temp.	ISO 11357	57°C
Vicat softening temp.	ISO 306	60°C

Additional information:

Due to its low tendency to warp PLA can also be printed without a heated bed. If you have a heated bed the recommended temperature is ± 35-60°C. PLA can be used on all common desktop FDM or FFF technology 3D printers. Storage: Cool and dry (15-25°C) and away from UV light. This enhances the shelf life significantly.

Last change: 2019-09-09
The data correspond to our knowledge and experience at the time of publication. They do not on their own represent a sufficient basis for any part design, neither do they provide any agreement about or guarantee the specific properties of a product or part or the suitability of a product or part for a specific application. It is the responsibility of the producer or customer of a part to check its properties as well as its suitability for a particular purpose. This also applies regarding the consideration of possible intellectual property rights as well as laws and regulations. The data are subject to change without notice as part of MakerPoint's continuous development and improvement processes.

APPENDIX H: CREATIVE SESSION

Creative session

To get inspiration on how to apply the shape memory properties of PLA in a real-world application/product, a creative session was organised. In this session, a group of people was asked to brainstorm about possible applications and products where the shape memory capabilities of PLA could be used. The group consisted of a total of 6 people:

- 1 facilitator (me)
- 3 IPD master students
- 1 recent graduate of IPO (Industrieel Product Ontwerpen) of the Hogeschool Rotterdam
- 1 student without a background in industrial design engineering

This mix of people was selected to get input from different viewpoints. Since the methods used in this session were easily understandable, and all participants had experience in working in creative teams, everyone was able to participate in an active manner. Due to Covid-related policies, it was not possible to have a ''physical'' meeting, so the creative session was performed online using Discord as a communication tool and the online whiteboard tool Miro to work together and visualize the process. Since all participants were native Dutch speakers, it was chosen to perform the session in Dutch. The images of the mind maps created in this session provided in this report are therefore in Dutch, but the transcription of the activities performed and the results of the session will be translated to English.

Setup

The setup of this session was based on the Creative Problem Solving Process (CPS) by Buijs and Tassoul (2005). This process consists of three phases, where the results of each phase are used as a basis for the next phase:

- Problem statement
- Idea generation
- Concept development

Based on the three phases of the Creative Problem Solving Process, a program for the creative session was created:

- Introduction (15 min.)
- Warm up exercise (10 min.)
- Problem statement (15 min.)
- Idea generation (50 min.)
- Concept development (15 min.)
- Wrap up (5 min.)

Before the meeting, a discord server and Miro board were created, and the links to both shared with the participants. The setup for the Miro board is shown in figure 175. Since the creative session was online, it was not possible to show samples of the material to the participants in person. To introduce participants to the material and shape memory effect in an effective way, two short clips were shared: one YouTube clip showing the general process of shape memory in polymers (link below) and one clip showing the recovery of a double hinge sample, made during the double hinge testing. The participants were asked to watch these clips before the creative session.

Link to the YouTube clip:
https://www.youtube.com/watch?v=4JuHBtquP1I&ab_channel=%E3%82%AD%E3%83%A7%E3%83%BC%E3%83%A9%E3%82%AF%E6%A0%AA%E5%BC%8F%E4%BC%9A%E7%A4%BE

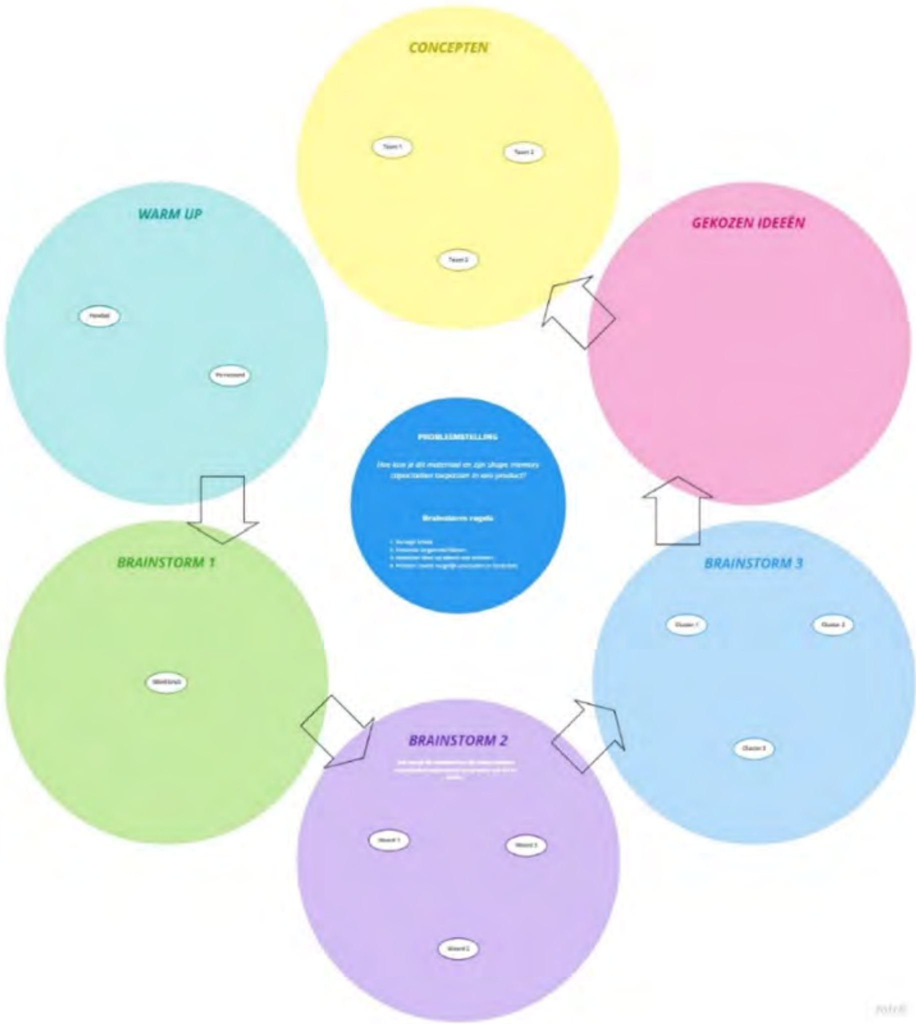


Figure 175 Miro board setup

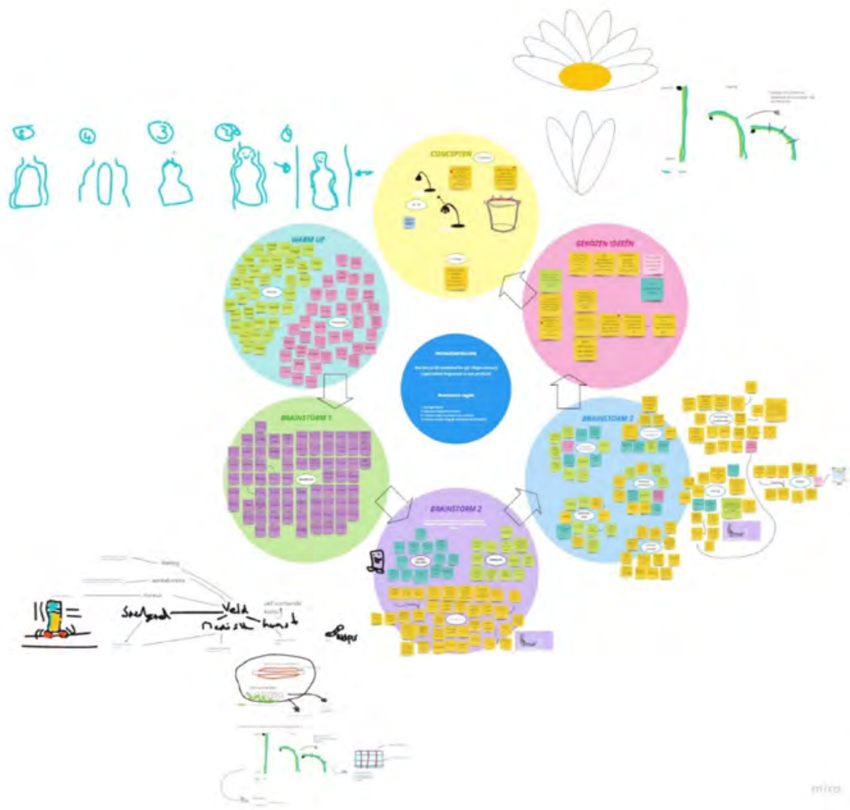


Figure 176 Miro board after the session

Figure 176 shows an overview of the board after the session.

Introduction

In the introduction, the project, material and setup for the creative session were explained. After shortly introducing the participants to each other, the project was explained, followed by a short introduction of the shape memory effect and the material (PLA). The technical specifications and limitations of the material and shape memory effect were not explained as to not limit the participants in the creative process. Furthermore, the problem statement was introduced:

Hoe kun je dit materiaal en zijn shape memory capaciteiten toepassen in een product?

How can you apply this material and its shape memory capabilities in a product?

Lastly, the program for the session was explained, as well as Miro, the whiteboard tool which we would be using

Warm up exercise

As a warm up exercise, the participants were given 10 minutes to think about products and other words that would come to mind when thinking about two words:

- Flexibel (flexible)
  This word was chosen due to its relation to the shape memory properties of the material (e.g. the material becomes flexible when heated) and because it was thought to be a word for which the participants could easily come up with lots of products, therefore being suited as a warm up.
- Verrassend (surprising)
  This word was chosen to be the second part of the warm up. For this word, it was expected for the participants to think on a more abstract level, as ‘’surprising’’ is not a material property, but more of a subjective term. Therefore, triggering participants to think in a different way.

This exercise is done to give participants not familiar with Miro the opportunity to get used to the tool, and as an icebreaker for people to start sharing ideas and actively participate in the session. The results from the warm up exercise are displayed in figure 177, and transcribed below.

Flexibel (flexible)

Clothing, parties, plastic, water/liquids, metal wire, paperclip, fast, paper, rope, fabrics, thin metal strips, certain types of candy, assembly robots for the automotive industry, yoga, tolerant, cables, shoes, hair elastic, tires, zip ties, manoeuvrable, aerodynamic, silicon, snakes, plants, springs, mirror, band of a wristwatch, shoelaces, textile, decorations, rubber bands, baking mould, straps

Verrassend (surprising)

The weather, new technology, extra-terrestrial life, scaring someone, sudden loud noise, foldable, plot twist, jump scares, foldable, present, books, computer bugs, jack in the box, haunted house, art, my bank account, fireworks, your alarm in the morning, wait there is more…, parties, unexpected, growth, movies, theatre, clock, glow in the dark, music, pop-up card, theatre props (retractable knives etc.), beauty, horror, dishes (food), computer games, my inability to spell words, Bakugan, dance

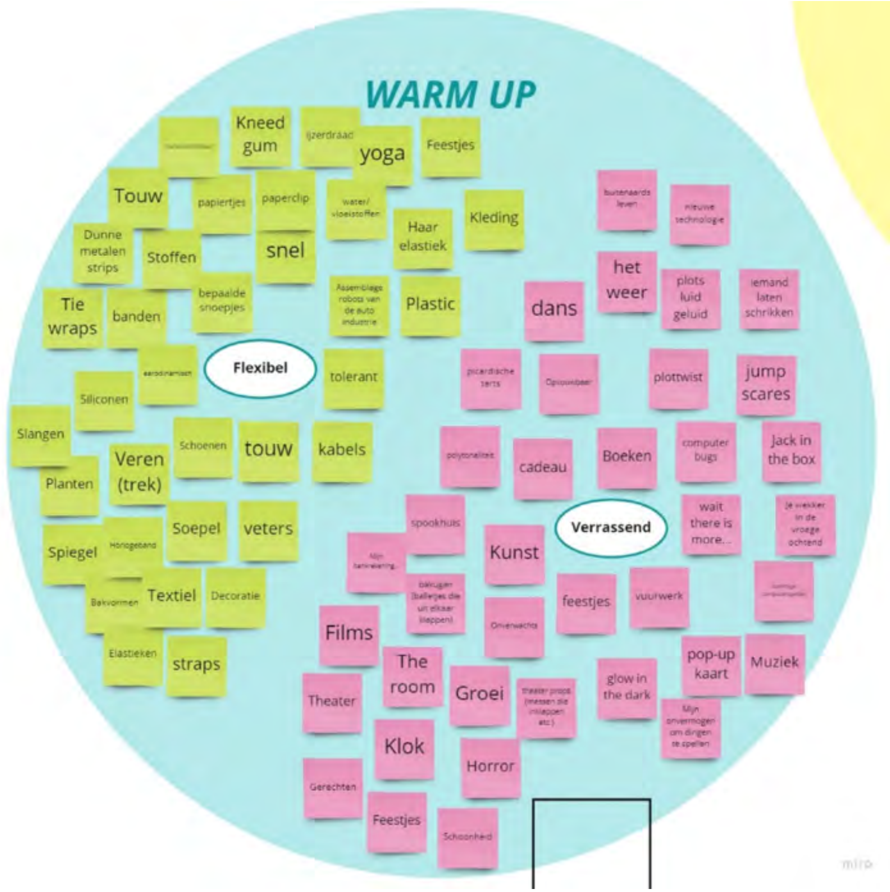


Figure 177 results warm up

Problem statement

Brainstorm 1 (15 min.)

In the first real brainstorm phase of the session, the participants were asked to come up with verbs related to ''beweging'' (movement). The results from brainstorm 1 are shown in figure 178. From all verbs that were written down, three were chosen to expand the problem statement introduced earlier:

Hoe kun je dit materiaal en zijn shape memory capaciteiten toepassen in een product om het te laten 1.lopen/kruipen, 2.wiebelen, 3.uit/openklappen?

How can you apply this material and its shape memory capacities in a product to make it 1.walk/crawl, 2.wiggle, 3.unfold?

<u>Beweging (movement)</u>

Wiggling, waving, squirming, dancing, strolling, throwing over, buckling, bouncing, shortening, hitting, turning, playing lacrosse, rolling, pulsating, growing, shrinking, swinging, crawling, driving, falling, lengthening, slithering, sliding, friction, jumping, snake-movement, collapsing, bending, rotating, faltering, running, walking, flying, swimming, twisting, spinning, polonaise, launching, worm-movement, vibrating, burpees, digging, compression, unfold, unrolling, scrubbing, sailing, push-ups, stretching, pressing, tiny jumps, cranking, stopping, floating, tapping your fingers, jazz hands

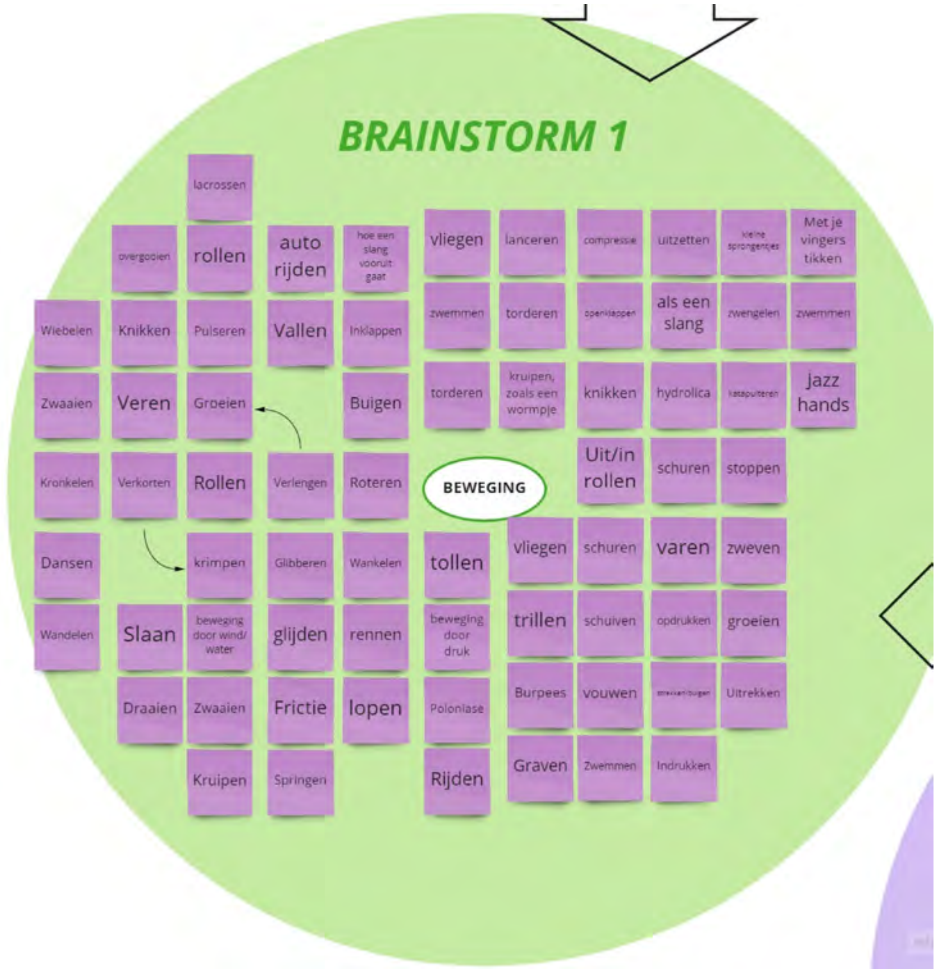


Figure 178 results brainstorm 1

Idea generation

Brainstorm 2 (30 min.)

In brainstorm 2, the participants were asked to start generating ideas based on the three different problem statements (the three chosen words) defined at the end of brainstorm 1. The participants were free to come up with ideas for all three questions, there was no set time/ planning for working on each of the words. The results from this brainstorm round are show in figures 179 through 181. At the end of the round, the ideas were clustered in different categories:

- Cooking
- Tools
- Medical/healthcare
- Entertainment/leisure
- Climate control
- Clothing and accessories
- Household/furniture
- Other

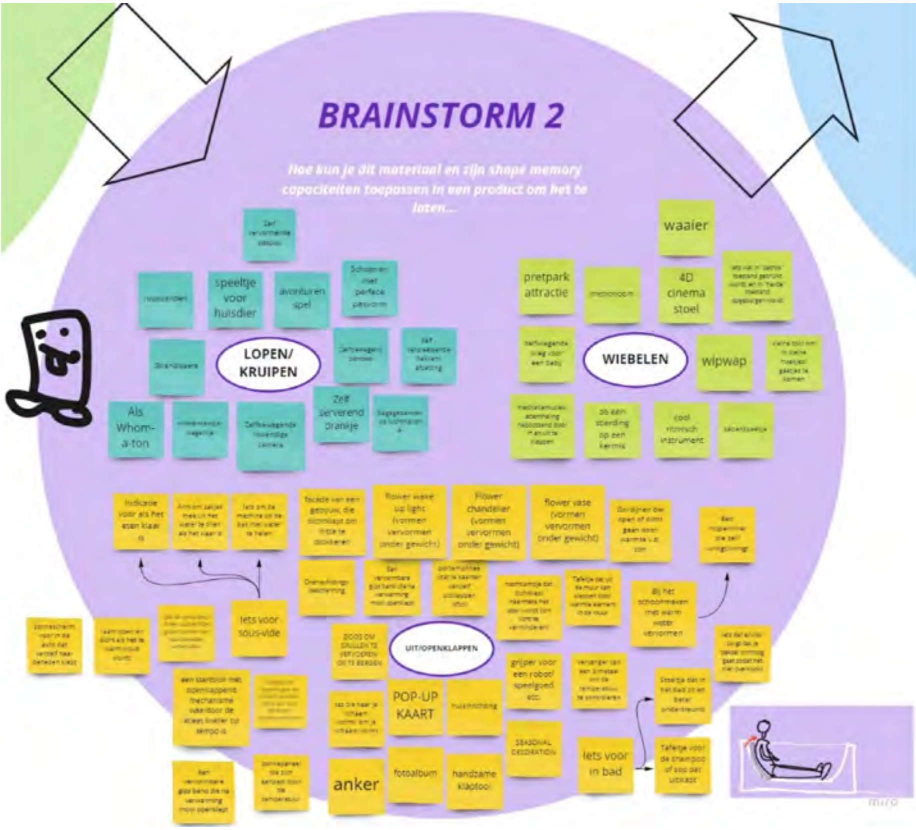


Figure 179 results brainstorm 2

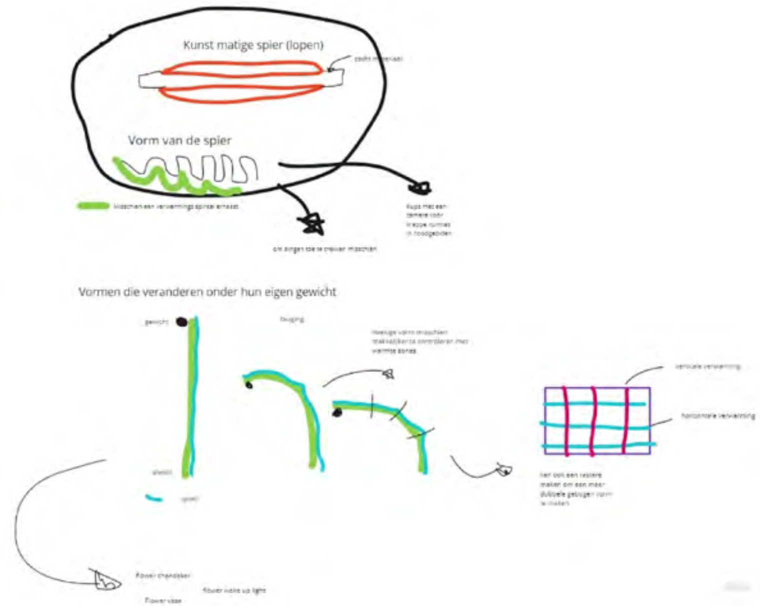


Figure 180 drawing made during brainstorm 2

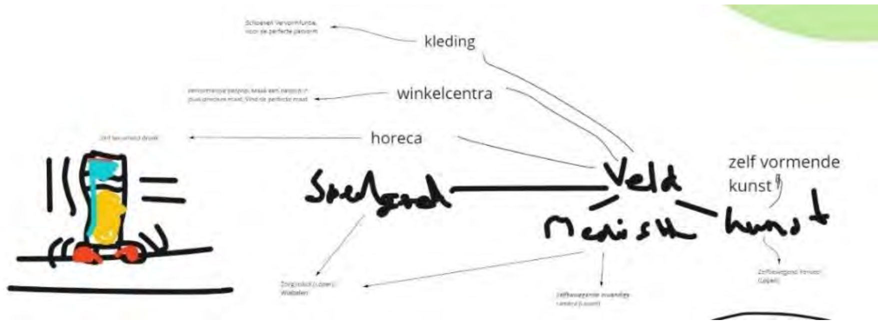


Figure 181 additional results from brainstorm 2

Brainstorm 3 (15 min.)

In the third brainstorm round, the participants were given 2 minutes for each cluster to individually think about other possible applications that would fit this category. After two minutes, the participants would move on to the next cluster. This was repeated until each participant had worked on each cluster. The results are displayed in figures FIXME to FIXME, and transcribed below.

Cooking

Something for sous-vide: indication for when the food is ready/ tool to take the bags out of the hot water once the food is done/ something to get the machine out of the water, colander that reacts to warm water, **egg basket to boil eggs perfectly**, baking moult that slowly expands a bit to make the pie easier to take out of the mould, something that indicates when water is boiling, **something that lifts the lid to prevent overcooking**

Figure 182 Cooking results

Tools

Shopping basket/cart, small collapsible tool, claw for a robot/toy, tool to reach small corners, self-moving crowd barriers/fences, baggage belts on an airport, something that warms the nozzle of your printer is still hot after turning your 3d-printer off, tool to open oysters, **handgrips that change shape when touched to provide extra grip and safety**

Figure 183 Tools results

Medical/healthcare

Care robot, self-rocking cradle, self-moving internal cameras, condoms, bed construction that reacts to the heat cycle of sleep, **a deformable cast that unfolds/opens when heated**, braces, plug to stop internal bleedings, plug that can stop the bleeding of bullet wounds, menstrual cup, **a device mimicking breathing by folding and unfolding as a form of meditation**

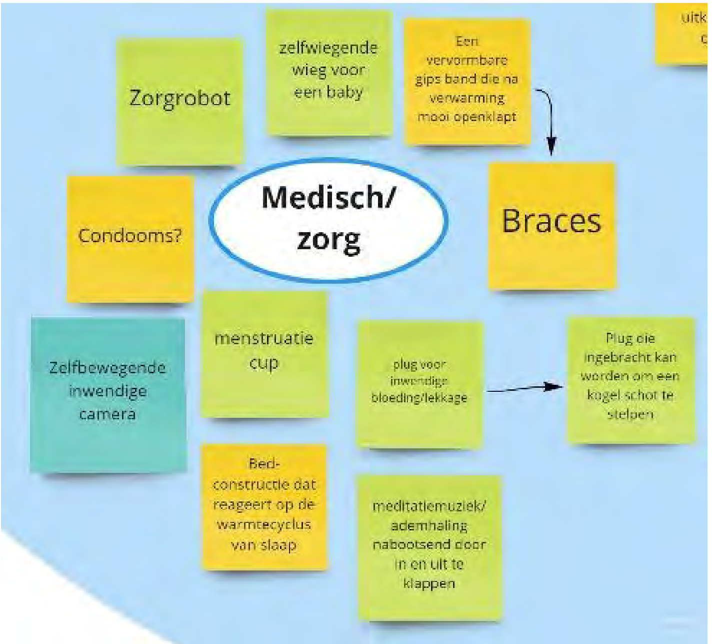


Figure 184 Medical/healthcare results

Entertainment/leisure

Amusement park attraction, mechanical bull-like machine, rhythmical instrument, metronome, toy for a pet, boardgame, 4d cinema chair, seesaw, self-moving pencil, self-serving drink, adventure game, cat toy, using plastic to clay different structures: create Lego like parts

Figure 185 Entertainment/leisure results

Climate control

Automatic sunscreen for in your car, something that contracts/expands when the temperature rises/falls, Solar panel adapting to temperature, device to show your plants need water, valves for heating elements for a garden pool, thermostat, glasses that turn to sunglasses once heated, by lowering a set of sun blocking glasses, something to maintain the temperature in a pond, replacement of a bi-metal to control temperature, building façade that closes when heated to block heat, window closing when it gets hot/cold, overheat protection, **to measure the size of something: putting a device around something to measure it**

Figure 186 climate control results

Clothing and accessories

Bag that forms after your body/ wraps around you, wallet where your cards pop out automatically, shoes with the perfect fit, fan, helmet with air holes that open/close based on temperature, cap with automatic sun visor, **self-forming mannequin**, ring that adapts to the size of your finger, bracelet that warns you when you're overheating, clothing that deforms in the summer to cool you down, dog hood that is comfortable for the animal, ''spider-dress'' but with temperature (dress that deforms to keep people at distance)

Figure 187 clothing and accesories results

Household/furniture

Nightlight that folds itself around the lightbulb when it gets later, **flower wake up light which deforms because of weight**, flower vase that deforms because of weight, box for storing/shipping, flower chandelier which deforms because of weight, desk lamp, seasonal decoration, table that unfolds from the wall with a heating element, something that deforms with warm water when cleaning, a mop bucket that wrings out the mop, laptop hinge attachment that automatically deforms when you need to take a break, laptop stand, doorstop or something that opens the door, furniture, dampening when closing drawers, **curtains that open or close based on the sun, sun shading that automatically opens and closes**, shower accessories, **things that deform to make them easier to clean**

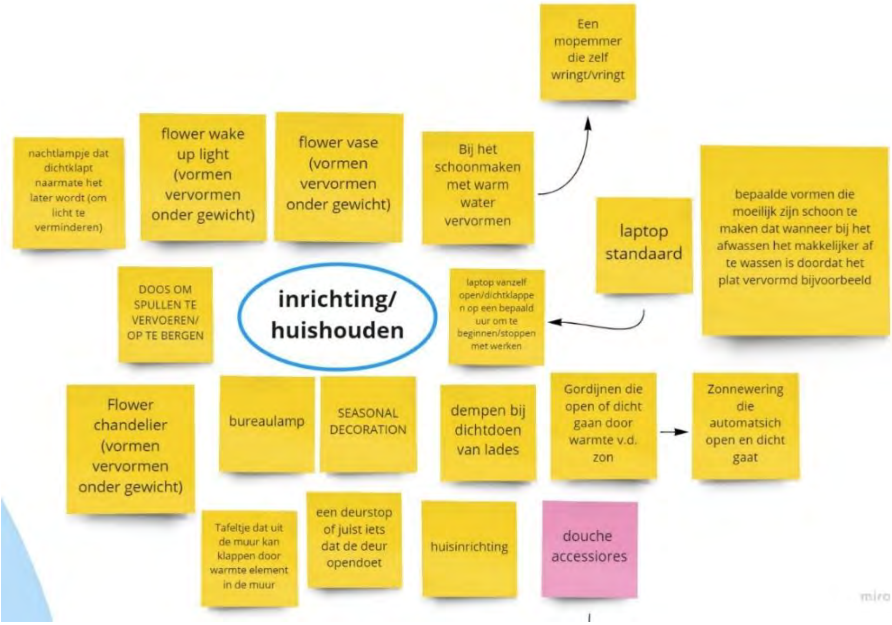


Figure 188 household/furniture results

Other

Pop-up card, anchor, photo album, strandbeest, whomp-a-thon, storage box that you can adapt based on what you're storing, tracks (e.g. like with an army tank), rescue robot, something for in your bath tub: seat that supports you/table for your soap that expands, **braking mechanism based on friction**, **Olympic equipment that deploy themselves like gymnastics equipment**, a starting block that helps athletes accelerate faster

Figure 189 Other results

Selecting ideas (5 min)

At the end of the brainstorm round, each participant was asked to choose three ideas which they thought had the most potential, resulting in the overview shown in figure 190.

<u>Chosen ideas</u>

egg basket to boil eggs perfectly, something that lifts the lid to prevent overcooking, handgrips that change shape when touched to provide extra grip and safety, a deformable cast that unfolds/opens when heated, a device mimicking breathing by folding and unfolding as a form of meditation, curtains that open or close based on the sun, sun shading that automatically opens and closes, things that deform to make them easier to clean, Nightlight that folds itself around the lightbulb when it gets later, flower wake up light which deforms because of weight, Olympic equipment that deploy themselves like gymnastics equipment, self-forming mannequin, braking mechanism based on friction, to measure the size of something: putting a device around something to measure it

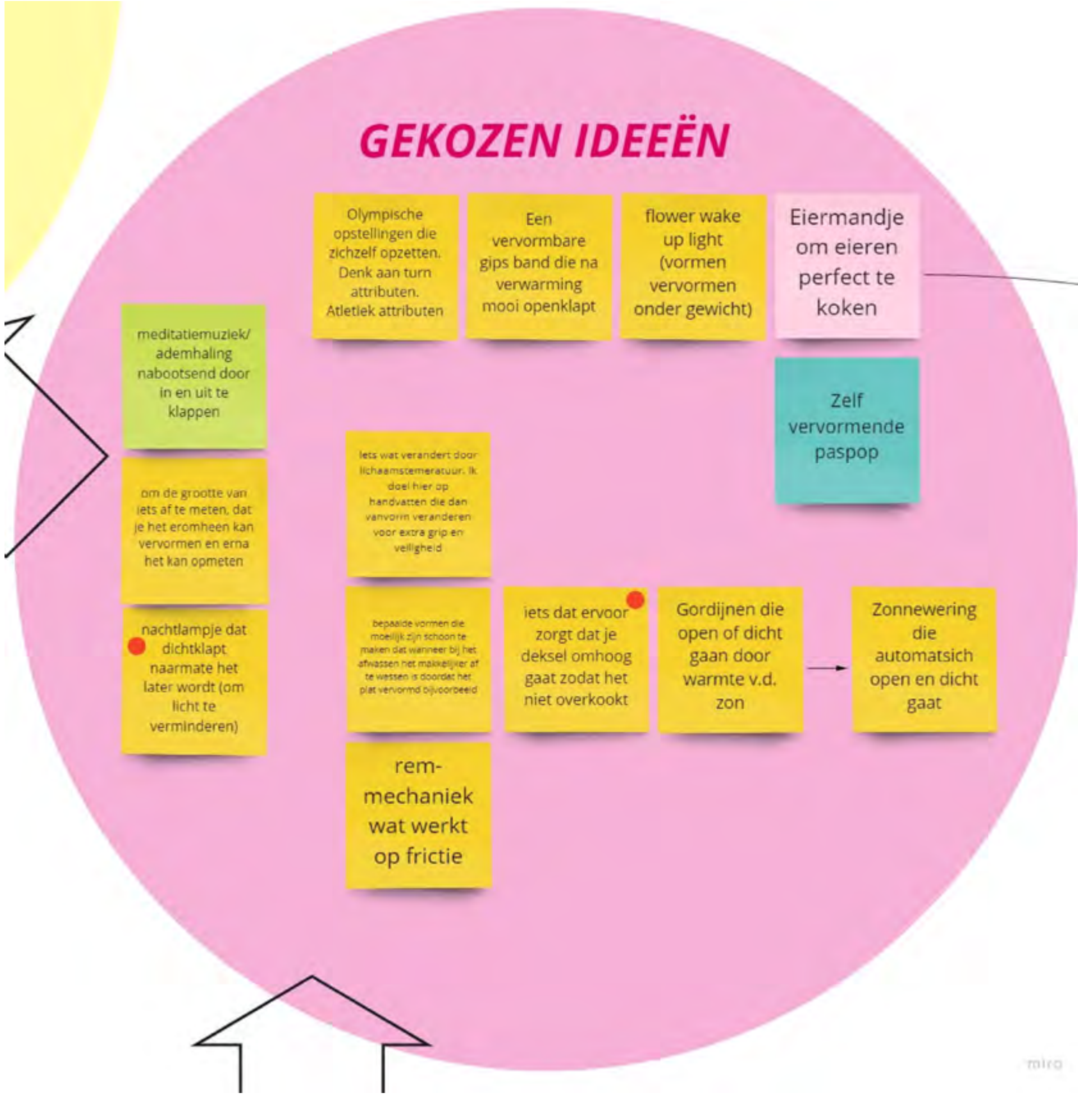


Figure 190 selected ideas

Concept development

Concept development and presentation (15 min.)

The participants were divided in pairs and asked to pick one of the ideas chosen at the end of the previous step to develop a bit further, with one pair consisting of a participant and the facilitator (me). Participants were given 10 minutes to envision things like the functioning and design of the product. After that, they were asked to shortly present their concept.

<u>Adjustable mannequin</u>

The adjustable mannequin is meant for people working in fashion, especially tailors who need to make suits and costumes made for one specific individual. It works by first making a mould of the body of the person for who the garments need to be made. This mould can then be heated and used to form a mannequin made out of shape memory material, resulting in a mannequin with the exact bodily dimensions as the customer. Tailored clothes can then be made using this mannequin. Figure 191 shows the process of mould making and deforming the mannequin. Once the clothes are done, the mannequin can be heated again, returning to its original shape. Then the mannequin can be used again for the next customer.

Figure 191 adjustable mannequin

<u>Closing night light / Overcooking prevention</u>

(This duo developed two ideas together)

The closing night light was envisioned to help people fall asleep by slowly covering the light source over time. Once you would lie in bed and turn the light on, it would give of a certain amount of light, and as time goes by and it gets later, the light bulb slowly gets covered by the external parts of the lamp, actuated by one or more shape memory materials.

The overcooking prevention was envisioned to ensure that things in pans would not overcook because the lid is closed. This special lid/ add-on device for a lid lifts the lid once the water inside is close to overcooking. It would lift the lid using small shape memory polymer tubes that deform once the water starts rising.

Figure 192 closing night light and overcooking prevention

Wake up light

The wake up light is a lamp which slowly opens up to let more light through. The idea is that this is used as a lamp to help you gradually wake up in the morning. The wake up light is shaped as a flower, with the petals being actuated by the shape memory material. In its initial state, the petals cover the light source. But once the lamp is turned on, the petals heat up and slowly unfold over time. Once the light is turned off, either some sort of weight or a spring forces the petals to form around the lightbulb again when the shape memory polymer loses its recovery force.

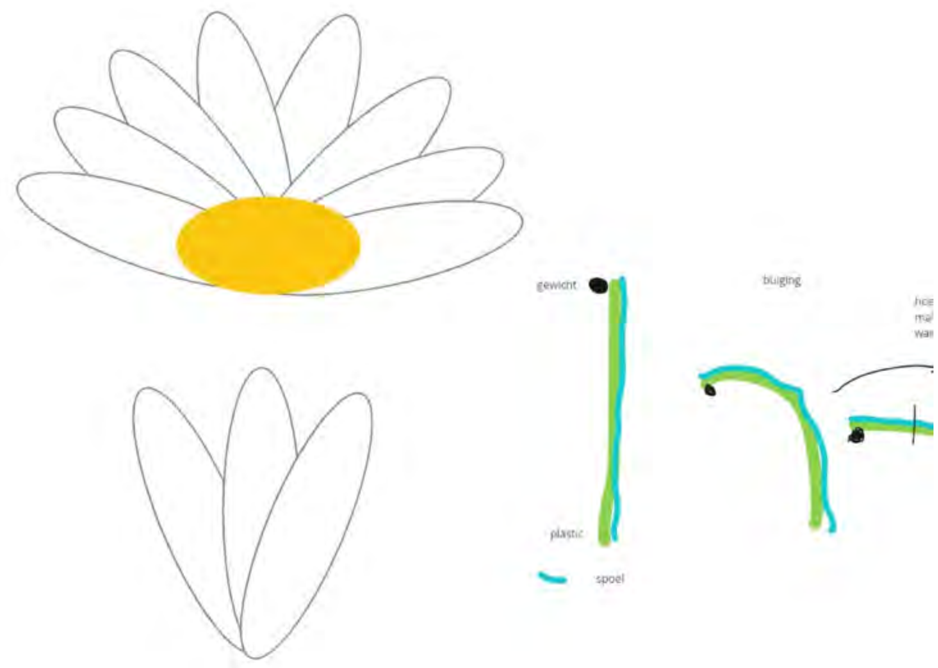


Figure 193 wake up light

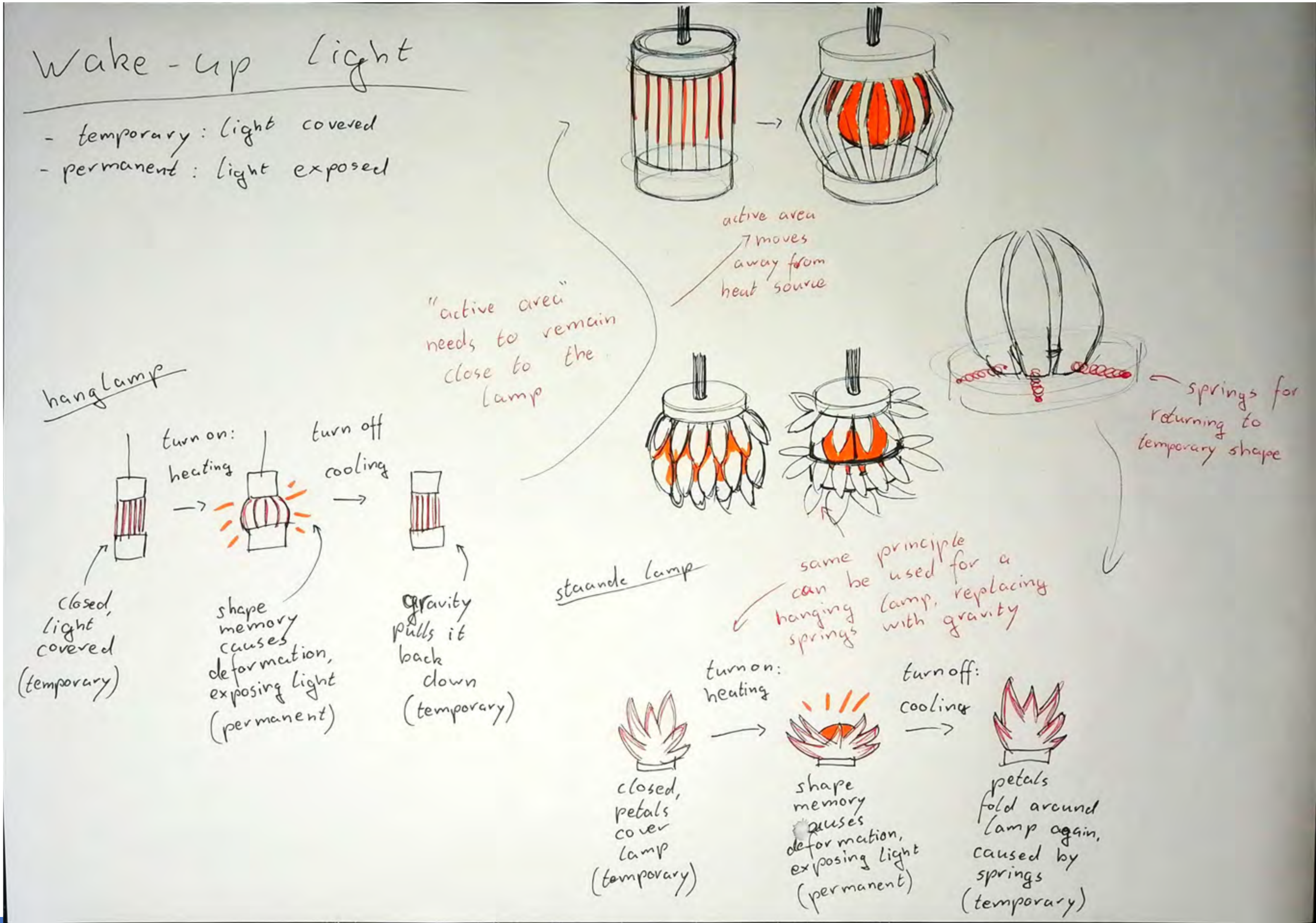
Wrap up (5 min.)

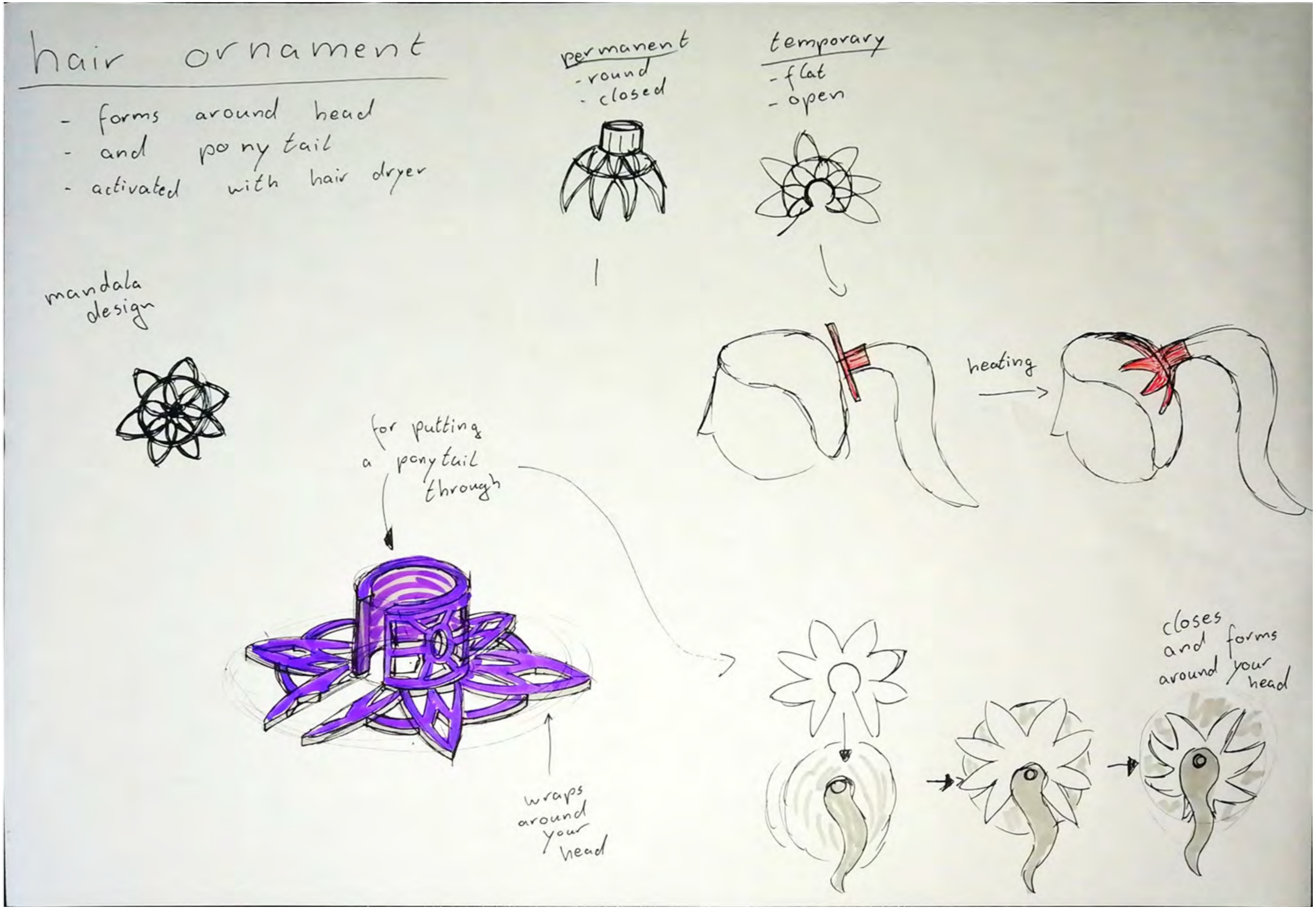
At the end of the creative session, the participants were thanked for their participation and the course of the creative session was discussed, so people could say if there were things that could be improved for a next session. The feedback received from the participants was positive, with no specific points to improve mentioned.

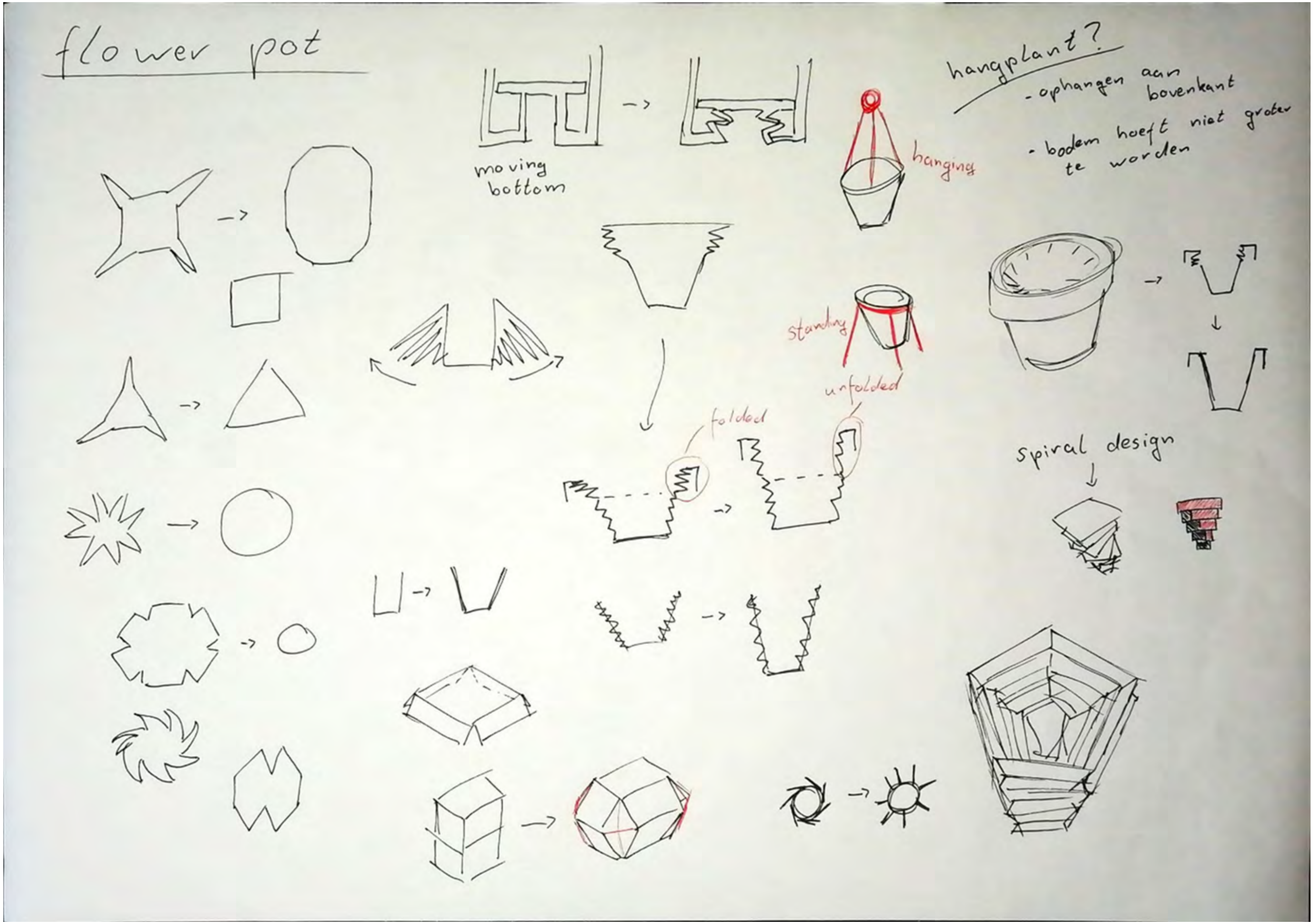
APPENDIX I: ASSESSMENT OF SELECTED IDEAS

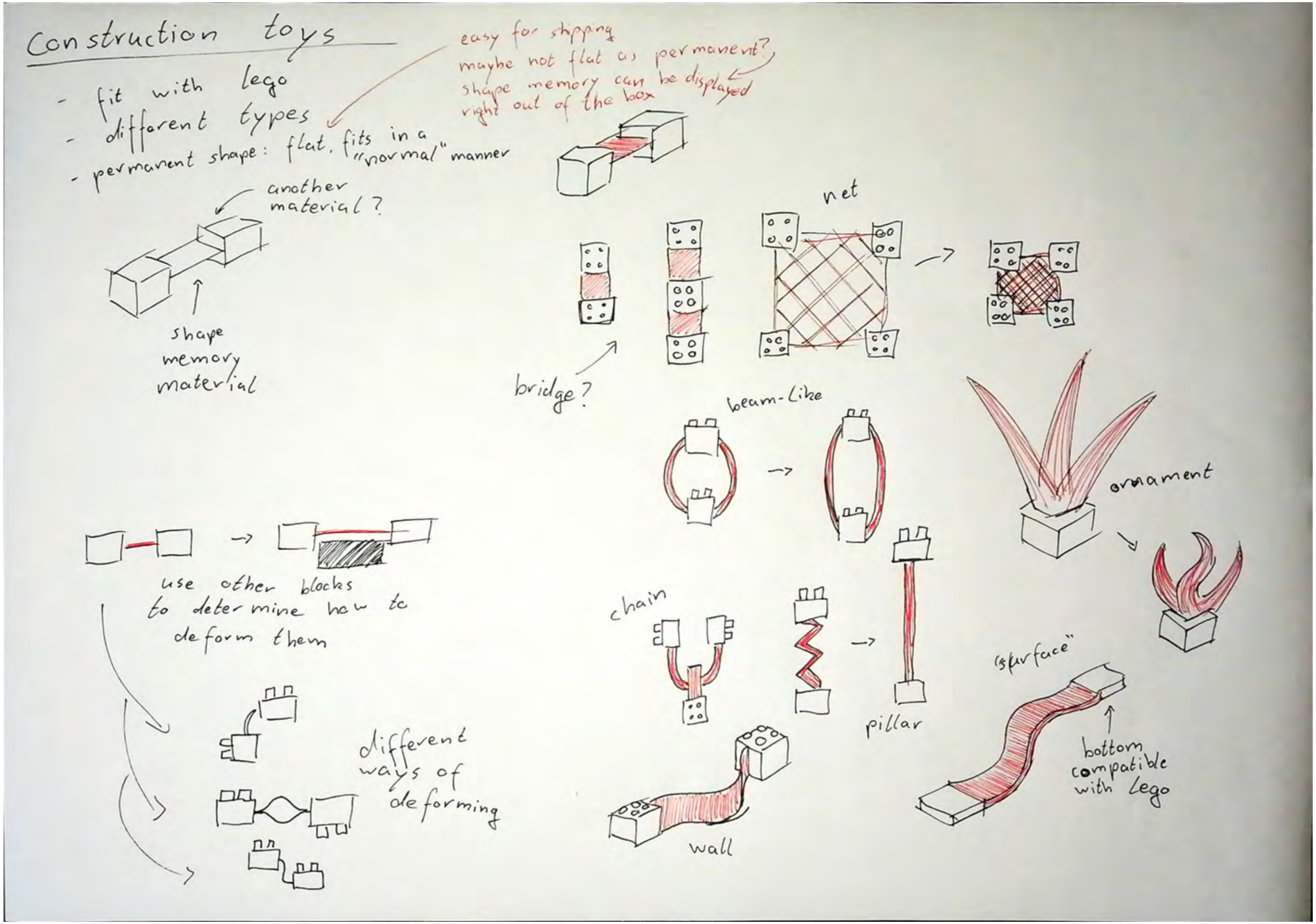
		Permanent shape	Temporary/programmed shape	What is the added value of shape memory?	Can heating be done in a practical and safe manner?
1	**Hair ornament**	Closed around head (perfect fit)	Open, able to put on or remove from head	Shape memory could provide a tailored fit in an easy way	Heating can be done with a hair dryer. The temperature needed is safe for your hair, but on the high side
2	**Modern locket necklace**	Opened, you can see what's inside	Closed, protecting what's inside	Shape memory could cause the locket to open on itself in a visually interesting way	Can be done using a hair dryer when not being worn, so there is little risk of injuries
3	**Form to fit bracelet**	Formed around your arm/ wide (able to put around your arm)	Wide (able to put around your arm) / formed around your arm	It can return to a state where it is easy to remove or to create a tailored fit	Heating needs to be done when the bracelet is not being worn, as 65 degree air can burn the skin
4	**Adjustable cup grip**	''standard'' position	Right position, fit to your hand	Shape memory does not seem to create real added value	The grip can be heated without being touched, but needs to be touched to form to your hand, but this is possible
5	**Seasonal decoration**	3D decoration	Flat, easy to store	Easy deployment of possibly intricate decorations	Heating can be done either in hot water or with a hair dryer, which can be done in a safe manner
6	**Wake-up/night light**	Closed, blocking light / Open, letting light through	Open, letting light through/ Closed, blocking light	Shape memory can make the process of opening and closing automatic, which is desirable in a product like this	The material is heated by the lamp, so the user won't need to touch the material for either deforming or recovering
7	**Protective coaster**	Molded around cup	Flat, easy to store	It can automatically form around a cup, so the user does not have to touch it further before it is deployed	Heating is done by the hot beverage, although it is possible the outside of the cup is not hot enough to let the material reach its activation temperature
8	**Adjustable storage box**	Flat, easy to store and easy for shipping	Box with the shape and size of what you want to store in it	Whatever the temporary shape, the box will return to its original shape so it's easy to deform again	Heating can be done either in hot water or with a hair dryer, which can be done in a safe manner
9	**Flower pot**	Big, non-folded pot for big/grown plants	Small, folded pot for smaller/ growing plants	The pot can return to its original shape without removing the plant inside, so there is no need for repotting	Heating can be done with a hair dryer,
10	**Pop-up card/gift box**	''popped-up'' or opened	Closed, for sending	Shape memory could add an extra element of surprise for the receiver	Heating can be done in water or with a hair dryer, and can be done in a safe manner
11	**Rc-car wheels**	''driving configuration''	Shaped for the occasion: sailing, climbing obstacles etc.	The wheels return to their original shape, so it can be immediately used again in its normal configuration	If the wheels can be taken of, they can be easily heated in water or with a hair dryer, and heated safely
12	**Construction toys**	''normal'' configuration	Parts deformed to create new constructions	Whatever the temporary shape, the parts will return to their original shape so it's easy to deform them again	The parts can be safely heated using water or a hair dryer. The user won't have to touch it when heating

APPENDIX J: CONCEPT DEVELOPMENT SKETCHES

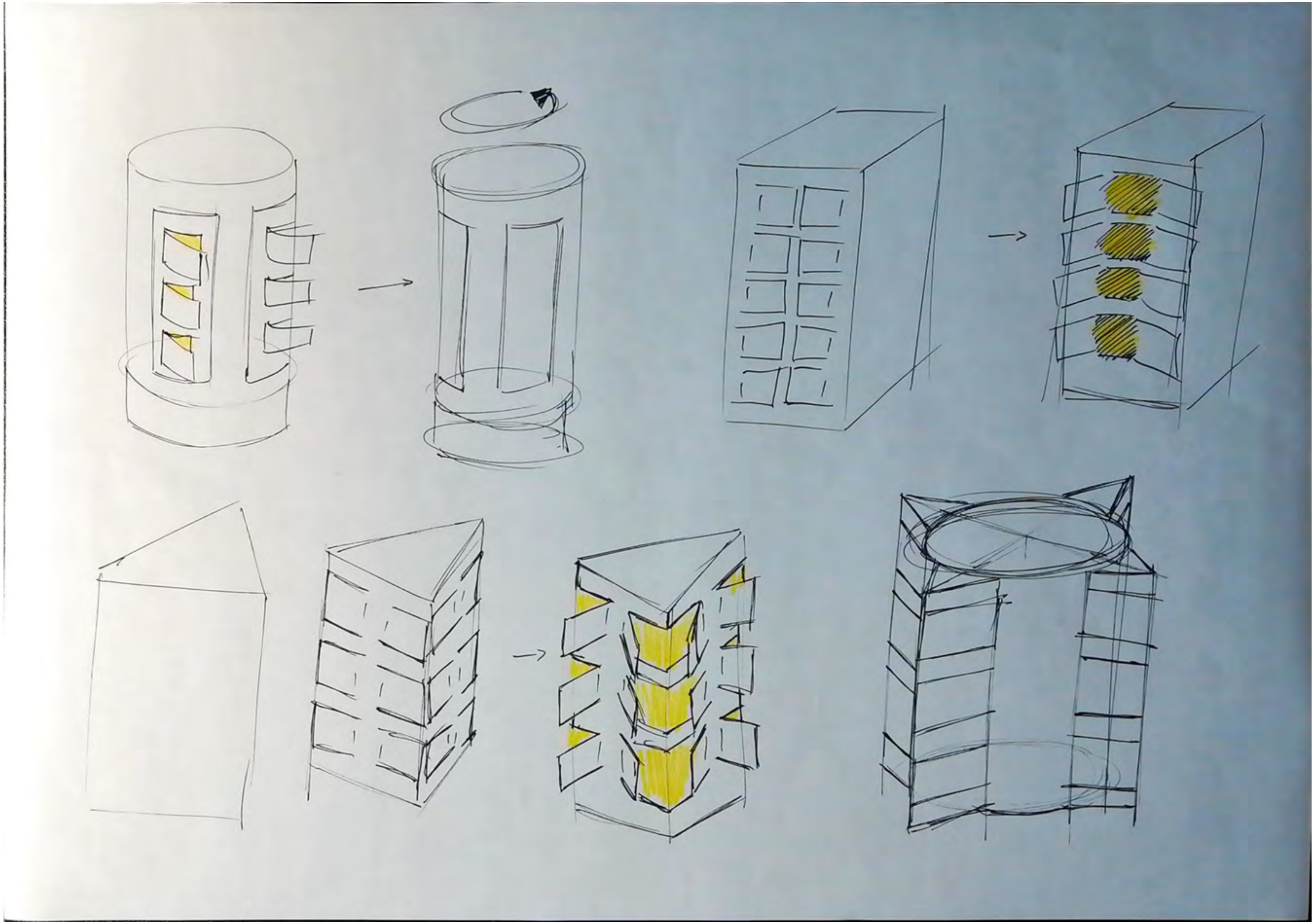


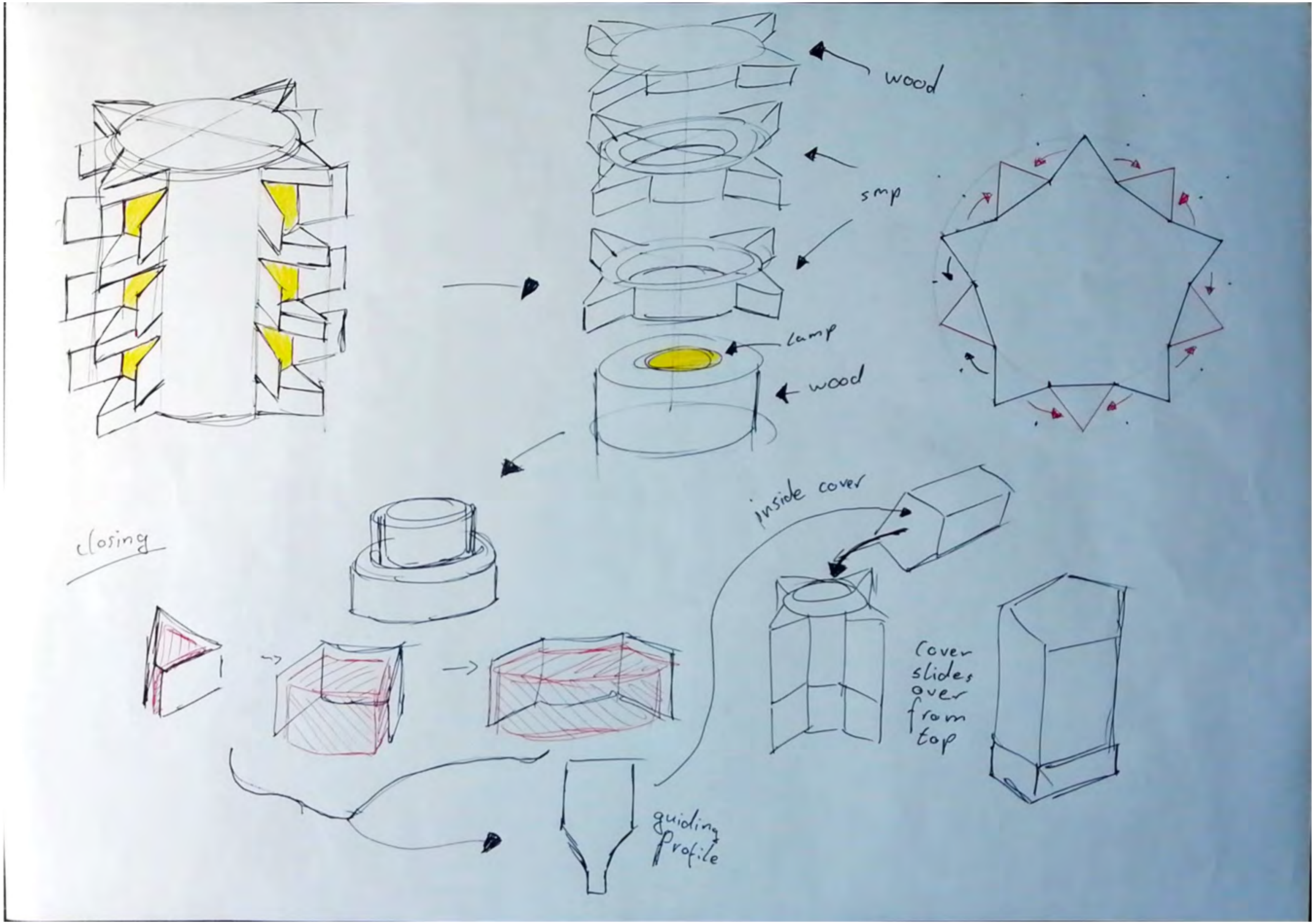

hair ornament
- forms around head
- and pony tail
- activated with hair dryer
permanent
- round
- closed
temporary
- flat
- open
mandala
design
heating
for putting
a pony tail
through
wraps
around
your
head
closes
and forms
around your
head


flower pot
moving
bottom
hanging
hangplant?
- ophangen aan bovenkant
- bodem hoeft niet groter te worden
standing
unfolded
folded
spiral design


Construction toys
- fit with lego
- different types
- permanent shape: flat, fits in a "normal" manner
easy for shipping
maybe not flat as permanent?
shape memory can be displayed right out of the box
another material?
shape memory material
net
bridge?
beam-like
ornament
use other blocks to determine how to deform them
chain
pillar
"surface"
bottom compatible with Lego
different ways of deforming
wall

APPENDIX K: CONCEPT ELABORATION SKETCHES




wood
smp
lamp
wood
closing
inside cover
cover slides over from top
guiding profile

APPENDIX L: ORIGINAL PROJECT BRIEF

Procedural Checks - IDE Master Graduation

TUDelft

APPROVAL PROJECT BRIEF
To be filled in by the chair of the supervisory team.

chair Dr. Ghodrat, S. date 23 - 11 - 2020 signature

CHECK STUDY PROGRESS
To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 30 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 30 EC

List of electives obtained before the third semester without approval of the BoE

(X) YES all 1st year master courses passed

( ) NO missing 1st year master courses are:

name J. J. de Bruin date 24-11-2020 signature JdB

FORMAL APPROVAL GRADUATION PROJECT
To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: (V) APPROVED ( ) NOT APPROVED

Procedure: (V) APPROVED ( ) NOT APPROVED

comments

name Monique von Morgen date 7/12/2020 signature MvM

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 2 of 7

Initials & Name J Holierhoek Student number 4457145

Title of Project Designing 3d-printed deployable structure with Shape Memory Polymers

Personal Project Brief - IDE Master Graduation

TUDelft

Designing 3d-printed deployable structure with Shape Memory Polymers project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 19 - 11 - 2020 06 - 05 - 2021 end date

INTRODUCTION **
Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The adoption of a new material from technical innovation up to the widespread uptake of the material typically takes more than 20 years (Bengisu & Ferrara, 2018). When a material is launched commercially, its performance and utilitarian advantage should be clear and make sense. However, a material should also be socially and culturally accepted or acceptable for widespread use. In the case of shape memory polymers, there is great interest in the capabilities and use of these materials, but it will still take time before use of these materials is widespread.

Shape Memory Polymers, or SMP's for short, are a specific type of polymer based materials which can respond to external stimuli like heat, light, or PH-value by changing shape. Compared to the more familiar SMA's (shape memory alloys) SMP's offer more flexibility in design and have the potential to be less costly. Other characteristics compared to SMA's include lower densities, much larger strains (400% compared to 8% for SMA's), lower manufacturing temperatures and pressures, and easier shape programming (Bengisu & Ferrara, 2018).

SMP's can be shaped using the same manufacturing methods that are typically used for regular polymers. Machining processes like CNC-milling or laser cutting, as well as injection and extrusion molding can be used to shape SMP's. A very promising fabrication method for SMPs is 3D printing. 3D printing of shape memory materials introduces an extra dimension, which is why it is often referred to as 4D printing. This extra dimension refers to the ability of the material to transform over time. 4D printing makes it possible to print objects that would normally be too large or too time consuming to print due to additional support material. By printing a shape in a folded state, objects that would otherwise have to be printed as several separate components can now be printed in one piece (see figure 2C). The other way around is also possible: by printing a specific object which can then be compressed or folded for easy transportation, after which it can be brought back to its intended shape.This technique, combined with the characteristics of SMP's, gives SMP's great potential for a wide variety of applications.

Currently, SMP's are mainly used for industrial and medical purposes. One of the first applications was in robotics where shape memory foams were used to provide initial pretension in gripping. In the medical field, SMP's are for example used in orthopedic surgery as implants. But also in fashion, SMP's are being used to create clothing which reacts to weather activity and activity of the wearer. Possible future applications include self repairing and self assembling structures like car fenders and furniture, products for minimal intrusive surgery like stents and biodegradeble and self tightening sutures, and personalised and smart consumer products like adaptable clothing and electronics.

While numerous applications have already been defined, SMP's have still almost exclusively been applied in very specific fields such as the medical industry. In general, these materials are relatively unknown, also in design. This is due to the fact that these materials are not yet developed enough for widespread use. More research is needed on the properties and applications for these materials before they can be applied more regularly.

Bengisu, M. & Ferrara, M. (2018). Materials That Move: Smart Materials, Intelligent Design (1st ed.) Cham, Switzerland: Springer

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Initials & Name J Holierhoek Student number 4457145

Title of Project Designing 3d-printed deployable structure with Shape Memory Polymers

Introduction (continued): space for images

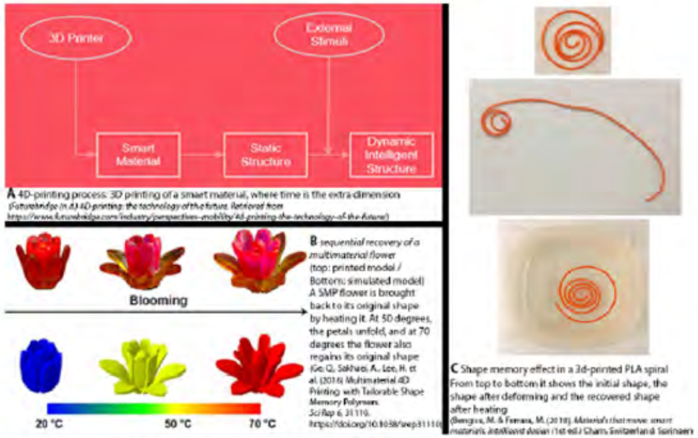

image / figure 1: A: 4d printing principle / B: heat activated SMP flower / / C: PLA shape recovery

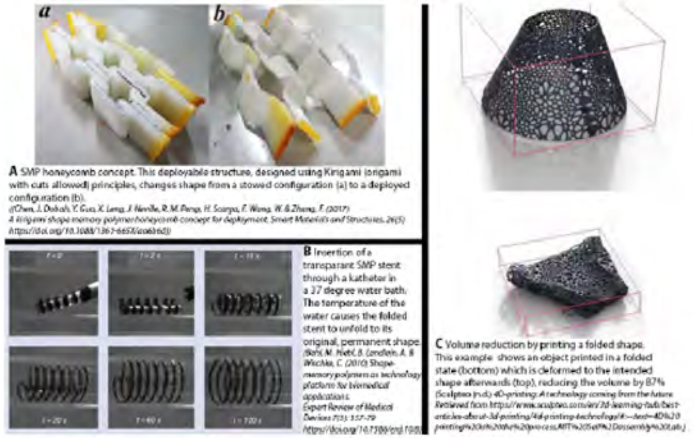

image / figure 2: A: SMP honeycomb structure / B: foldable stent / C: unfolded and folded printed shape

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

To make the use of SMP's more widespread, it is important to research these materials, and inspire and enable designers to work with these kinds of materials. Insufficient research has been done to prove the materials capabilities, hindering widespread application and production. Due to this, the treshold for designers to use this material is high. So the question is what needs to be done to make SMP's ready for widespread use, and how to inspire designers and lower the treshold to work/design with these materials.

While SMP's and the shape memory effect in general are already well documented, 4d printing of SMP's is still in its infancy. (practical) research still needs to be done on both 4D-printing as a manufacturing method and the properties of 4D-printed SMP objects, like accuracy and reliability. Some of the questions related to 4D-printing are how to make active hinges and complex geometries. Also, how do these SMP objects need to be designed so they fold/unfold in the desired way (e.g. folding in a specific order)?

In 2015, Elvin Karana et al. presented a method for designing with a material as a starting point: the material driven design (MDD) method. Through a four step design process, starting with understanding the material, followed by developing a material experience vision and manifesting material experience patterns, which in turn is used to design product concepts, a product is designed around the material properties of the starting material. For this project however, the material (group) and manufacturing method are chosen as the starting point. Therefore, the approach for this project will be a combination of MDD and a kind of manufacturing driven design approach. As this combination of approaches has not been documented yet, this raises the question on how the design process exactly takes shape and how this influences the eventual outcome of the project? What are the benefits and drawbacks of a design process based on these approaches, and how does this influence the end result?

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

The aim of this project is to improve the understanding of the Shape memory properties of 4d-printed SMP's, and the parameters that influence these properties. Through systematic testing, the parameters which influence this will be identified and researched. The results are used to create a deployable structure which will serve as a demonstrator showing the capabilities of SMP's, as well as a set of design guidelines for designing 4d-printed SMP structures

In this project, research will be done on the parameters that influence the shape memory properties of 4d-printed structures. The focus will be on the printing parameters and material properties, to get a better understanding on how to manipulate the shape memory properties to serve a specific purpose and what the possibilities are for applying these properties in design.

Based on the research done in this project, two deliverables will be created: a demonstrator and a set of guidelines. The demonstrator will be a 4d-printing deployable structure, which will show the capabilities of the SMP in terms of shape memory ability and design possibilities. The guidelines will be an extension of the MDD process, in the sense that they are meant to provide other designers with the knowledge needed to design 4d-printed objects with the Shape memory properties of these materials as the central driver for the design.

Both these deliverables combined are meant to serve as inspiration and a way to lower the treshold for designers to start working with these kinds of materials and manufacturing technique. Next to this, the data generated during this project will be valuable for models aimed at simulating and predicting the behaviour of a new to-be-printed object. In this project the MDD method will be the guideline for the design process.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 19 - 11 - 2020 6 - 5 - 2021 end date

The Gantt chart displayed above shows the general planning for this project. The project starts with a parallel study of SMP's and 4D-printing technology. Findings from this phase will form the basis for the first step of the MDD method: Understanding the material. In this step the chosen material(s) and their properties will be tested with a hands-on approach: printing and testing the material(s) in different configurations. When a clear understanding of these properties is reached, a materials experience vision is created, followed by manifesting materials experience patterns to envoke the envisioned material experience. This will be used in the fourth and final phase of the MDD process, where concepts will be developed. As a first step of this phase, an application field will be chosen. Concepts will then be developed, which will be used as a base for the final demonstrator and guidelines. The demonstrator will be designed to show the possibilities of 4d-printing with SMP's. Based on the research on 4D-printing and SMP's, as well as the results of the MDD process, guidelines for designing 4d-printed SMP objects will be set up, to help other designers in designing these kinds of objects.

Within the period of the project, there are four days which will be considered non-working days in accordance with the TU Delft calender for the academic year 2020/2021, which are: April 2nd, April 5th, April 27th and May 5th
Apart from the aforementioned public holidays, two other days will be considered non-working days for personal reasons: november 20th, and april 26th.
Important dates:
- Kick-off meeting 19-11-2020
- Mid-term meeting 28-01-2020
- Green-Light meeting 01-04-2021
- Graduation ceremony 06-05-2021

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

Ever since my bachelor in industrial design engineering at the TU Delft I've been interested in material science, the properties of different materials and how to use these properties in design. I always enjoyed the projects where material was played a more central role in the design process as opposed to projects where choice of material was a decision made late in the project, thus barely influencing design. In this project, material takes a central role and the design is based on the unique properties of the chosen material, in this case a SMP, which is why I was immediately interested in this project. Also, I haven't had the opportunity the work on a project where I was able to work with SMP's and their shape memory characteristics, so this seemed like a great opportunity to do so.

Another important aspect of this project is 3d/4d printing. In several projects during my bachelor, as well as my master, the use of 3d-printing has proven to be an amazing technology for prototyping and producing. Also during my master internship I witnessed the convenient use of 3d printing first hand in a "real-world" setting. My experiences with 3d-printing during my education have inspired me to purchase my own FDM-printer, which I enthusiastically use for my education as well as for personal projects. Although I've been printing solely with PLA on this printer up to this point, I was only recently made aware of the shape memory capabilities of this material. This renewed my interest in exploring the possibilities of this technology, and inspired me to work on this project.

As this is a research-based project where material plays a crucial role, this is good opportunity for me as a designer to gain more experience with a different kind of project with a different kind of design method. In this project I will be using the MDD design method, which I haven't used before. Apart from the approach of this method being different from what I used to, it provides a set of design tools which focus on material experiential qualities, enabling me to use these qualities in my design. I'm curious to see how this will influence my creative process and designs, and if this will lead to innovative designs utilizing the materials characteristics to the fullest.

Main learning goals:

- Gain experience and knowledge in using the MDD method
- Expand my knowledge and experience with 3d/4d printing
- Get experienced with designing SMP-based objects
- Gain experience in working on and documenting of a research-based project, as well as learning and empowering my scientific/technical debate skills.
- Further develop my prototyping and modelling skills, and possibly develop additional skills related to prototyping and testing

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.