4D Printing: Post-processing for the masses

Master thesis integrated product design

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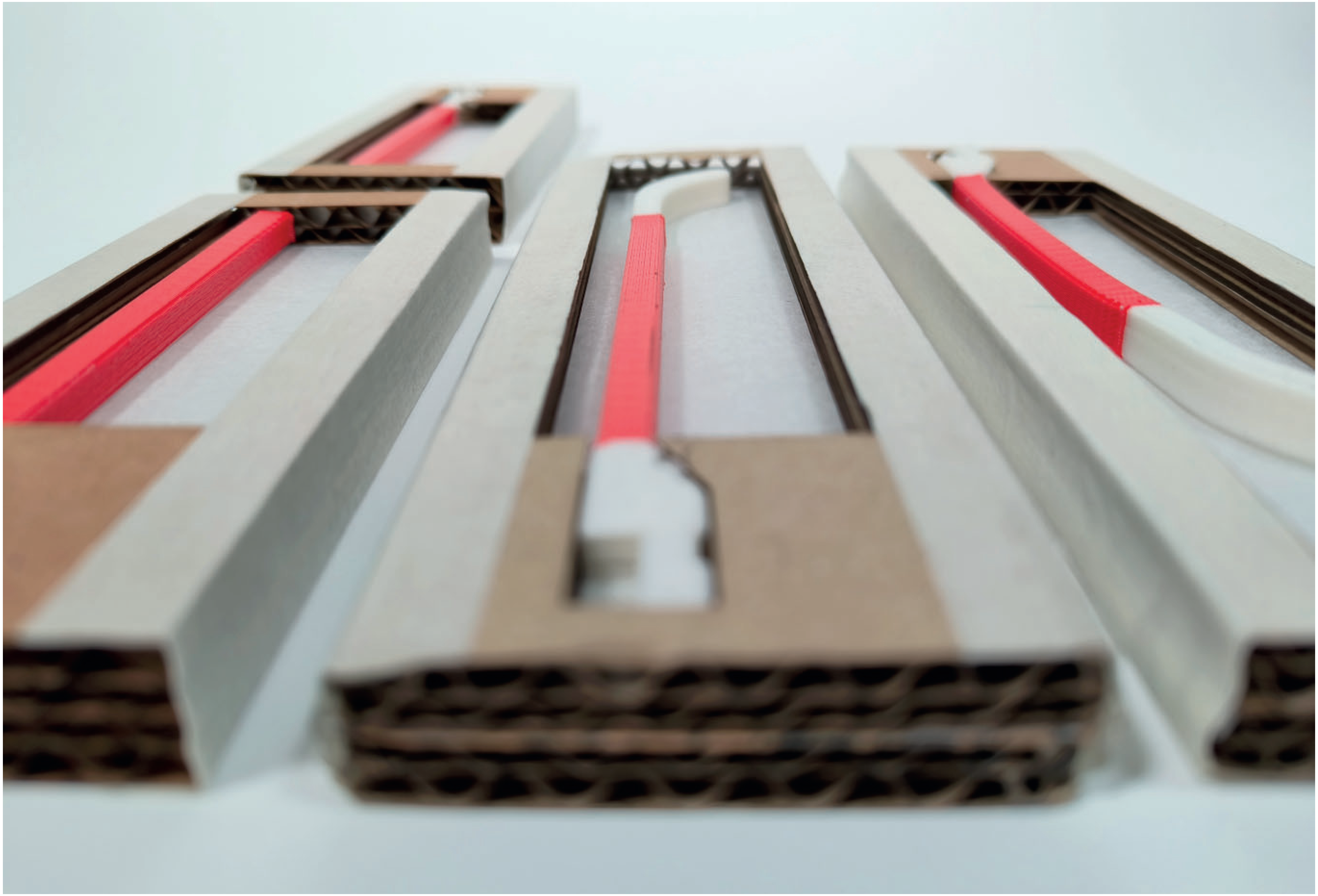


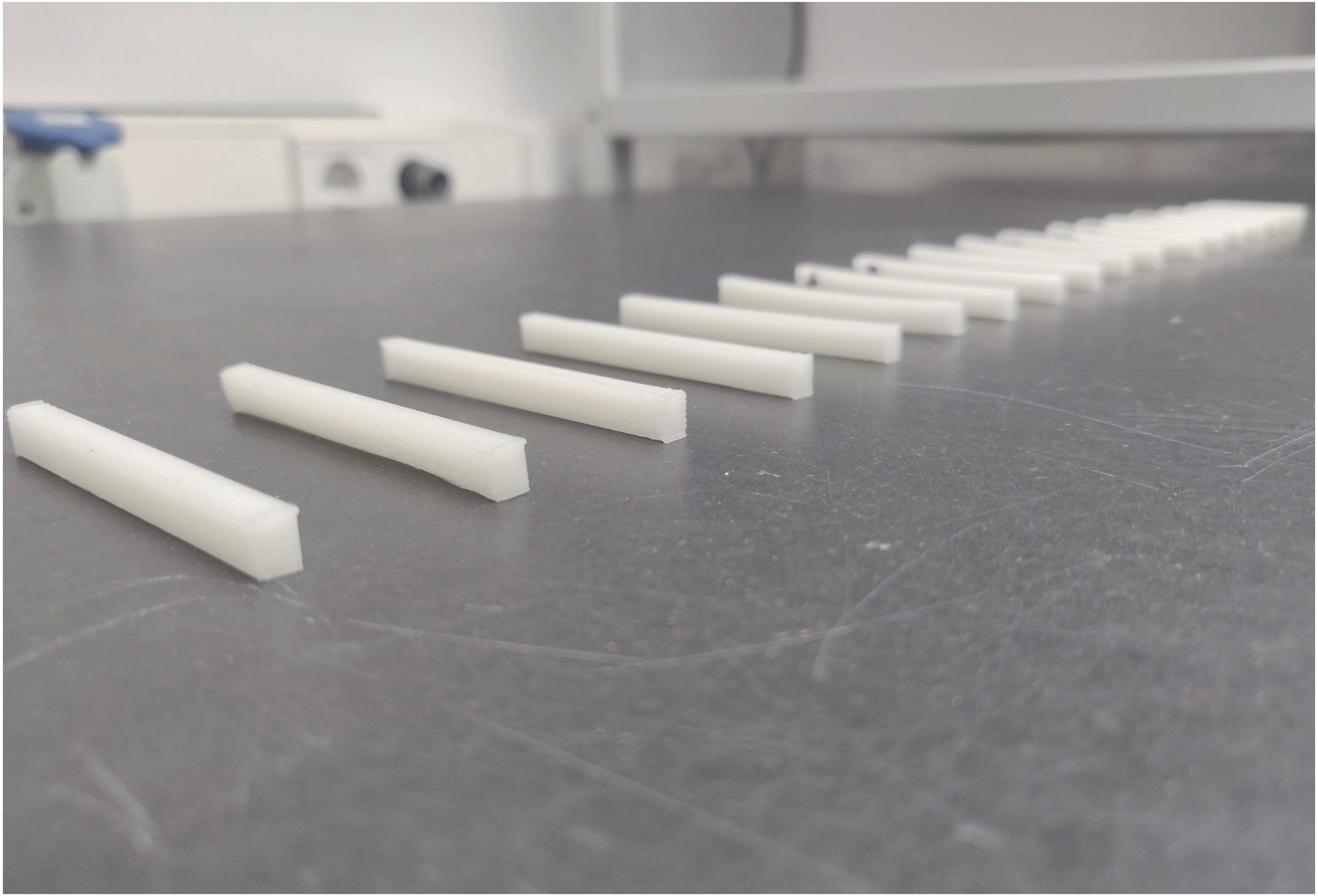
ABSTRACT

This research investigates the challenges a user faces in the activation step in shape-changing products. First, previous research on the topic of 4DP is reviewed and important factors are described. Namely, activation temperature, print temperature, print speed, and layer height have a significant impact on the shrinkage of SMPs, during the activation step in 4DP. These shrinkages can be applied to an object through the use of varying strategies. These strategies show there are two ways of applying SMPs to a design, either calculate the shrinkage or create limits with the use of geometry-based end stops. Lastly, a further review is conducted into the type of products made with 4DP. These products turn out to be made out of three categories; flat-packed, custom fitment, and energy-absorbing structures.

The second chapter, Material Tinkering & Exploration, delves into the material characteristics of LW-PLA, showcasing its utility for shape-changing. LW-PLA can be used both as a passive and active element, reducing environmental impact by enabling or disabling shape memory through micro-scale structural changes. This material is then used to find a correlation in curvature and ratio of active versus passive elements within a design. Furthermore, the material is used to find the best type of heat source, trying to create the most consistent outcomes. The oven without convection is then chosen as it creates the most consistent outcomes by limiting user interaction and making use of slower response times.

The following chapter brainstorms ideas that can make use of shape change. Through the use of criteria and Edison profiles a direction is chosen. This is the direction of the temples of glasses. Shape change can add to this product as the temples vary in length to fit different users. This chapter also creates two prototypes to be tested, differing in the type of measurement method.

Lastly, the design is evaluated through the use of two user studies. In the first study, the focus is laid on the type of measuring method. The external measurement method comes out as the most promising as it creates the most consistent outcome with the users. The second test tries to minimize the error between the targetted length of the temple and the actual length after the activation process has ended. The result is an addition of two test samples that educate the user. Through the education of the user, a consistent result with minimal error can be achieved. The activation step also requires a homogeneous method of heating the temple, small deviations in this heating lead to unwanted curvature. This is combatted by creating a tray, that is delivered together with the temple.



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I would also like to thank my girlfriend, Michaja, for her support during my time studying and writing this thesis. Lightening my mood when needed helped me a lot.

Next, I would also like to thank my family for their support during my studies. Without them, this would not have been possible.

Abbreviation	Definition
3D	3 Dimensional
3DP	3 Dimensional printing
4D	4 Dimensional
4DP	4 Dimensional printing
ABS	Acrylonitrile butadiene styrene
CFPLA	Carbon fiber reinforced polylactide acid
CAD	Computer aided design
FDM	Fused Deposition Modeling
Tg	Glass transition temperature
LW-PLA	Light weight polylactide acid
PLA	Polylactide acid
PVA	Polyvinyl alcohol
SMA	Shape Memory Alloy
SME	Shape Memory Effect
SMM	Shape Memory Material
SMP	Shape Memory Polymer

One of the earlier papers on 4DP, Tibbits (2014), states “The fourth dimension is described here as the transformation over time, emphasizing that printed structures are no longer simply static, dead objects; rather, they are programmable active and can transform independently”. This answers what the fourth dimension within 4DP is.

Tibbits gives a definition that focuses on the state of the printed object. In a world where nearly all materials and objects are viewed as static, it raises the question of how such a shape-changing object can become “... programmable active and transform independently.” (Tibbits, 2014). Mehrpouya et al. (2021) give a more detailed description of 4DP: “... 4D printing or precisely controlled 3D printing in which materials can be deformed when exposed to an external stimulus”. Thus, thereby it becomes clear that material and external stimuli are important factors when it comes to 4DP. Now what makes material special? And how do external stimuli play a factor in shape memory?

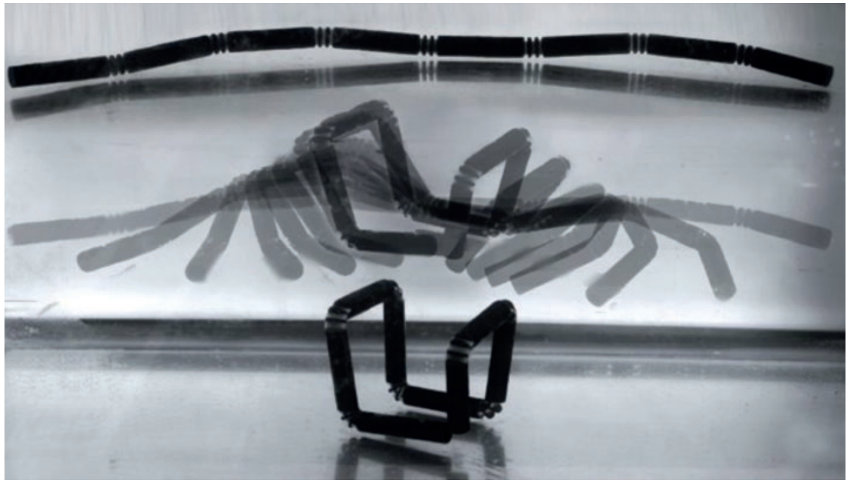


Figure 01: Shape change from line to a 3D structure using water as stimuli (Tibbits, 2014)

An important factor within 4DP is the used material, which has to be able to respond to environmental conditions. For example, not all materials exhibit sufficient shape change when exposed to stimuli. Shape-changing materials have to be printable and also be precisely manipulated by stimulus (Mehrpouya et al., 2021). Such materials are called shape memory materials (SMM). These materials have the capability of temporarily maintaining a stress-free state after being deformed. These stresses can then be released with the use of stimuli. Within SMM there are two categories of materials; shape memory alloys (SMAs) and shape memory polymers (SMPs). In this project, the focus will be on SMPs because they are easier to 3D print when compared to SMAs. There are many SMPs available able to react to different stimuli like; light, heat, humidity, and electricity (Behl & Lendlein, 2007).

The shape recovery of SMM works by building up internal stress and releasing the stored energy by applying stimuli. The stored energy and internal stress are the driving forces causing the shape memory effect. This internal stress can be created by deforming the original shape or by programming stresses into the material. Although there are various 3D printing technologies available for 4DP (Rastogi & Kandasubramanian, 2019), this thesis will focus on the technology of FDM.

FDM is a method of 3DP that builds parts layer by layer. A bit of molten material is selectively deposited in each layer on a predetermined path. This technique of printing an object is frequently used (Barletta et al., 2021). As such there are many advanced programs available to control the process of FDM printers, these programs are called slicers. To create a 4DP object precise control is needed over print parameters (Mehrpouya et al., 2021) allowing for the programming of such a shape-morphing object. Using FDM allows this control over print parameters, as such the object can be programmed upfront to exert various types of motion during actuation.

Although a significant amount of papers have been produced about 4DP, more development, and improvement of materials, and printing methods are needed (Chu et al., 2020). Where current papers have studied the programming of 4DP (Joharji et al., 2022), there are few studies about the implementation of shape-changing products. Many papers do foresee possible implementations in high-tech applications like bio-medical support structures, self-assembling objects, and soft robotics. However, these papers focus on the manufacturing of such objects, not on the use of a shape-changing product.

Although there is a good collection of knowledge on the technical aspects of manufacturing 4DP objects, it remains unknown how 4DP can be applied to consumer products. This also raises the question of what category of product 4DP can be applied meaningfully and how users interact with such shape-changing objects. These questions will be examined in this thesis by taking a look at the implementation of 4DP products. The focal point of this study is the user interaction with the shape-changing product. Therefore the activation step is examined as this is the step where the user gets to interact with the shape-changing product.

Q1: What are the challenges of involving a user in the activation step of a shape-changing product?

To answer this overarching question, the investigation will be divided into the following sub-questions:

Q1.1: What category of products can make use of 4DP?
Q1.2: What is needed to facilitate the user in post-processing a 4DP object?
Q1.3: How can 4DP be made accurate and reproducible?

In addressing these questions, the study seeks to contribute valuable insights into the growing field of 4D printing and its application in consumer-oriented contexts.

Making a 4DP object accurate and reproducible can be very challenging. Therefore literature research is conducted. This will set boundaries for the possibilities within FDM 4DP, and give handles to control shape change within a 3D printed object. First, the print path will be examined and how it can impact the outcome of a 4DP product. Next, a closer look is taken at strategies that can be applied to 4DP. Followed by an examination of print settings and their impact on shrinkage. Finally, various papers discussing possible applications for 4DP are discussed.

1. SHAPE MEMORY IN FDM PRINTING

On a smaller scale, in FDM, 4DP can be described as the shrinking and swelling of an SMP under the influence of stimuli. The shrinkage happens in the longitude of the printing path and the expansion happens perpendicular to the printing path. In figure 2 it can be seen how fabrication with 4DP takes place. First, the material is printed at temperatures much higher than its glass transition temperature. This allows the polymer chains to be stretched and aligned along the direction of the print path. After the polymer is extruded it cools down very quickly, this is due to fans blowing onto the printed material in combination with much cooler surroundings. This cooling down right after extruding locks the polymer of the material in place, allowing stresses to be frozen in the material. Once stimuli force the material to have a temperature higher than its Tg it shrinks and swells, allowing for the polymer chains to get back into their less stretched and stress-free shape.

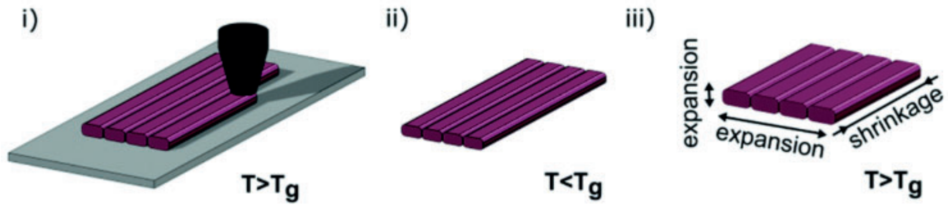


Figure 02: Production and actuation of a 4DP object on a micro-scale (Van Manen et al., 2017).

On a larger scale, the active change in a 4DP object can be used as the active part of a design. Complex 3D structures can be achieved by arranging the print path in such a manner that it shrinks and contracts where desired in the design. One such method is by making multi-ply constructs; if a part shrinks on one side and expands on the other it will curve as seen in Figure 3. The differences in shrinkage and expansion allow forces to act on the SMP in its soft material state. A more detailed explanation of those forces can be seen in Figure 4, where Zeng et al. (2019) have made a decomposition of the forces within such a shape-morphing object. As van Manen et al. state “3D printing provides an alternative route to the programming of shape-shifting: the spatial arrangement of active (and passive) elements”. Papers like Van Manen et al. (2017) and Wang et al. (2019) describe the changing of these parameters and thus the programming of the shape change up front. Doing this requires knowledge of the effect of parameter changes to generate a desired outcome.

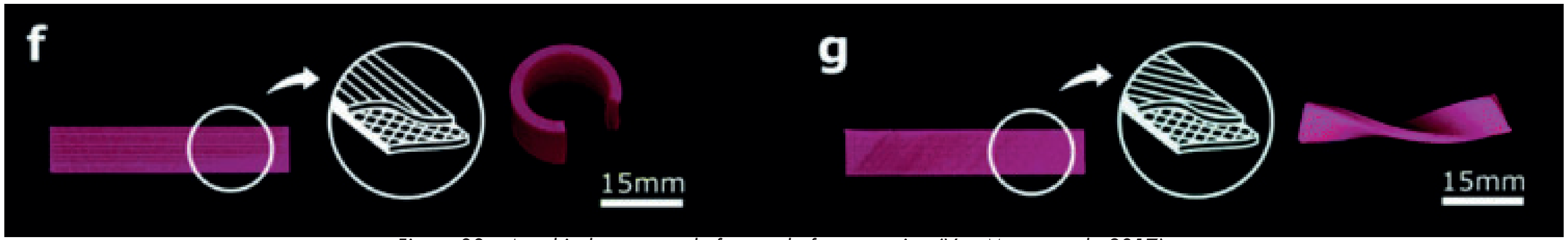


Figure 03: A multi-ply construct before and after actuation (Van Manen et al., 2017).

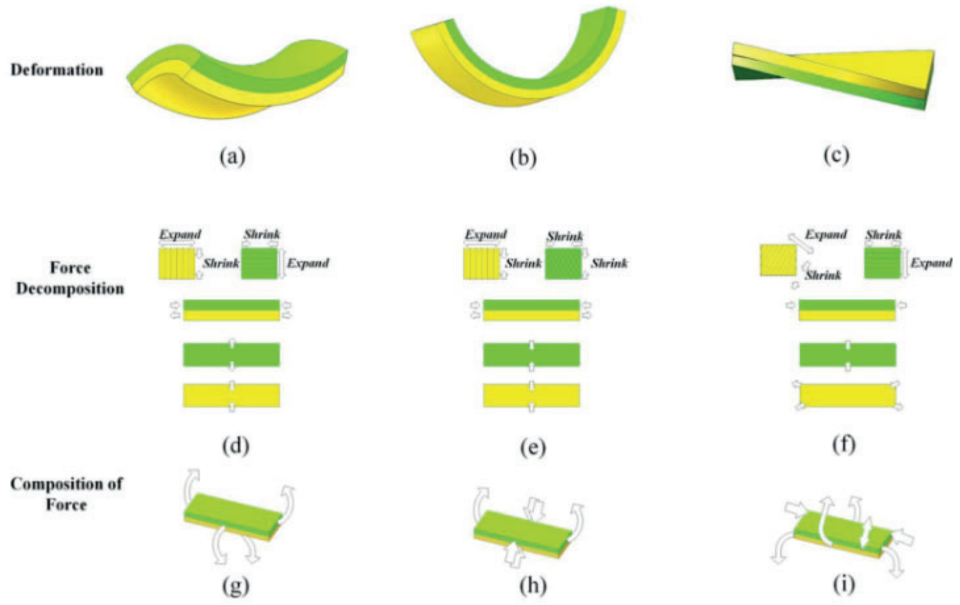


Figure 04: Decomposition of forces within a shape-morphing object (Zeng et al., 2019).

2. CONTROLLING SHAPE MEMORY

While the previous chapter gives a small overview of how FDM can facilitate 4DP, it is not yet clear how this shrinkage can be used, what types of SMPs can be used, and how precise control of FDM can impact shrinkage. First, some 4DP strategies are explored. Next material is reviewed and how it impacts shrinkage. Finally, parameters critical to FDM shape memory, are explored.

2.1. 4D PRINTING CONTROL STRATEGIES & FORM MANIPULATION

When making an object with a manufacturing process there are always limitations in design. Such limitations define what you can and cannot make with that manufacturing process. These processes require guidelines and strategies to create a desired outcome. This is no different for 4DP. Within the literature, a few different guidelines and strategies are found.

For 4DP, Nam & Pei (2019) have suggested an overview of potential types of shape-change, serving as a guideline. These shape changes include basic, complex, and combination shape changes (Figure 5). Where basic shape-change provides a singular motion within an object, complex forms provide multiple basic shape-changes of the same form that react together. Combination shape-changes provide a conglomeration of basic and complex shape-changes. When designing it is useful to keep these types of shape-changes in mind.

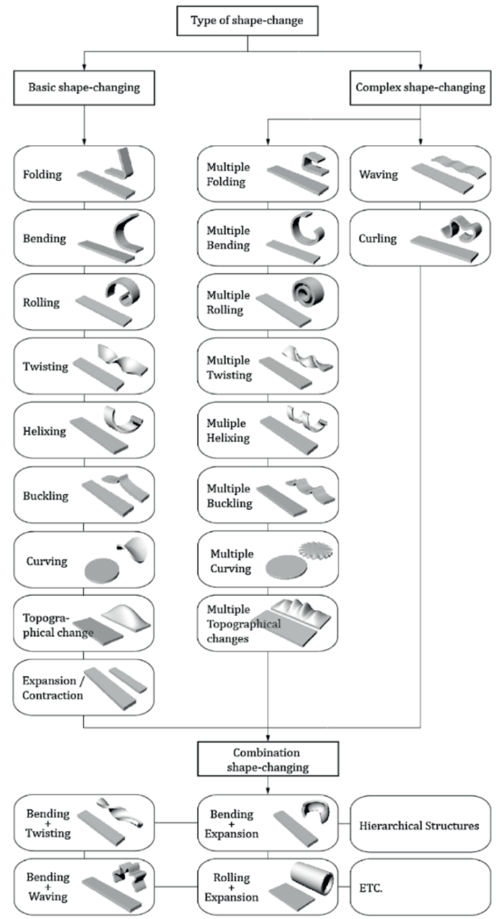


Figure 05: Possible types of shape change (Nam & Pei, 2019).

Tahouni et al. (2020) found a way to create forms through the use of origami. In their testing, they experimented with a type of origami curve which led to an out-of-plane reaction once actuated. By applying this strategy they can control the angle of the final product by adjusting the crease line in the designed part (Figure 6).

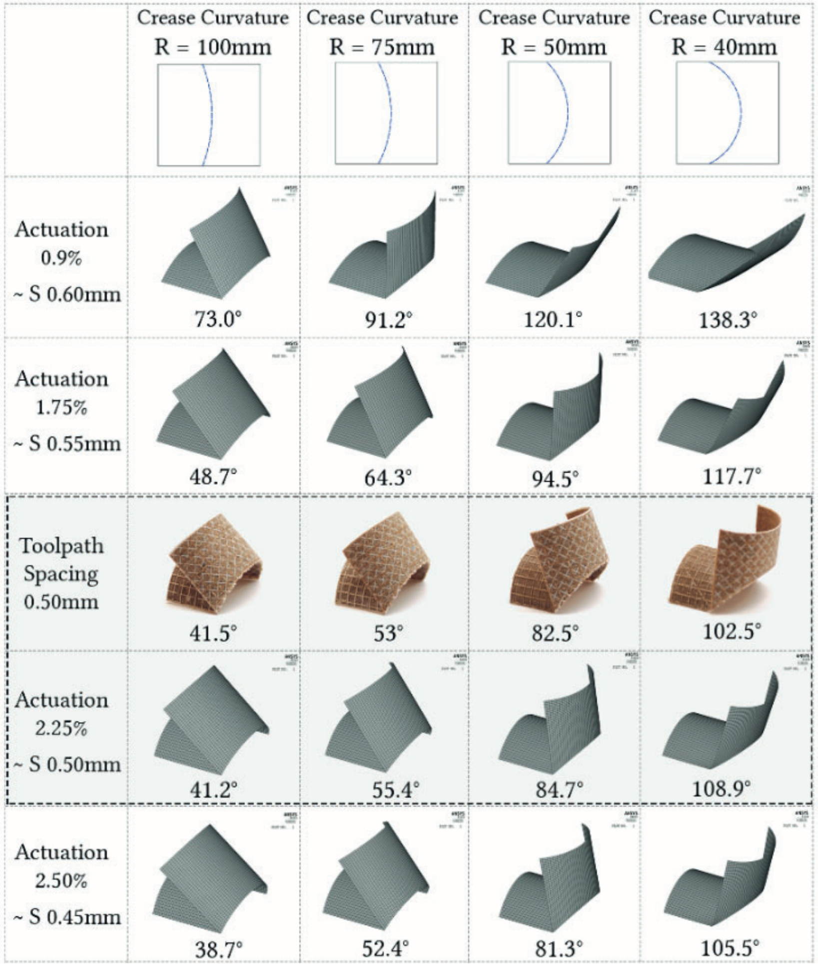


Figure 06: Origami creases in relation to their angle (Tahouni et al., 2020).

Another strategy for controlling the form of the object is by creating a raster that actuates (Figure 7). Yu et al. (2020) do this in their research coupling it with FEA simulations. Although their design can be accurately predicted through the use of those simulations it is a process that requires high computational power, limiting the workflow, making it impossible for real-time interactive design.

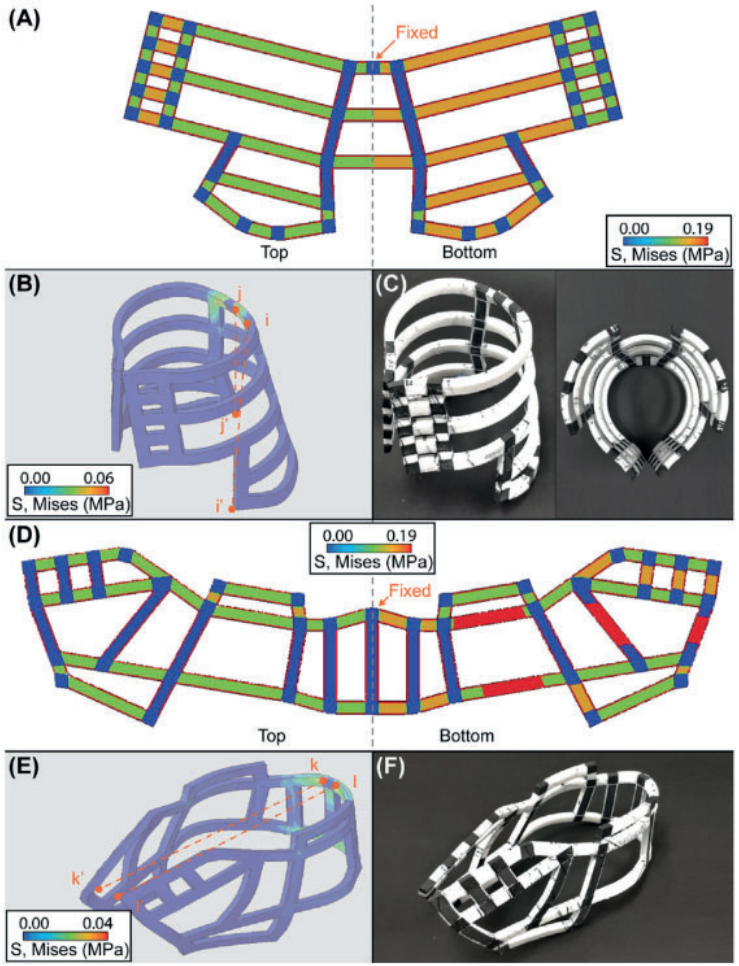


Figure 07: Shape memory raster in relation to inherent stress (Yu et al., 2020).

The last strategy reviewed is that by Kwok et al. (2015) who make use of a combination of origami and applied cuts. By creating cuts on specific places a 3D object can be flattened, creating a 2D object. Through technical characterization, an accurate assumption can be made as to what degree the creases can bend. This is done in previous research where they made the geometry limit the amount of angle a hinge can have. By obstructing the hinge a precise final angle can be achieved (Deng & Chen, 2015). With this information, the original 3D object can be replicated from the flattened-out object (Figure 8).

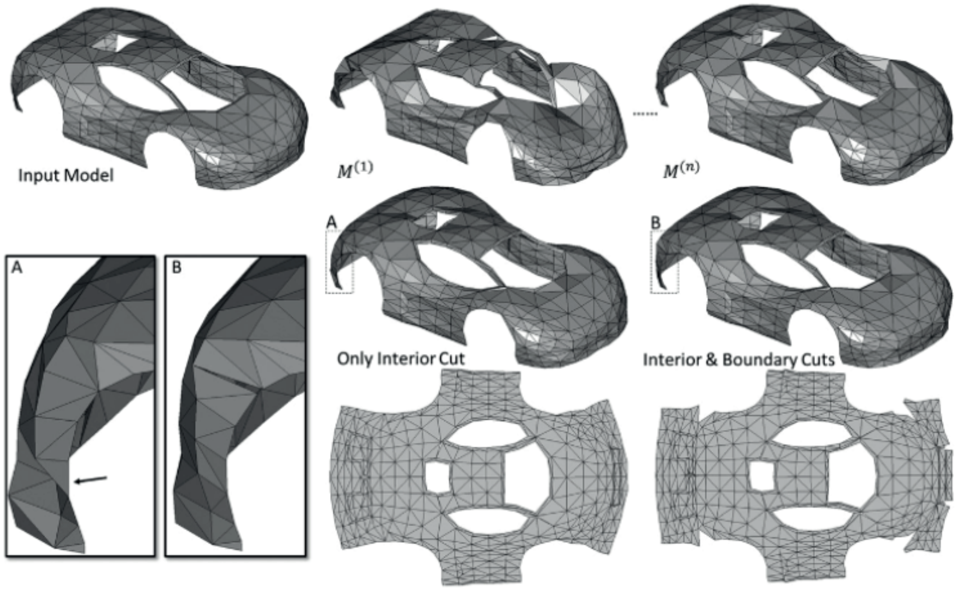


Figure 08: Activation temperatures versus strain. (Left, Van Manen et al., 2017) (Right, Wang et al., 2023)

2.2. SHAPE MEMORY CONTROL THROUGH MATERIAL

In the previous chapter multiple strategies are displayed. Two of these strategies rely on the precise control of the shrinkage of the material. Through this precise control, they can predict the outcome of the object after actuation. This raises the question of whether different types of material give different shrinkage results and, if these materials do give different results, can different materials be combined resulting in a more predictable outcome?

One way to impact shrinkage and thus control the 4DP object is the choice of material, of which there is a wide range (Pinho et al., 2020). Common materials for FDM 4D printing are polylactide acid (PLA), acrylonitrile butadiene styrene (ABS), and polyvinyl alcohol (PVA). One difficulty in 4DP is the degradation of the material. Over time material can degrade, reducing the capability to remember its shape. Joharji et al. (2022) advise researching materials that are printable and will not degrade during application. Therefore PVA is excluded from this research as it dissolves in water, therefore not being able to function properly in non-labcontrolled environments. ABS has a glass transition temperature starting at 109 degrees Celsius. This means that ABS requires a setup providing much higher temperatures for activation, when compared to the glass transition temperature of PLA at 60 degrees Celsius (Huang et al., 2017). This factor in combination with the toxicity of FDM printing ABS (Farcas et al., 2019), gives the use of PLA in FDM 4DP the upper hand.

There are many forms of filament SMPs as there are many shape memory composites available on the market. These composites can include fibers, nanoparticles, or a mixture of polymers. Many of these mixtures come forth out of ‘classic’ reinforcements (Salimon et al., 2020). Due to the wide range of possible filament SMPs, the focus will be on regularly used materials and materials that have been tested or are being tested. It is for this reason that PLA is chosen as the material to work with.

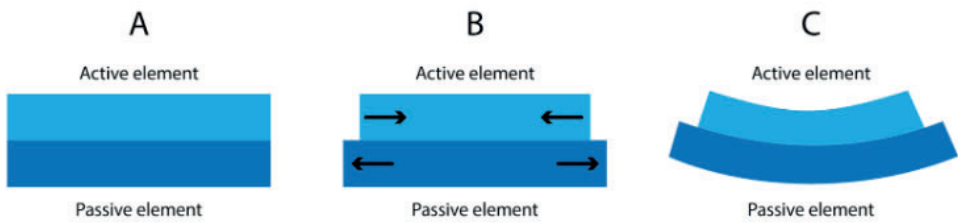


Figure 09: A) object as printed. B) Active versus passive elements during actuation, active elements exert force upon the passive element that counteracts this force. C) The result of the forces happening in B.

To predict 4DP precisely it is needed to know how much shrinkage takes place at certain areas of the object. These areas or elements can be classified as passive and active. Active elements shrink in the desired direction. Passive elements counteract this by not shrinking or expanding, creating an opposite response to the active element. For example, if the active element contracts in direction A, the passive element can expand in direction A or it can not change in size, as illustrated in figure 9. The material choice in 4DP therefore is important as it needs to facilitate the creation of active and non-active elements. Materials need to allow for the storage of stress which can be released under stimuli. The second factor is the programming of this material; how it is applied and printed.

PLA is available in many forms on the market, including fiber-induced PLA. These added fibers range in type of use, from appearance to preferred mechanical preferences. One such fiber combination is carbon fiber PLA (CFPLA). The paper by Yu et al. (2020) uses this composite as a restrictive layer within their testing. The CFPLA-PLA mixture is compared to a conventional PLA-PLA mixture. The tests done, show that the CFPLA-PLA mixture increases in movement when actuated under the same condition. This can be attributed to the fact that CFPLA shrinks less when compared with regular PLA. This is also discussed by Meng & Li (2013) who state fillers can significantly improve the recovery stress of SMPs but, under most circumstances, will reduce the recoverable strain of an SMP.

One specific kind of PLA stands out from the rest in terms of properties; LW-PLA by colorfabb (LW-PLA, n.d.). This PLA has a foaming agent added into the mix and allows for the PLA to change its properties when the printing temperature changes. If the printing temperature is increased to 250 degrees Celsius the PLA fully foams up and reduces in weight by nearly 66% Hermann (2020). Among features such as appearance, strength, and difference in impact strength, the PLA also loses the ability to perform as a shape memory polymer. This latter fact can be used when designing a 4D print. The foamed PLA can be used as a restrictive element for the 4DP object creating a non-shrinking portion which helps increase the bending once actuated.

2.3. CRITICAL PARAMETERS IN 4D PRINTING

4D printing, an evolution of 3D printing, introduces the dimension of time to the manufacturing process. The ability of printed objects to undergo dynamic transformations relies on precise control over various parameters. In this section, we will explore the fundamental factors that play a pivotal role in shaping the outcomes of 4D printing: extrusion temperature, activation temperature, layer height, and print speed.

Van Manen et al. (2017) state that “The percentage of the decrease in the filament length could be controlled through adjustment of the printing parameters including the extrusion and activation (i.e. triggering) temperatures as well as the layer thickness”. Thus temperature of both the extrusion and activation are important as well as layer thickness. Wang et al. (2023) found the same conclusions as Van Manen when it comes to extrusion temperature, activation temperature and layer thickness. Where they vary however is on the topic of print speed, Van Manen sees no significant difference while Wang does see a significant difference.

Extrusion temperature

Extrusion temperature, also known as printhead temperature, is a critical parameter governing the behavior of the printing material during the deposition process. This temperature setting impacts the flow characteristics of the material, influencing how easily the polymer chains align and stretch. A careful adjustment of extrusion temperature can significantly alter the degree of actuation, with lower temperatures resulting in increased strain and enhanced deformation of 4D printed objects.

Van Manen et al. (2017) found an increase in strain from 13% to 36% when lowering the extrusion temperature from 240C to 195C (Figure 10 (a)). Wang et al. (2023) also found a significant change in shrinkage when changing the extrusion temperature. In their testing, a temperature range was taken from 185C to 210C. Pivar et al. (2022) see a similar correlation where lower temperatures give more strain. The significant change in strain can be attributed to the viscosity during printing. When printing with higher temperatures the material is less viscous when compared with lower temperatures. Less viscosity of material can flow more freely, therefore the polymer chains are less stretched when printing, reducing total actuation.

Activation temperature

Activation temperature represents the environmental conditions under which the 4DP object undergoes its dynamic transformations. The activation process is triggered by exposing the material to a specific temperature. Understanding how activation temperature influences the actuation is crucial for designing 4D prints that respond precisely to their intended environmental conditions.

For their testing Van Manen et al. (2017) used a hot water bath. In their testing, they found a significant increase in the amount of shrinkage going from 13% to 29% when increasing the temperature of the bath from 65C to 95C. Wang et al. (2023) took a bigger range in temperature and also saw a significant change, going from 0% shrinkage at 50C to 27% shrinkage at 100C. It must be noted that 50C is below the Tg of PLA, the tested material. Besides the lower than Tg starting point the graph does display a linear line (Figure 11). This can be attributed to the fact that the glass transition temperature is a gradient in temperature and not a set temperature. A higher temperature therefore means a lower viscosity and thus the polymer chains are more free to move into their relaxed state.

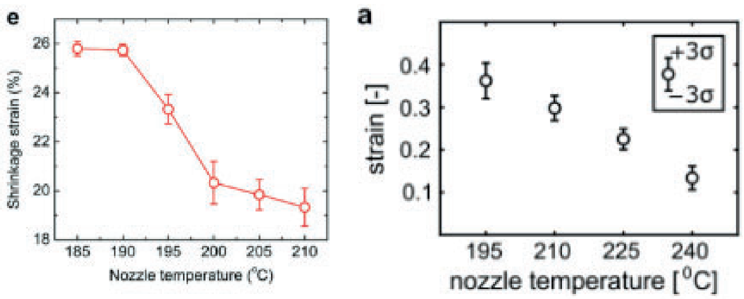


Figure 10: Differences in nozzle temperature relative to strain, (a, Van Manen et al., 2017) (e, Wang et al., 2023)

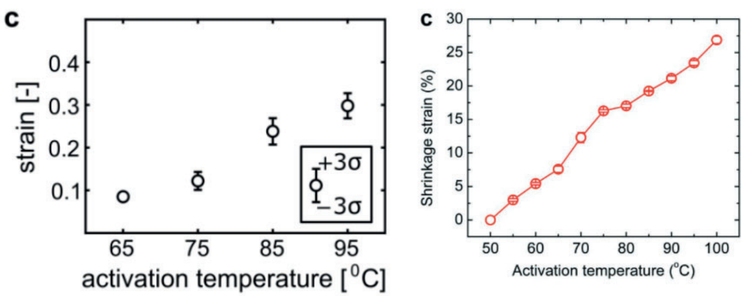


Figure 11: Activation temperatures versus strain. (Left, Van Manen et al., 2017) (Right, Wang et al., 2023)

Layer height

Layer height dictates the vertical resolution of the 3D-printed layers that compose the final object. In the realm of 4D printing, layer height plays a substantial role in determining the deformation capabilities of the active areas. Smaller layer heights allow for increased deformation in the active segments of a 4D object.

Van Manen et al. (2017) also see a significant effect with layer height. Samples are printed ranging from 50 to 200 micrometers. When actuated the result was a 3-fold increase in maximum strain. Smaller layer height therefore increases the amount of deformation in the active part of a 4DP object. Wang et al. (2023) saw the same significant difference. In their test, however, they varied layer height from 100 micrometers to 300 micrometers in combination with a significant change in shrinkage going from 11,5% to 3% respectively (Figure 12). Gu et al. (2019) found a similar result where going lower in layer height resulted in much more shrinkage. Their experimentation incorporated the range of both Wang & Van Manen.

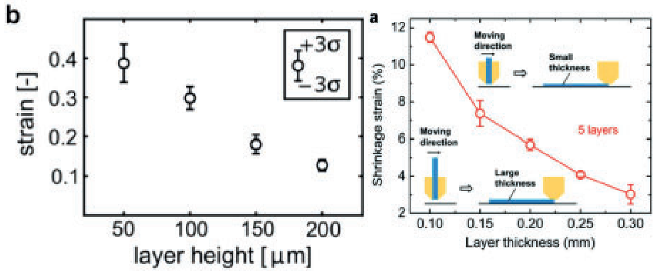


Figure 12: Layer height versus strain. (b, Van Manen et al., 2017) (a, Wang et al., 2023)

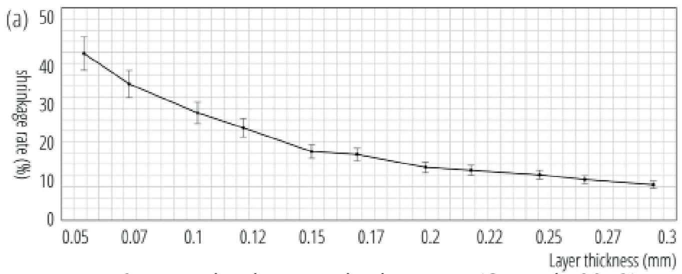


Figure 13: Layer height versus shrinkage rate (Gu et al., 2019).

Print speed

Print speed refers to the rate at which the 3D printer deposits material to build each layer. While print speed may seem like a straightforward parameter, its influence on 4D printing is nuanced. Studies have shown that adjusting the print speed can impact shrinkage, but this effect is more pronounced at lower speeds. A comprehensive understanding of how print speed influences the final actuation provides valuable insights into optimizing the 4D printing process.

The results of Wang et al. show a significant change in shrinkage within the lower print speeds, ranging from 5 to 35 mm/s. Afterward, the shrinkage factor stays relatively level. Alshebly et al. (2021) found a similar conclusion in printing with speeds ranging from 10 mm/s to 60 mm/s. Van Manen et al. start their testing at 30 mm/s going to 90 mm/s. In their testing no significant change is observed, this can be attributed to the fact that change in shrinkages happens at a lower print speed than tested. Therefore there can be a significant change in shrinkage when changing print speed, but only at print speeds lower than 30 mm/s.

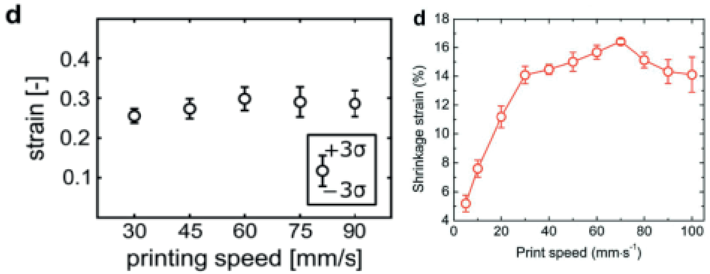


Figure 14: Print speed versus strain. (Left, Van Manen et al., 2017) (Right, Wang et al., 2023)

Another factor discussed by Wang et al. (2019) is the amount of curvature. This is done by altering the print path in such a way that one side of a sample shrinks while the other side prohibits shrinkage. This is achieved by creating print paths in the longitudinal direction of the sample to promote shrinkage and creating perpendicular print paths to decrease shrinkage. Elements within the object that promote shrinkage are called active elements, elements that decrease shrinkage or even stop shrinkage in the same direction are called passive elements. A logical factor that impacts the amount of curvature is the amount of active element within a 4DP object. This is also discussed by Wang et al. (2019), who test differences in the percentages of active versus passive layers.

Taking a look at the results of Wang et al. (2019), figure 15, shows that changing the ratio gradually impacts the amount of curvature after actuation. The actuation of the test took place with a hot water bath in combination with precise control over temperature.

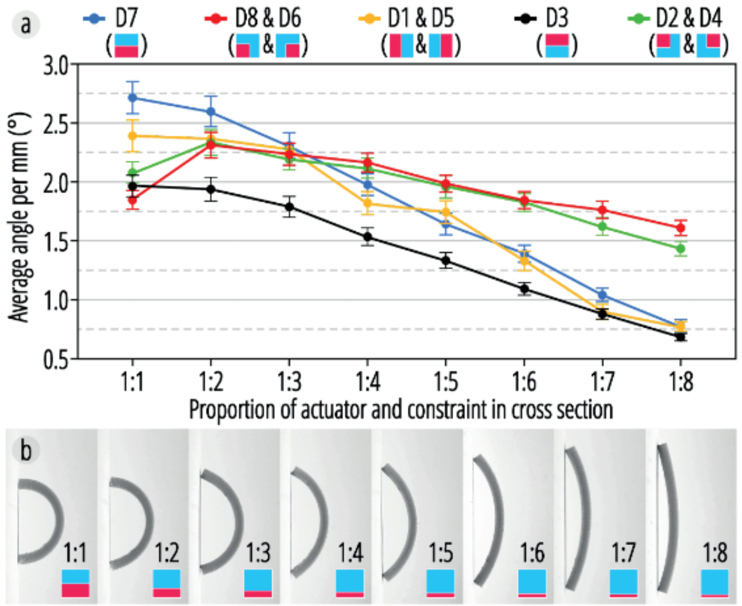


Figure 15: Measured curvature with different ratios of active versus passive elements (Wang et al., 2019).

2.4. CONCLUSION

Through the use of 4DP strategies a designer can create 3D objects that translate to a shape in 2D for printing. After printing it can be activated to create the same 3D object. Although these strategies generate handles to design products there are some difficulties, namely the needed computational power that limits the workflow. If these strategies were to require less computational power in the future they would serve as useful programs to common designers being able to make products without prior knowledge. The implementation of such a strategy also requires material characterization to determine how the material will behave during actuation.

Before doing material characterization it is important to determine the type of SMP that will be used. For this project LW-PLA by colorfabb is used as this material has the option to be active and passive during activation. This allows for more design freedom, while still being made out of one material. Using one material is beneficial to the environmental impact of the produced product.

Where the material choice gives the option to turn shape-change on and off, print parameters give the option to determine the amount of shape-change taking place. Through varying the amount of shrinkage it is possible to create variations of outcomes with products that are made with the same material and the same print path. Doing this will allow a designer to fine-tune a design to create a perfect fit for the user.

3. APPLICATIONS AND PERSPECTIVES OF 4D PRINTING

To know what can be made with shape change, it is smart to take a look at the produced results of previous papers. These papers are limited to showcases of 4DP. This is due to 4DP being a very recent technology, where the first papers produced on 4DP are at the time of writing about 10 years old. Nevertheless, these papers do give a good representation of the possibilities within implementing shape-change in objects.

Zhang et al. (2019) talk about three categories of products. The first category is self-constructing structures. This includes containers, locks, and safe boxes. These items showcase the ability to self-construct. “Self-construction structures have evolved from a conceptual stage to an experimental stage” Zhang et al. say. These structures do show promising prospects but have yet to evolve into consumer products.

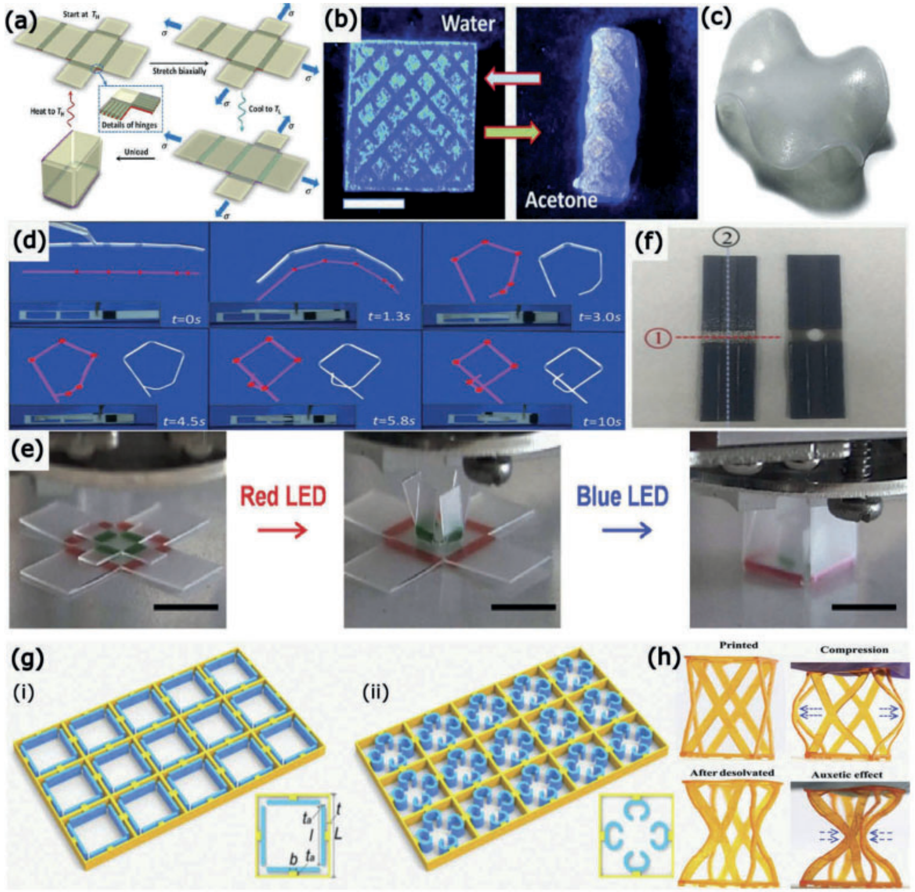


Figure 16: A) A self-assembling box (Ge et al., 2013). B) A self-roling tube (Kaur et al., 2018). C) A moisture-responsive double-curved surface (Tibbits, 2014). D) Self-interlocking structure (Mao et al., 2015). E) Light wave-dependent self-assembling box (Liu et al., 2017). F) folding samples made with PVA (Kolarova Raskova et al., 2018). G) Self-forming lattice structure (Zhang et al., 2016). H) Structure with a tunable Poisson’s ratio (Wu et al., 2018).

The second product type is medical devices. These medical devices can be used for targeted drug delivery, stents, and splints. Targeted drug delivery showcases some containers that release their drugs and grippers that hold onto cells as they actuate at a temperature of 32 degrees Celsius. The stent makes use of integrated SMP wires which make the form expand once applied in the body. The splints provide a very useful application yet require a lot of knowledge about geometry in design to create the perfect match for a user.

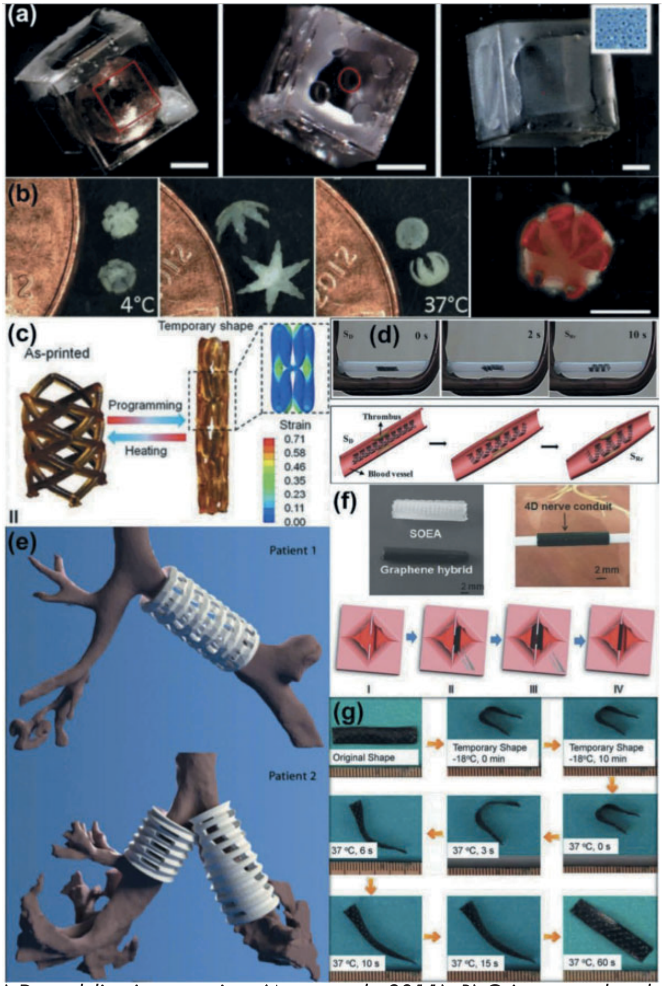


Figure 17: A) Drug delivering container (Azam et al., 2011). B) Gripper produced to handle cells (Malachowski et al., 2014). C) Stent activated by heat (Ge et al., 2016). D) Stent activated by magnetism (Wei et al., 2017). E) Stents with air gaps (Medaglini et al., 2015). F) Nerve guidance device (Miao et al., 2018). G) 4DP scaffold (Miao et al., 2016).

Figure 18: The third case is soft robotics. The products in this category consist of grippers and actuators. These items use built-in hydraulic lines in combination with SMP structures to actuate. This category can make a lot of use of SMP as regular robotics can be limited by the use of rigid materials (Zhang et al., 2019).

The third case is soft robotics. The products in this category consist of grippers and actuators. These items use built-in hydraulic lines in combination with SMP structures to actuate. This category can make a lot of use of SMP as regular robotics can be limited by the use of rigid materials (Zhang et al., 2019).

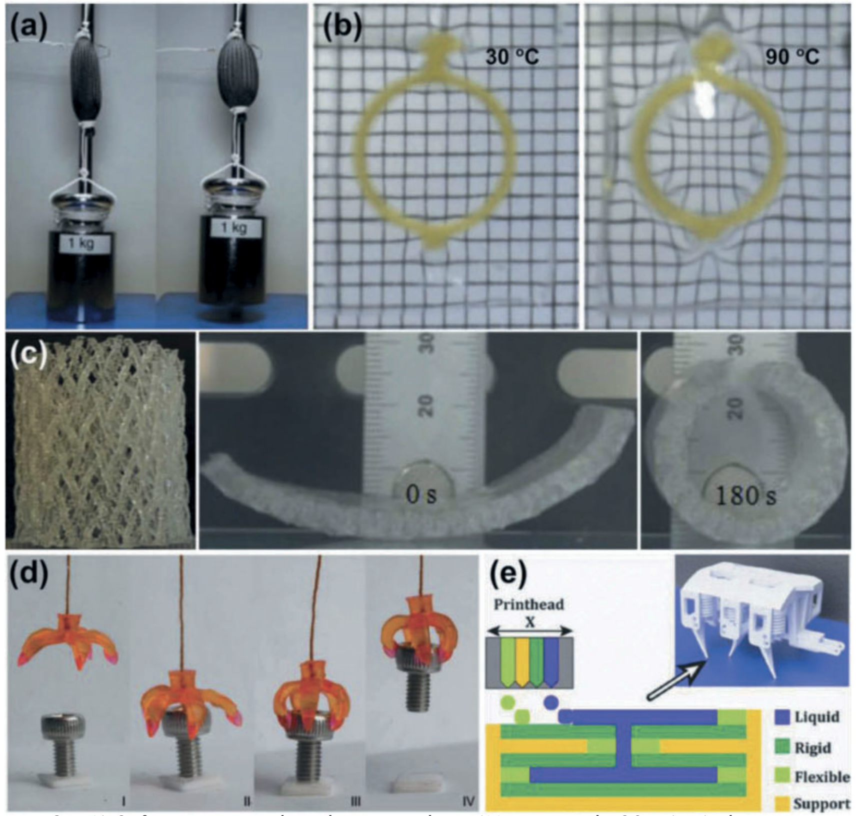


Figure 19: A) Soft actuator made with porous silicon (Miriyev et al., 2017). B) Thermo-responsive adaptive optics (López-Valdeolivas et al., 2018). C) Gripper made with FDM (Zhang et al., 2018). D) Gripper made with SLA (Ge et al., 2016). E) Hydraulic robot using actuating bellows (MacCurdy et al., 2016).

Khalid et al. (2023) provide less conceptual products. Among the products presented are shades that can close and open depending on the conditions of the environment. Another product showcased by Khalid et al. is a 4DP aperture, which works by having several motion zones. Depending on the thickness of the zone it will actuate earlier, with fewer layers, or later, with more layers. These products are closer to implementation in a consumer product but also have yet to be implemented.

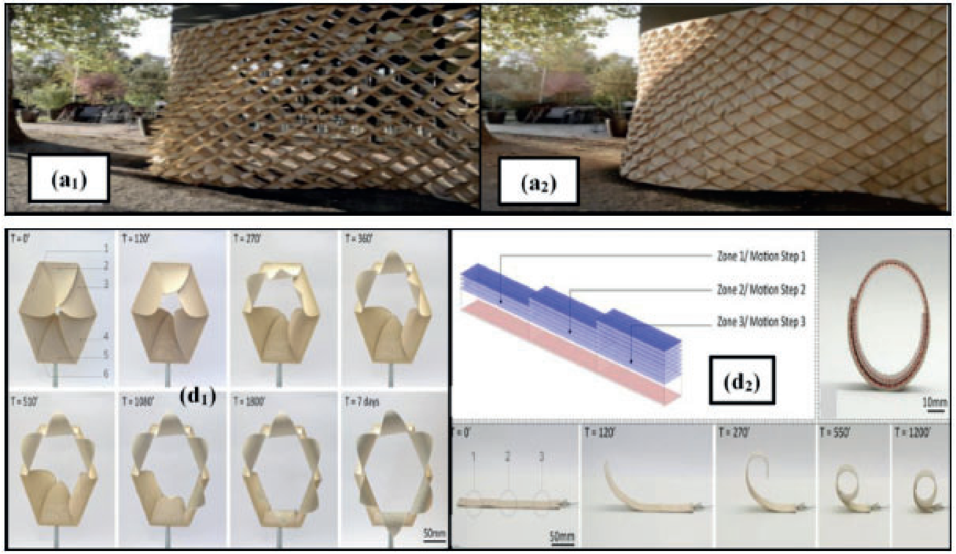


Figure 20: A) Wall that changes its permeability depending on the environment (Menges & Reichert, 2012). B) Shape-changing aperture (Tahouni et al., 2021).

Mehrpouya et al. (2021) present self-recovering materials as a mechanism for a product. In the paper, three objects are presented that heal themselves when actuated by a high enough temperature. The first product is a cylindrical object which can be compressed and twisted. The second product makes use of a microstructure and the third product makes use of compliant mechanisms. All of these products can recover to their original shape once actuated by the right amount of temperature.

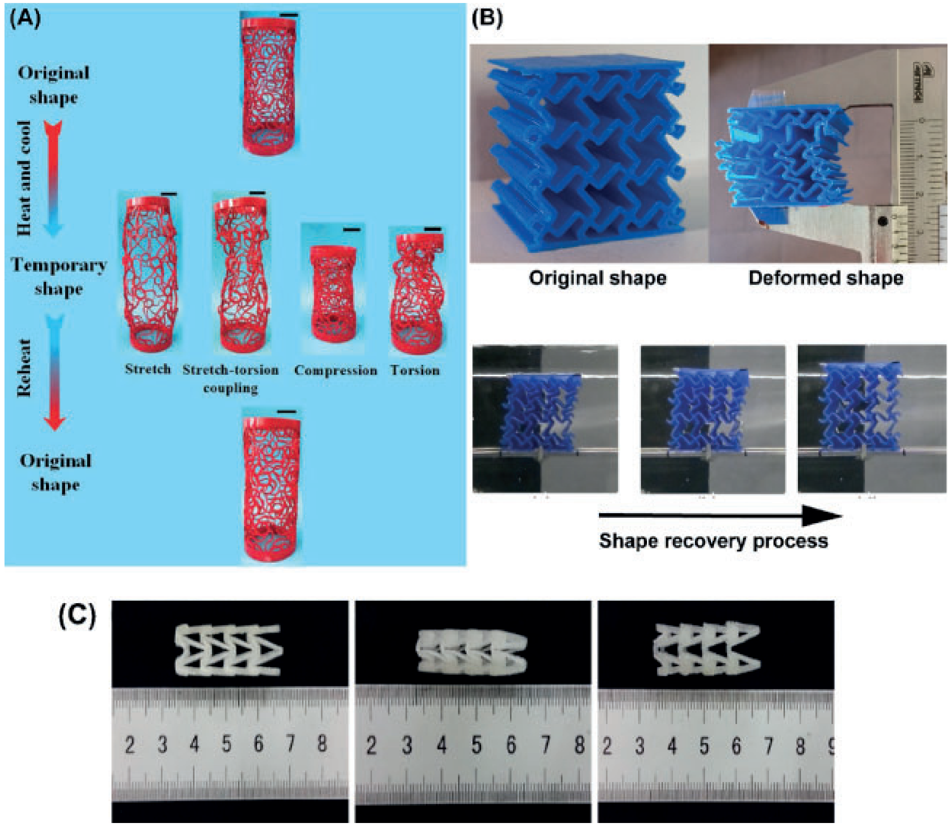


Figure 21: A) Energy absorbing tube (Xin et al., 2020). B) Energy absorbing structure (Barletta et al., 2021). C) Shape recovery of a stent (Wu et al., 2018).

Many of these products give a clear representation of the use of SMPs in products. Catagorising these products a distinction can be made in the type of shape-changing objects presented in papers. First and foremost are the flat-packed items, these expand into a 3D object from their initial flat, 2D, state. The second category is custom fitment, allowing objects to fit around their environment to create the perfect grip or support. The last category is that of energy harvesters. This category allows objects to absorb energy that can be distributed at a later stage. Although these products are not yet consumer products and available in stores it is easy to see how these structures can be implemented in consumer products. Changing a design to fit such a smart structure can be a way to control 4DP, thereby giving yet another insight into the answer to Q1.1.

4. CONCLUSION

A shape-changing product where users get to interact with the actuation of the product requires an accurate and reproducible shape-changing action. The accuracy of this action can be tuned by decreasing or increasing shrinkage, done through precise programming of the 3DP process. By decreasing shrinkage, the total deformation of the product can be reduced. Increasing shrinkage can boost the total deformation. These correlations can be especially useful when a product needs fine-tuning, for example when adjusting to the size of a user.

However, not all methods need fine-tuning. By using a geometry-based strategy it is possible to let the design not be guided by the amount of shrinkage that takes place, but by the designed end stops that are created. This way a product only has to reach a minimum amount of shrinkage, after which it locks at an angle or length through clever use of geometry.

By varying the temperature it is possible to create a quick or slow reaction. This is also a useful tool when designing for the interaction a user has during the shape-changing process. If a product is meant to be shaped to one position a quick response can be preferred. However when a design is created that uses different end positions a relatively colder actuation temperature can be used. This allows for users to stop the shape-changing process halfway in a controlled manner.

Finally, there is also the category of products. As this study focuses on applying shape change in a meaningful way, it is useful to take a look at what type of product directions are deemed useful by other papers. Reviewing these papers shows that a general trend of three categories appears; flat-packed, custom fitment, and energy-absorbing devices. The categories of flat-packing and custom fitment can be handy for trying to find a product that studies users in applying shape change, as the users get to either activate their product or shape it to their needs. In either case, these options require the product to be formed at the last step and thus with the user.

The correlations found in the literature research are valuable when it comes to creating a guide that can be followed when designing a shape-changing object. It is important to note that these correlations are not exact numbers. Multiple papers showed similar correlations but with different values. In these papers, it is also noted that each setup differs slightly, creating different outcomes, while using the same input file. Thus the variation lies in the printer, material, and activation of the shape-changing object. To overcome this variation and create consistency it is important to keep all factors the same, this also accounts for the user interaction. To keep this interaction as similar as possible it is best to restrict user interference in the process to improve consistency.

Generally, when results show the same correlation but vary in results, the systems used to create those results have to be calibrated. The same will be done for the setup used in this study. This will help by being able to create consistent outcomes which can then be benchmarked to one another. Throughout this study, the same material will be used, LW-PLA by Colorfabb (n.d.). As mentioned in the literature research this material can foam up, restricting shape change. This raises the question of whether this material can restrict all shape changes or whether it still changes shape but at much lower percentages.

After characterizing the type of material the question becomes how LW-PLA can be used to create shape change within an object. To be able to compare the results of the test a simple shape-changing motion is selected. This creates the opportunity to compare with papers about FDM shape change and helps to calibrate the printer to the material.

Once the material and printer have been calibrated there is one step left in the process that needs to be detailed; the activation of the shape-changing object. Within the literature, there are few papers differentiating from using hot water as a means of activation. One wonders why and if another type of activation can perhaps be more useful. This will help answer the question of what type of activation creates the most consistent outcome. Thus allowing for further benchmarking of results.

When the setup is calibrated two questions remain. The first question comes from the fact that samples are always straightforward volumes like cubes and spheres. Taking a look at various products reveals that they can rely on different structures, to facilitate different properties. As such the question remains how can different structures impact the result of shape change?

1. SETUP

As aforementioned it is important to calibrate the process to allow for accurate testing. As such it is also important to not change the setup during testing. This reduces the time spent on calibration. The workflow for creating test samples is the same for all tests. The initial step involves designing the object using computer-aided design (CAD) software, with Onshape being the chosen tool for this project. Subsequently, the designed 3D file is exported to a slicer, specifically Cura version 5.2.1 in this study. The slicer transforms the 3D object into G-code, a format readable by the 3D printer. Speaking of the 3D printer, an Ultimaker 3 is utilized in this thesis. Notably, the Ultimaker 3 features dual extrusion capabilities, enabling the printing of objects with two distinct settings.

Figure 22: Ultimaker 3 (Ultimaker 3 Review | PCMag, n.d.)

2. MATERIAL CHARACTERIZATION OF LW-PLA

The filament by colorfabb, LW-PLA, was used for material characterization. This filament is chosen as it possesses the ability to change on a microstructure, creating the opportunity to enable and disable shape memory. When using this material in FDM it is advised to be printed between 195 to 260 degrees Celsius by the manufacturer. What makes this type of filament special is the added foaming agent. At higher temperatures this foaming agent will cause the extruded filament to inherit bubbles, foaming up. This is particularly interesting for 4DP as it causes a degradation in the ability to memorize its shape. This function, or disfunction, can be used to create passive elements within the design.

This material is relatively new, being released in 2019 (Colorfabb, n.d.). Therefore this material has yet to be characterized. To find out how this material behaves when used in a 4DP object, it is tested. Five different settings are created, differentiating in temperature and flow. Temperature is the primary impact of foaming, this activates the foaming agent. Flow, the amount of material extruded, is the secondary impact as it either gives or withholds the space for the extruded material to foam up.

Important here is to measure how the material behaves. Regular PLA without additives behaves by shrinking in the direction of the printpath and expanding in the directions perpendicular to the printpath. Although it is known that the foaming agent will impact shape memory it is still useful to find out if the material can shrink in lesser amounts, for example, 2% instead of the regular 20%. A small amount of shrinkage would mean a final design still has to take shrinkage into account when actuating.

Set up

The test uses cubes of 20 by 20 by 20 millimeters. Each cube is measured before and after actuation in weight, length, width, and height. Length and width differentiate from each other in printed line direction. Length is the distance along the printpath, width is the distance in the same plane but perpendicular to the printpath (Figure 23). Actuation takes place in a bowl of hot water. This method of actuation was done as this is the choice of activation for papers by Van Manen et al. (2017) and Wang et al. (2019). The process goes as follows:

1. The cubes are measured
2. The cubes are activated in boiling water
3. The cubes are dried and measured again

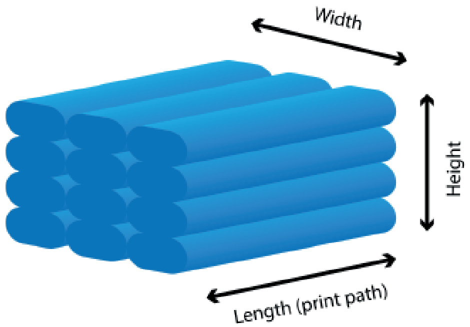


Figure 23: Width, height and length relative to the printpath.

Figure 24: Samples activated in hot water (left) and weighed before and after activation (right).

The samples consist of the following variable parameters (Figure 25). Temperature differences allow for samples 1 to 3 to foam up. Samples 4 and 5 compensate for extrusion flow for the amount of expansion within the material at lower temperatures.

Sample	Temperature (Celsius)	Flow rate (%)
1	195	55
2	220	55
3	245	55
4	195	105
5	220	70

Figure 25: Samples 1 to 5 with their varying parameters

Per type of cube, three samples were made. Other important parameters were the same for all cubes. These parameters were set at the following values:

Layer height	0.1 mm
Infill percentage	100%
Infill type	Lines
Buildplate Temperature	60C
Print speed	70 mm/s

Results
For each of the results, the change is displayed in percentages as not all cubes had the same dimensions coming out of the printer.

Within the weight section, there is one outlier, this is the 9,53% of sample 1. This difference can be attributed to water being stuck within the cube. This was possible as the cube was experiencing under-extrusion when printing.

Difference in **weight (g)**			
	Before actuation	After actuation	Difference
195 deg, 55 flow	4,65	5,10	**9,53%**
220 deg, 55 flow	4,67	4,71	0,86%
245 deg, 55 flow	4,84	4,97	2,74%
195 deg, 105 flow	8,39	8,40	0,16%
220 deg, 70 flow	4,92	4,98	1,08%

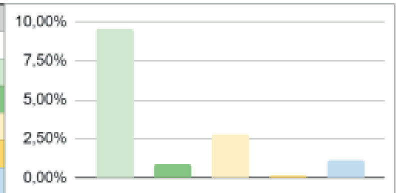


Figure 26: Difference in weight

The difference in volume depicts the biggest change with the sample printed at 245 degrees Celsius in combination with a 55% extrusion flow rate. The volume is calculated by multiplying height with length and width. Each of these measured distances are the most average distances meaning peaks on the surface of the cube were avoided.

Difference in **volume (mm3)**			
	Before actuation	After actuation	Difference
195 deg, 55 flow	7982,371255	8219,046693	2,96%
220 deg, 55 flow	8160,595725	8798,350396	7,82%
245 deg, 55 flow	7994,014166	8824,930665	10,39%
195 deg, 105 flow	8057,286061	8573,519376	6,41%
220 deg, 70 flow	8184,9488	8451,942598	3,26%

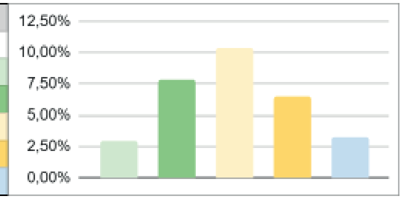


Figure 27: Difference in volume

The length along the layer lines showed significant differences at lower print temperatures.

Difference in **length along the layerlines (mm)**			
	Before actuation	After actuation	Difference
195 deg, 55 flow	20,40	18,96	-7,08%
220 deg, 55 flow	20,56	20,44	-0,62%
245 deg, 55 flow	20,48	20,44	-0,23%
195 deg, 105 flow	20,56	19,55	-4,88%
220 deg, 70 flow	20,69	20,57	-0,55%

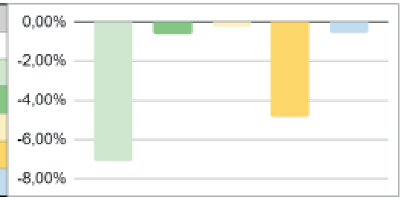


Figure 28: Difference in length along the layerlines

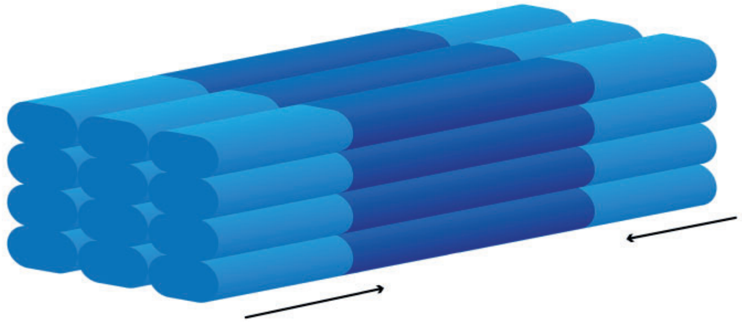


Figure 29: Change in length during actuation.

The width, or length perpendicular to the layer lines showed some differences, however, these differences can not be seen as significant due to their low percentages (1,54% & 2,93%)

Difference in **length perpendicular to the layerlines (mm)**			
	Before actuation	After actuation	Difference
195 deg, 55 flow	19,48	19,78	1,54%
220 deg, 55 flow	19,78	19,80	0,08%
245 deg, 55 flow	19,60	19,53	-0,37%
195 deg, 105 flow	19,66	20,24	2,93%
220 deg, 70 flow	19,76	19,77	0,05%

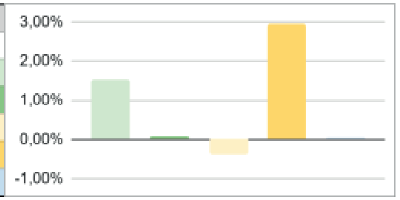


Figure 30: Difference in length perpendicular to the layerlines

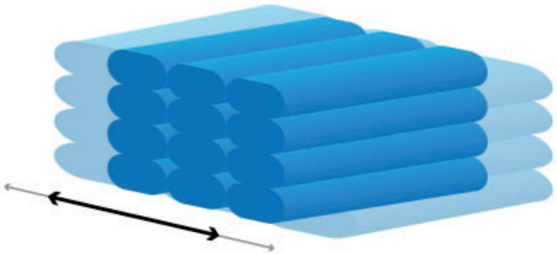


Figure 31: Observed difference in width.

The difference in height shows a significant change in all samples.

Difference in **height (mm)**			
	Before actuation	After actuation	Difference
195 deg, 55 flow	20,08	21,93	9,21%
220 deg, 55 flow	20,06	21,74	8,39%
245 deg, 55 flow	19,91	22,11	11,06%
195 deg, 105 flow	19,94	21,67	8,68%
220 deg, 70 flow	20,02	20,78	3,78%

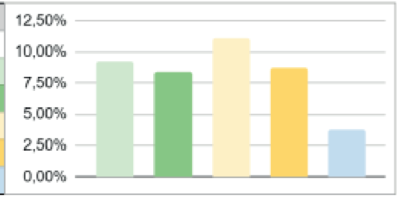


Figure 32: Difference in height.

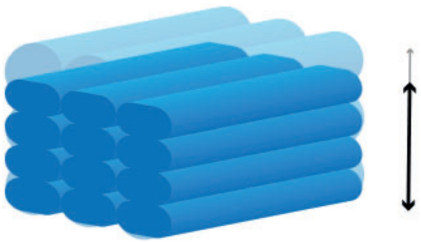


Figure 33: Observed difference in height

It is interesting to see all samples gaining a positive height difference. When however the samples are compared with the length and width a clear distinction can be made between samples that are foamed and samples that are not. Putting these results together the following statements can be observed.

- Samples that have not foamed up still allow for the storage of inherent stress, therefore allowing them to be used in active elements of a 4DP.
- Samples that have foamed up only gain a significant height difference once actuated.

Especially the second point is very useful for this study. Where it was first known foaming restricted shape change to some extent, now the amount of shrinkage is more accurately defined. With a shrinkage of less than 1% over all three setups for foamed cubes the material can now be considered, in its foamed state, as restrictive along the printpath and perpendicular to the printpath. This change in properties can be very beneficial for creating a shape memory object allowing for a relatively positive increase in environmental impact and ease of use. The object can now be constructed with just one type of material, not needing to be separated at the end of life cycle. Additionally, a printer with one printhead could be used allowing for wider adoption of 4DP.

3. CURVATURE CONTROL

Characterising the material helps to create a general sense of how the material behaves. The next question is how this behavior can be utilized within 4DP.
A product requires the use of different forms and shapes as discussed in the previous chapter on 4D printing control strategies & form manipulation. However, to compare with other papers a similar form must be used. In this case, a single curvature.

3.1. CURVATURE THROUGH RATIO DIFFERENCES

As discussed by Wang et al. (2019) curves can be controlled by adjusting the ratio between passive and active elements in an object. The discussed gradual increase could mean a lot to the design of a shape memory object and as such the test was replicated. Where the main question was whether the results of Wang could be replicated. Ten samples were made ranging from a 1:1 ratio, active to passive, to a ratio of 1:10 (Figure 35). The infill type was lines and the infill percentage was at 100%. Each sample code corresponds with the total thickness of the active ply, 1.0 consisting of 10 active layers. The restrictive layer was the same for all samples, at 1.0 mm or 10 layers thick. These samples were actuated in regular boiling water until no more actuation was observed.

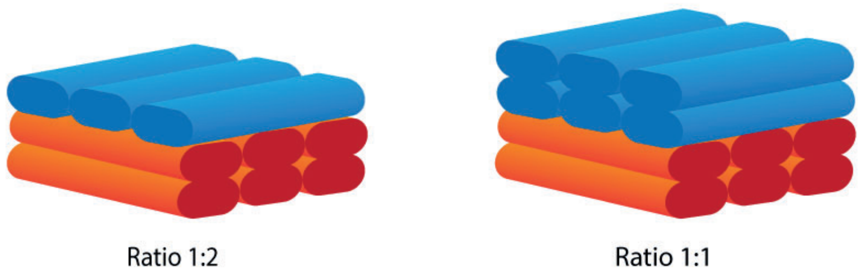


Figure 34: Adding layers changes the overall ratio.

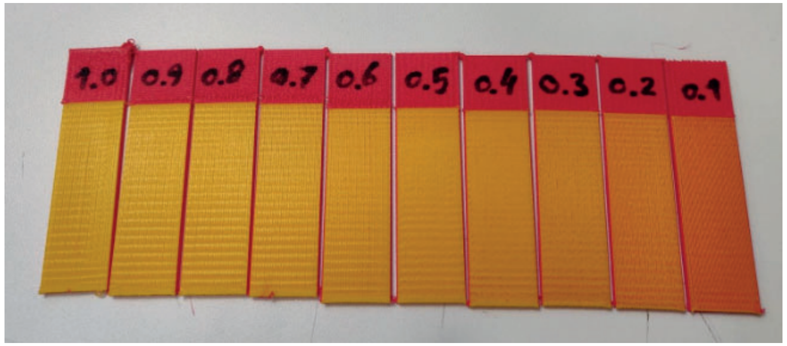


Figure 35: Samples ranging from a 1:1 ratio to a 1:10 ratio before actuation.

Results from this test showed less curvature when the ratio nears 1:1 as seen in figure 36. This contradicts the findings in the paper by Wang et al. (2019) where a ratio closer to 1:1 comes with an increase in curvature. A significant change is seen between samples 0.1 to 0.4. From samples 0.4 to 0.9, no significant difference is seen. Only sample 1.0 differs significantly again. The question thereby arises whether the height has something to do with the outcome, as the ratio was adjusted by adding a layer, therefore the samples varied in thickness.

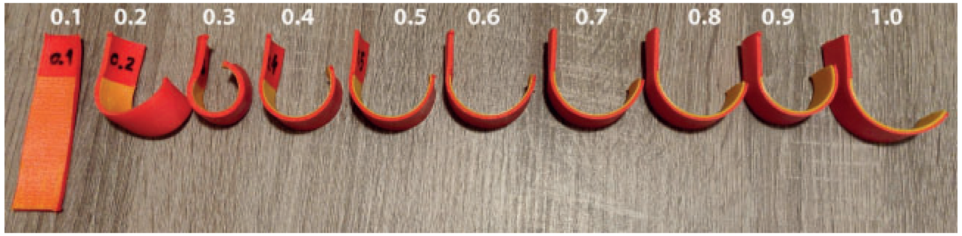


Figure 36: Samples ranging from a 1:10 ratio to a 1:1 ratio after actuation.

3.2. CURVATURE THROUGH INFILL DIFFERENCES

To verify if the total thickness was not the limiting factor another test was performed. This time each sample would still have a similar infill, line pattern, but would now change in infill percentage. The passive layer was kept the same, 1.0 mm thick in total consisting of 10 layers, and the active ply was kept at a total thickness of 1.0 mm also consisting of 10 layers (figure 37).

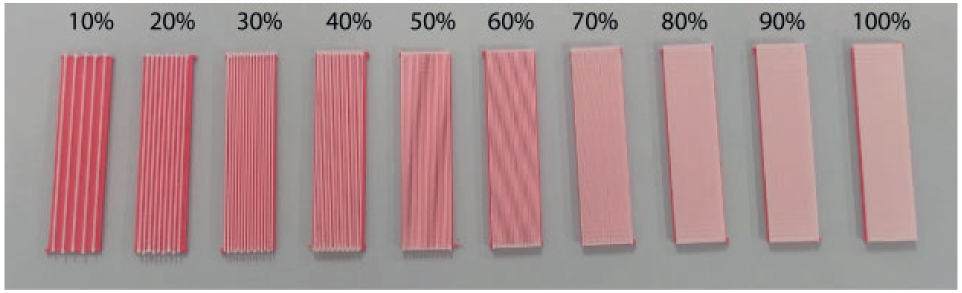


Figure 37: Samples with line infill where the infill percentage ranges from 10% to 100%.

After actuation, a similar trend can be seen, where infill percentages nearing 100% reduce in curvature relative to smaller percentages. It is hard to conclude as to why the samples nearing 100% infill curve less but two separate reasons could be having to do with structure.

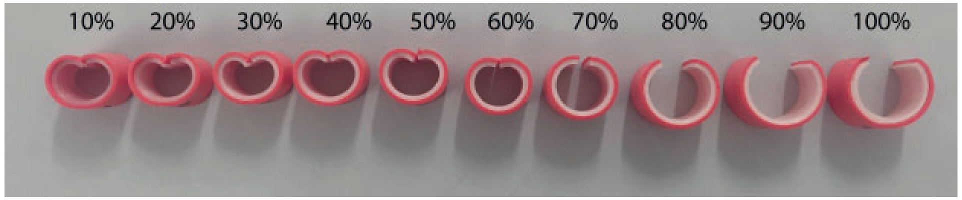


Figure 38: Samples with infill percentage ranges from 10% to 100% after actuation.

For the first test, it seems logical to concentrate more active elements on the layers furthest away from the center, thereby the curvature increases. When doing a regular bend test it can be observed that the surface experiences the highest stresses. By placing SMPs in those regions more actuation can take place as it results in a higher use of stored stresses in the SMP. Placing active elements closer to the center makes for less efficient use of those stresses.

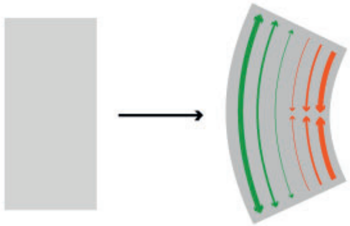


Figure 39: Concentration of stresses and their directions during a bend test.

The second test can attribute its results to infill. A lesser percentage of infill gives more gaps between the SMP, creating a bigger contact surface. It could be that samples with a higher percentage needed much more time to actuate.

Besides the contradicting results from performed tests compared with the paper by Wang et al. (2019), the results do show a very controllable process. Especially the difference in infill percentages shows a good gradient with which the curvature can be controlled.

4. ACTUATION THROUGH DIFFERENT HEAT SOURCES

Within the literature, many studies use hot water as a way to stimulate heat-sensitive SMPs. However, hot water is not the only readily available heat source that can be used. Following the origination of this study; investigating the user interaction with 4DP, it is logical to assume more options of heat stimuli are available. As concluded in the literature research the temperature has a big impact on the speed at which the SMP reacts. This goes to show that temperature and thereby also application of temperature has a big impact on a final product with integrated shape-change. In this test, a heat source, readily available to consumers, is chosen that facilitates the user during shape change, while also creating the most consistent outcome.

A scope is created for heat sources to create a selection of consumer-available appliances. For this scope, the following criteria are set up.

- The appliance must produce heat
- The appliance must have a variable input
  - ~ This can be a target of temperature or amount of time.
- The appliance must be a common household item.

The most common appliances that meet those criteria are:

- Stove
- Water cooker
- Microwave
- Oven

Since the activation temperature is advised to be between 80-100 degrees Celsius (Van Manen et al., 2019) (Wang et al., 2023), the stove is left out. Temperatures on the stove exceed aforementioned temperatures unless a pan filled with water is used, this however fulfills the same function as the water cooker. The way a water cooker can be used also differs. Hot water can be poured on top of the object, from the side, or the object can be dipped in. Each of these could have different results as more or less external forces act on the object. The same goes for the oven where regular ovens have the option to apply heat with or without convection, allowing for flows of air to disrupt the 4DP actuation process. The microwave will require the assistance of a bowl of water, this is because a microwave has hot zones which could result in unwanted local deformation in an object. As such six tests are set up where the variable is the heat source or how it is applied:

1. Oven, without convection
2. Oven, with convection
3. Water cooker, poured on top of the object
4. Water cooker, poured beside the object
5. Water cooker, object dipped in
6. Microwave in conjunction with a bowl of water

For each heat source, three test strips are prepared. These test strips are printed at 0.1 mm layer height, consist of a 1:1 ratio of passive and active elements, and have a dimension of 80x20x3. The active elements of the strips are printed with the line infill type with the direction in the length of the part. The passive elements are also printed with the line infill type but oriented perpendicular to the active line direction. Before use the oven is preheated.

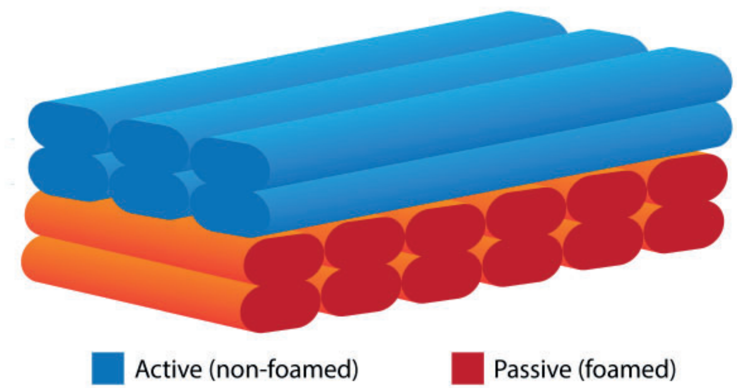


Figure 40: Active and passive elements in a designed shape-changing object.

Criteria for choosing the right method of activation are consistency of form and ease of use. Ease of use includes the chance for a user to apply an error in the process, thereby being dissatisfied. These criteria are formulated from Q1.2 and Q1.3, trying to create a consistent product that satisfies the user.

Results

The first test was done with the oven without convection. The temperature was set at 100 degrees Celsius. This temperature target is chosen as most consumer ovens cannot heat below 100 degrees Celsius. The samples were put in the oven for 2:30 minutes. The outcome is consistent among the three samples. The process was also easy to follow and set up as there were few actions to set up the actuation. Namely, the oven had to be preheated and a tray had to be prepared with the samples.

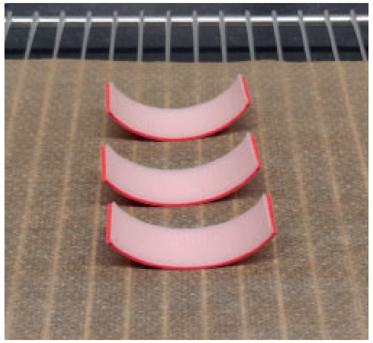


Figure 41: Samples after actuation in the oven without convection.

The second test was again with the oven, this time however with convection. The samples were again put in the oven for 2:30 minutes. The samples form a nearly closed circle, showing much more actuation when compared with the samples in the oven without convection.

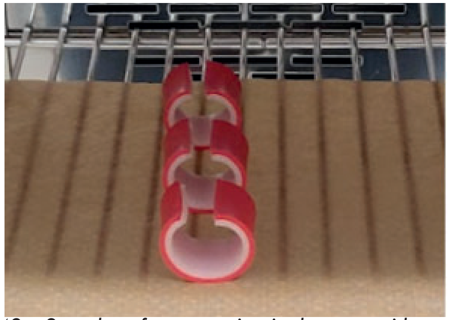


Figure 42: Samples after actuation in the oven with convection.

Next up are the water cooker samples. The first of these is with hot water poured on top of the samples. The samples lay for a total of 2:30 minutes in the hot water. The samples that had the water poured on top clung together as soon as the samples touched each other. After taking out the samples they are still firmly gripped together.

Figure 43: Samples after actuation with hot water poured on top.

The second water cooker test involves pouring hot water from the side. These samples rotated a lot in the pan when the water was poured in. Again after touching one another the samples stuck together with a firm grip.

Figure 44: Samples after actuation with hot water poured from the side.

The last water cooker sample involved pouring the water into the pan and then dipping the samples one by one. This time the samples did not cling together. During all of the hot water pouring and dipping the reaction of the 4DP mechanism was quick (15-30 seconds), all reaching their final form at about 1 minute in the hot water.

Figure 45: Samples after actuation by hot water dip in.

The last of the heat source tests was the test with the microwave. This time the sample was placed in a microwavable pan filled with water. The pan was then put into the microwave and heated until the water started boiling. The outcome is very uniform among the samples. The process required the user to keep a close eye on the microwave to avoid overheating the pan.

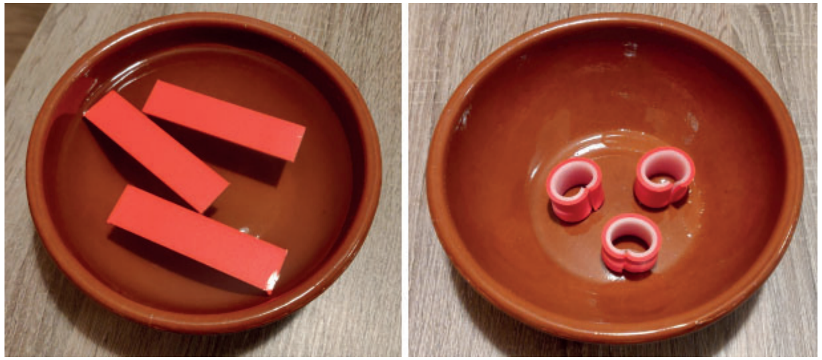


Figure 46: Samples before (Left) and after (Right) actuation by using the microwave.

Testing showed that samples activated using hot water, either via a water cooker or in a microwave, tend to actuate fast (15-30 seconds). Samples used in the oven are much slower to react. This can be attributed to the heat transfer difference between water and air.

When taking a look at consistency samples actuated with poured water fall off. These samples were very inconsistent due to the ability to cling together. If these samples were to be put alone in a pan and actuated it would still result in consistency. This can be viewed with the dipped samples as samples were not all orienting in the same direction, resulting in slight inconsistency among samples. Another difficulty was taking the samples out of the hot water. A wooden spoon was used for this, however this did impact the form of the product. Letting the samples cool down with the water was also an option, although this removes the option to take the samples out when they are actuated for 50% of their full movement.

The microwave test showed some difficulties regarding ease of use. Due to the safety factor, not wanting the water to boil over and burn the user, the ease of use for a microwave is not there. The samples in the oven displayed a slower actuation over the samples. This slower actuation can result in a more consistent process where not only the object has a final state but also multiple possible states in between. This leaves a lot of possibilities to design with and therefore can be very beneficial.

5. STRUCTURES WITH SHAPE MEMORY

Besides slicing settings, material properties, and type of heat source actuation it is also possible to influence the behavior of 4DP actuation through the structure. This can help by creating options for various designs, in turn creating a wider option list to facilitate the user (Q1.2.). To test what kind of effect structure can have on the design of a 4DP object a closer look was taken at the effect structure has on shrinkage, the main factor in 4DP. Three types of structures are examined in combination with one structure as the control group. Each of the samples is printed at 0.1 mm layer height and starts with a dimension of 150x6x6 mm. The activation method was an oven without convection at 100 degrees Celsius.

The control group is a fully active sample. It is built up with line-type infill at 100% and with the infill's direction in the beam's longitude. Once this sample is actuated it shrinks by 22,2%.

The first structure is inspired by Nam & Pei (2019). This structure has a waving pattern. By alternating curves it is possible to shrink the total length of the beam, thereby getting a uniform shrinkage. A waving pattern does make the total length shrink by 10,1%.

Figure 47: Wave structure sample.

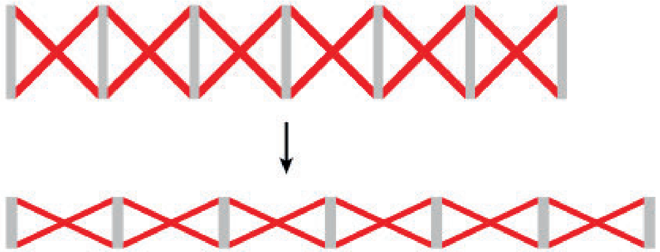


Figure 48: How a scissor structure moves when actuated. White is non foamed PLA and red is foamed PLA.

The second structure seeks to expand instead of shrink. This is achieved through the employment of scissor-like structures (figure 48). The active elements (in white) contract, making sure the passive elements change angle and thus increasing the total length.

This sample had a 4% increase in length after actuation. As seen in figure 49 the sample had some defects during actuation which led to being unable to use the sample to its full potential. These defects shortened the sample and thus can be improved to increase the total gained percentage in length.

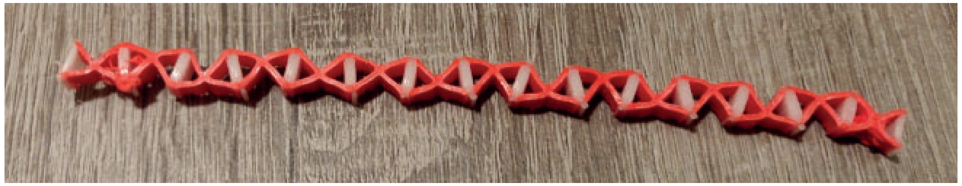


Figure 49: Scissor structure after being actuated in an oven.

The last structure type was a sandwich structure. This time a restrictive element was placed on the top and bottom of the active element (figure 50). The passive layers were each 0.2mm thick. This thickness was chosen as it can be used as an outer shell, possibly inheriting the 4DP capability while having a different-looking surface. The shrinkage factor was 18,30%.

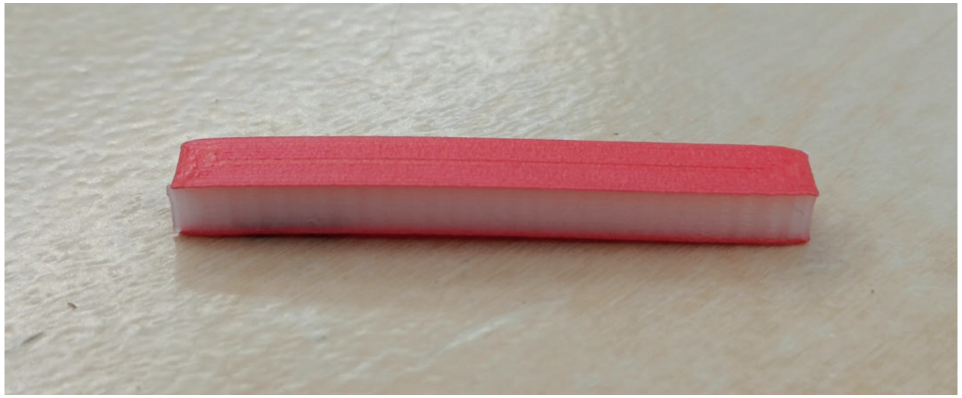


Figure 50: Sandwich structure after actuation in the oven.

During the actuation of the sandwich sample, not all samples came out straight. This curvature was undesired as it was not planned, thereby creating an inaccuracy. Although each layer was printed at the same settings, the curvature still occurred. This led to the question arising why some of these samples curved. The only possible difference could be a heated bed, where sample 1 started on a cold bed and the next started on a bed that was warm from the previous print.

To make sure the bed temperature was the factor causing this a test was performed with bed temperatures ranging from 10 to 60 degrees Celsius. This test was also performed on a control group which consisted of the same dimensions but without the restrictive layers on the top and bottom. To measure the amount of curvature the sample was laid on the table with the curve facing up (figure 52). With a pair of calipers, the gap from the table to the highest spot of the curve was measured. This resulted in the following graph (figure 51).

The results show that the control group experiences the least amount of curvature distance at 60 degrees Celsius, for the sandwich structure the temperature with the least distance is 30 degrees Celsius. This observation can be useful when using a sandwich structure.

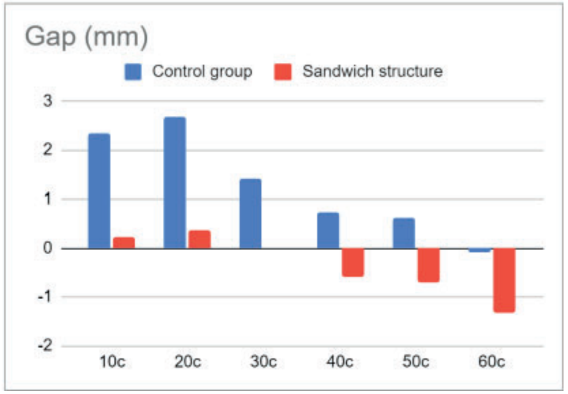


Figure 51: Amount of gap between the highest spot of a curved sample and the table.

Figure 52: Measuring the gap between the sample and the table with the back of the calipers.

6. MOUSE TINKERING

Another method of calibrating the system is by replicating an existing object. By checking for repeatability and resemblance of form a conclusion can be drawn whether the process is calibrated right. To test this a computer mouse was chosen. This product provides many challenges like double curvatures and textures. These double curvatures are chosen as they require precise programming of the material to be replicated.

Out of this testing, four prototypes came forth (Appendix A). The produced objects all had the same form, this was done to see the effect of 4DP parameters. This form was obtained by making a computer mouse in CAD and flattening the surface. The surface is flattened to help the object be stackable, thus increasing the transport efficiency and eventually helping decrease the environmental impact. Flattening the surface also resulted in a visual guide, showing on the flattened object how much an area had moved from the original shape.

By tinkering with the mouse three useful insights were gained. The first insight is the difficulty of predicting double-curved surfaces. Double curved surfaces need multiple active elements creating shrinkage in different directions. Tuning one of these elements results in over-compensation by the other active element, making it hard to fine-tune a double-curved design.

The second insight is the use of a deformation graph. Where some strategies reviewed in the literature require a lot of computational power, the deformation graph does not. Although the deformation graph does not give an elaborate prediction of the outcome, it does show in what direction shrinkage has to happen. Thereby it is a tool useful for placing printpaths.

The last insight is added texture through infill variation. By using different types of infill on the foamed PLA there is an option to create different textures. These variations in infill impact the design minimally. Thus this can be a useful option for a designer to create local texture differences.

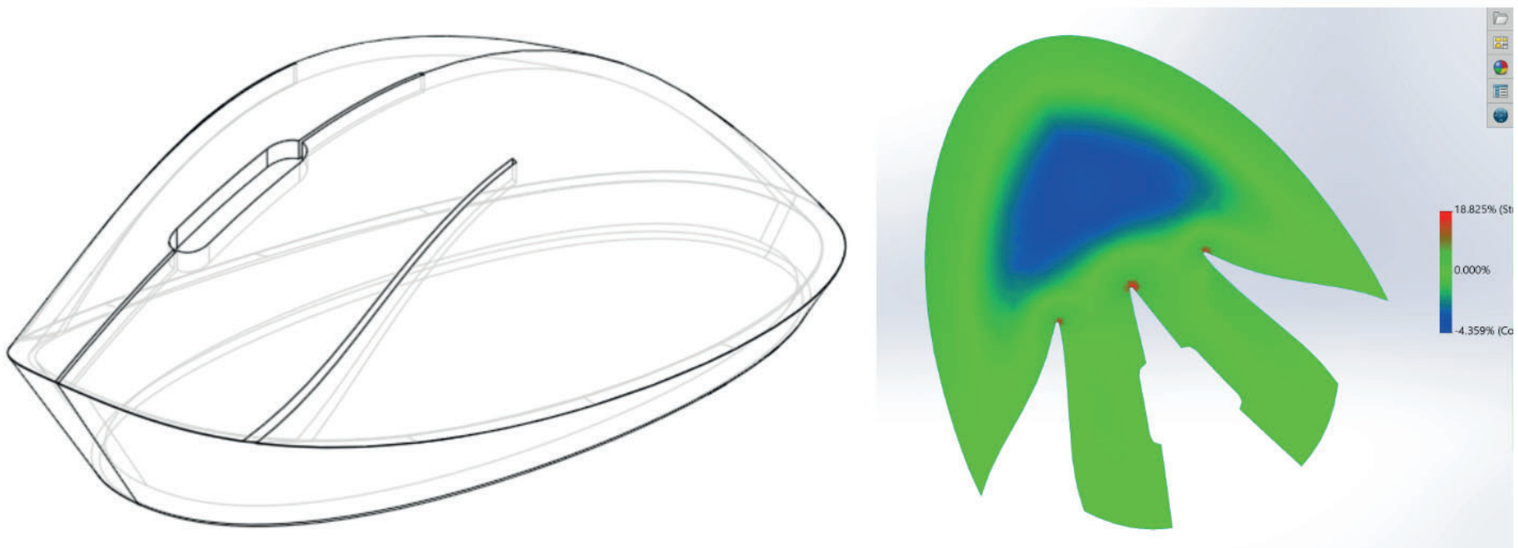


Figure 53: 3D shape of the mouse (Left) & flattened out top part of the mouse with deformation hotspot (Right).

7. CONCLUSION

To summarise the characterisation of the material has calibrated LW-PLA with the current setup. Being able to reduce the amount of shrinkage means that it can be used efficiently as a passive element within a shape-changing product. Printing with the same material yet being able to change the structure of the material on a micro-scale helps reduce the environmental impact of the material. The expansion of the material in the z, or height, direction is something to keep in mind when designing with LW-PLA.

The amount of curvature is dictated by the amount of shrinkage happening within the material. It is however difficult to get accurate predictions on the degrees of angle. What can be seen is a correlation taking place, where more active elements create less curvature, be it via ratio or infill percentage. A more massive object is harder to bend during actuation.

How the object is actuated plays a big role in the outcome of the object. Varying sources create different types of heat applications, indirect or direct. Having a less direct application such as the oven slows down the process of actuation. Another benefit is that the oven creates an environment where the user can interfere much less with the product, resulting in a more consistent outcome. Having a process that is easy to follow and creates a consistent outcome is what helps facilitate the user doing the post-processing themselves (Q1.2.).

Varying structures help the designer by giving them options to design with. Although many more structures can be explored, the structures tested show that partial actuation (reducing total shrinkage from 22,2% to 10,1%) and even expansion (4%) can be achieved. The tests also help create consistency by tuning the heated bed parameter.

Applying shape change to a mouse has resulted in an object that can be shipped flat but once actuated forms in the right shape. This test showed that it is hard to deal with double-curved surfaces and that although printpath dictates the direction of actuation, varying parameters such as ratio and infill type play a big role during actuation. Interesting patterns can be created by changing the type of infill. These different patterns or textures can be useful to a designer when creating different types of grips in an object.

The result of all this tinkering has led to a designer guideline (viewed below) that can be used to create a 4DP product. In addition to the literature research performed in the previous chapter, these outcomes should be sufficient to create an object that can be tested with users and formulate an answer to Q1.3. and partial answer to Q1.2.

Guideline during the design of a 4DP product:

Accuracy can be improved by:

1. Creating a design without curves.
2. Limiting user interaction with the product during the activation step.
3. Using the oven without convection as a heat source.

The following actions can be expected of LW-PLA during the activation step:

1. Non-foamed PLA shrinks in the longitude of the print path and expands in perpendicular directions.
2. Foamed PLA does not shrink in the longitude of the print path but does expand in height.
3. The use of structures can alter the outcome during the activation step, choosing a linear infill results in the most predictable outcome.

1. SWOT ANALYSIS

To create a concept first the advantages and disadvantages of 4DP within FDM as a technique must become clear. To encapsulate this a SWOT diagram is made. This analysis will help in the search for a viable concept.

As seen in the chart one of the core components of 4DP FDM is scalability in combination with personalization. It is good to dive deeper into personalization as other plastic-producing techniques can produce parts cheaper when produced in large volumes. What these techniques lack however is the customisability that 4DP can offer.
Something that also has to be addressed in the final design is safety. This factor mainly encapsulates the safety of the user during the actuation of a 4DP object as temperatures needed for actuation can cause burns.

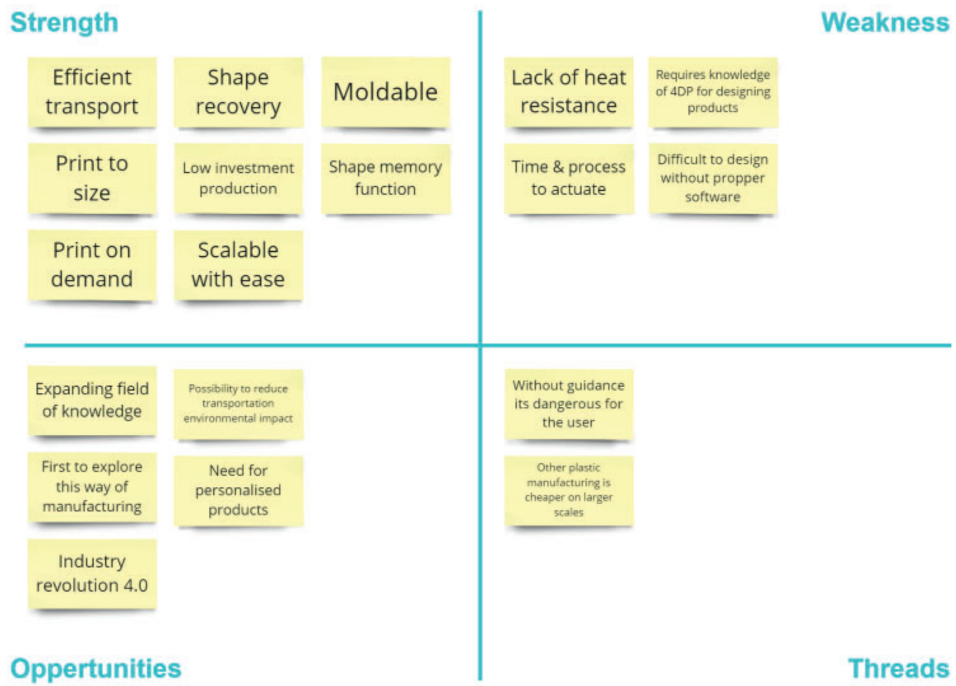


Figure 54: SWOT analysis of 4DP as a technique.

2. PRODUCT JOURNEY

The production and distribution of 3DP products can vary a great deal. Products can be made in a central place and shipped out or products can be made locally. Where the customer buys a product also matters, therefore a scope is created through the product journey.

The product will be produced beforehand in local factories. This will make the product ready for use out-of-the-box. This also makes sure the amount of variation between products is limited as printers and print conditions are kept the same. After production, the product is shipped to the store where it is sold to the customer. The customer takes it home and shapes the product into the final desired form or size. At the end of the life cycle, the product can be industrially composted as it is all made out of the same material; LW-PLA. Reducing the environmental impact of the produced product.

The blue segment is the focus of this study where the question is examined how a user can use a shape-changing product through proper instructions and whether the outcome thereby is accurate or not.

3. USER SCOPE

The user for which this product will be created will be an adult user, this is to not limit the use of 4DP in common areas. These common areas have yet to be explored, high-tech areas on the other hand have seen some papers on applying 4DP. This user also has enough knowledge on how to operate appliances at home. Being able to think rationally and operate appliances safely. This ensures that 4DP objects can be used by a common user, as stated in the main research question.

Although the average user is concerned with safety they are also curious. This curiosity will have an impact on the design. If for example a consistent outcome is desired the user must not be able to interfere. Handling curiosity can be done through proper guidance or limiting the user.

The user has a problem in that he/she has an object that is not easily fixed by use of regular methods. This means, as an example, that the user will not cut into his chair to fix it to the appropriate height. If the chair has a built-in latching system, however, the user will be able to get near to his ideal length.

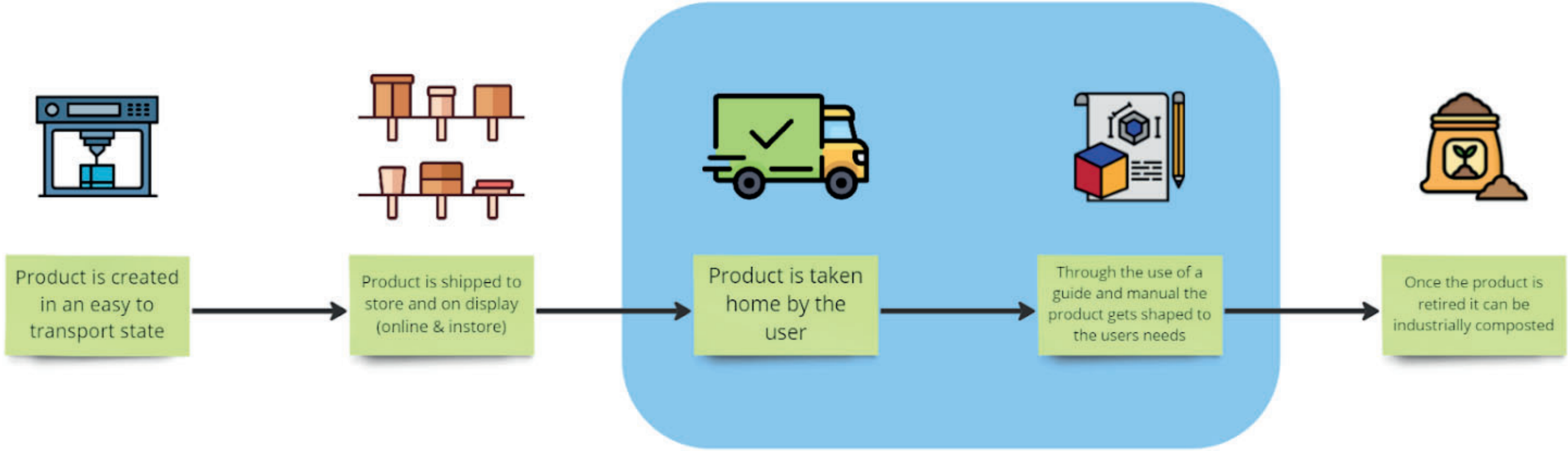


Figure 55: Product journey from manufacturing to end of life.

4. CONTEXT SCOPING

Through the use of a mind map three core features of 4DP are depicted. These core features are then extrapolated giving a more abstract sub-topic. Next, potential areas or areas within the sub-topic are thought of, stimulating out-of-the-box thinking. Within the mind map the ideas do not have to fit 4DP, this way new areas for concepts can be gained. The way the mindmap is built can be seen in figure 56.

The three sub-topics are; gradual change, semi-permanent change, and expansion & contraction. Gradual change focuses on continuous change allowing for adaptation to a scenario or setting. This category focuses more on the impact of the outside world, as it is that world that brings stimuli to actuate the 4DP product.

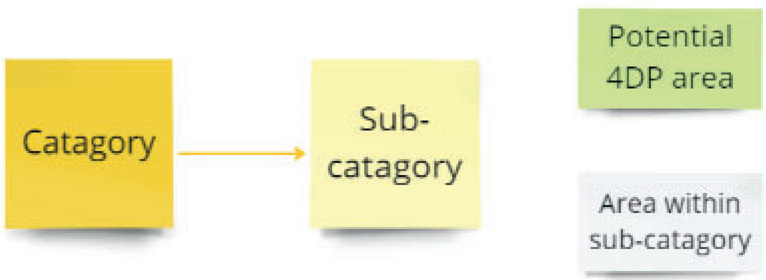


Figure 56: Mind map buildup.

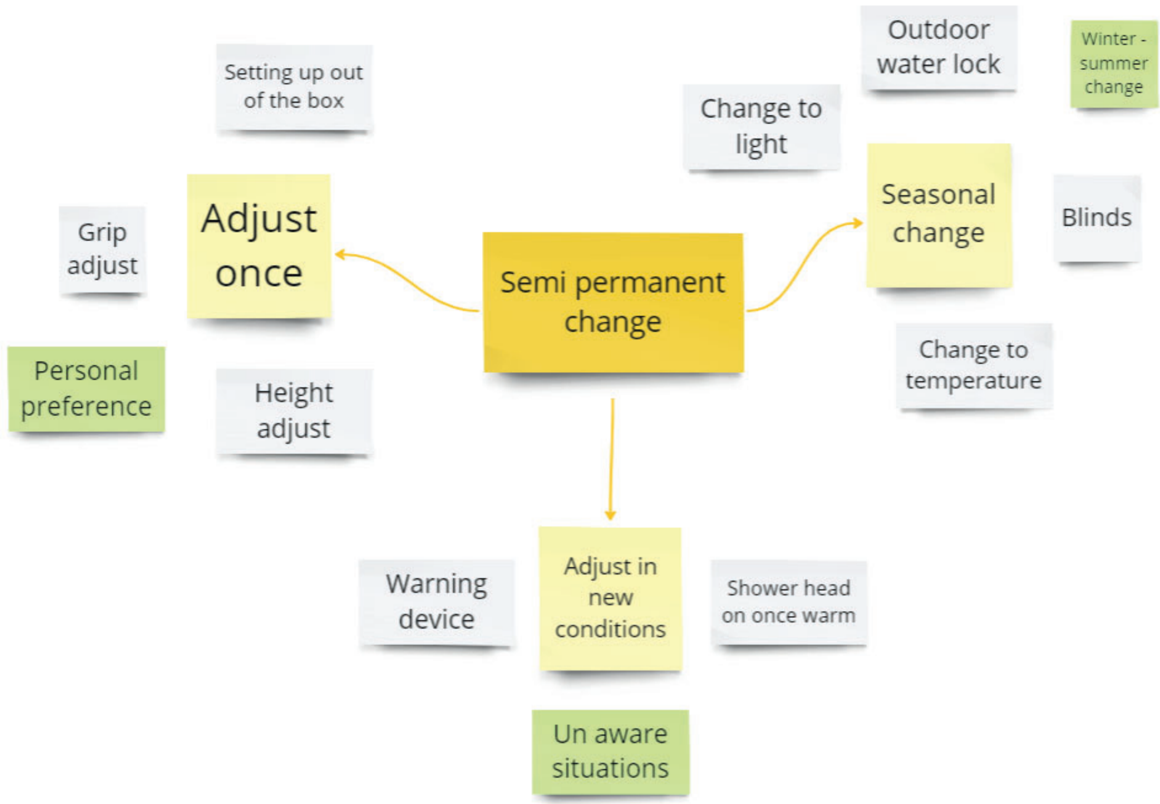
The second category, semi-permanent change, focuses on the usability of an object. Where if an object is used the user would like to customize it to his/her needs. If the user outgrows the product or the product moves to a different user the needs can then again be altered hence semi-permanent change.

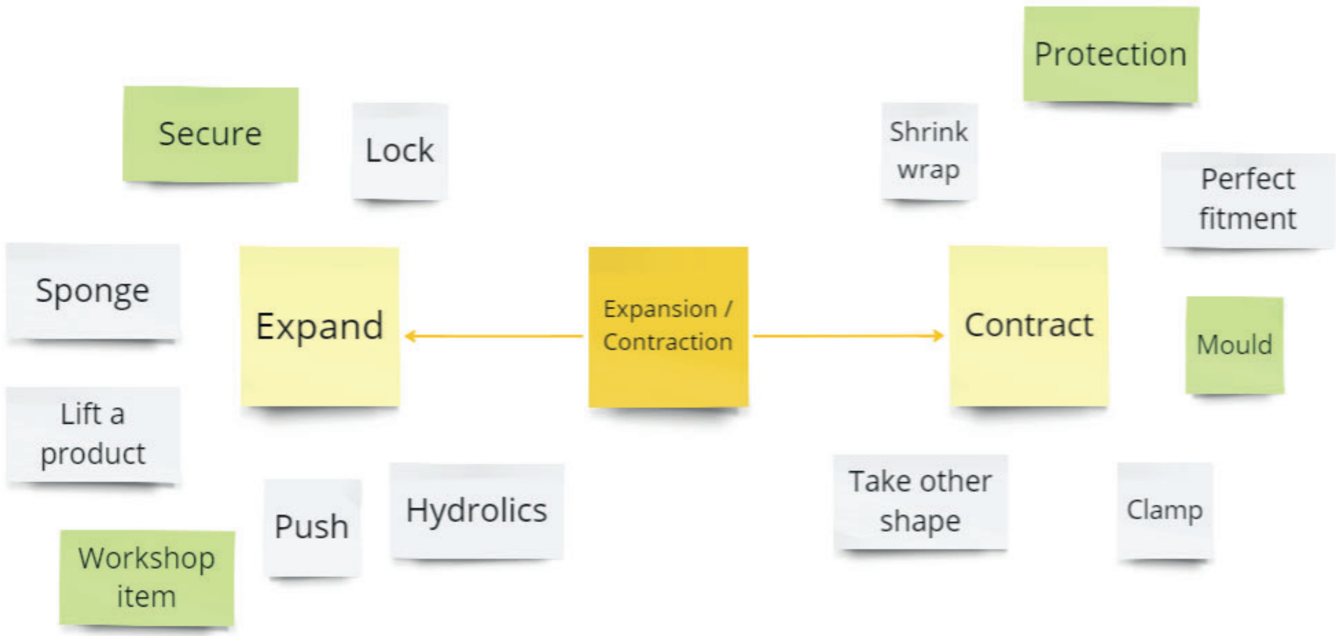
The third category, expansion & contraction, focuses on the core ability of 4DP. It takes a look at how current products apply expansion and contraction, and whether 4DP could be introduced into those areas.

Through the use of these three categories, an onion model is created with 4DP at the heart. The next layer consists of user needs, and the last layer takes a look at environmental conditions.

Figure 57: Onion model of 4DP.


Art
Round shapes & edges
Rust
Feel without sight
Mass dependend
Trains
Colour change
Erosion
Mining
Cars
Rollercoaster
Accelleration
Gradual change
Heat & stress forces
Water through a landscape
Wear and tear sign
Time dependend design
Showering
Cooking
Braking
Warming up
House utensils
Room heating
Daily cycle
Danger prevention
Routine


Semi permanent change
Adjust once
Setting up out of the box
Grip adjust
Personal preference
Height adjust
Seasonal change
Outdoor water lock
Winter - summer change
Change to light
Blinds
Change to temperature
Adjust in new conditions
Warning device
Shower head on once warm
Un aware situations


Protection
Secure
Lock
Shrink wrap
Perfect fitment
Sponge
Expand
Expansion / Contraction
Contract
Mould
Lift a product
Take other shape
Clamp
Push
Hydrolics
Workshop item

5. BRAINSTORMING

A brainstorming session will help gather possible product directions, generating an answer to Q1.1. After the brainstorming session, the ideas are grouped. This grouping of ideas makes for an easier oversight of the type of products.

The first group in red is about customizing a product for the user. Making sure to get personal touches into the product, thereby creating a single product that fits nearly everyone. This group is interesting as product designers have always had to make concessions when it comes to designing for the masses. Applying 4DP to a product could help designers go from a product that helps p90 to a product that helps p99.

The yellow group presents furniture products. These products can be found in and around the house and mainly focus on smart packaging. Transporting these items in their flat state can benefit the user and supplier. A moulded dish rack for example can be efficiently stacked to go from the factory to the store. Once the user buys one however he/she has to transport this home. Since the user most likely buys one or two of these there is no way to stack other bought products efficiently. When however the product is sold to the user as a flat pack it is much easier for the user to transport it home.

The third group is the green group, this group consists of products that form around other objects to create an object that fits with multiple products. A good example is the phone holder in a car. Not only do different types of phones have to be able to fit but there is also the matter of securing the holder to the car. Finding a perfect match between two categories of products, in this case, cars and phones can be very hard.

The next group is the purple group. This group consists of lighting objects such as lamps and shades. A user usually adjusts the specifics of a light source once. After which the light is put on and off. This is a perfect opportunity for a technology that is semi-permanent, such as 4DP. For this reason, 4DP can be beneficial to this category, changing the light source to the setting it is in.

The fifth and last group is the blue group. This group consists mostly of gadgets that solve minor problems. Although this group did have its uses within the process, leading to other ideas, it does not show 4DP as a valuable technology.

Out of three categories found in literature in the section Application & Perspectives of 4D printing two categories are mainly found within this brainstorm session; flat packing design, and custom fitment. The third category, energy harvesting, appears to show less when brainstorming for user products. This is logical as this is more of a high-tech category, where user products usually on average require less technologically advanced solutions.

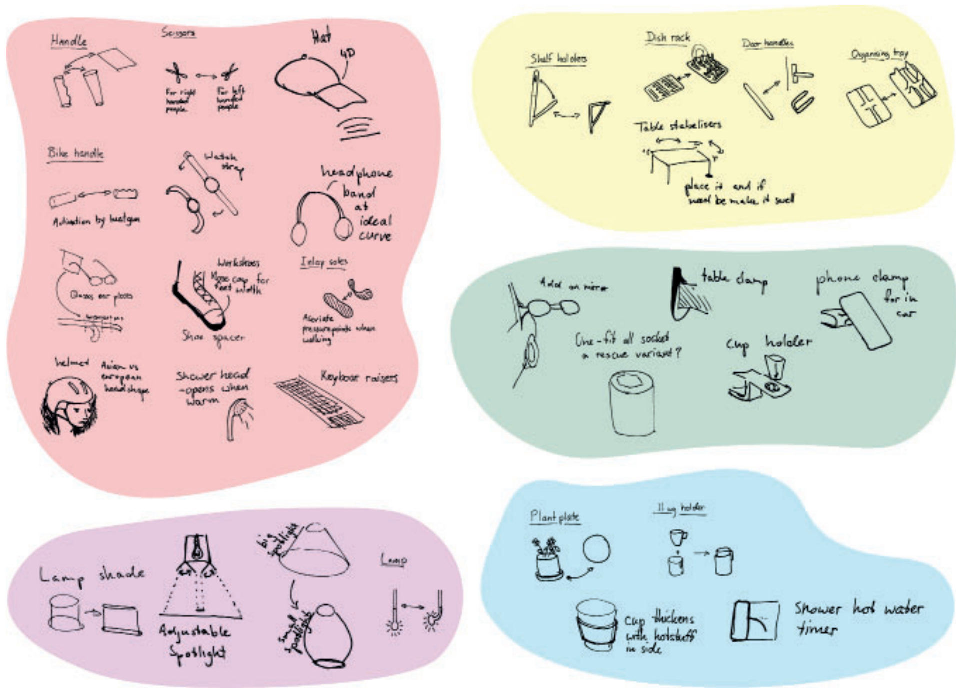


Figure 58: Brainstormed ideas.

6. SCOPING DOWN ON 3 CONCEPTS

The brainstorming session brought numerous applications for 4DP to the table. To make a selection some criteria were set up. These criteria consisted of requirements and wishes. Some key requirements have to do with temperature. Because the stimuli used for the 4DP process is the temperature it is necessary to keep the use case of the design within the limits. The limit is set at 55 degrees Celsius as this is the glass transition temperature of PLA, thus the object could deform in an uncontrolled manner if the temperature were to be higher.

The second requirement addresses the ability of shape change to fit to many different shapes and sizes. To show that shape change can be a valuable technique, its strong point must be addressed. Using a step-less design allows for 4DP to fit many scenarios. Where current designs are mostly limited by steps 4DP is not.

The object also has to be printed to be able to test the object. Therefore the current setting must be taken into account. For this setting, it means the object has to be printable on an Ultimaker S3 and as such cannot exceed the build volume of this printer.

Requirements

1. The temperature during the use of the object can not exceed 55 degrees Celsius.
2. The object must use a step-less adjustment method.
3. The object must be manufactured on an Ultimaker S3.

As the reason for this study is to see whether 4DP can be useful in consumer devices, it is important to make the user prefer 4DP over another technique. Therefore 4DP must be the most logical option for the problem in the product. If another solution can achieve the same result, regarding reliability and user needs, there is no strong case for 4DP to resolve this problem. How a product applies 4DP can differ, thereby the useful amount of applied 4DP can differ. As such this is a wish on which products can be scaled.

The user is central to the main research question. Where the product has to cater to the needs of the user. Therefore the ideas are measured on how many users can use the object and if their needs are met.

Last but not least the product also has to be bought by users. Users find it important to address the looks of a product as this displays their personal preference. Although a product can be redesigned to be more aesthetically pleasing, it is still important to have an object with a pleasing exterior to start with. This will help to make a realistic case once the product is tested with users. The wish therefore is still incorporated in the selection process but not as important as the other wishes.

Wishes

1. The object shows the best application of 4DP.
2. The object allows a wide range of users to use the product.
3. The exterior of the object looks pleasing.

After running the requirements and wishes through the brainstorming session, three ideas came out. These ideas were a lampshade, spacers, and a pair of glasses. The lamp shade caters to users by being able to address different room types. The shade can be opened up to pass through as much light as possible, or it can remain closed, creating dim lighting.

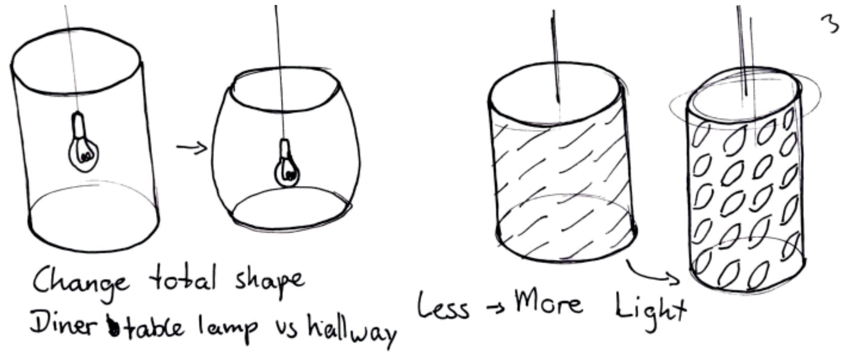


Figure 59: Lamp shades

The spacers cater to desk products where a user can change the level of their utensils to their liking. An example of this is a keyboard, with the integrated spacers a keyboard can be either elevated or not elevated. A 4DP spacer can get a height in between, allowing for more users to use current desk appliances.

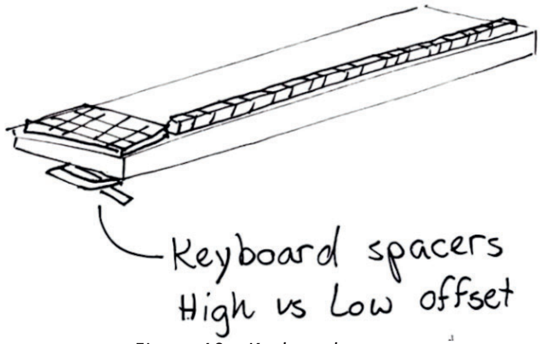


Figure 60: Keyboard spacers

The third application is a pair of glasses. Regular glasses have a fixed length, users do not have a fixed head dimension. This would allow a user to buy a product that can be very customized to his/her dimensions. Glasses already are a highly customized product, catering to different eyesights, therefore the application of 4DP is very fitting.

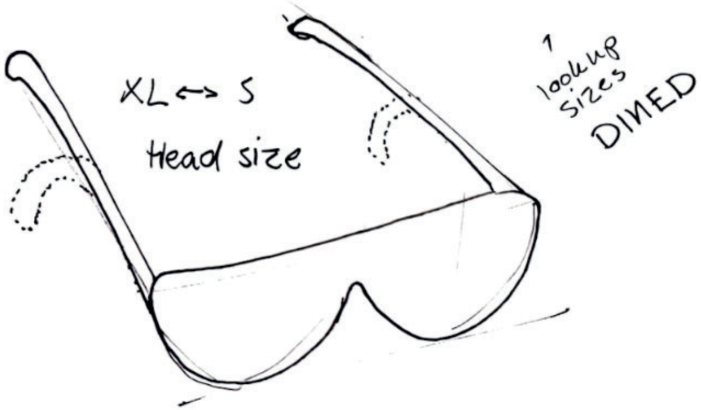


Figure 61: Sizable glasses

To better decide between the three concepts an Edison profile was created for each concept. The profile consisted of the following questions:

- How easy is it for the user to actuate the product?
- Does the design incorporate a mechanism for users to be able to check their preferred size or customization goal?
- How novel is this concept?
- How big of a problem does the concept solve?
- How much design freedom is there within the concept?

Ease of actuation is crucial for user acceptance and widespread adoption. If a product is challenging or complicated for users to activate or manipulate, it may deter them from using it. Ensuring a straightforward and user-friendly actuation process enhances the usability and appeal of the 4D-printed object.

Allowing users to check and select their preferred size or customization goal contributes to a more personalized and user-centric experience. It addresses the diverse needs and preferences of users, making the product adaptable to various requirements. Incorporating a mechanism for customization enhances the product's versatility and utility.

A novel concept in 4D printing signifies advancements and contributions to the field. Understanding the degree of novelty helps in positioning the product within the broader context of 4D printing technology and identifying its unique selling points.

Evaluating how significant of a problem the concept solves is essential for determining its real-world applicability. If the 4D-printed product addresses a substantial problem or fulfills a critical need, it is more likely to gain traction and make a meaningful impact. Question 4 thereby helps prioritize concepts that have the potential to bring about positive and practical changes.

Assessing the design freedom within the concept considers the level of flexibility and adaptability the concept provides to designers and users. A concept that allows for diverse design possibilities offers more creative freedom, enabling the development of unique and tailored solutions. Therefore the last question encourages exploration and innovation within the 4D printing space.

In summary, these considerations focus on ensuring user-friendly experiences, adaptability to diverse needs, technological advancements, practical problem-solving, and creative freedom within the realm of 4D printing. They collectively contribute to the evaluation and development of impactful and user-centric 4D-printed products. Based on the Edison profiles the temple is chosen.

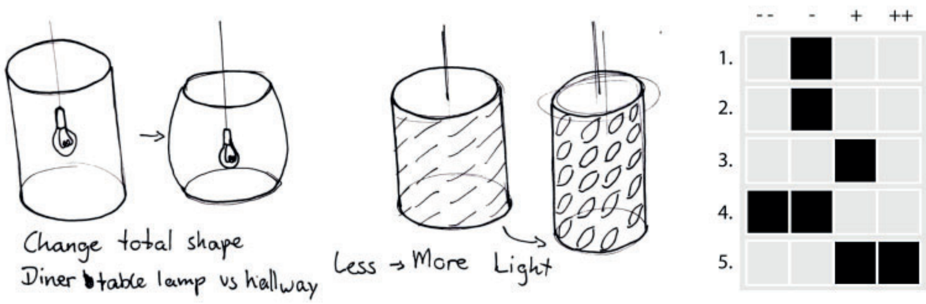


Figure 62: Lampshade rated by an Edison profile.

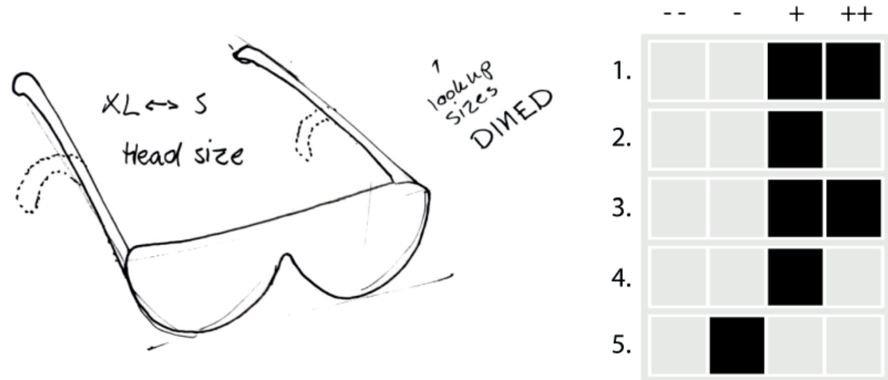


Figure 64: Resizable glasses rated by an Edison profile.

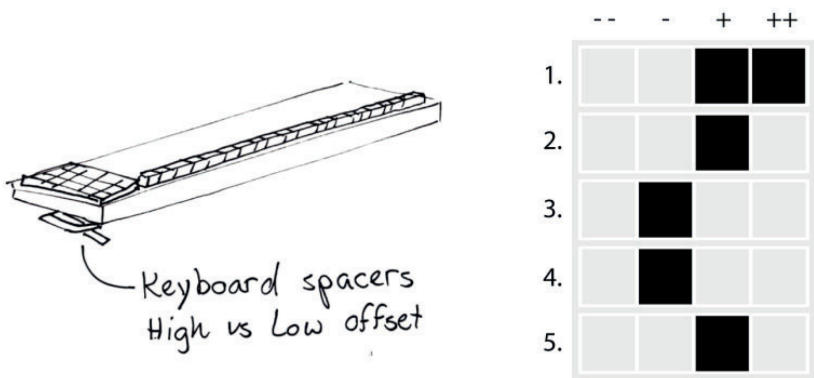


Figure 63: Keyboard spacers rated by an Edison profile.

7. GLASSES TEMPLE PROTOTYPING

Now that a concept is chosen there are still some leftover questions. The first of which is the range of required size. To get to the correct length a few opticians are referred to. The first of which is Zonnebrillen.com (n.d.), which states their glasses come in different sizes of temples, where the most common sizes are 140 to 150 millimeters. Visio-Rx.Nl (n.d.) states that temples can range from 125 to 150 millimeters. Another interesting thing stated on their site is that the size of the user depends on which type of glasses they can buy. In other words, the user is limited to a selection of glasses of his size and can only search in that direction. This is again a strong suit for 4DP, catering to users by letting them browse through all types of glasses as size does not matter.

Taking a look at the total length difference, while catering to the largest group of users, shows that a range of 125 to 150 mm has to be reached with the temples. This accounts for a difference of 16,7%. This number can be reached with ease by use of 4DP, where 4DP can achieve a difference of at least 22,2% in testing.

7.1. FLATPACK TEMPLE

The first concept was to show the idea can function and that 4DP can also create perfectly straight actuating shrinkage. For this prototype, the length was adjusted with 4DP as well as the curvature of the ear segment. The middle segment in white was scaled to the correct length to acquire a difference of 25 mm when fully actuated. The change in this prototype is measured by the use of external measuring devices used by the user. This gives that the prototype can have a cleaner look as no additional features are needed.

Figure 65: Flatpack temple as seen in the CAD software.

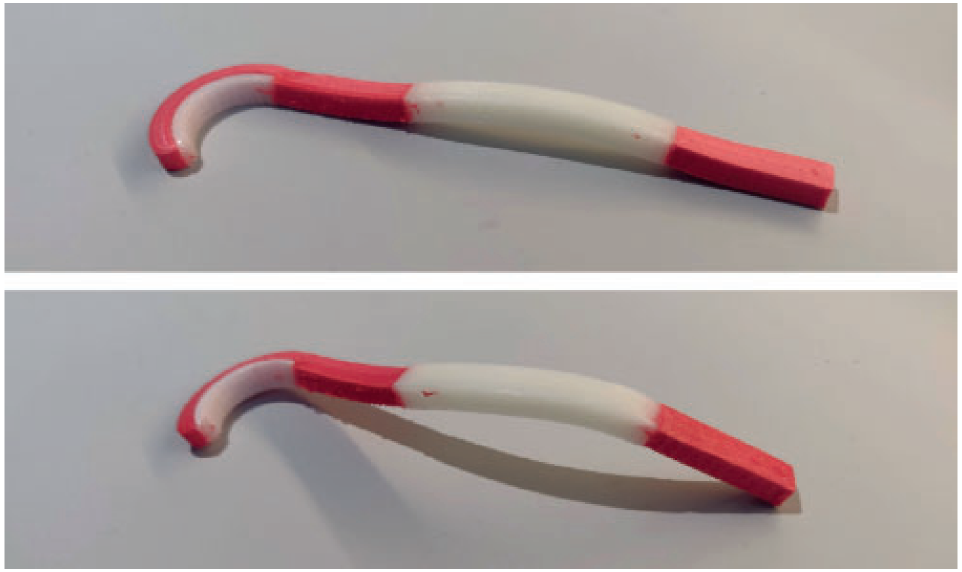


Figure 66: Actuated flatpack temple after 3 minutes and 30 seconds (top) and 7 minutes (bottom).

After actuation two things became clear. The first is the actuation in the earpiece cannot be actuated before the total length changes. Although this is logical the intent was to create a small strip of actuated material (white in figure 66) that actuated earlier because heat can more easily reach the core, of this active element, due to a smaller distance.

The second item that became clear was the undesired curvature. The prototype was designed to actuate in a straight line however the result came out different. This change in direction can be attributed to different settings for the first layer. This meant that the first layer was printed at 0.27 millimeters instead of 0.1 millimeters. As such this was enough of a difference to make the prototype curve.

7.2. RECIPE-DRIVEN USER ADJUSTMENT

The second test questions whether creating a recipe to adjust the temples can be a viable option. This recipe entails how long the user has to put the temple into the oven for it to actuate. Because the timing varies per thickness the dimensions were taken from the flatpack temple. This second test could therefore also be applied to the flatpack temple.

To see what the ratio of change is over time a test was set up. In this test 18 samples were put in the oven. After each half a minute a sample would be taken from the oven. These samples were printed with line infill at 195 degrees Celsius and had a layer height of 0.1 millimeters. The samples were measured before and after being put into the oven, resulting in figure 67 (Appendix B).

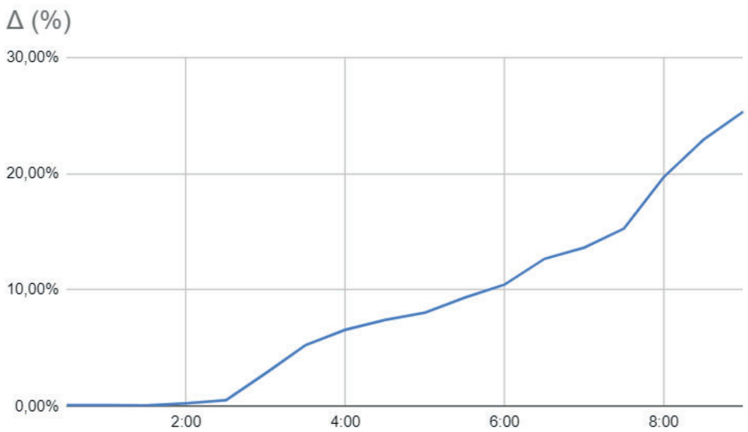


Figure 67: Shrinkage in length (%) over time.

This graph shows that the required length is reached at roughly 7:30. Another valuable insight is that the shrinkage process needs some time to heat up, therefore the actuation starts from minute 2:30. The process shows a linear reaction. This linear reaction is useful for the user as it means the user can expect a process to happen at one speed. Therefore the user can more accurately guess what will happen next.

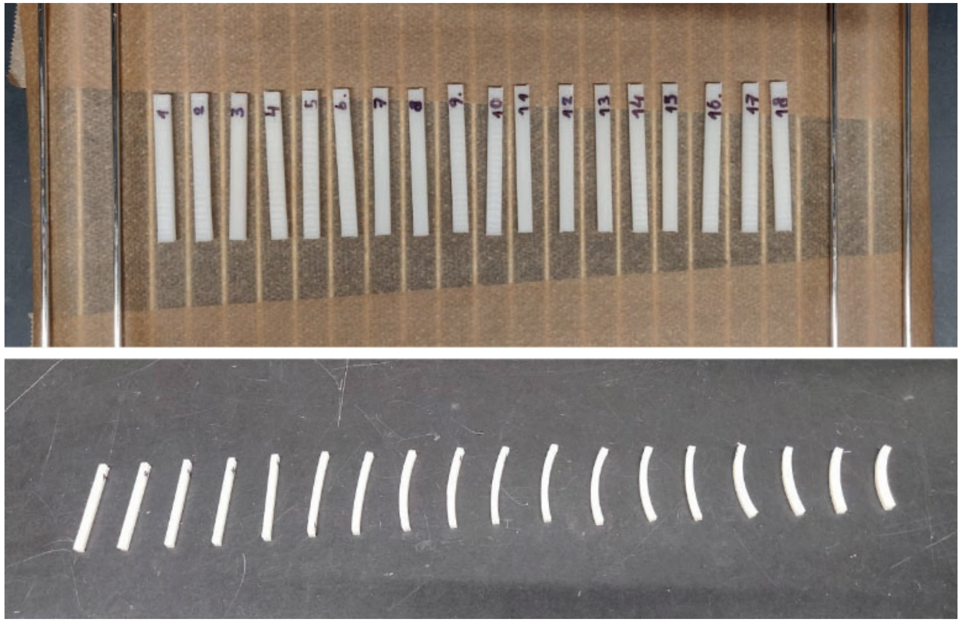


Figure 68: Samples before (top) and after (bottom) actuation in the oven.

7.3. INTERNAL MEASUREMENT

The third test makes use of an internal measurement device. This is achieved through the use of active and passive legs. As the active legs actuate they pull the end of the temple closer to the middle passive leg. Through this motion, the tip of the middle leg will shift through the predetermined path. Markers are applied on the top of the temple to create a visual guide. By reading the markers the user can determine if the temple is at the right length or whether it should remain in the oven for a bit longer. The correct length is stated in a table on the delivered instructions.

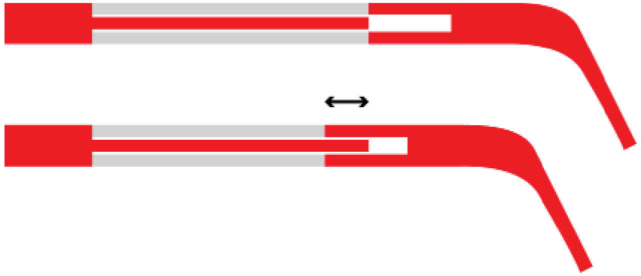


Figure 69: Internal measurement visually displayed.

By using an internal measurement the user can make fewer mistakes. Fewer mistakes lead to a more consistent outcome for the product. The one mistake which can still be made however is measuring error as the user still has to measure his dimensions.

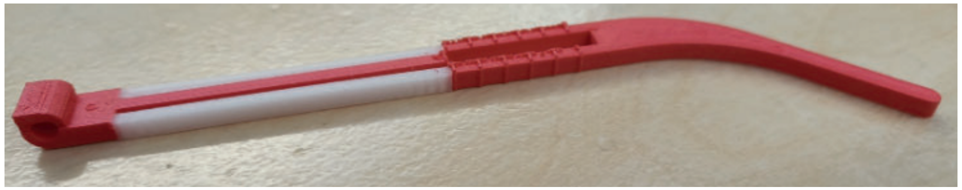


Figure 70: Temple before actuation.

When testing the temple worked as intended, slowly moving the middle marker to the end of the temple as can be seen in Figure 70.

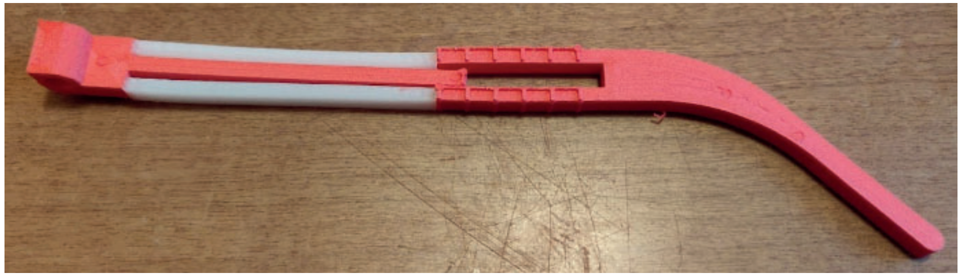


Figure 71: Temple after actuation.

As the markers on the temple determine the correct size, they need to be visible from the outside. Some experimentation was done with different types of markers to see which marker would be the most visible in the oven. It turned out that a mixture of white LW-PLA on red LW-PLA resulted in poor visibility. As such markers were chosen that had more relief and thereby created a better visible shadow, in the oven it can be assumed a light is on (figure 72).

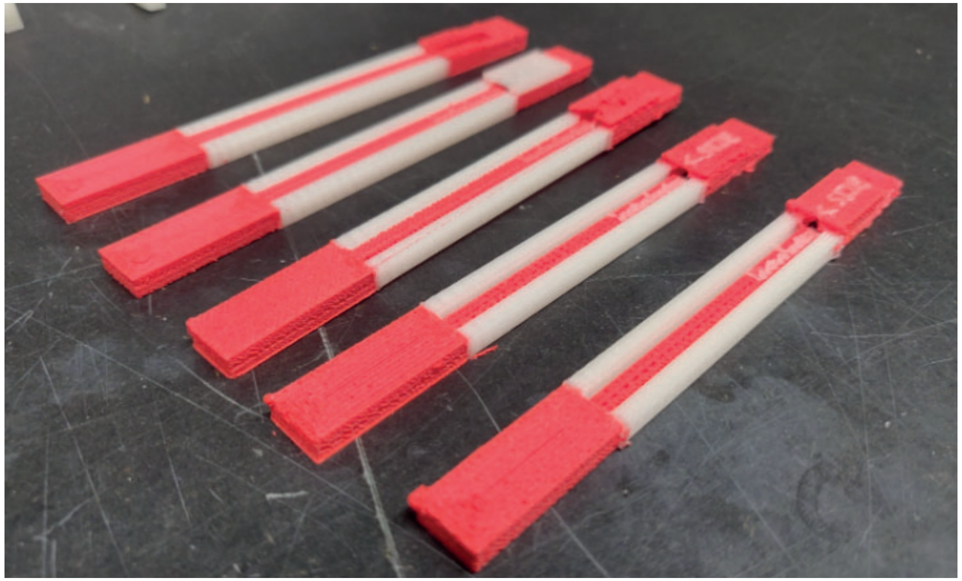


Figure 72: Several iterations on marker visibility.

Now that a conceptual implementation of shape change is created it must be tested on users. This is done to answer the main research question. The evaluation will consist of two test cycles with two corresponding iteration cycles. In the first test, the prototypes coming out of the concept decision will be tested on their different measurement strategies. After creating an iteration following the results of the first test, a second test will be performed with an accompanying iteration step.

1. EXTERNAL VERSUS INTERNAL MEASUREMENT

1.1. AIM

The first test on users will help to answer the question of which principle of measurement creates the most consistent and satisfactory outcome. for this two different prototypes are tested and the experience of the user is measured through a questionnaire. The main question for this test is which type of measurement gives the user the most consistent and satisfactory outcome. The result of the test will help answer all of the sub-questions by trying to find out whether users see value in this type of product (Q1.1), see if the user lacks something during the instruction, and actuation of the temples (Q1.2), and see if results show a consistent reproducible outcome (Q1.3).

The first of the two processes is the process of sample A. This sample requires the user to draw a line on the template which is attached to the temple. Once the marker on the temple reaches the marker on the template the process is complete and the user can take the temple out of the oven. Sample A consists of three elements, where the middle element is non-foamed LW-PLA printed with line infill oriented in the longitude of the temple. The outermost elements are foamed LW-PLA.

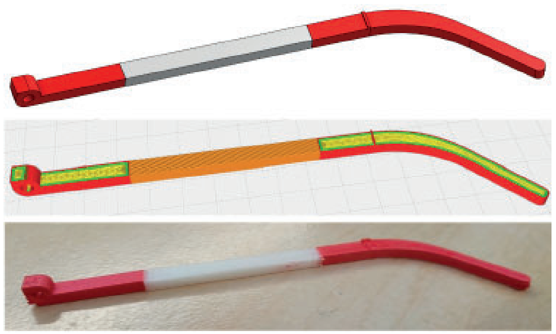


Figure 73: Sample A in CAD (top), sliced in cura (middle), and before actuation (bottom).

The second of the two processes is sample B. This sample relies on an internal measurement. In the middle of the temple is a part of foamed LW-PLA, not able to move, that has non-foamed LW-PLA on either side. Through shrinkage, the middle part can slide into the temple, where markers are placed. By reading at which marker the tip is the user can conclude whether the temple is at the right length or not. The marker will correspond with a length given in a table in the instructions.

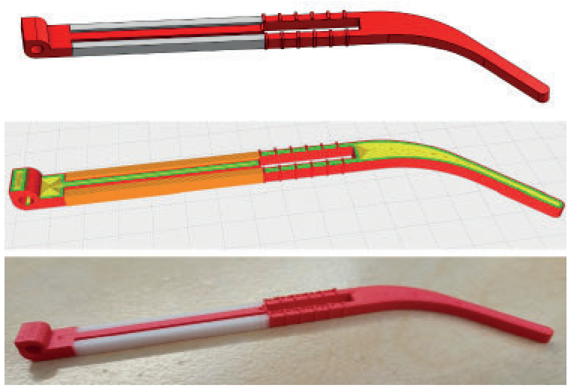


Figure 74: Sample B in CAD (top), sliced in cura (middle), and before actuation (bottom).

1.2. SETUP

The test has five tasks per prototype for the users.

Tasklist:

1. Answer questions in the questionnaire before shape-changing
   ~ This measures how much affinity the user has with the subject, be it shape-changing / glasses / 3D printing.
2. Perform the task by reading manual A and carrying out the shape change on temple A.
3. Answer questions for temple A after having shaped the temples, in the form of a questionnaire.
   ~ This measures their experience and how the shape-changing process on temple A is perceived.
4. Perform the task by reading manual B and carrying out the shape change on temple B.
5. Answer questions for temple B after having shaped the temples, in the form of a questionnaire.
   ~ This measures their experience of how they perceive the shape-changing process on temple B.

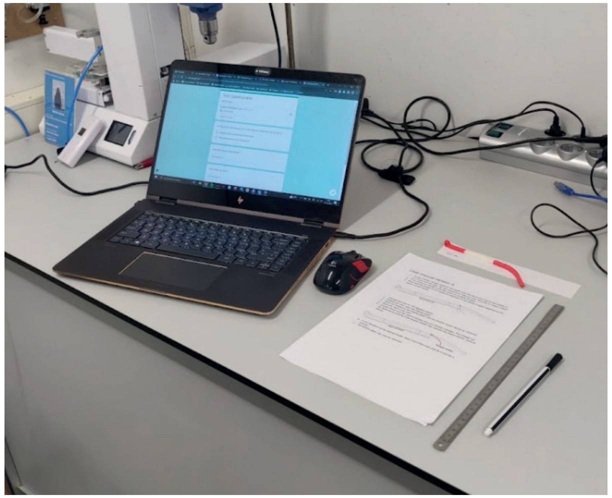


Figure 75: The user is presented with the questionnaire (left), temple (top right), and manual (bottom right).

The questions upfront helped to paint a picture of the user and whether he/she had any affinity with the subject. These questions were:

- How often do you wear glasses?
- How 'handy' are you?
- When it comes to customizing objects/products, would you rather do this yourself or have someone do it for you? And why?

Next up the test was performed for sample A. This sample required the user to measure their required length before sizing the temple, as can be read in manual A (Appendix C). The oven was already pre-heated and the plate in the oven was already prepared (figure 76).

Figure 76: The oven as presented during the test (top). Users reading the manual (bottom left) and using the oven (bottom right).

After testing sample A the following questions were asked:

- How hard was the process to follow?
- Were there any difficulties getting to the right length?
- Is there anything you would add to the instructions?
- What is the most unique quality of sample A?
- What is the most pleasant quality of sample A?
- What is the least pleasant quality of sample A?
- Considering regular frames cost between 70-250 euros in-store, how much would you value this total frame? (sizing the temple included)

These questions focus on the process the user has to follow and whether he/she likes it. The user is also asked about their interest in the shaped pair of glasses. At the end, the user is asked to value the glasses.

Having answered questions about sample A, the participant is given sample B and manual B (Appendix D) to follow. After completing the test the user is again presented with the questionnaire where the questions are the same as about sample A.

1.3. RESULTS

Before conducting the tests, a pilot test was performed. The pilot test went as expected, there were no unforeseen problems. The test was carried out with 8 participants. Per round of questions, some interesting facts are stated, all the answers can be seen in appendix E.

Participant profile

Three out of eight participants wear glasses daily, four use glasses as a sunblock, and one uses glasses during driving. Thus four out of eight are frequent wearers of glasses and have more affinity with glasses than the other four, who only wear glasses on sunny days. Nearly all of these participants also judged themselves as handy except for the one participant who called himself average. The same result was found in the third question where seven out of eight would customize a product themselves and one participant would look into the difficulty of customization, stating that if it is too hard he would not customize the product.

Sample A

With sample A the participants found the shrinkage process easy to follow and execute. This resulted in a few questions being asked during the process of shrinking the sample. When it comes to the manual there are some items to improve upon. First and foremost the manual was not visual enough for users to follow, thereby sometimes missing a minor step.

Secondly, the marker on the sample was sometimes hard to see. This was due to the absence of a light source in the oven. The oven was chosen as it was the only one in the lab with a see-through window. Ovens that consumers use at home always have a light, however a strong visibility of the marker is still important and thus has to be improved.

Last but not least is the result. Some of the users were not satisfied with the material finish. This, in their words, was due to it being 3D printed. This can however be improved by creating designs that embody the style of 3D printing. Some of the participants also experienced unwanted curvature during the actuation of the samples. This was due to the sample resting on a hot plate, as the plate was already preheated in the oven. As a result, this caused the underside, which laid on the plate, to heat up quicker thereby actuating the sample in different stages.

Sample B
Participants found sample B also easy to follow. The process felt more familiar to the participants as sample A had already been sized. A few participants noticed that they liked the internal measurement, although the markers were sometimes hard to see. This felt to them, in their words, that they did not have to draw a line and thus the process felt more accurate.

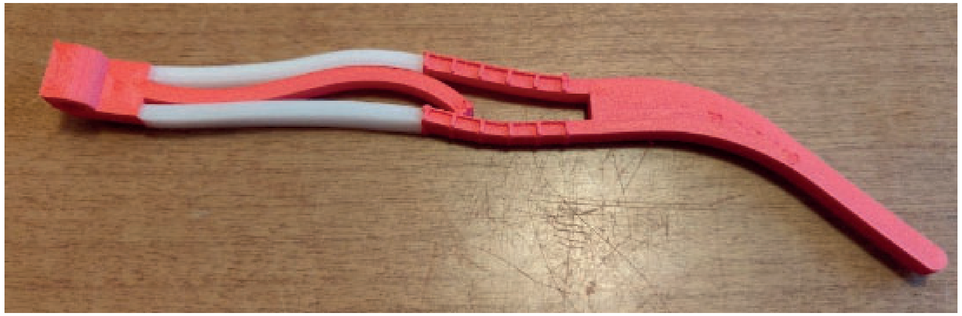


Figure 77: Undesired curling action within sample B.

The final result still was not perfect for all of the participants. Some worried the markers stuck out, thereby creating an unpleasant feeling. Others found that the temple curled internally. This latter phenomenon happened because the printer had somewhat of a misalignment. This caused the passive and active elements to be displaced and created bumps in the internal measuring portion where the inner passive part would stick to the walls, thus curling up (figure 77).

1.4. CONCLUSION & DISCUSSION

The test gave results which show that some further improvements are necessary. The first reason this test was conducted was to see if users see value in this type of product. In general, the users did see value in the technique of shape-changing but felt the look and feel could be improved. This study is conducted to see whether users are capable enough to use shape-changing to their advantage. As such the look and feel of a product is out of the scope, users seeing value in the technique however show value to 4DP within customer products. Users found the process of sample A and sample B relatively similar, giving slight preference to sample B.

The second question, regarding the clarity of the instructions and shape-changing process, resulted in some good points that have to be introduced for a shape-changing object to be easier to implement for users. The first point concerned the clarity of the instructions. As the process is something that users have not experienced before it is more useful to present instructions through visuals. This leaves out the guessing for the user on what type of action is needed. Secondly, the hard-to-see marker is something that has to be resolved. Users found it hard to see this marker in the oven and thus had the feeling they were not creating a very accurate product.

The consistent outcome also has some desires left to be fulfilled. During testing it became evident the printer was not calibrated well resulting in an undesired outcome. The test did show more troubles with version B when compared with version A. This was due to the internal measuring feature. A conclusion can be drawn from this that sample A is more resilient to bad tuning of the printer, resulting in more desired outcomes. As the best consistency of the outcome is a desire coming from Q1.2, sample A is chosen to continue with.

2. ITERATION 1

After concluding the results from test 1 the temple was iterated upon. The process of sample A was chosen to be able to result in a more consistent outcome. Therefore the shape of the new temple resembles that of sample A by a lot.

The bigger change lies in the manual. Where first the manual consisted of a lot of text with few visuals (Appendix C & Appendix D) the manual now has more visuals (figure 78). This step ensures the manual is more clear for users as to what is about to happen. In the manual, an additional step has been added to aid users in measuring the correct length. For this step, a cardboard pair of glasses has been added. The cardboard allows the user to draw on it, it is also cheap and more sustainable compared to a 3DP single-use measurement device.
In test 1 the temples, after being put into the oven, initially curved up and after a few seconds flattened out again. This was due to the bottom heating up quicker as the temple was resting on a preheated tray. This initial curve and flattening confused some of the users, and some were not sure if they made a mistake. To combat this the temple will come on a pre-assembled cardboard plate. Doing this makes sure the surface on which the temple rests is not preheated and heats up at the same time as the temple. This creates consistency and facilitates the user by reducing the amount of steps he/she has to perform.

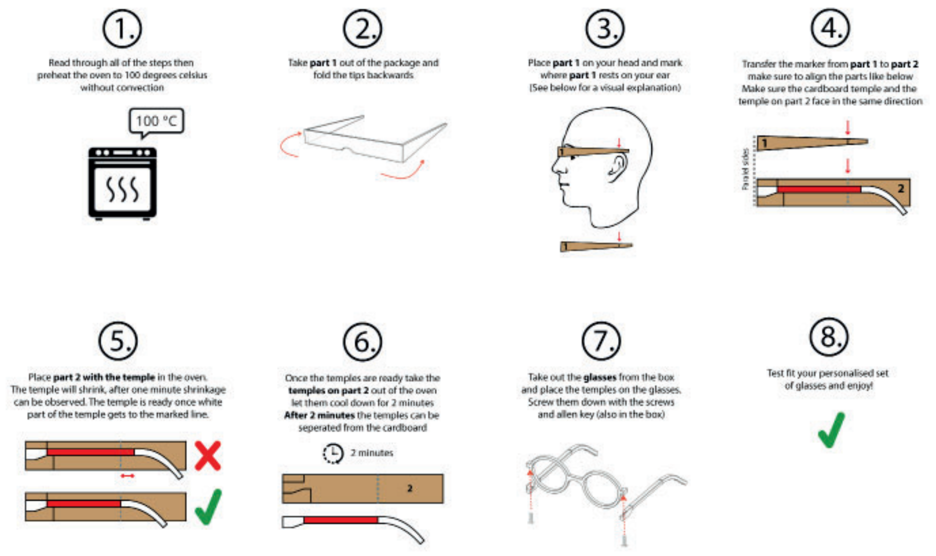


Figure 78: New manual after the measurement method test.

To verify the addition of the cardboard plate aids the design a test is performed where the temple is placed together with the cardboard in the oven. This test showed that the outcome of the temple was not predictable. The temple curved due to the introduction of the cardboard tray. Where the function of this tray was to prohibit curvature by heating up slower when compared with a preheated metal tray, the outcome caused an overreaction. The cardboard tray caused the surface to be much cooler compared to the air surrounding it, this made the temple curve in the other direction when compared with the pre-heated metal tray.

To combat the cooling of the temple the new version will incorporate baking paper. This is thin enough that it does not isolate the surface, thereby creating an unbalance in heating the temple. This new version resulted in figure 79. The underside is also raised to avoid contact with a pre-heated surface. During testing it became clear that this was a good solution where the result did not curl up.

Figure 79: New baking tray delivered with the temple viewed from the top and bottom.

3. USER ACCURACY

3.1. AIM

The second test aims to see how accurately the user can shape the temple. Where the first test took place in a controlled environment the second test will have the user shape change with their ovens at home. This ensures the design of the temples is not dependent on one type of oven and can work in varying environments.

3.2. SETUP

As the second test focuses mainly on the accuracy of the shape-changing process, it is split into two sections. First, a test will be performed where a line is drawn on the cardboard guide. Then a sample is shrunken to that line. This is repeated 6 times where the difference between the drawn marker on the paper and the marker on the temple is measured. The second part of the test is carried out by participants. They get the task to size two temples each, totaling 6 sized temples by participants. During the test, they are asked to follow the instructions (figure 80). Before the test takes place the following is read to them: *The glasses you are about to experience work with shape memory. The way it works is by shrinking in the oven. The glasses will start at size XXL and shrink to XS, creating the perfect fitment for your head.*

As the test takes place at the participants' homes there are plenty of variables. However, this is also part of being able to answer the question of whether the environment and appliances matter to the reproducibility of the shape-changing product. As such only the start of the test can be laid out. This is done by laying out the instructions, temples in their cardboard housing, cardboard glasses, and a pen (figure 81).

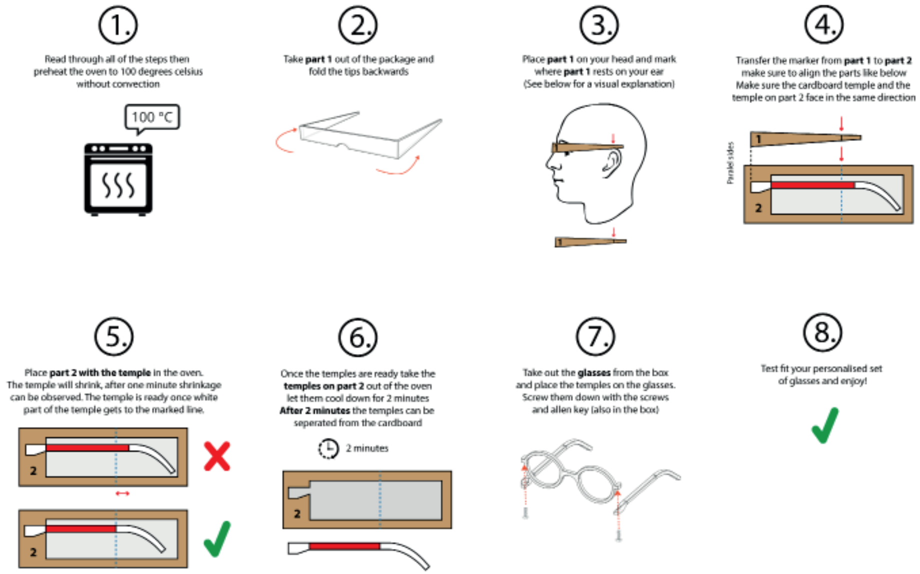


Figure 80: Instructions for the test.

Figure 81: Setup before the test takes place.

The users are, after shaping the temples, given an interview. In this interview, the focus is on how usable the instructions were and how they felt about the shape-changing process. These questions are addressed to make sure the instructions and post-processing did not lack in their setup. Once this is established the difference in target length versus actual length can be used to formulate an answer to the question of whether the differences in environment and appliances make an impact on the shape-morphing process.

Instructions

1. How difficult were the instructions to follow?
2. Scale of 7 points from easy to hard
3. Explain your answer to the previous question.
4. What would you add to the instructions?
5. What would you leave out of the instructions?

Post-processing

1. What did you expect of the size adjustment upfront?
2. How easy or challenging was it to post-process the temples?
3. Scale of 7 points from very easy to challenging
4. What was the easiest part of the process?
5. What was the most challenging part of the process?
6. Did you at one point think you needed more equipment? If yes at what point and what type of equipment?
7. How did you find the personalization process?
8. Scale of 7 points from liked very much to strong dislike
9. Explain your answer to the previous question.
10. Does the process of size adjustment make you feel in charge? Why?

3.3. RESULTS

The first part of the test resulted in 6 temples with a relatively similar error (Appendix F). This error is measured by measuring the distance between the drawn line on the cardboard housing and the middle of the marker on the temple (figure 82). This way, if the sample is not perfectly centered, it is still possible to get a consistent outcome.

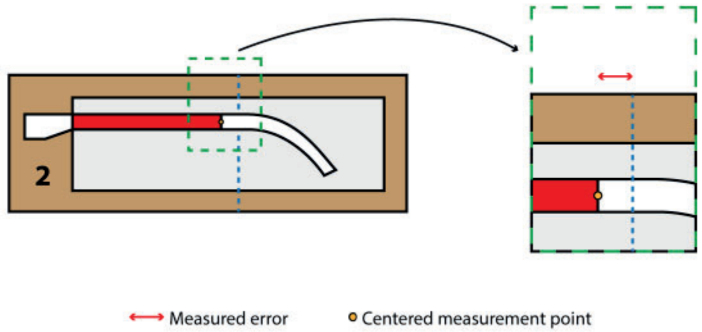


Figure 82: How the measurement error is recorded.

The same was done for the samples the participants had made (Appendix F). These results are compared to each other in Figure 83. Herein we see a significant difference between temples shaped by the users and temples shaped by the author. The reason for this became evident in the interviews (Appendix G).

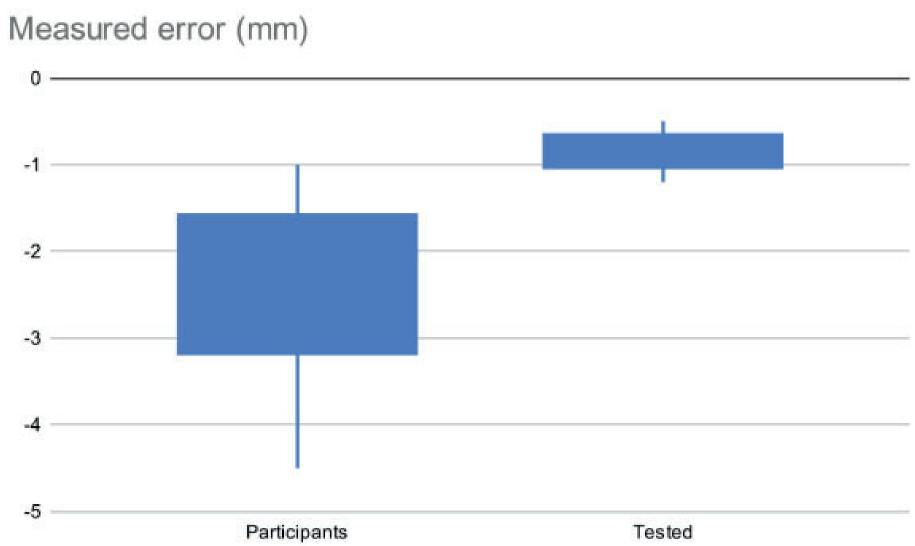


Figure 83: How the measurement error is recorded.

During the interview, the participants noticed that they felt little was lacking from the instruction manual. Apart from a note on duplicating the visuals, to represent both temples, no further points were addressed. Regarding the post-processing, an interesting result came forth where all participants were wondering whether they did it right and two of them noted they would rather have the sizing done by a professional. “Having a professional shape them for you is a logical step as you already go to an expert to measure your eyes,” Participant 3 noted.

Figure 84: One of the participants transfering the marking (left) and putting the temples in the oven (right).

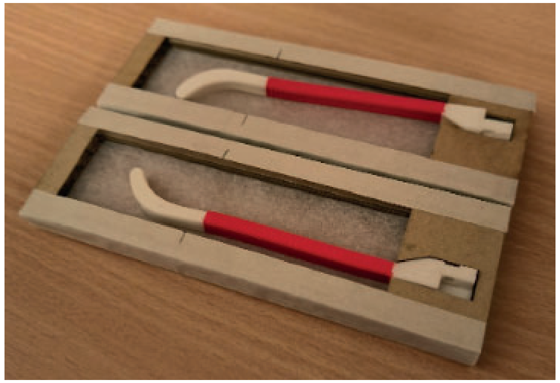


Figure 85: Temples after actuation. The measurement error can be clearly observed.

3.4. CONCLUSION & DISCUSSION

Coming back to the main reason the second test was performed: “to see how accurately the user can shape the temple” we see that users vary significantly in their outcome. Although the variation ranges from a measured error between -1 and -4,5 millimeters a trend can still be observed. This trend is observed in the fact that all samples, regardless of actuation by participants or author, come out with a negative measurement error. A negative measurement error means the object has shrunken further than the set target.

Besides the technical outcome, the interviews also reflect this behavior. Participants like the process but feel they need more experience to know how to approach the shrinkage of the product. This difference is seen back in the technical outcome where the test performed by the author resulted in a lesser measured error due to experiencing shrinkage in FDM prints.

The behavior of the object shrinking past its target can be attributed to the slow process of cooling down after the object is taken out of the oven. This process can be solved with three different methods. The first method accounts for extra shrinkage. For this to happen the extra shrinkage has to be measured in various conditions. Where ambient temperature in the summer may cause extra shrinkage, ambient temperature in the winter can reduce shrinkage. This reduction in temperature brings up the second method. For this variation, the object is cooled down more quickly when compared with air cooling. Last but not least there is also a third option where the shrinkage is blocked thereby not allowing for further shrinkage past the target.

4. ITERATION 2

The focus for this iteration is to create a temple that solves the problem found in test 2. As alluded to in the conclusion of test 2 there are three possible types of solutions. The first is accounting for the extra shrinkage taking place, the second is increasing the cooling to combat possible shrinkage, and the third is blocking extra shrinkage.

The solution has to facilitate the user in the process. While doing so the solution must also not lose one of the strong points in shape-changing products. This makes the third solution type fall off. This solution would either create steps in the sizes thereby not allowing for in-between sizes or create a bulky solution that makes the process of post-processing much more complicated.

The first and second solution types give interesting directions. To create a list of implementable solutions, how-to's are created. For the first solution type the following how-to is created: "How to account for extra shrinkage". The second how-to is: "How to cool down an FDM shape-changing temple quickly" (Appendix H).

Regarding how to account for extra shrinkage there are a few criteria that have to be met. First and foremost is the reproducibility and consistency. Next up is ease of use for the user. This leaves two options; educating the user by supplying test samples, and preventing by creating a measurement device that accounts for the deviation in error. Of these two the first option most likely results in the most repeatable outcome. Where the results of test 2 show that education reduces the error to nearly 1 mm. Also, a notable thing is the range of error among participants, this varies from 1 to 4,5 millimeters. This would make a new measurement method that accounts for shrinkage still deviate among users.

The second type of solution; how to cool down an FDM shape-changing temple quickly, also has to meet the previously mentioned criteria. Reproducibility and consistency leave out options that move the temple, like dunking it in cold water or blowing cold air over it. These options would make the temple move, therefore the temples are less likely to come out in their desired shape. This also leaves out spraying water onto the temple. While spraying is not likely to move the temple through force it will impact the consistency. As seen at the beginning of test 2, the temple can curl due to slight temperature differences. Spraying the temple would result in one-sided cooling as the bottom can not be reached, thus curling the temple. The last method, putting the samples in the freezer, could have a too-slow reaction time due to the slower dissipation of heat when comparing air with water.

To conclude the user is given test samples to educate him/her when to take the temple out of the oven. The user is given two test samples to make sure there are enough opportunities while not creating a redundant product.

1. WHAT IS IN THE BOX

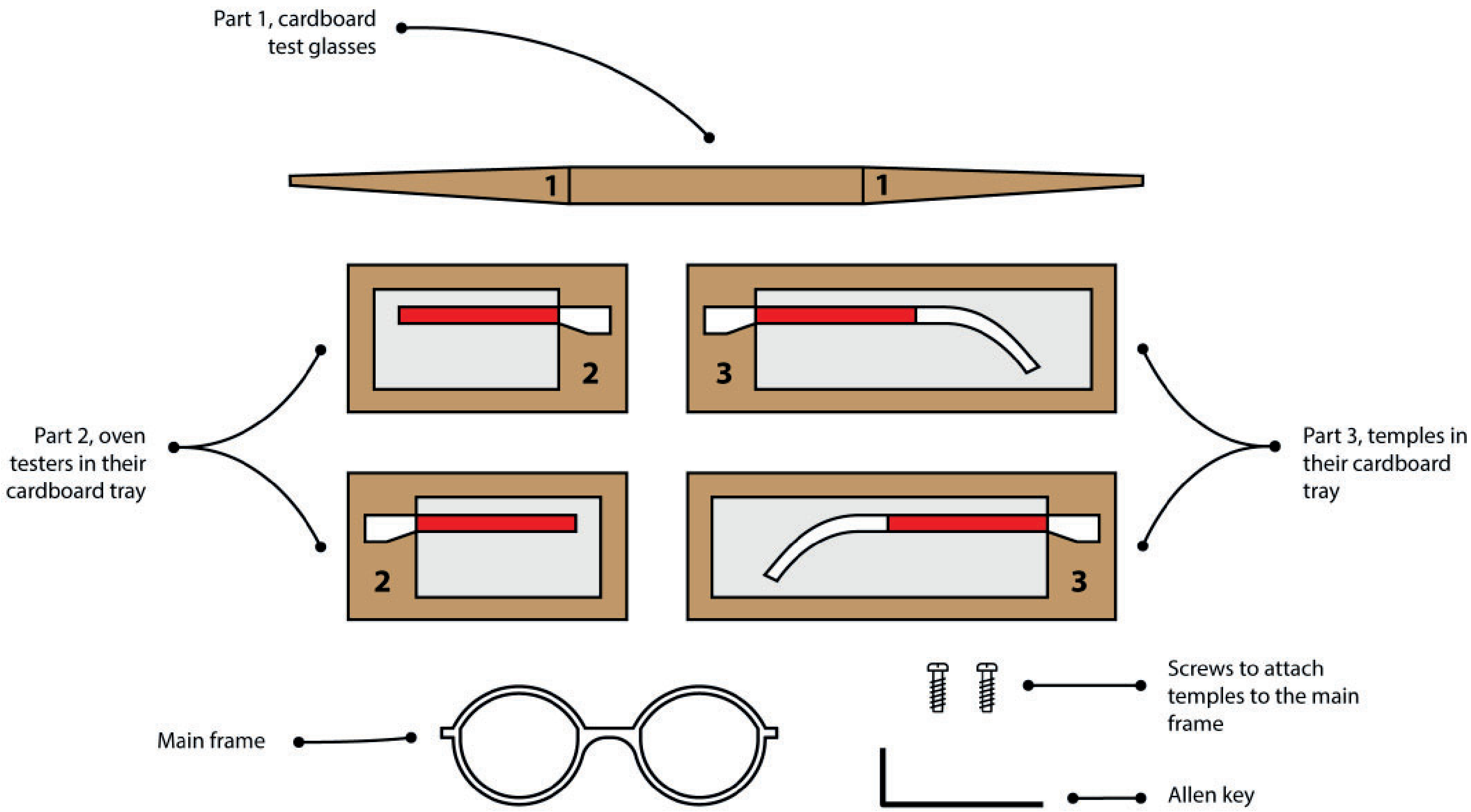


Figure 86: Items needed to produce a pair of shape-changing glasses, excluding an oven.

2. INSTRUCTIONS

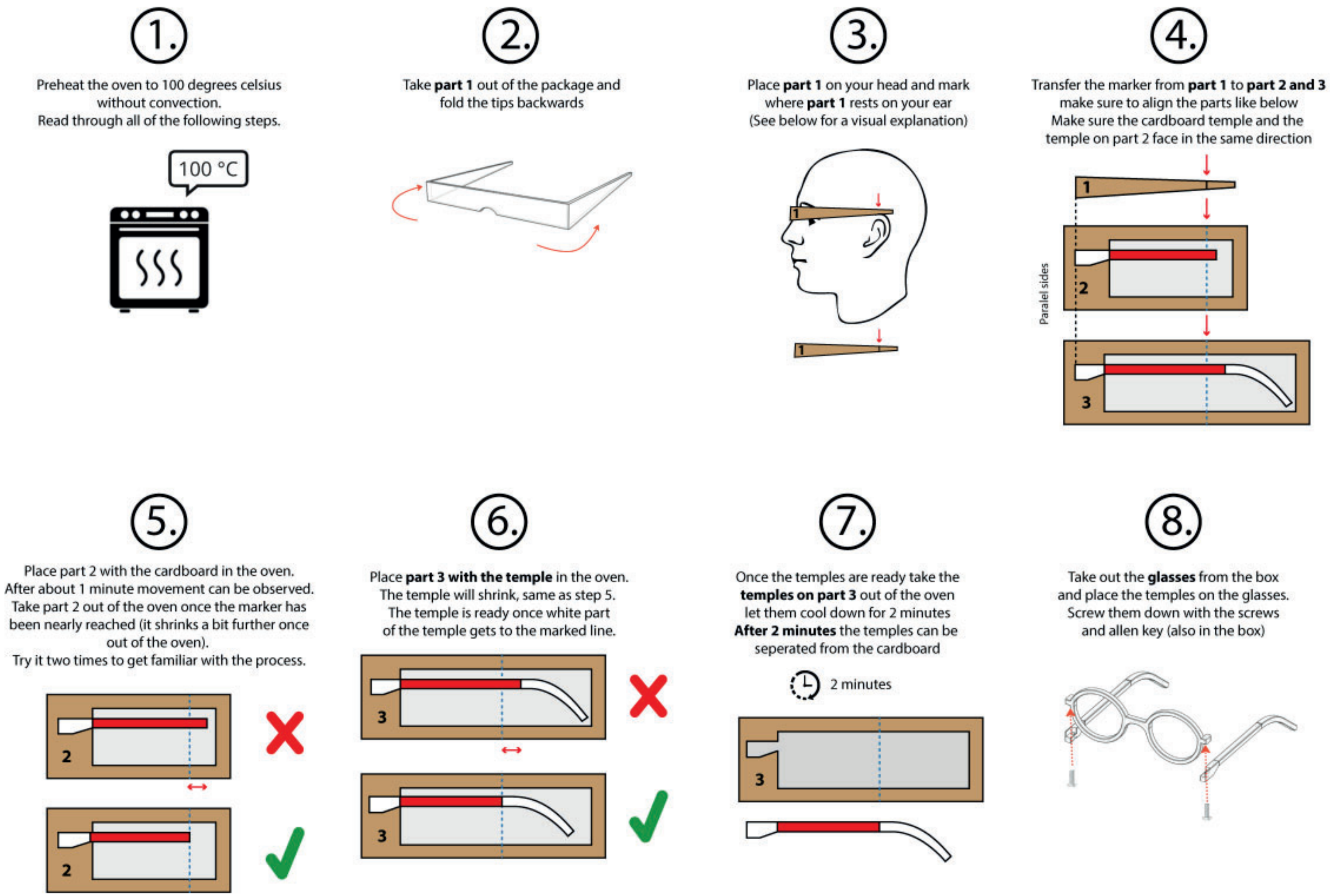


Figure 87: Instructions given to the user needed to assemble and shape the glasses.

3. END PRODUCT

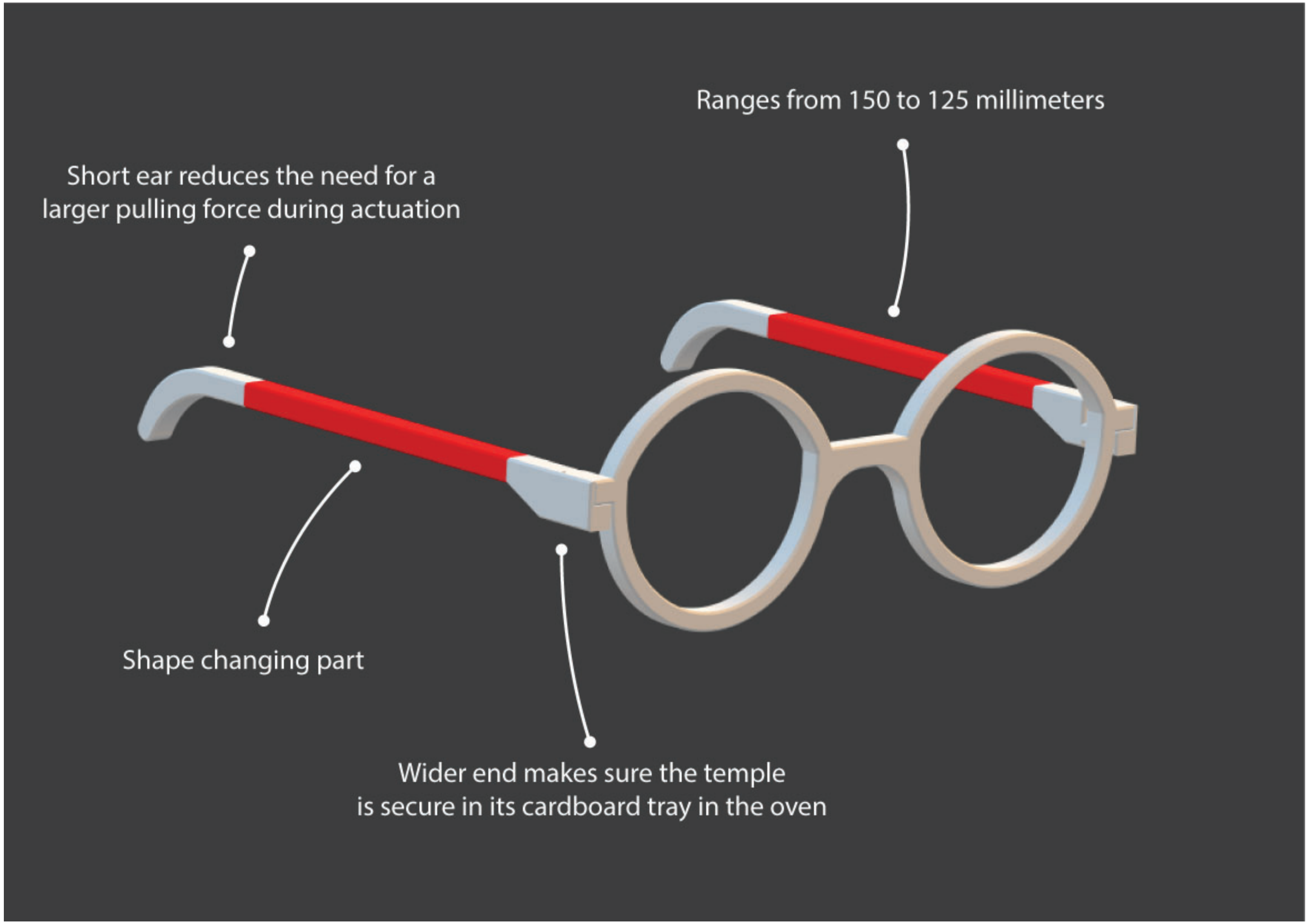


Figure 88: End product after actuation with its features.

1. CONCLUSION

By investigating previous research, three categories of products can be distinguished; flat-packed products, custom fitment products, and energy harvesting structures. From these categories, two can be implemented in a design that can be used to examine users during the activation step of shape-changing products. Therefore focus is laid on these categories resulting in a frame of a pair of glasses. Initially, this product sought to include both of the categories. However, due to the activation of these systems taking place at the same time a decision had to be made between the two of the categories. This resulted in custom fitment being the primary focus, thereby answering sub-question Q1.1 ‘What category of products can make use of 4PD?’.

The second sub-question Q1.2 ‘What is needed to facilitate the user in post-processing a 4DP object?’ required the examination of the user during the activation step in the 4DP process. Studying the user during the activation step shows that the initial use of the shape-changing product is clear for the user. The user found that the process was easy to carry out. This ease of use can be attributed to the use of common appliances within the process. It was noted, however, that the instructions have to use clear visuals describing which actions are happening and what can be expected. As the process of shape change is new to the user, he needs to be educated. This is done by adding test samples to the received package. This allows the user to experiment with two samples, to get a feeling for the process. After experimenting with the two samples, they are capable of predicting how the shape change will affect the object. With this extra step, the error between the target on the cardboard tray and the actual length is decreased.

Making a 4DP product accurate and reproducible can be a challenging task. However, when proper strategies are used, a shape-changing product can be made that shapes in the same direction as the modeled 3D object. To get this product to have the same angles and curves as the original modeled object, tuning is needed in the amount of shrinkage. The shrinkage can be increased, creating smaller curves, or decreased, allowing for larger curves. This tuning of shrinkage is done by addressing the parameters set in the slicing software. The most important parameters are; extrusion temperature, activation temperature, layer height, and print speed. Each enables the designer to tweak the amount of shrinkage taking place during the activation step. These aspects affect the accuracy of the final form thereby answering the first part of the third sub-question Q1.3 ‘How can 4DP be made accurate and reproducible?’.

The second part of the sub-question Q1.3, reproducibility, relies on several factors. Depending on the design criteria a product can be made to have two states or multiple end positions. Having two states increases the reproducibility of the object as geometry can now play a factor by creating end stops. The most important factor however is the activation environment and temperature. If the desire is to have each part end up in the same form or shape it is necessary to limit user interaction. Doing this reduces the risk of undesired shape change. The activation temperature should be kept as homogeneous as possible over the entirety of the object. Allowing for temperature differences can affect the outcome of the product by shrinking more in the relatively hotter areas. This is especially hard with objects that require their shape-changing elements to lay flat on a surface. The surface is either hotter as it is preheated, or colder when put in the oven at the same time as the product. Reducing the thickness of this surface is therefore important to allow minimal interference of heat transfer. Additionally, the type of material used for this surface is important.

Last but not least there is the main research question ‘What are the challenges of involving a user in the activation step of a shape-changing product?’. Adding user interaction within the activation stage of the shape-changing process introduces the challenge of consistency. By using the right kind of heat source this activation step can be much more consistent. The main factor here is to limit the user interaction, achieved through the use of an oven where the user cannot interact with the object during activation and by pre-installing the object on a cardboard tray. This does have an undesired side effect; user engagement. Where the limitation of user interaction does improve consistency, the user has a higher chance of being distracted as the activation process takes roughly one to three minutes in the oven. This reduction in interest was also because the user did not know what to expect. This is an inherent problem for creating shape-changing products for users who do not have prior knowledge of shape change. To combat this the user is educated in the process of shape change by testing two samples. This education step allows the user to get familiar with the shape-changing process and ensures the user knows what to expect.

2. DISCUSSION

Slicer add-ons

This study examines the challenges of user interaction in the activation step of shape change on a linear changing product. Through this, the user can vary the length of the object. This linear action creates a relatively simple motion for the user to follow. Also in designing this object the direction of movement can easily be predicted. Creating objects that curve are much harder to predict as can be read in the conclusion of material tinkering & exploration.

The first found difficulty was the workflow for creating curved products. In this, it became evident that there are few supporting programs. Those who do allow for simulation require a lot of computational power as can be read in the chapter Applications and Perspectives in 4D printing. Therefore it can be interesting to take a look at a slicer addition or separate program that takes the printed parameters and shows how the product behaves during activation. If a program were to be created that easily shows the outcome of the 4D printed part, a further study can be conducted that adds curves to the designed products. Being able to predict curves by their material properties, not through geometric end stops, can create new ways to design objects.

Material

The material used to create the frame of the glasses, LW-PLA has the beneficial option to enable and disable shape memory. This is done by activating the foaming agent. For the sustainability factor, this is very valuable as this creates a product out of one material while keeping the shape-changing function. During printing, however, this foaming agent causes some difficulties. The expansion of the material in the nozzle creates a positive pressure, continuously extruding material. This causes the material to string a lot during printing. As such it can cause imperfections during the printing process, allowing strings of foamed PLA to be sandwiched between non-foamed PLA. To resolve this further tuning is required of LW-PLA in its foamed state.

Application of activation

In this study consistency among outcomes was a big factor. This caused the user to have as little as possible interaction in the activation step. However not all products need this level of consistency, there can be the desire to have a product stand out from its counterparts thereby being unique. This type of product has not been explored during this study but could result in outcomes that use shape memory differently. Therefore it is interesting to take a look into how this type of product can impact how heat or stimuli are applied in the activation step. The freedom of application is interesting in that the experience of the user can be measured. It allows for a different type of interaction with the process of 4DP.

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1. APPENDIX A: MOUSE PROTOTYPING

Mouse V1.0
The first tested version of this mouse consisted of a three-ply structure. Where one red ply of 0.6mm is the restrictive layer and two yellow plies of 0.7mm each are active layers. The red ply had a lines infill pattern which when from the clicking fingers to the back of the palm rest (figure 89, A). The layer printed on top of the red ply was printed in a perpendicular direction, to promote curvature from left to right (figure 89, B). The last ply was printed again with line fill and oriented in such a way as to increase the curvature from the back of the mouse to the clicking fingers while promoting side curvature (figure 89, C).

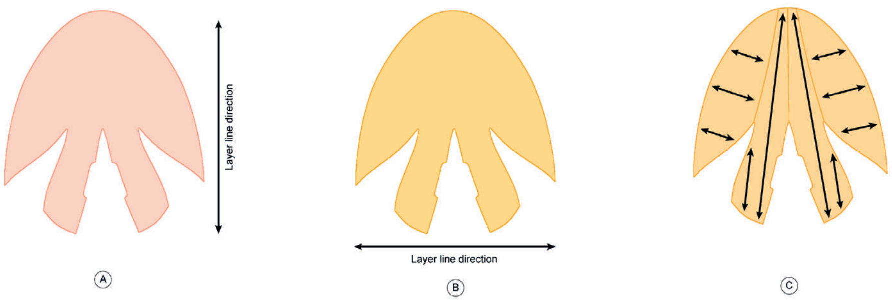


Figure 89: Print path directions of mouse V1.0

After printing the mouse was flat. After actuation in hot water, the mouse formed the shape in Figure 90. The clicking fingers of the mouse turned out alright although the curvature was a bit too strong when compared with the CAD model. The shape also has two elements pointing forwards, in hindsight, this is attributed to the layer line directions in those areas. With a difference of less than 5 degrees, these areas are more inclined to curve from side to side instead of creating a double-curved surface.

After the print came off the printer the red ply felt slick as it was the first printed layer on the glass plate of the 3D printer. Once the part had been actuated the texture changed into a rough feeling texture, resembling fine grid sandpaper. This made the object look matt in contrast to the shiny surface coming off the printer.

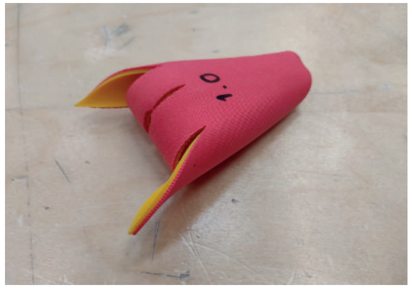


Figure 90: Mouse V1.0 after actuation

Mouse V1.2
The second test included a two-ply structure. It captures the same type of areas as version 1.0 but excludes an active ply. This time the restrictive layer is 1.0 mm in height. Similar to version 1.0 it uses lines as infill type and the direction is also the same (figure 91, A). The bigger change is in the active ply of the object, where one layer is removed resulting in a singular layer of line directions (figure 91, B). The active ply is also 1.0 mm in height giving a distribution of 50% passive and 50% active, in contrast to version 1.0 which had a 30% passive and 70% active ratio.

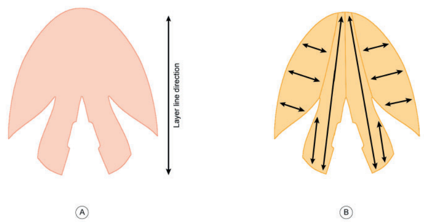


Figure 91: Print path directions of mouse V1.2

Actuating the print resulted in a shape seen in Figure 92. This shape shows stronger curvatures which can be attributed to the singular line direction. Although the shape has a ratio with less active elements, compared to version 1.0, the curvature is increased. Version 1.2 shows it is more than capable of getting a small curvature when compared to overall dimensions, as such it overshoots and thereby needs to find a way to reduce the actuation.

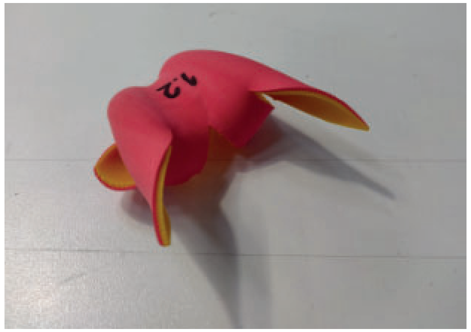


Figure 92: Mouse V1.2 after actuation

Mouse version 2.0

Version 2.0 took a different approach with active elements in the object. The mouse has to move into a double curved form therefore this design focussed on creating a radial pattern (figure 93, B). This pattern, in theory, should pull the outer edges inwards creating a bowl-type shape. Again the ratio was held at 50% passive and 50% active and two plies were used. Another change was the type of infill in the passive layer, this time the type of infill used was cross 3D (figure 93, A). This type of infill makes use of the Hilbert curve. Cross 3D was initially chosen to equalize strain in all directions. The short line segments result in less space for the material to shrink and thus reduce the shrinking of the passive layer, trying to get as close as 0% shrinkage.

The result is a very disorganized shape. Where the outer edges have a radius too small, the side-to-side has no radius at all. This result of having a radius in one direction, in contrast to a double-curved surface, can be attributed to the different sizes of active sections. It can be seen that the largest active surfaces

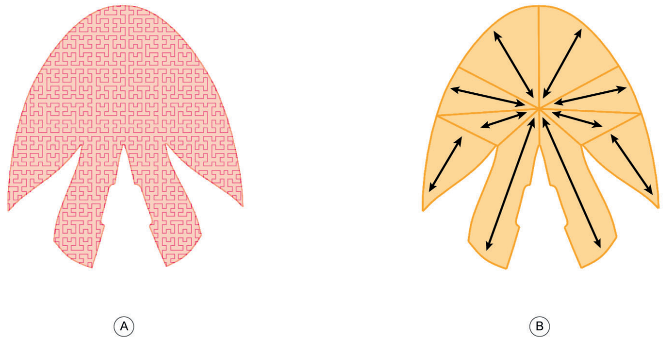


Figure 93: Print path directions of mouse V2.0

experience actuation in the direction of their extrusion direction. Smaller surfaces don't experience this as their inherent stress cannot overcome that of larger surfaces. The thing to note here is to keep a balance between active areas to stimulate a desired outcome.

The second interesting thing to note is the texture on the surface. The cross 3D infill pattern has caused the surface to create a uniform texture of small bulges and divots. This pattern gives more grip when compared to lines infill. This pattern did not seem to impact the curvature by a lot but did make for an interesting texture. As such this can be used as an advantage when designing for grip.

Figure 94: Mouse V2.0 after actuation

Mouse V2.1

The fourth version, version 2.1, uses a similar pattern of layer lines as version 2.0 with a small adjustment in two active sections at the back of the palm rest. The difference in this version is the decreased percentage of the active ply versus the restrictive ply. Now the active ply counts for 25% of the total height, at 0.5 mm high, and the restrictive ply for 75%, at 1.5 mm high. This decrease in the active ply should reduce the total curvature of the object, as concluded in the study by Wang et al. (2023). Another small adjustment is the type of infill on the restrictive ply. It has been changed to lines to try to make use of the perpendicular expansion of the extruded line direction. This could help the surface curve from side to side.

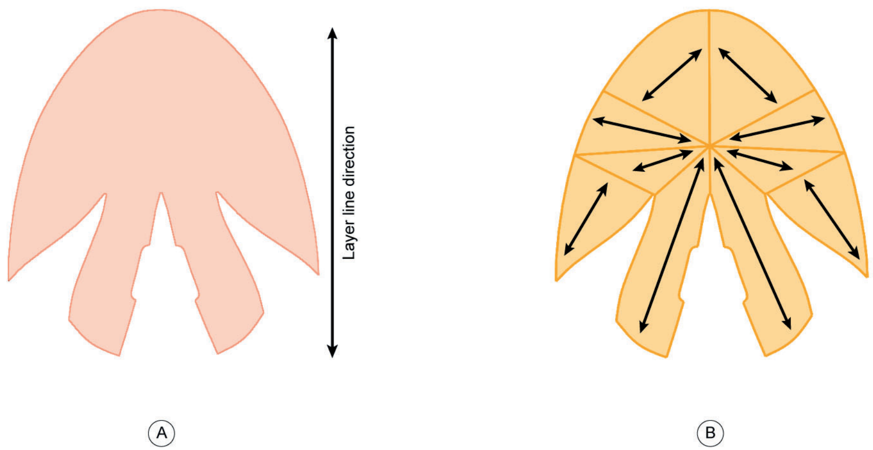


Figure 95: Print path directions of mouse V2.1

The result shows that the made improvements positively impact achieving a similar shape to the CAD model. Although the shape is not perfect it resembles the CAD model the closest. Areas of improvement are the clicking fingers which have a too small radius. Although the palm rest has improved it now forms an obstacle for further side-to-side curvature.

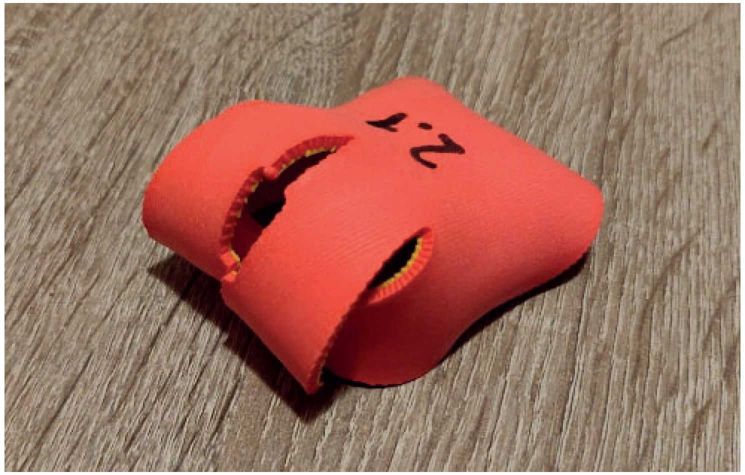


Figure 96: Mouse V2.1 after actuation

2. APPENDIX B: SHRINKAGE OVER TIME

Sample	Time	L,before (mm)	L,after (mm)	deg Celsius	Δ (mm)	Δ (%)	Δ (Δmm)
-	0:00	-	-	97	-	-	-
1	0:30	60,67	60,6	94,2	0,07	0,12%	0,07
2	1:00	60,77	60,7	91,2	0,07	0,12%	0,00
3	1:30	60,66	60,6	89,7	0,06	0,10%	-0,01
4	2:00	60,71	60,54	89,2	0,17	0,28%	0,11
5	2:30	60,73	60,4	89,5	0,33	0,54%	0,16
6	3:00	60,69	58,95	89,7	1,74	2,87%	1,41
7	3:30	60,65	57,45	90,3	3,2	5,28%	1,46
8	4:00	60,68	56,68	91,4	4	6,59%	0,80
9	4:30	60,75	56,23	92	4,52	7,44%	0,52
10	5:00	60,7	55,81	92,2	4,89	8,06%	0,37
11	5:30	60,71	55,03	91,4	5,68	9,36%	0,79
12	6:00	60,7	54,34	92	6,36	10,48%	0,68
13	6:30	60,77	53,06	93,1	7,71	12,69%	1,35
14	7:00	60,77	52,48	93,1	8,29	13,64%	0,58
15	7:30	60,89	51,58	94,3	9,31	15,29%	1,02
16	8:00	60,64	48,69	94,7	11,95	19,71%	2,64
17	8:30	60,71	46,79	95	13,92	22,93%	1,97
18	9:00	60,77	45,38	95	15,39	25,32%	1,47

Figure 97: Measured results

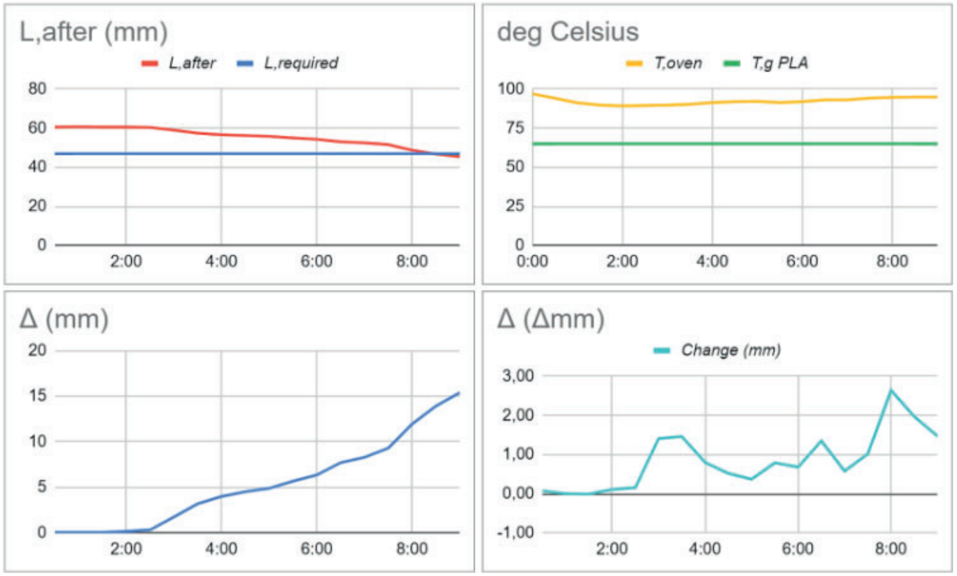
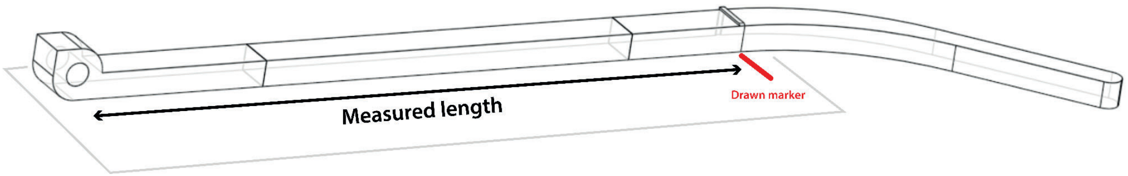


Figure 98: Change in length, temperature, and increments of change in length.

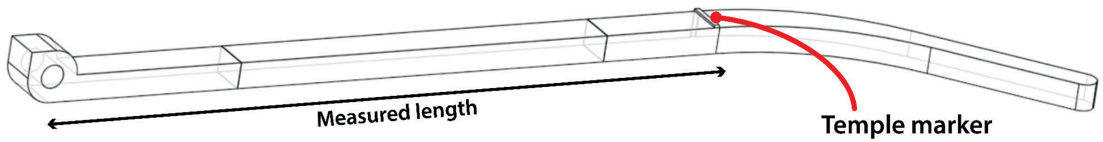
3. APPENDIX C: MANUAL A

User manual version A

1. To get a perfect temple measure the length from the top of your ear to the middle of your nose from the side. Tip: get someone to help you with this step to make it easier.
2. If you know your length, write this down on a piece of paper.
3. Now draw the length of the measured distance on the piece of paper attached to the bottom of the temple.



1. Preheat the oven to 100 degrees celsius
2. Prepare an oven rack with baking paper.
3. Place the temple on the baking paper with the temple marker facing up. (picture)
4. Place the rack in the oven.
5. Visually check over the next 5 minutes how your temple changes. The change can be observed by looking if the temple marker has reached the drawn marker. (picture below)



6. If your temple is at the desired length, take it out of the oven and let it cool for 2 minutes.
7. The bottom paper can now be removed.

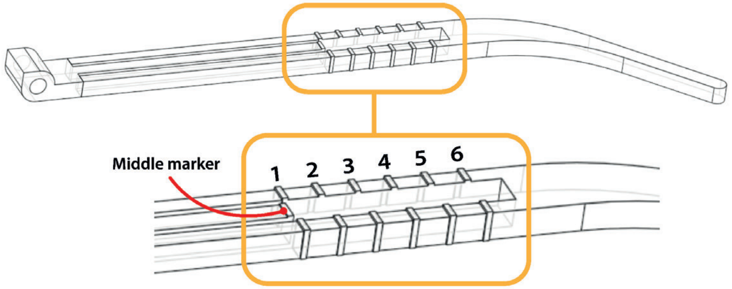
4. APPENDIX D: MANUAL B

User manual version B

1. To get a perfect temple measure the length from the top of your ear to the middle of your nose from the side. Tip: get someone to help you with this step to make it easier.
2. If you know your length, write this down on a piece of paper. Take a look at the measurements in the table and with which number it corresponds. The number represents the number at which the middle marker must be.

Measured length	**Marker**
90- mm	Above 6
90 mm	6
95 mm	5
100 mm	4
105 mm	3
110 mm	2
115 mm	1
115+ mm	Do not place into the oven

1. Preheat the oven to 100 degrees celsius
2. Prepare an oven rack with baking paper.
3. Place the temple on the baking paper with the stripes facing up. (picture below)



4. Place the rack in the oven.
5. Visually check over the next 5 minutes how your temple changes. The change can be observed by looking at the top of the temple as indicated above. Read where the middle marker is to know the size of the temple.
6. If your temple is at the desired length, take it out of the oven and let it cool for 2 minutes.

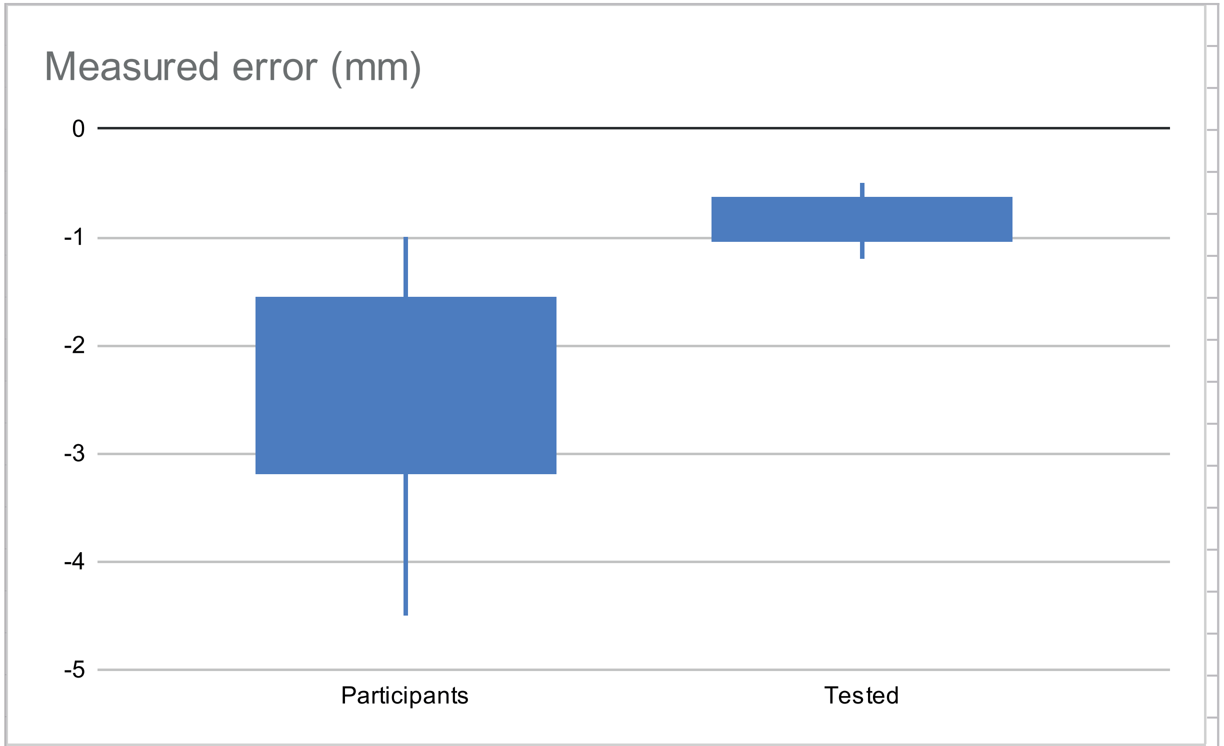
5. APPENDIX E: RESULTS USER TEST 1

Tijdstempel	Can we use the following as part of this research? (tick box if we can use it) :	How often do you wear glasses?	How 'handy' are you?	When it comes to customising objects / products, would you rather do this yourself or have someone do it for you? And why?	How hard was the process to follow?	Were there any difficulties getting to the right length?	Is there anything you would add to the instructions?	What is the most unique quality of sample A?
12-12-2023 16:07:50 (pilot test)	Pictures of you during testing (anonymized), The outcome of your test (anonymized)	Almost daily (contact lenses when doing sports)	Not very handy, I leave klusjes to my boyfriend	I would rather have someone do it for me, because of the fear of doing it incorrectly	Not very hard. However, I was still afraid to do something wrong.	The timing of when to take it out of the oven. However, the process went quite slow and when keeping an eye on it you almost can not ruin it.	No. Maybe the temple marker can be a bit more clear (different colour or a higher mark)	The manual adjusting
14-12-2023 11:05:49	Pictures of you during testing (anonymized), The outcome of your test (anonymized)	Regularly in the summer	Very	Myself, I work in a garage so I feel comfortable working with tools.	The wording of the questionnaire was sometimes a bit confusing, but overall clear to follow.	The temple curved up instead of just contracting.	Introduction to what a temple is and maybe the steps for the oven.	Is shape morphing property
14-12-2023 14:27:12	Pictures of you during testing (anonymized), The outcome of your test (anonymized)	Every day	Most of the times I fixes things myself. I won't fix something if I don't have time at all.	I would say that most of the times I do it myself, as I'm really passionated with 3D printing and I try to use this method in many different fields.	It's pretty easy, everyone can do it at home.	Not really.	I would say there's too much text and not very clear visuals, missing visual hierarchy.	Easy process
14-12-2023 14:55:20	Pictures of you during testing (anonymized), The outcome of your test (anonymized)	In de zomer 5 keer per week	Best handig als je het vergelijkt met mensen die geen io doen.	Myself, maybe depending on the product, but when you make something yourself it makes you feel more proud.	Not that hard, the steps were clear, I was just afraid of doing something wrong.	No, Bas helped me measuring it.	Maybe that you have to make sure that you can see the mark still if the temple is placed in the oven.	That you can adapt the length yourself.
15-12-2023 11:54:48	Pictures of you during testing (anonymized), The outcome of your test (anonymized)	when its sunny	quite	Myself, if i feel capable enough	quite easy	yes, the plastic curled upward, while the paper stayed flat. that mede it hard to see the change in length. The temple turned out too short.	add a step to ensure it cannot curl upward	it shrinks when heated
15-12-2023 12:29:30	Pictures of you during testing (anonymized), The outcome of your test (anonymized)	Daily	Very	I prefer to do it myself because other people (especially vaklieden) are beunhazen	Not very difficult, however some additional remarks and information was necessary.	None	Some clarifying remarks on certain terminology	Its ability to be traploos instelbaar
15-12-2023 13:03:53	Pictures of you during testing (anonymized), The outcome of your test (anonymized)	sunglasses when driving (3-5 times a week)	average	myself, i am cheaper	mostly clear	did not realise the drawn line needs to line up with beginning of temple	to begin the drwn line at start of temple	thermal expansion
15-12-2023 13:29:34	Pictures of you during testing (anonymized), The outcome of your test (anonymized)	Every day	On a scale of 1 to 10, probably 8	Depends on how complicated it is. I like make/do things myself, so if its doable, than I enjoy doing it.	Not hard	No	Maybe a picture of the side of a face and where to measure	That only the white part shrinks. Its cool to see the difference in printed materials
15-12-2023 13:57:58	Pictures of you during testing (anonymized), The outcome of your test (anonymized)	Daily in the summer, whenever it's sunny	very	generally myself, because i trust myself, and for cost reasons	not hard. easy peasy	no, but i assumed a loose tolerance of a couple mm	maybe more measuring directions/side view. clarity on measuring point at the hinge	straightforward one-point measurement makes it a no-brainer

What is the **most** pleasant quality of sample A?	What is the **least** pleasant quality of sample A?	Considering regular frames cost between 70-250 euros in store, how much would you value this total frame (sizing the temple included)?	How hard was the process to follow?	Were there any difficulties getting to the right length?	Is there anything you would add to the instructions?	What is the most unique quality of sample B?	What is the **most** pleasant quality of sample B?	What is the **least** pleasant quality of sample B?
It feels personalized by adjusting the length yourself	With this process you are afraid to ruin your freshly bought product	25 euro	Easy. It was easy to see where the material was at. I had also become more confident in the process because of the experience before.	Not really. Maybe a little bit when the material started to curve separately.	No	The markings.	The markings made it very easy to follow the process.	I think sample A looks better. So the looks are less pleasant for sample B. And the three bars are sensitive for curving when sizing the temple.
aesthetically pleasing proportions between the red and white	Surface finish	around €100	Easy	Not really, again the structure first curved up before contracting.	Not anything in addition to what I mentioned in A	The length indicator	Proportions and fitment of the different parts	Finish, with B also the indicators aren't as pretty.
the DIY feature brings some value to the user	not very precise length of the legs after putting them in the oven	30 euros	Way easier than before, 9/10.	Not really, more clear than before.	Colors so the user can identify which part does what	Visible movement of the parts (more active)	It's nice that you can see the length difference because of the marks.	Deformation of the legs
It was easy to adapt the lenght of the temple.	As a consumer I could be worried that I do something wrong and I mess up the temple	On the higher side of this range, so 200-250	Easy to understand! (Maybe also because I already read the first version?)	No, the fact that you did not have to draw your own mark was actually easy.	No	The shape is interesting, the red part in the middle gives me the feeling that the glasses will stay in shape.	That the measurements are already on the temple itself, which makes it easy to understand what to do.	The temple curved in the oven, which made me worry a bit.
its simpel	ugly colors	i wouldn't buy it, i have no trouble with exiting standard frames.	not hard	again, it curled upward, while the middel part stayed flat. but the temple layed flat again quite quickly.	maybe also make it so the temple is placed, with the measurements facing the user/window. so it i easier to see.	it shrinks when heated	the shrinking feature	after heated it is not uniform, the white parts look warped
No steps in adjustments	Working with an oven	80	Very easy	None	No	The length indication markers	No pen needed	Warping of the sample
customisibility	material finish	70. The production costs are cheap (no injection molding) and the material finish is not good)	no	the temple deformed sideways	no	thermal expansion	customisibility	markers sitch out against head
That it shrinks (mostly) uniformly	I dont like waiting. But that being said, 5 minutes is acceptable for a process like this.	From a technology perspective, quite high. Lets say around 200. However, form the perspective of looks, feel, and quality, very very low. No more than 10.	Also very easy, same as sample A	Not really, although the temple was bending so a bit difficult to see	A picture of the side of a face and how to measure.	The meaurement stripes are on the temple	The middle part slides in	The temple bends in unwanted directions
the fact that i know what the part is and that I can see it adapt. in short, I understand what is happening	not knowing when it would start moving	small surplus of 20-30 euros	easy	visibility between marker and sides (contrast) and warping	might mention the marker separately/beginning	integrated measurement	integrated measurement	warping, contrast thing, considerations of durability?

Considering regular frames cost between 70-250 euros in store, how much would you value this total frame (sizing the temple included)?	Thank you for participating in the test, is there anything you would like to add?
60 euro	XOXO
€125	-
50 euros	
Same as last answer, maybe a bit higher, 220-250	Lekker bezig
like 20. Also because they are 3D printed, maybe if they look more like the existing frames, i would pay more	no
100	(☞ﾟヮﾟ)☞
70. fdm is cheap and it is DIY, little overhead costs.	nee
Same as sample A.	
same, plus 20-30	i need to run

6. APPENDIX F: RESULTS USER TEST 1, MEASURED ERROR



	Median	Min	Max	Q1	Q3
Participants	-2,0	-4,5	-1,0	-3,175	-1,575
Tested	-0,8	-1,2	-0,5	-1,025	-0,65

Participant	Outcome (mm)
1, left	-1,8
1, right	-2,2
2, left	-1
2, right	-1,5
3, left	-3,5
3, right	-4,5
Test 1	-0,8
Test 2	-1,2
Test 3	-1,1
Test 4	-0,5
Test 5	-0,6
Test 6	-0,8

7. APPENDIX G: RESULTS USER TEST 2, INTERVIEWS

Participant 1

1. Instructions

- How difficult were the instructions to follow? Scale of 7 points from easy to hard
  ~ 5
- Explain your answer to the previous question.
  ~ It was hard to get the sample to the right length, although the illustrations on the manual were clear.
- What would you add to the instructions?
  ~ That assistance can be helpful when drawing the line on the cardboard glasses. Make sure to tell the user mistakes are fine to happen.
- What would you leave out of the instructions?
  ~ Nothing, they were clear and helpful.

2. Post-processing

- What did you expect of the size adjustment upfront?
  ~ I through it would get smaller, and more personalized for me. Never thought this was possible for glasses. Personalization adds something if the glasses are cheap. Although I would prefer to buy a pair of glasses in the store that are perfect already. Either that or have an expert do it, they have to fit perfectly in order to use them every day.
- How easy or challenging was it to post-process the temples? Scale of 7 points from very easy to challenging
  ~ 3, its hard to measure yourself. If there is something to show that the sample is ready in the oven that would be nice.
- What was the easiest part of the process?
  ~ Placing the markers on the cardboard temple holder.
- What was the most challenging part of the process?
  ~ Measuring my nose to ear length.
- Did you at one point think you needed more equipment? If yes at what point and what type of equipment?
  ~ A mirror would have been nice for measurement in combination with something in the oven to show the glasses are ready.
- How did you find the personalization process? Scale of 7 points from liked very much to strong dislike
  ~ 4
- Explain your answer to the previous question.
  ~ Because you do it yourself, you feel that you have control over it and therefore it is not that accurate. Because you have to put in the effort yourself, it is not a seven. idea that things can also go wrong.
- Does the process of size adjustment make you feel in charge? Why?
  ~ Well, just not with the oven because I didn't know exactly whether I could take it out.

Participant 2

1. Instructions

- How difficult were the instructions to follow? Scale of 7 points from easy to hard
  ~ 1
- Explain your answer to the previous question.
  ~ Everything is clearly illustrated and explained.
- What would you add to the instructions?
  ~ Comfort the user with one sentence by telling them the temple can deform slightly.
- What would you leave out of the instructions?
  ~ Nothing

2. Post-processing

- What did you expect of the size adjustment upfront?
  ~ I expected it to be more difficult. The size adjustment in the oven goes very slowly, which makes it easy to observe when the correct size of the temple has been reached.
- How easy or challenging was it to post-process the temples? Scale of 7 points from very easy to challenging
  ~ 2. I was only doubting myself a little bit. Did I take it out of the oven at the right moment?

- What was the easiest part of the process?
  - ~ Preheating the oven.
- What was the most challenging part of the process?
  - ~ Drawing the lines from my ear to part 1.
- Did you at one point think you needed more equipment? If yes at what point and what type of equipment?
  - ~ Someone to assist me to draw the lines from the ear to part 1.
- How did you find the personalization process? Scale of 7 points from liked very much to strong dislike
  - ~ 3
- Explain your answer to the previous question.
  - ~ I like the feeling of having a personalized item. I don't like the possibility of ruining my newly bought item. It is a responsibility.
- Does the process of size adjustment make you feel in charge? Why?
  - ~ Yes! I adjusted this item myself.

Participant 3

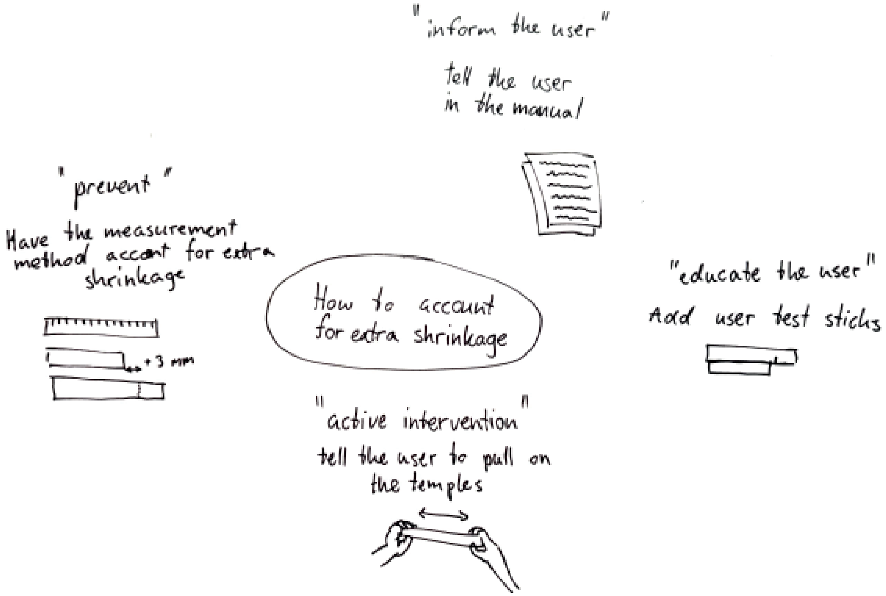
1. Instructions

- How difficult were the instructions to follow? Scale of 7 points from easy to hard
  - ~ 3
- Explain your answer to the previous question.
  - ~ Easy to follow, however its not clear that the instructions are about two of the temples as only one is shown.
- What would you add to the instructions?
  - ~ Swich up step 1 with the oven / read through. Make sure the instructions are more with bullitpoints. Step 4 caused a bit of confusion as it showed one sample in the visual not two.
- What would you leave out of the instructions?
  - ~ Less text more bullitpoints

2. Post-processing

- What did you expect of the size adjustment upfront?
  - ~ Quite nice, kinda cool that the material hardens up again.
- How easy or challenging was it to post-process the temples? Scale of 7 points from very easy to challenging
  - ~ 5
- What was the easiest part of the process?
  - ~ The process was easy, perhaps it is better to tell the user to take out the glasses earlier. The marker has now gone to far and one temple is somewhat warped, I'm not sure if this is my mistake. Would rather have a professional do it for me like the optician. When I'm buying glasses I already go there anyway. A cheaper set of sunglasses makes more sense for this.
- What was the most challenging part of the process?
  - ~ Measuring myself to get the correct length.
- Did you at one point think you needed more equipment? If yes at what point and what type of equipment?
  - ~ Propper measuring equipment to get the right length.
- How did you find the personalization process? Scale of 7 points from liked very much to strong dislike
  - ~ 2
- Explain your answer to the previous question.
  - ~ Nice that you can do it yourself, however, it also leaves a lot of room for error. Would rather have this process done by an expert.
- Does the process of size adjustment make you feel in charge? Why?
  - ~ Yes and no, it was easy to do but I do not feel the end result is the best possible. I would want to get the hang of it by doing it a couple of times before applying it to something I use every day.

8. APPENDIX H: HOW-TO'S ITERATION 2



4D printing: Post-assembly for the masses

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 11 - 09 - 2023

16 - 02 - 2024 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, ...).

4D printing brings the advantage of possibly efficient transport and customizability, as products are able to efficiently be stacked due to their simple initial form and be moulded by the user once the product arrives at the destined location. This could make 4D printing a viable option for manufacturing when taking sustainability and personalisation in mind. In contrast, 3D printing (the core element of 4D printing) is more expensive on a larger scale when compared to traditional plastic manufacturing methods.
Many projects have been done with 4D printing. However, these projects all end with a small scale object which find no use other than to demonstrate. As such a real life test is needed to see the viability of 4D printing within everyday objects. This will fill the knowledge gap between lab testing and commercial implementation.

The project will entail making a product with 4D printing and applying it in a real life scenario. This topic is chosen as there currently are no 'real' products on the market which use the technology of 4D printing. This project will therefore provide a use case where 4D printed is presented in a real life scenario.
The project will test the initial reaction of users, by looking if users are able to set up the product all while being guided by an instruction manual.

Stakeholders for this project are the following:
- Scientific community (TUDelft): They have a desire to see 4D printing be implemented in a real scenario and to test whether or not this technology is viable on a bigger scale.
- Users: Users want a product that works and prefer a product which is moulded to their needs while keeping the budget for the product in reasonable terms.
- Myself: I want to get a deeper understanding of 3D and 4D printing.
- 3D printing farms: Their toolset could be broadened by being able to apply 4D printing. Allowing for potentially better products and increased profits.
- Product stores: Stores like IKEA could find a new way to product products and make this interesting for the masses, possibly allowing for a bigger profit and more diverse catalogue.

To get to a good result the project will be done in a few phases (figure 1). Where first the user is studied which leads into a design. Second the design will be transfered into a user manual and last but not least the design is then tested together with the user manual on the user once more. In the end both the design and manual are the deliverable as both are used in the user test.

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introduction (continued): space for images

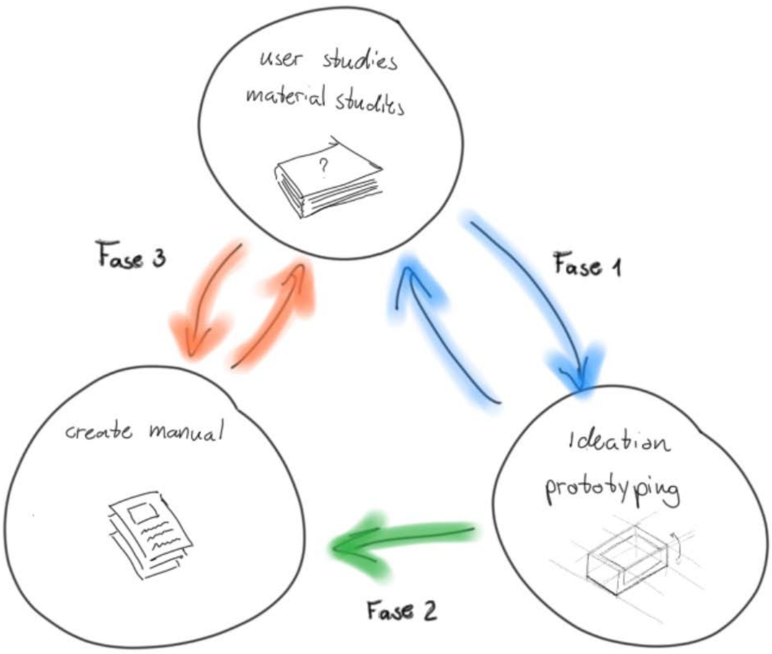


image / figure 1: How I think the project will be handled

TO PLACE YOUR IMAGE IN THIS AREA:

- **SAVE THIS DOCUMENT TO YOUR COMPUTER AND OPEN IT IN ADOBE READER**
- **CLICK AREA TO PLACE IMAGE / FIGURE**

PLEASE NOTE:

- **IMAGE WILL SCALE TO FIT AUTOMATICALLY**
- **NATIVE IMAGE RATIO IS 16:10**
- **IF YOU EXPERIENCE PROBLEMS IN UPLOADING, COVERT IMAGE TO PDF AND TRY AGAIN**

image / figure 2:

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.

3D printing has been booming in the last couple of years. However due to it's inferior strength and cost, when compared to traditional methods like injection moulding, it has not cought on to the bigger scale of manufacturing. These inferior factors could be improved by creating a 4D design which uses the main manufacturing method of 3D printing in combination with smart design. This smart design will allow for the object to fold, creating layer lines in impossible to print directions, and thus improved strength. Another benefit is the folding of the object, this can be done within the home of the user. As such an object can be transported in a flat or transport efficient shape, in the end saving transportation polution and costs.

As of yet many papers foresee good oppertunities for 4D printing to be implemented. Many of these papers show the workings of 4D printing and provide possible solutions for producing 4D structures with the use of CAD software. However none of these papers actually present 4D printing in a realistic use case scenario. Therefore the knowledge of applying 4D printing to actual use cases has yet to be found.

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.

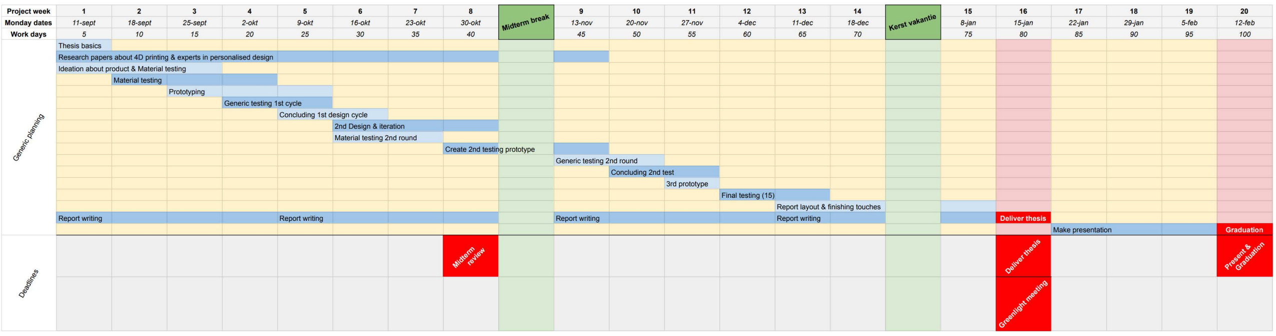
Create a real life use case for 4D printing where users are given a manual to assemble the product at home. Make sure this product adheres to efficient transportation (manufacturer-shop) and is easy to assemble. The goal for this project is to make a solution which the majority of the users know how to implement.

The finalisation of this project will most likely result in a product which can be assembled by the user at home. This assembly will take regular household items into account like hot water to actuate the 4th dimension. The product will come in a pack together with a manual. This manual will guide the user step by step on how to assemble the product. The end result of the project is the 4D printed product in combination with the manual.

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 11 - 9 - 2023 16 - 2 - 2024 end date



Blue: Project focus at that moment
Red: Important deadlines
Green: Holidays

The planning incorperates two itteration cycles. Each cycle is tested with a group of 5 people. The final testing takes place with a group of 15 people.

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.

I myself am very interested in 3D printing, I also have a printer at home and I really like to play around with it. As a designer my interest also lies in the manufacturing part of product making, especially knowing one manufacturing difference can make or break a product. It is for this reason I also opted to seek electives that fit within this interest area, electives like Repair!, Fundamentals of Textiles, Designing with Composites, Material Driven Design & Digital materials. Everyone of these electives highlight a different part of a huge field of manufacturing.
It is due to the course Material driven design that I came to know about 4D printing. To me the subject is very interesting and since I don't know the full extent of what 4D printing is capable of I felt like doing a graduation project with it. A factor which also attracts me is that the possible outcome of this project can be used by a lot of people since hobby 3D printers are used to make the end result.
For me 4D printing presents a topic which falls very much within my interest area but also still challenges me as I don't fully know the topic yet. I want to learn how to create 4D products but perhaps also find out if there is software to work with/to be made for.

FINAL COMMENTS

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