Active matter:
4D printed transformable Architechture

Diplomarbeit

Thema

Active matter:
4D printed transformable Architechture

ausgeführt zum Zwecke der Erlangung des akademischen Grades
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Senior Scientist
Dipl.-Ing. Dr.techn Oliver Schürer.

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von

Michaela Gebetsroither
01246037

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Abstract

Active Matter: 4D printed transformable architecture

The transformations and adaptability to changing environmental conditions play a significant role in the resilience of biological systems. The ability of SMP to sense and react to heat, light (UV), and moisture enables the development of beneficial designs for future energy-efficient shape-changing architectural building elements. SMP materials present new ways of designing shape-changing programmable materials that are triggered by distinct environmental stimuli. This work focuses on designing shape-changing multi-material prototypes as part of the Fused Deposition Modelling (FDM) process. The multi-material prototypes consist of the Shape Memory Polymer (SMP) and commercially available PET (Polyethylene terephthalate glycol), TPU (Thermoplastic polyurethane), and PLA (Polylactide) filaments. (1) The first section of this research project is a material science review of the properties and the Shape Memory Effect of SMPS. (2)
The second part is an experimental study that concentrates on the manufacture of SMP-TPU and SMP-PET, as well as SMP-PLA composites to further design shape-changing multi-material composites. (3) The third part deals with an activation strategy with embedded heating wires and an Arduino. (4) The last part is the design of an SMP/TPU and an SMP/PET surface prototype.

Results: The study confirmed the feasibility of creating a 4D print with a hobby printer and showed the limitations of this technique. Low cohesion within the composites lead to the proposed geometrical connection strategy to design shape-changing material composites.
The research revealed the exceptional effect of shape-changing behaviour that can be achieved by simultaneously preserving the flexibility in an SMP/TPU composite.

Abstract

Aktive Materie: 4D gedruckte verformbare Architechture

Die Anpassungsfähigkeit durch veränderbare Umwelteinflüsse ist eine Haupteigenschaft von resilienten, biologischen Systemen. Formgedächtnispolymer (SMP) besitzen die Fähigkeit auf Hitze, Licht und Feuchtigkeit zu reagieren und eine Formveränderung von einem weichen zu einem harten Zustand zu durchlaufen. Diese Fähigkeiten eröffnen vorteilhafte Eigenschaften für Anwendungsgebiete bei architektonischen Bauteilen. Mit SMP können programmierbare Materialien kreiert werden, die mit einer Formveränderung auf bestimmte Umwelteinflüsse reagieren. Diese Arbeit legt den Fokus auf das Design von „Multimaterial Prototypen" mit der „Fused Deposition Modelling Methode". Die Multimaterialien bestehen aus einer Kombination von Filamenten, wie aktiven Formgedächtnispolymeren und handelsüblichen PETG (Polyethylene Terephtalateglycol), TPU (Thermoplastic Polyurethane) und PLA (Polylactide). (1) Der erste Abschnitt dieser Diplomarbeit ist eine Zusammenfassung von materialwissenschaftlicher Literatur, um die Eigenschaften von Formgedächtnispolymeren und deren Formgedächtniseffekt zu beleuchten. (2) Der zweite Teil ist eine experimentelle Materialstudie. Hier wird die Herstellung von Verbindungen zwischen (SMP -TPU) geprüft. Formgedächntispolymere in Verbindung mit (SMP-PETG) und (SMP-PLA) wurden getestet, um weiterführe formverändernde Multimaterialien zu erforschen. (3) Der dritte Teil dieser Arbeit beschäftigt sich mit der intrinsischen Aktivierung von SMPs durch eingebettete Heizdrähte. Diese werden mit einem Arduino zusammengeschlossen, um eine Formveränderung zu aktivieren. (4) Der letzte Teil befasst sich mit der Herstellung von SMP/TPU und SMP/PET Prototypen.

Resultat
Diese Studie bestätigt die Machbarkeit eines 4D Druckes mit einem Hobby Gerät und zeigt die Einschränkungen, die diese Technik mit sich bringt. Die Limitierung zeigt sich in den langen Druckzeiten und schlechten Verbindungen zwischen den Materialien. Die teilweise unbrauchbaren Ergebnisse führten zu der vorgeschlagen geometrischen Verbindungsstrategie. Innerhalb des SMP/TPU Komposites wurde ein interessanter Effekt gefunden. Das Material zeigte eine formveränderbare Fähigkeit bei gleichzeitiger Flexibilität des Materials.

acknowledgement

I would like to express my special thanks of gratitude to my mentor Senior Scientist Dipl.-Ing. Dr.techn Oliver Schürer. who gave me the opportunity to do this research project on the topic active matter: “4D printed transformable architecture”

I am thankful for the opportunity to go beyond a classic architectural master thesis and explore the possibilities of innovative new materials with an experimental study for architectural use. It helped me to broaden my horizon and explore the possibilities of tomorrows. Thank you for enough patient and guiding me through the process. You encouraged me to conduct this research with optimism and inquisitiveness.

Secondly, I would like to thank my family and my partner and friends who helped me a lot in finishing this project in this challenging time of the corona pandemic. They gave fresh heart and good mood in times of unsteady and unclear developments

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Active matter

"man is just about to begin to participate consciously and somewhat more knowingly and responsibly in his own evolutionary transformation. I include evolution of the environment as a major part of the evolution of humanity."

Buckminster Fuller believed that all the answers to our world problems are included in the beautiful design of the universe.

Introduction

The American engineer Buckminster Fuller once said, "man is just about to begin to participate consciously and somewhat more knowingly and responsibly in his own evolutionary transformation. I include evolution of the environment as a major part of the evolution of humanity." (R. Buckmister Fuller, 2020) Buckminster Fuller believed that all the answers to our world problems can be found in the beautiful design of the universe.

The major issues of our time— climate change and the industrial pollution that is co-created by the construction industry— require a re-consideration of the use of former building materials and the chosen production strategies. The necessity of applying sustainable, recycled, and energy-efficient building materials is evident to stop the depletion of world resources. Aside from the urgent need to develop biodegradable materials and sustainable building strategies, a new factor has come into play with possibilities for the evolution of our environments that cannot yet be foreseen. The latest advancements in science and technology at the intersection of architecture, material science, biotechnology, information and communication technologies showed outstanding developments in active matter research.

Active Matter studies are focused on the design of materials in conjunction with the function and behaviour of biological systems. Architects like Frei Otto and Buckminster Fuller have already embraced the meaningfulness of structures in nature and transferred them into their biomorph architecture. Beyond the natural strategies for creating lightweight and functional designs that have already been adapted, another factor enhances the resilience of biological systems. The adaptability and transformation to changing environmental conditions are the most significant strengths nature offers. Living things like the mutual rain frog, the mimic octopus, and the sunflower are only a few examples of astonishing animals and plants that demonstrate the adaptability of natural systems to changing environmental conditions. The ability to sense and react to specific natural phenomena by changing shape, changing colour, and self-healing have, in the past, been reserved to these biological systems. Nowadays, the fusion of certain factors enables the development of bioinspired materials that notably exceed the properties of former building materials. Materials that self-heal, change shape, grow and decay or adjust their colour according to distinct changes in the environment may seem like concepts that belong in science fiction novels. This is similar to Wellstone as devised by Will Mc Carth, which is a material that emulates any natural, artificial or even hypothetical substance. Although we are far from realising Mc Carth's visions, materials with inherent dynamic behaviour have already become a reality in impressive projects in art and architecture. Architects, in cooperation with scientists, have envisioned new concepts for designing constructions based on new dynamic materials. As pointed out by Neri Oxman, the combination of the following factors paved the way for these recent advancements. Firstly, the possibility of applying computational design; secondly, additive manufacturing, and thirdly, advances in material science and synthetic biology . All these factors enabled projects like Daan Roosegard's glowing floor panels from light-emitting algae. Furthermore, Neri Oxman's 3D printed chitin-based growing materials and Achim Menges' shape-changing wood construction and self-shaping wood towers.

These projects are based on a deeper understanding of the underlying natural principles associated with dynamic construction materials. A novel way of thinking about the evolution of our environments seems possible as these developments take place. As Erwin Viray suitably said: "Being an architect means being an intermediary, the connecting link between ideas and materials […] " (Schröpfer,2011).The importance of materials for architecture is indispensable. "Architecture is defined by physical components that are materials. Materials are the substance of things. There is no way to convey oneself except by language – language created by means of an impression in a particular medium. Expression is possible only by using specific materials. We perceive reality through materiality, in the reality of matter." (Schröpfer,2011)

TABLE 2 Shape-changing materials and their use in design research

MATERIALS	REFERENCES
Shape Memory Alloy	(Diniz, Branco, & Sales Dias, 2017); (Lignarolo, Lelieveld, & Teuffel, 2011); (Decker & Zarzycki, 2014); (Juaristi, Monge-barrio, Sánchez-ostiz, & Gómez-acebo, 2018); (Hannequart, Peigney, Caron, Baverel, & Viglino, 2018); (Abdelmohsen, Massoud, & Elshafei, 2016); (Jun et al., 2017); (Khoo et al., 2012); (Khoo & Salim, 2013); (Formentini & Lenci, 2017); (Verma & Devadass, 2013); (Coelho & Maes, 2009); (Doumpioti, Greenberg, & Karatzas, 2010); (Mokhtar, Leung, & Chronis, 2017); (Pesenti, Masera, & Fiorito, 2018)
Shape Memory Polymer	(Doumpioti, 2011); (Clifford et al., 2017); (Yoon, 2019)
Thermo Bimetal	(Juaristi, Gómez-Acebo, et al., 2018); (D. Sung, 2016a); (Adriaenssens et al., 2014); (Pasold & Worre Foged, 2010)
Composite Bilayers	(Worre Foged & Pasold, 2015); (Worre Foged, Pasold, & Pelosini, 2019); (El-Dabaa & Abdelmohsen, 2019); (Mazzucchelli, Alston, Brzezicki, & Doniacovo, 2018)
Electroactive Polymer	(Kretzer & Rossi, 2012); (Shimul, 2017); (Kolodziej & Rak, 2013)
Wood	(Holstov, Farmer, & Bridgens, 2017); (El-Dabaa & Abdelmohsen, 2018); (Vailati, Bachtiar, Hass, Burgert, & Rüggeberg, 2018); (Augustin, 2018); (Reichert et al., 2015); (Holstov, Bridgens, & Farmer, 2015)(Correa & Menges, 2017); (Correa et al., 2015); (Vazquez, Gursoy, & Duarte, 2019); (Anis, 2019)
Hydrogel	(Markopoulou, 2015) (Khoo & Shin, 2018)

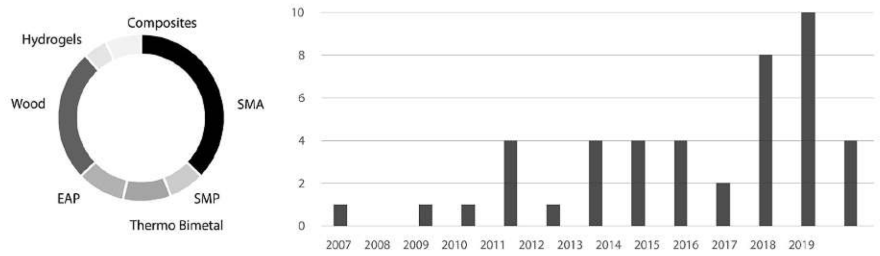

Fig: 1. Shape-changing materials in Architechture

Architecture is now at a pivotal point where the available tools and materials enable advances to be made in the integration of dynamic behaviour into design decisions. One promising principle that continues to evolve with the use of new SMART material is the effect of changing shape. In recent years, a growing interest in shape-changing materials in architectural research can be observed. Research was mainly done with Shape Memory Alloys and Wood, Fig(1). Even though Shape Memory polymers exhibit desirable properties that may be suitable for architectural purposes, they are rarely researched. The ability of SMP to sense and react to heat, light (UV rays), and moisture may enable beneficial designs for future energy-efficient, shape-changing, and self-healing architectural building elements.

Methodology literature review

Before beginning work on this master thesis, literary research was conducted in order to get a general understanding of the developments in the field of modern material science in architecture. The terms ‘matter’, ‘materials’ and ‘materiality’ were described in an architectural context. Furthermore, the material terms coined by László Moholy-Nagy are presented in connection with modern material research and achievements in modern additive and robotic fabrication. As a result, the term ‘dynamic material’ was added to László Moholy-Nagy’s terms. The last part of the literary review included research on the internet in connection with active matter. The developments were displayed by outlining the highly innovative projects that are at the intersection of architecture and biology, architecture and computer science, as well as architecture and material science. The last part of this master thesis consists of bottom-up research on multi-material SMP composites to design shape-changing materials. The material exploration is further discussed in the chapter on 4D-printed programmable materials.

Goal

This master thesis aims to design a programmable material based on a thermo-responsive shape memory polymer. The study engages with creating feasible material combination and the shape-changing behaviour of these composites to open up further design possibilities and prototypes with the Fused Filament Fabrication (FFF).

Matter, materials, materiality

This chapter aims to briefly discuss the terms matter, materials, and materiality in architecture. It serves as a starting point to discuss the latest developments of new programmable shape-changing materials in the field of Active Matter.

Matter

Matter in architechture

Matter is a general term widely discussed in distinct research fields, from chemical and physical science to philosophy. The Merriam Webster dictionary defines matter as a "material substance that occupies space, has mass, and is composed predominantly of atoms consisting of protons, neutrons, and electrons, that constitutes the observable universe, and that is interconvertible with energy" . In physics, matter is described in reference to density, refraction, magnetisation, and chemical composition. Matter undergoes specific phase transitions, depending on changed matter properties and it is in constant alteration. The distinct observable states of matter are liquid, solid, gas, and particular mesophases between solid and liquid also exist. Some may wonder how matter and its phase transitions are related to the field of architecture. Architects operate on a much larger scale than physicists and chemists and mainly work with building elements that "appear" static. However, as Antoine Picont puts it, "Above all, architecture is matter that is arranged at a large scale for the purpose of resisting gravity and the elements as well as for beauty and use (Picont,2020,p.2)."
Moreover, architecture is constantly correlated with natural phenomena and, by extension, the different states of matter. Mohysen Mostafavi and David Leatherbarrow describe architecture in the following manner: "as matter that weather and thus reminds us that buildings live not only in space but also in time." (Mostafavi and David Leatherbarrow,1993) Architectural transformations were formerly very subtle and hidden behind the lasting appearance of buildings. These changes appeared in patina, transformed ground plans or rebuilding, among other things. Nowadays, with the new developments in adaptable and interactive architecture, the transformation of architecture accelerates. These changes happen either autonomously, as influenced by natural phenomena, or they are programmed based on interactions with humans.

Materials

Materials in architechture

Matter is described as "the substance of which a physical object is composed of" . (Merriam Webster,2021) However, materials are generally associated with human uses "Some of them, like stone, are given by nature, while others, like steel, are the result of complex, often industrial processes. What materials have in common is that they are mostly defined through properties that can be mobilised to achieve certain goals. These properties may be entirely natural, or they may depend on the way the materials are extracted or produces." (Picon,2020, p.9). In addition to the aesthetical component of materials, the properties and functionality are a decisive factor for applications in a building. The functionality and opportunities are changing with the introduction of new SMART materials. Modern science offers new possibilities to design materials that undergo specific phase transitions or undergo changes in properties as well as matter. The potential of new materials goes far beyond that of classic materials. "The properties of materials are, by the way partly defined by humans through research, experimentation, and subsequent conventions." and furthermore "materials and their properties are always socially constructed, at least to a certain extent." (Antoine Picon,2020,p.9) The development of sophisticated SMART and biomaterials marks a turning point in the evolution of our environments. Plus, new additive fabrication techniques enable the manufacture of multifunctional material composites. Furthermore, beyond the technical and aesthetical aspects in architecture, a particular emphasis is placed on the material composition. The applied use of distinct materials in the substance of a building is described as materiality. (Venkatesan, 2014,p.81) As in the case of matter, the term 'materiality' in architecture is understood in many ways.

Materiality

Materiality

This chapter gives a short overview into the debate surrounding materiality in architecture. Historically, the idea of materiality first appeared in nineteenth-century German aesthetics. The space-empathy relations of Robert Vischer, August Schmarsow's spatial awareness, and Alois Riegl's Raumwirkung, among others, describe distinct attempts to capture the material world intellectually (Loschke, 2016, p.18). Antoine Picon describes materiality as "not corresponding to a preexisting substance without or with definite properties."(Picon,2020,p.10) Materiality cannot be separated from the way humans understand themselves in relation to matter and materials. Materiality designates a phenomenon of a material dimension, a thing or a system with regard to humans (Picon,2020,p.9) The importance of materiality seems to be undergoing a renaissance with the development of new digital production systems. Gramazio and Kohler, who work in the field of digital fabrication, describe architecture as follows: "not only as the activity of performance optimisations but as multifaceted cultural production. It is precisely digital materiality that shows us quite plainly the essential human dimension and quality of this production". Additionally, Gramazio and Kohler formulated the idea of digital materiality. "Digital materiality evolves through the interplay between digital and material processes in design and construction. Digital materiality changes the physics of architecture, changes the Gestalt, and ultimately the image that society has of architecture." . Materiality is a phenomenon that is intangible and atmospheric, tightly interwoven with the perception of the materials' expression. Many of the ideas of Gernot Böhm, Robert Vischer and Alois Riegl, "re-emerged transformed in the early avant-garde projects of László Moholy-Nagy, Walter Gropius and others."(Loschke,2016,p 18)

"Matter architecture" is solidified in form by arranging materials that are under constant alteration and correlate with natural phenomena. Alterations can be triggered by humans or natural phenomena. This change may be seen in the form of transformable architecture, subtle rebuilding or at the smallest scale in architecture, specifically, in the material itself.

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from material to architechture

Art historians formalised the idea of materiality. Nevertheless, the avant-garde aspired to unlock and apply its transformative powers (Loschke,2016,p.18). Ephemeral materials such as light, colour, image, and projections were a central part of their experiments. László Moholy-Nagy's Light Space Modulator illustrates this idea figuratively (Loscke,2016,p.18).

Furthermore, The Bauhaus education emphasised the sensual experience of materials. The artists Albers and Itten developed specific concepts in matter studies, each with their own distinct emphasis. Albers insisted on a difference between "matter" and "material" and developed material studies. Itten, on the other hand, concentrated on basic training in materials. Being restricted to one material should encourage students to discover the essence of the chosen material. The exercises were specifically designed to understand how materials such as wood, glass, fibre, paper, and metal have behave in their own way.(Getty Research) László Moholy-Nagy once said, Technology is a developing living factor. There is an interaction with technology and the growth of humanity. That is, it is organic authority. (See: László Moholy-Nagy,1929,p.12) To further discuss the changes in modern architectural research, I will turn to the material terms of László Moholy-Nagy. He formulated the terms Häufung (the amassing of matter), Faktur, texture and Struktur. Häufung describes the ordered or disordered amassing of matter. Furthermore, Faktur concentrates on the evolving changes that take place on the surface as a result of an outside impact. The texture is the natural outer layer of a material exposed to the environment. Lastly, the structure designates the inner composition of a material. (see: László Moholy-Nagy,1929,p.33)The following examples show advancements in architectural design, which are closely connected with new production methods like 3D printing, robotic fabrication, and material research. These projects are associated with László Moholy-Nagy's material terms. It visibly validates the importance of material studies in modern architectural research. Furthermore, the description of dynamic material behaviour is added to the terminology of László Moholy-Nagy, which comprises the observable matter changes in the level of organic and inorganic materials.

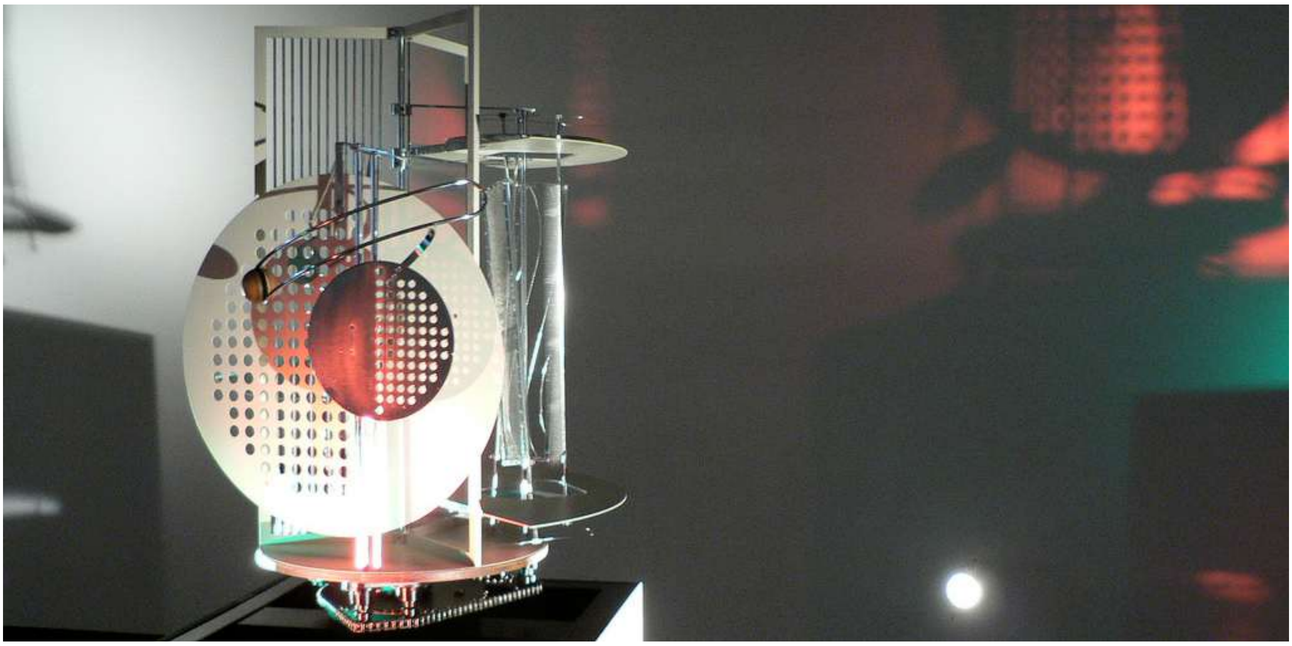


Fig: 2. Light Space Modulator

Amassing of matter

Amassing

The first term is the amassing of matter, which László Moholy-Nagy described as a material condition that is difficult to determine. The amassing of matter is either regular and rhythmic, structured or irregularly structured. It is easy to change the organic connections while amassing, but they are often difficult to determine. He pointed out that “it is not synthesis. It is addition.” (See: László Moholy-Nagy,1929,p.33)

An enthralling example of irregular amassing may be seen in the work of Gramazio and Kohler. The research group experimented with granular matter at the mesoscale. They used a principle called jamming, which usually prevails between the nano and the mesoscale. The project rock print presented the possibility of cramming gravel together with the aid of a robot so that it holds its shape and behaves like a solid. (Gramazio Kohler,2015) The principle of jamming is described by Bulbul Chakraborty and Bob Behringer “[…] as the extension of the concept of freezing to the transition from a fluid state to a jammed state.”(2009) The transformation from a “fluid” and loose gravel state to a solid state may be among one of the first projects that show a phasal transition of matter on the mesoscale.

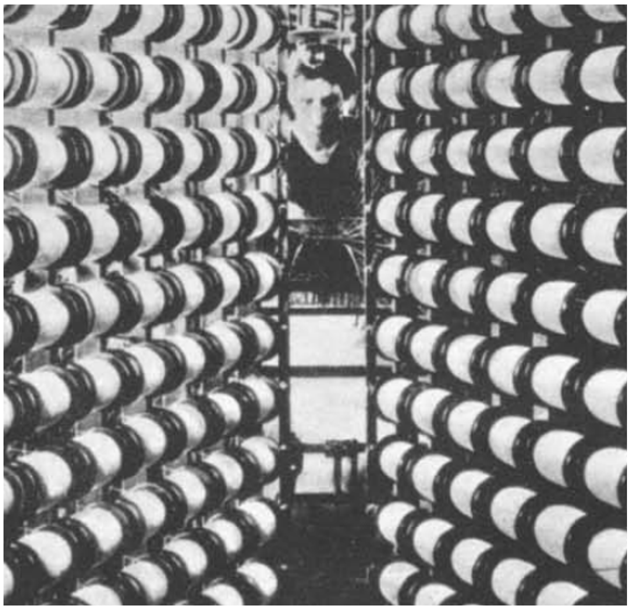


Fig: 3. Rhythmic amassing of matter, László Moholy-Nagy

Fig: 4. Modern rhythmic amassing of matter

Fig: 5. Modern rhythmic amassing of matter with a robot

Irregular amassing

Fig: 6. Irregular structured amassing - László Moholy-Nagy

Another project was carried out by Karola Dierichs and Achim Menges, which experimented with static particles and particles enhanced by the dynamic behaviour of programmable materials. In their project, they used parts of wood, plastic, and metals(Dierichs, Menges, 2016,p.9) In contrast to the static particles, the reactive wood particles can transform at a specific relative humidity. The change in shape that could be observed was the curling and uncurling of the particles. (Dierichs, Menges, 2016,p.9)

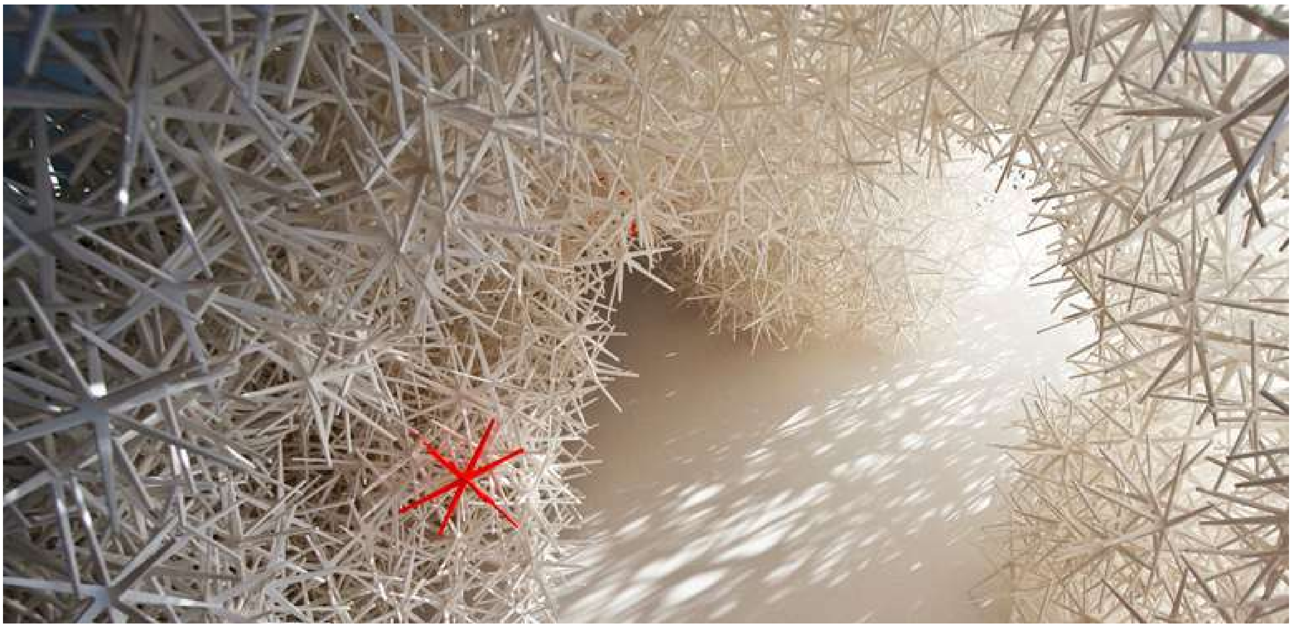


Fig: 7. Modern irregular structured amassing

Programmable particles

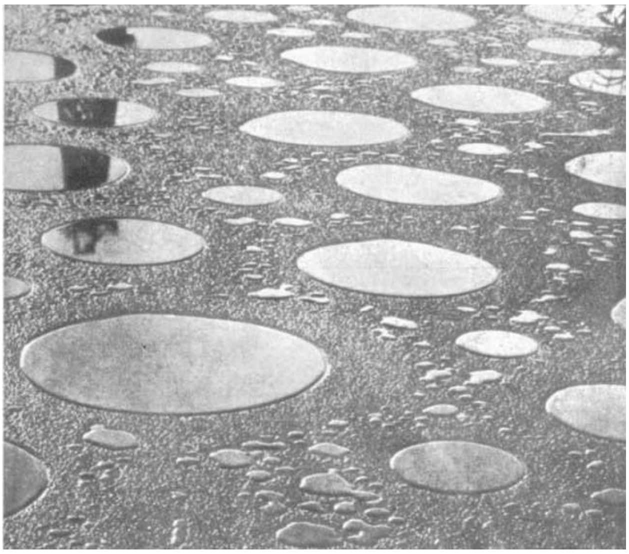


Fig: 8. Petroleum on water

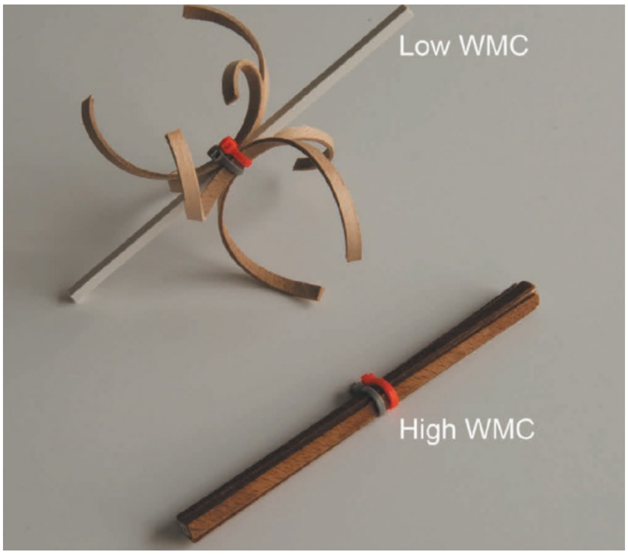


Fig: 9. Programmable wood particles

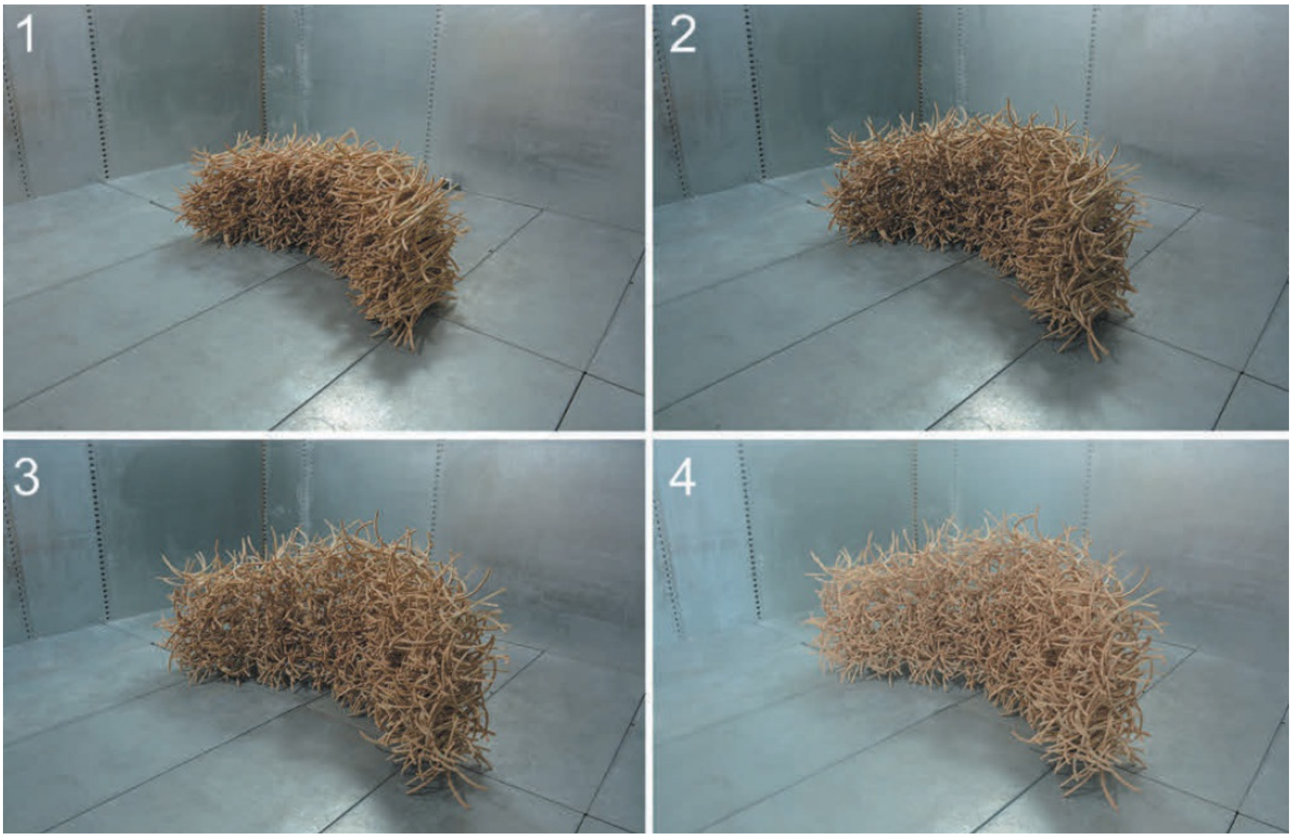


Fig: 10. Programmable wood particles - irregular amassing

Faktur

The second material term described by László Moholy-Nagy is the Faktur. The German word Faktur has its origin in the Latin word 'facture' or the Italian word fattura , which can be referred to as the English term 'machining'. Faktur relates to the nature and appearance, the sensual observable impact of the work process, which is noticeable on every material after machining. The surface of the machined material is the epidermis, it is artificial. As he described, the outer impact can be both elementary (influenced by nature) and mechanical, as is the case, for example, when machines are involved. ." (See: László Moholy-Nagy,1929, pp.33-56)

Fakturen can appear on an object in different ways. For example, on a metal bowl it can become visible as: (See: László Moholy-Nagy,1929, pp.33-56)

1. Patterns
2. Perfect smoothness (pressed or polished)
3. Light (mirroring, reflections, light, and colour refraction) (See: László Moholy-Nagy,1929,pp.33-56)

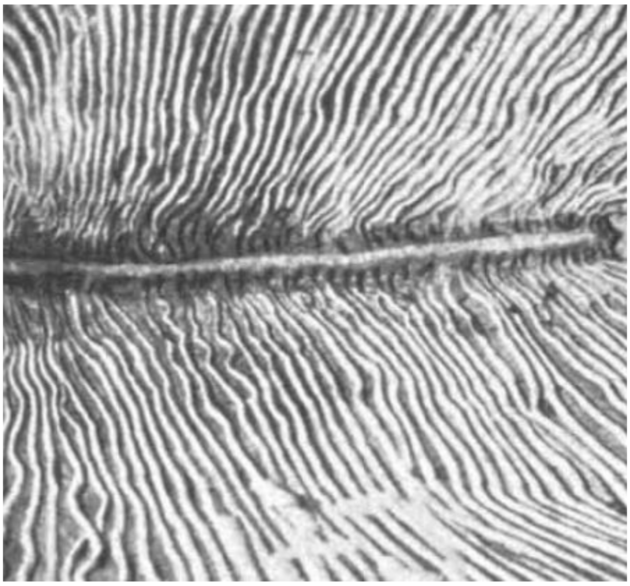


Fig: 11. Faktur in nature: Picture of spruce which were eaten by bark beetle

Fig: 12. Modern faktur - 3d printed concrete

Fig: 13. Concrete Choreography - Faktur 3D printed concrete

The tools and the materials, which we use to produce constructions elements, are changing on account of technological advances. With the launch of 3D printing, robotic fabrication, and new digital modelling tools, we can perceive the development of a new expressive formal language that was not possible 30 years ago. As Henriette Bier pointed out, "[a]dditive manufacturing technologies have enabled architects and designers to create architectures that are far beyond the Architect's capacity as a craftsman, and that as a result surprise and astonish us with complex forms which could never previously be produced" (Bier, 2019,p.38). Examples of this would include Neri Oxman's Glass II, the Concrete Choreography project created at ETH Zurich and Michael Hansmeyers "Digital Grotesque". The conspicuous skeins produced by 3D printing technology are an excellent example of a material's modern Faktur. Another prominent example of how the Faktur is influenced by new digital tools can be seen in the advances of machining stones and marble. The following projects all focus on a new expression of materiality in connection with a unique quality of materials.

Digital Grotesque II

7 ton, 3.5 meter high block, 3D printed sandstone structure.

Fig: 14. 3D printed sandstone

Neri Oxman Glass II

3D printed glass column

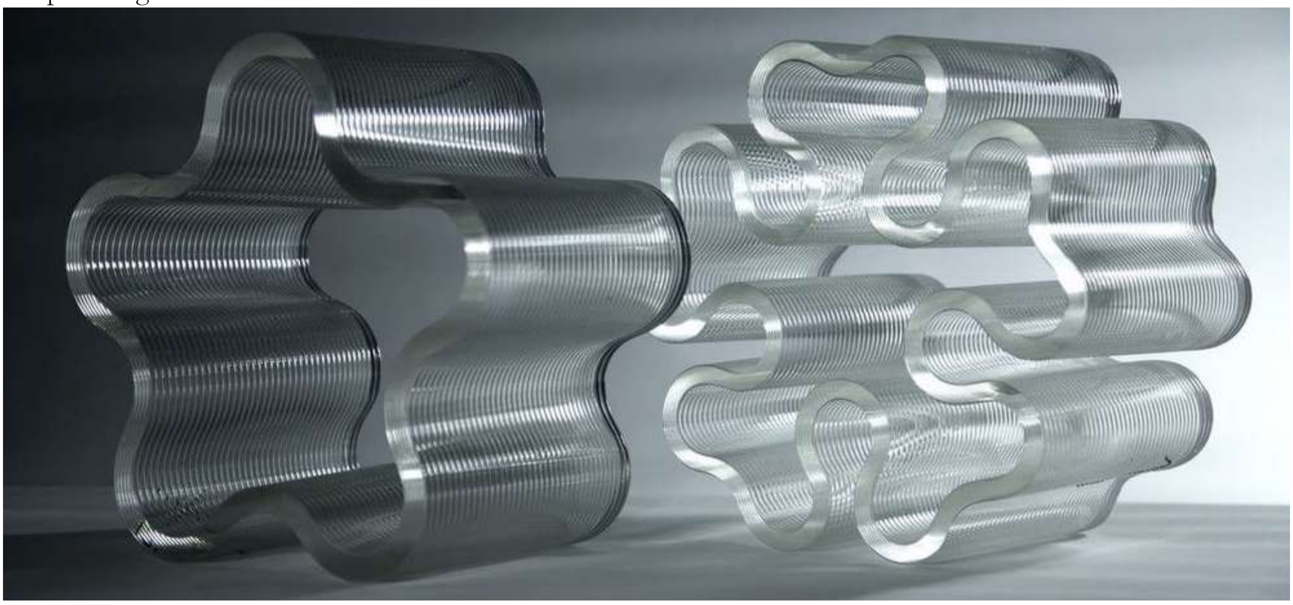


Fig: 15. Top & bottom parts glass column

The developed organic surface from every structure to the outside is called texture. (epidermis, organic) VGL. (the top layer of the skin) (abb 22 -25). (See: László Moholy-Nagy,1929, pp.33-56)

Fig: 16. Texture: 130 year old american from minnesota

Fig: 17. Skin like elements - Neri Oxman

As pointed out before, matter can undergo specific natural changes. The outermost layer, the epidermis of a material, is often the first level where changes are likely to occur. For example, over a lifetime, human skin develops wrinkles and discolourations. Materials likewise exhibit the same behaviour: they weather and put on patina-like copper and brass. Depending on their materiality and the conditions the materials are exposed to, distinct textures would develop. Lucretius described this causal relationship as "everything we perceive is eternal and solid, but will change its properties eventually, either through direct influences, like force or temperature, or indirect environmental impact" (See: Kretzer, 2017,p.2). When referring to material textures, Neri Oxman, an architect who works on the boundary between architecture and biology, experiments with new ways to design organic materials. She shaped the idea of Material Ecology and continues to develop new building materials with her interdisciplinary research team. As part of the project called Aguahoja, an architectural pavilion constructed with elements similar to shell and skin, they invented a biopolymer skin developed from shrimp shells and fallen leaves. Over time, the pavilion transforms from a flexible, relatively weak system to a rigid one. The structure can adjust to specific environmental conditions, such as humidity and heat. If the building is exposed to rainwater, it will degrade with the help of programs. “Surface features, patterns and colors are computationally ‘grown’ and additively manufactured with varied mechanical, optical, olfactory and gustatory properties, utilising organic waste streams while preserving ecological niches.” (Oxman,2021) Aguahoja is an example of a highly technological architectural project that is strongly influenced by material inventions, which is printed in 3D by a robot. The following pictures demonstrate variations of the biopolymeric skin with its distinct textures. (Oxman,2021)

Fig: 18. Aguahoja

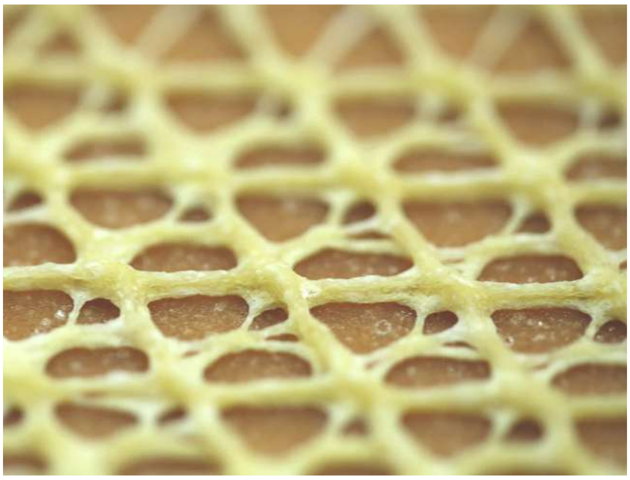


Fig: 19. Texture:3D printed cellulose, a plant derivative

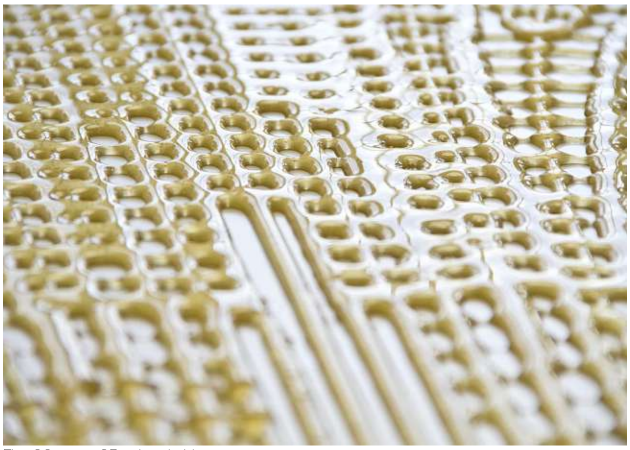


Fig: 20. 3D printed chitosan

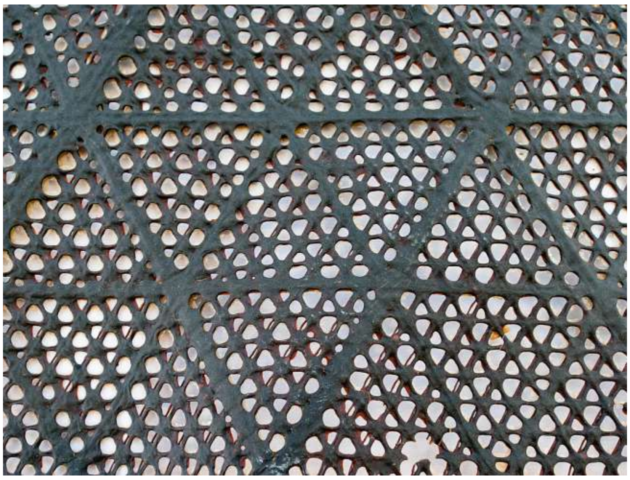


Fig: 21. Texture:3D printed chitosan over pectin, a plant derivativ

Structure

Structure

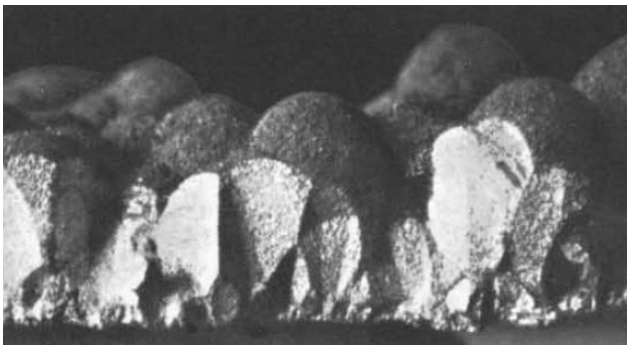


Fig: 22. Crystalline structure - László Moholy-Nagy

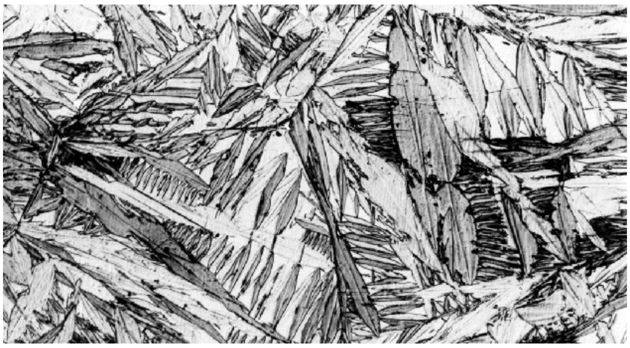


Fig: 23. Structure: FeC alloy

The unchangeable compound of materials is called structure. Thus, every material has structure; metal, for example, has a crystalline one, paper has a fibrous structure. (See: László Moholy-Nagy,1929 p.33-56)

To form a clear understanding of the term structure, it is crucial to differentiate between specific scales. Moreover, the context in which László Moholy-Nagy developed the terms amassing, Faktur, texture, and structure have to be kept in mind. Ever since 1929, which is when László Moholy-Nagy wrote his book „From material to architecture", disciplines like crystal chemistry and metallography have been evolving. (See: László Moholy-Nagy,1929,p.33-56) Nowadays, it is possible to investigate the inner structures of materials to a very high resolution, from the macroscale to the atomic scale. In recent years, scientists have invented materials that can change their inner molecular or crystallographic structure. Depending on different stimuli, the internal transformations result in a change in colour, a deformation, a change in volume, or a change in the refractive index.
(See: Casini, 2016,p.84)

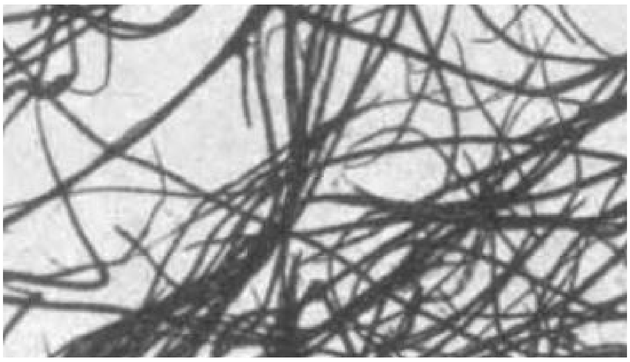


Fig: 25. Fibrous structure - László Moholy-Nagy

Fig: 24. Ferroelectric polymers - electromechanically active materials

Dynamic material behaviour

As mentioned before, scientists from diverse disciplines design sophisticated materials from the bottom up. Materials nowadays have properties that go beyond the potential of classic materials. These smart materials can change their colour, shape, and exchange energy, to only name a few possibilities that modern science offers.(See: Casini, 2016,p.84) As due to these developments, I would suggest expanding the material terms of László Moholy-Nagy to the new additional term of dynamic material behaviour. This term is occurring in material science papers and architectural research in connection with new material exploration. (See: Marc André Meyers,1994) The dynamic material behaviour encompasses the ability of materials to sense and react on altered environmental conditions and transform accordingly.

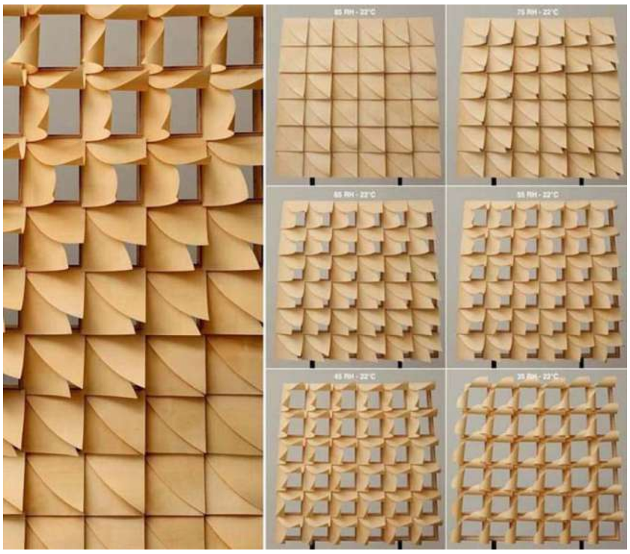


Fig: 26. Dynamic material behaviour - wood

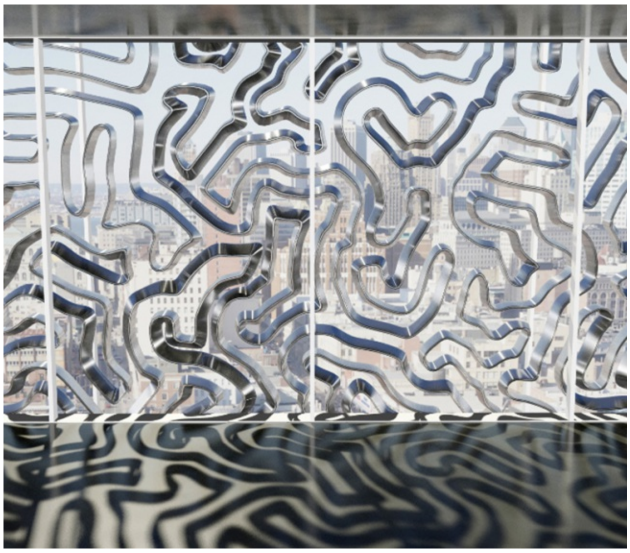


Fig: 27. Dynamic material behaviour - R-Phase shape memory alloys

The resulting changes can be manifold, and the possibilities are not limited to SMART materials. Living organisms inherently exhibit behaviours, such as, for example, the swelling and shrinking of wood or the glowing light-emitting algae. As interest in dynamic material behaviour and its opportunities evolves, architectural projects can be seen which utilities the shape changing behaviour of smart materials like wood and shape memory alloys. The debate surrounding this new material behaviour may lead to the formation of design principles within the discipline of architecture. Principles like self-assembly, self-shape, and shape-change are already at the centre of admirable projects in Active Matter research.

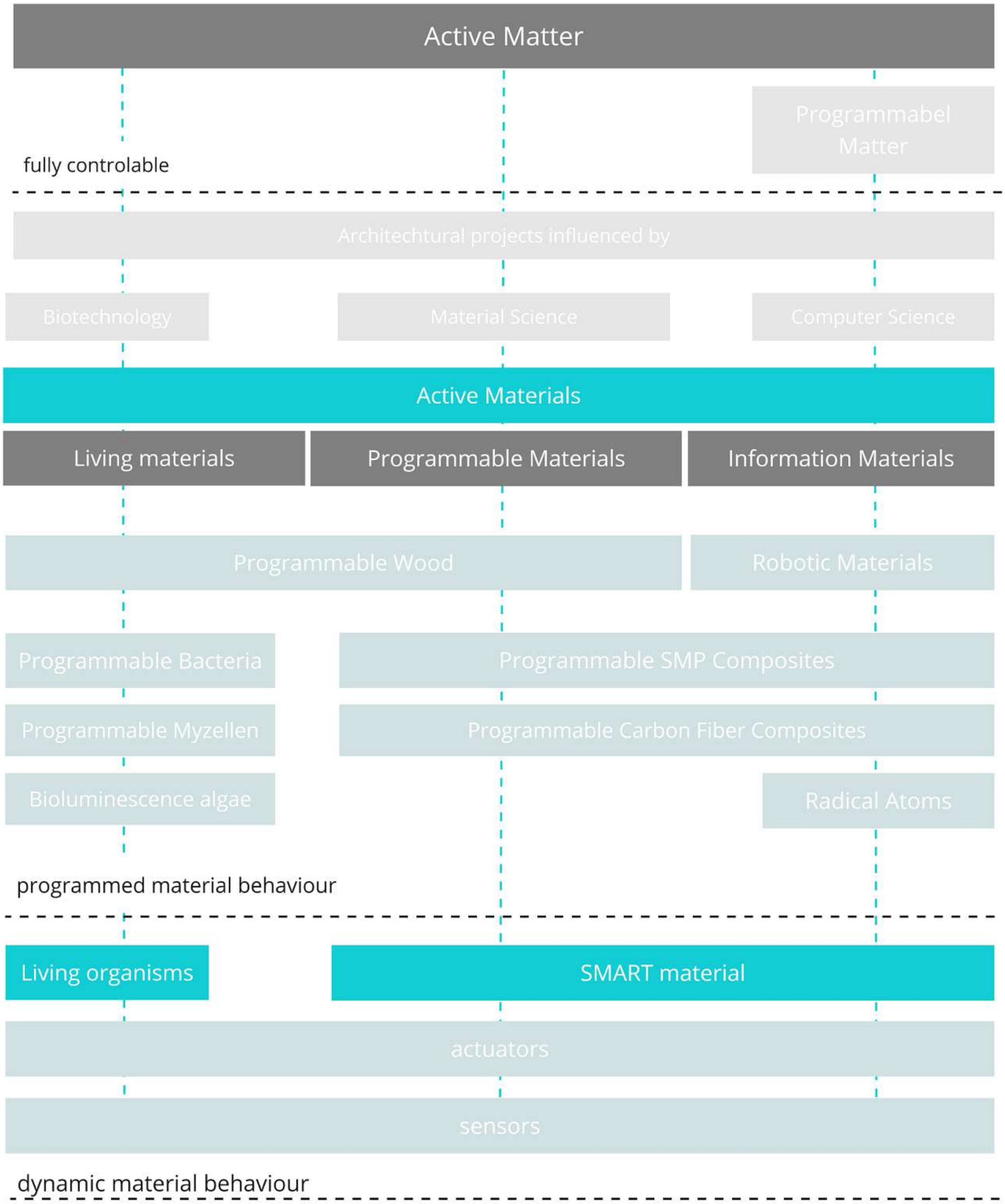
Based on the material terms as understood by László Moholy-Nagy, they can be seen as the interplay between the changes in the material dimension and modern production systems. It would not be conceivable to achieve a planned phase change within the project rock print that could be observed at the mesoscale without modern production methods. The changes in the Faktur of modern materials with the additional fabrication technique is displayed in new aesthetic expression. The project Ahohajoa shows an artificially designed biological material that is capable of growing and decaying. The artificially generated original texture of these materials shows an accelerated transformation of the surface texture, which is triggered by natural phenomena. The unchangeable structure can also be observed in the dynamic material behaviour of Smart materials. The dynamic material behaviour is not, however, limited to Smart materials and can also be seen in living materials, for example, wood. The dynamic material behaviour forms the basis of developments in the research of active matter.

Active Matter the nature of changing Architechture

Active Matter

Introduction - Active Matter

Active matter is a vast and new field that is evolving in modern architectural research. There is no established terminology in this discourse due to the novelty of this subject. Thus, it seems appropriate to turn to the term Active Matter in Skylar Tibbits' book of the same title. In his book, he summarises projects from distinct research fields with an emphasis on transformable materials. The works range from large-scale architecture to applications at the microscopic scale. For Skylar Tibbits, Active Matter is a "[…] newly emerging field focused on physical materials that can assemble themselves, transform autonomously, and sense, react, or compute based on internal and external information." (see:Skylar Tibbits, 2017,p.11) In this section, Active Matter serves as a generic term for the research field, which concentrates on the materials that combine programmability, transformation and/or adaption, and assembly.
In general, Active Matter research focuses on materials that emulate specific behaviour and properties found in living matte(Fraden). Living matter exhibit a multitude of desired properties and abilities. These range from self-healing, growing, adapting, regenerating, biodegrading to adapting to stress. Furthermore, individual biological units display the ability to "dynamically self-organise into larger ensembles, as in birds' flocking behaviour, schooling of fish, and swarming of bacteria"(Fraden)" For Skylar Tibbits, Active Matter goes beyond the functions of SMART materials. "Active matter makes it possible to make any material a smart material." If yesterday we programmed computers and machines, today we program matter itself" (2017,p.12). This field of research is not limited to a particular discipline. The following examples show a spectrum of architectural projects and principles that evolve as part of Active Matter research. A rough roadmap was designed to get an overview of the particular attempts. 'Active Materials' is chosen as a subgroup of Active matter, and it categorises new dynamic materials according to the disciplines that are of influence. First, I turn to Manuel Kretzer's information materials, which describe active materials based on Information and Communication Technologies (ICT). Secondly, I turn to the architect Benjamin David and his project Living matter, which highlights developments in biotechnology and architecture. The third section shows materials based on advances in material science as described by the term Programmable materials. However, they all take different approaches; the observable common feature in the whole project is the underlying goal of embedding and using certain natural behaviours and properties in inanimate materials, see Fig. (). Before going into more detail, the term 'programmable matter' will be briefly discussed, as it is crucial for an overall understanding of the diverse terminology.



Active matter - overview

Programmable Matter

The science-fiction author Will McCarthy popularised the vision of Programmable Matter in his book The Collapsium. He described a material called Wellstone, "a form of programmable matter capable of emulating almost any substance: natural, artificial, even hypothetical"(McCarthy 2000). This idea is also presented by the Shapeshifter Odo in the science-fiction series Star Trek, who can transform into any desired state and form. In 2007, The Defense Advanced Research Projects Agency (DARPA) started an innovative programme called "Programmable Matter". This goal proclaimed by this project was to generate Programmable Matter by shrinking robotics and enabling new functionality at the millimetre scale. (Thomas A. Campbell Skylar Tibbits Banning Garrett, 2014) "The researchers developed smaller and - smaller-scale robotic modules with embedded electronics, power, actuation, sensing and communication that enables a variety of physical transformations and other behaviours." (Tibbits,2017,p.14). The small robots became a synonym for "matter". However, they were not just materials, they consisted of software and hardware devices. According to Tibbits, the Programmable Matter project laid the groundwork for today's Active Matter. He describes Programmable Matter as "the science, engineering and design of physical matter that has the ability to change form and/or function in a programmable manner." (Tibbits,2017). For Tibbits, Active Matter goes beyond the functions of Programmable Matter and it is more than just programming materials. Active matter includes a combination of programmability, transformation/adaption, and assembly. These materials are not accumulations of software and hardware devices; they are pure materials. (see: Tibbits,2017)

Programmable Matter

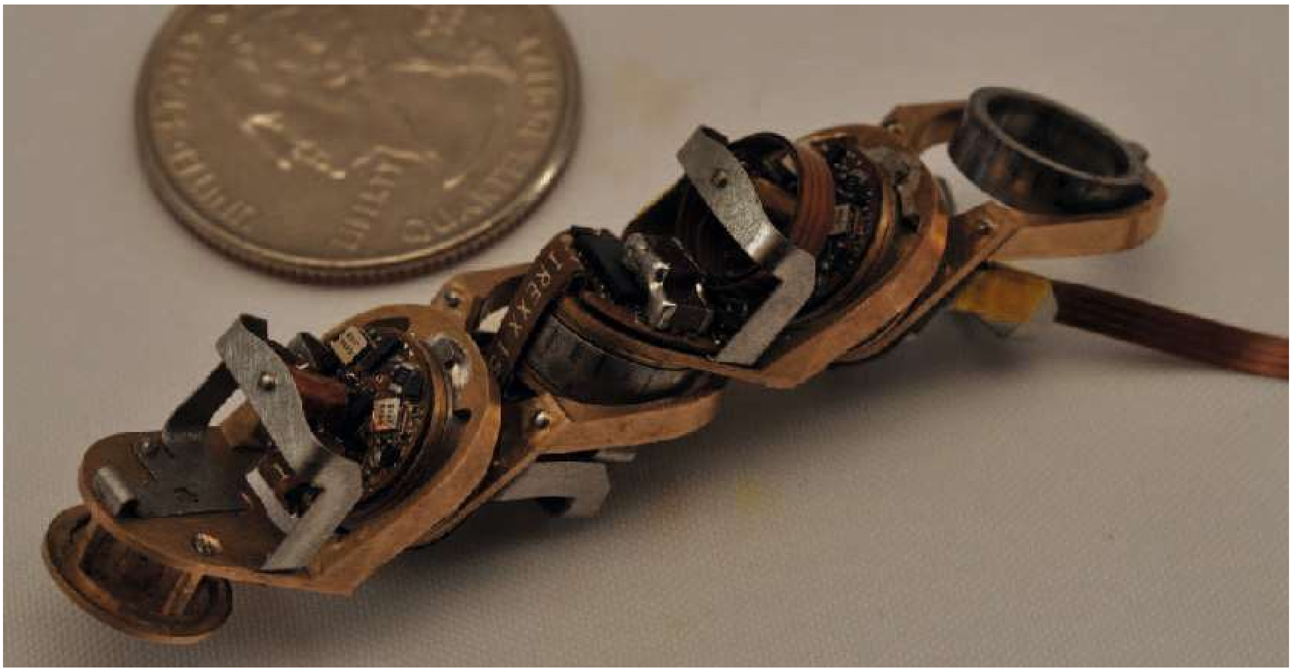


Fig: 28. Programmable matter - Milli-Motein

Active materials:

In this work, active materials are examined in relation to different compositions of materials with their underlying natural behaviours. The application of active materials in technology and the synergy of architecture offers new possibilities to develop innovative principles and architectural designs. As pointed out by Neri Oxman, there is a moment of convergence that promotes these developments in four areas: "(1) computational design – the ability to design complex shapes with very simple forms; (2) additive manufacturing- the availability of sophisticated tools to design by adding materials instead of carving them out; (3) materials science engineering – the availability of materials with very high spatial resolution for manufacturing; and (4) synthetic biology – the ability to design with the units of life."(See:Tibbits,2017, p.8)

Information Materials:

The computer science approach makes use of the possibilities of modern ICT. The architect Manuel Kretzer promotes the idea that information materials that have two characteristics, which are as follows:

"• First, information materials have the inherent capability to contain and harvest (digital) information and transform it into physical representation. Thus, they are dynamic and can change their state over time in a controlled way and in response to external influences."
"• Second, information materials are based on information technology. They are artificially created on a symbolic level by the combination of formerly distinct elements into functional assemblies using digital technologies. As such, they are not built upon anything that can be found in nature but are sole products of human intellect". (See:Kretzer,2017,p. 52)

Robotic material

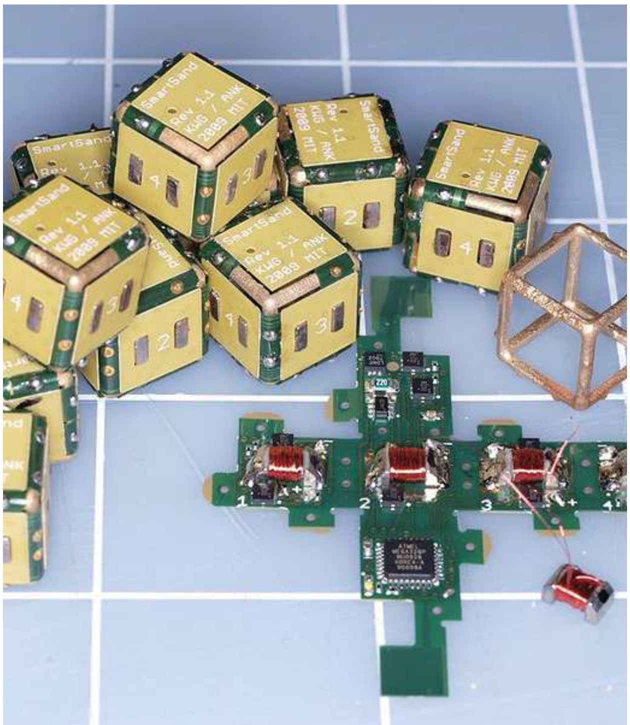


Fig: 29. Self-reconfiguring robots „electronic clay"

In the field of computer science, M. A. McEvoy and N. Correll describe the idea of a robotic material, which, "unlike conventional stimuli-response materials that change one or two physical properties in response to an external stimulus, [...] make[s] the relationship between signals measured from embedded sensors and the material properties activated by embedded actuators fully programmable." (McEvoy and Correll, 2015,p.) Hiroshi Ishi, a computer scientist who works on programming materials and overcoming the boundaries between digital and physical space, declared that "physical materials are, at a human scale, seemingly shy, inert, and frozen. In our eyes, these frozen atoms desire to be awoken: to dance, to leap, and to levitate around us. Using the power of computation, we aim to build a new expression, design, and communication, to breathe life into static forms." (See: Skylar Tibbits,2017,p.228) So what does that signify for the field of architecture as it aims to shift from static materials to programmable ones? How do the design processes change if we design animated materials with transformable conditions?

Pro - Skin

An example of information material would be the project Pro_Skin. It is a flexible and translucent membrane that sends real-time data feedback to the user and its immediate surroundings. It is a composite of a polymer and graphene, coupled with a microcontroller. The project team carries out rudimentary research on flexible elements that react to certain environmental conditions or the users' needs (IACC, 2016).

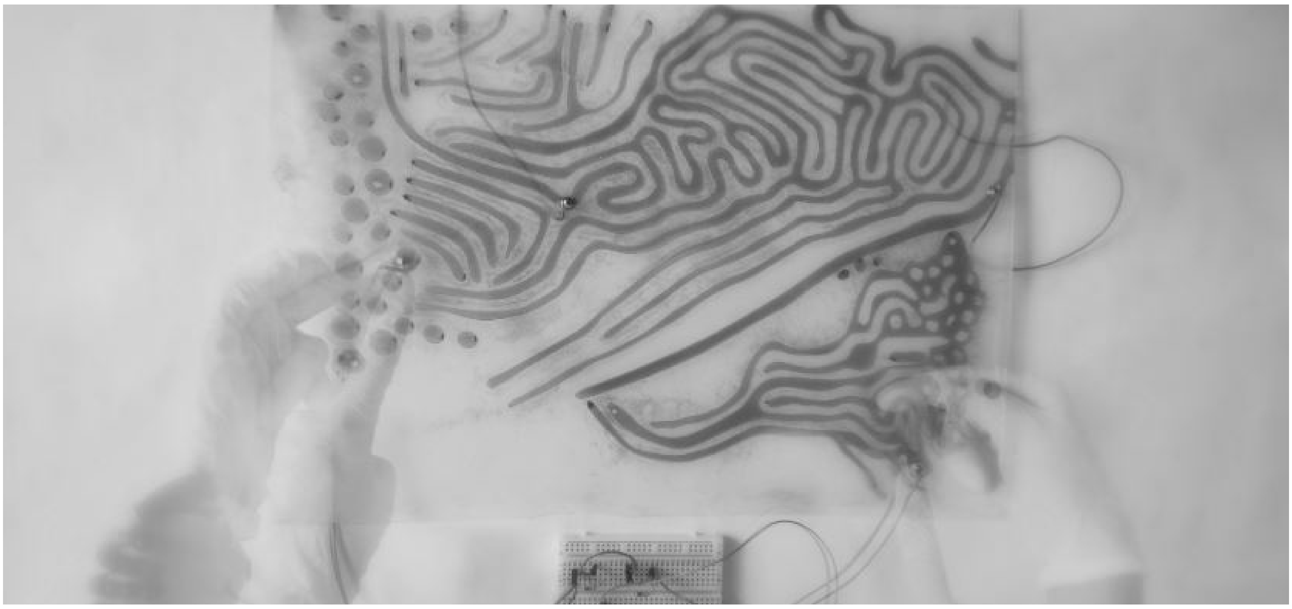


Fig: 30. Pro_Skin - membrane with real-time data feedback

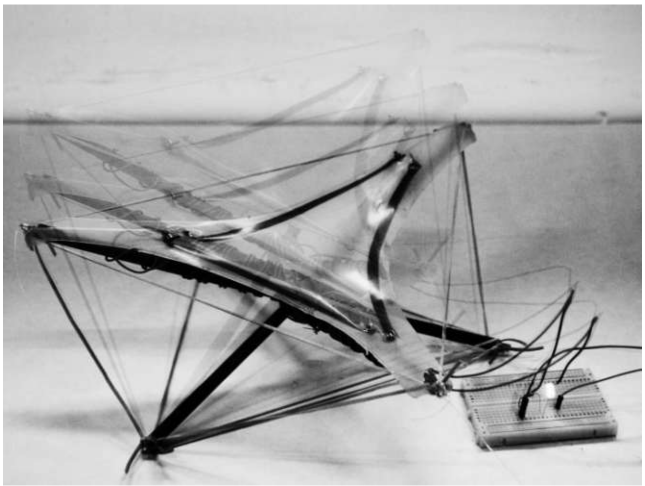


Fig: 31. Pro_Skin - graphene Architechture

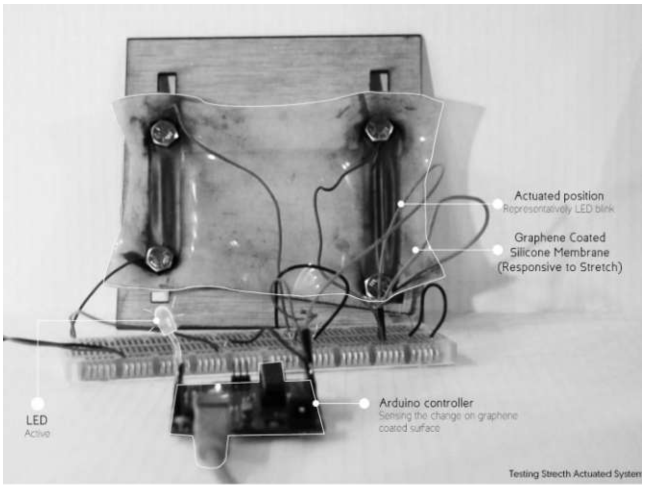


Fig: 32. Test stretch actuated system

SMAAD surface

The SMAAD Surface is a composite material composed of a fabric, a SMART material, and a flex sensor. This fabric can modify its shape with the help of manual operations. The shape memory alloy (SMA) is used to maintain its shape and the flex sensor transmits the data through a microcontroller to a CAD program. The designer can manually modify the fabric to send the freeform to the 3D program and vice versa, the data from the program can change the form of the fabric (Materiability,2021).

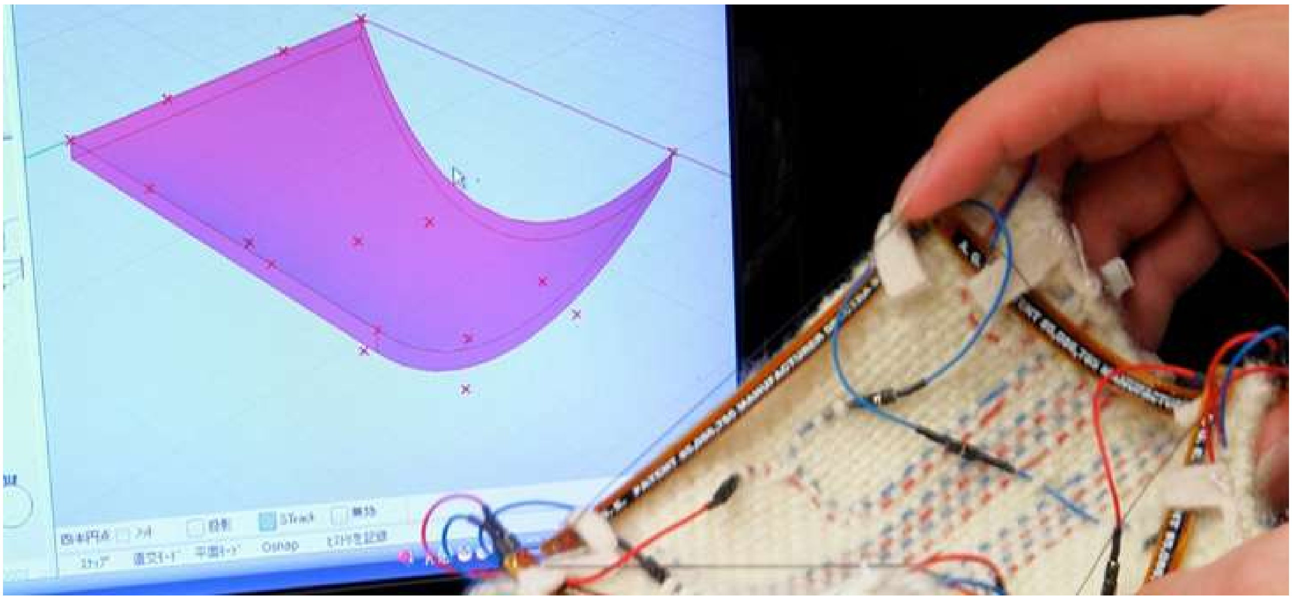


Fig: 33. Smart material aided design (SMAAD) - materialization of the virtual models into tangible

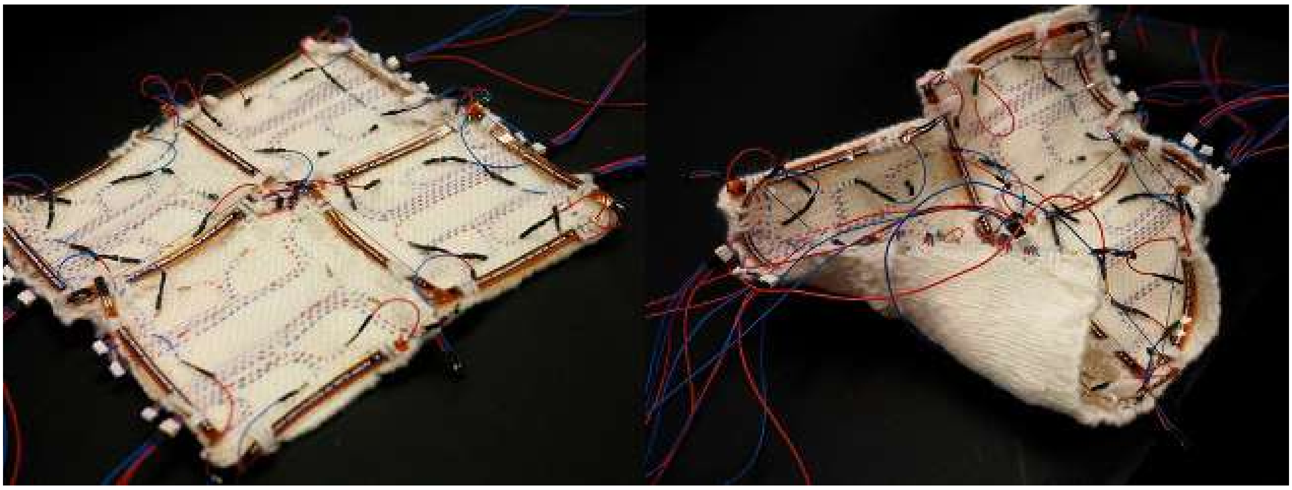


Fig: 34. Smart material aided design (SMAAD) - programmable surface

Living materials

Living materials

Nowadays, advancements in biotechnology are drivers of new developments in Active Matter and material research. Living organisms like plants and animals exhibit astonishing abilities and properties that enable them to react and transform according to distinct environmental changes. Cuttlefish, mimic octopuses, mutable rain frogs, skeleton flowers, light-emitting algae, bacteria, and mimosas are some of the most impressive creatures that display specific behavioural patterns. In this chapter, the term 'Living materials' refers to projects with underlying biotechnological processes. Among their other properties, they are able to grow, decay, emit light or change colour. Architects and designers that work at the intersection between biology and architecture are Neri Oxman, Benjamin David and Daan Roosegaarde

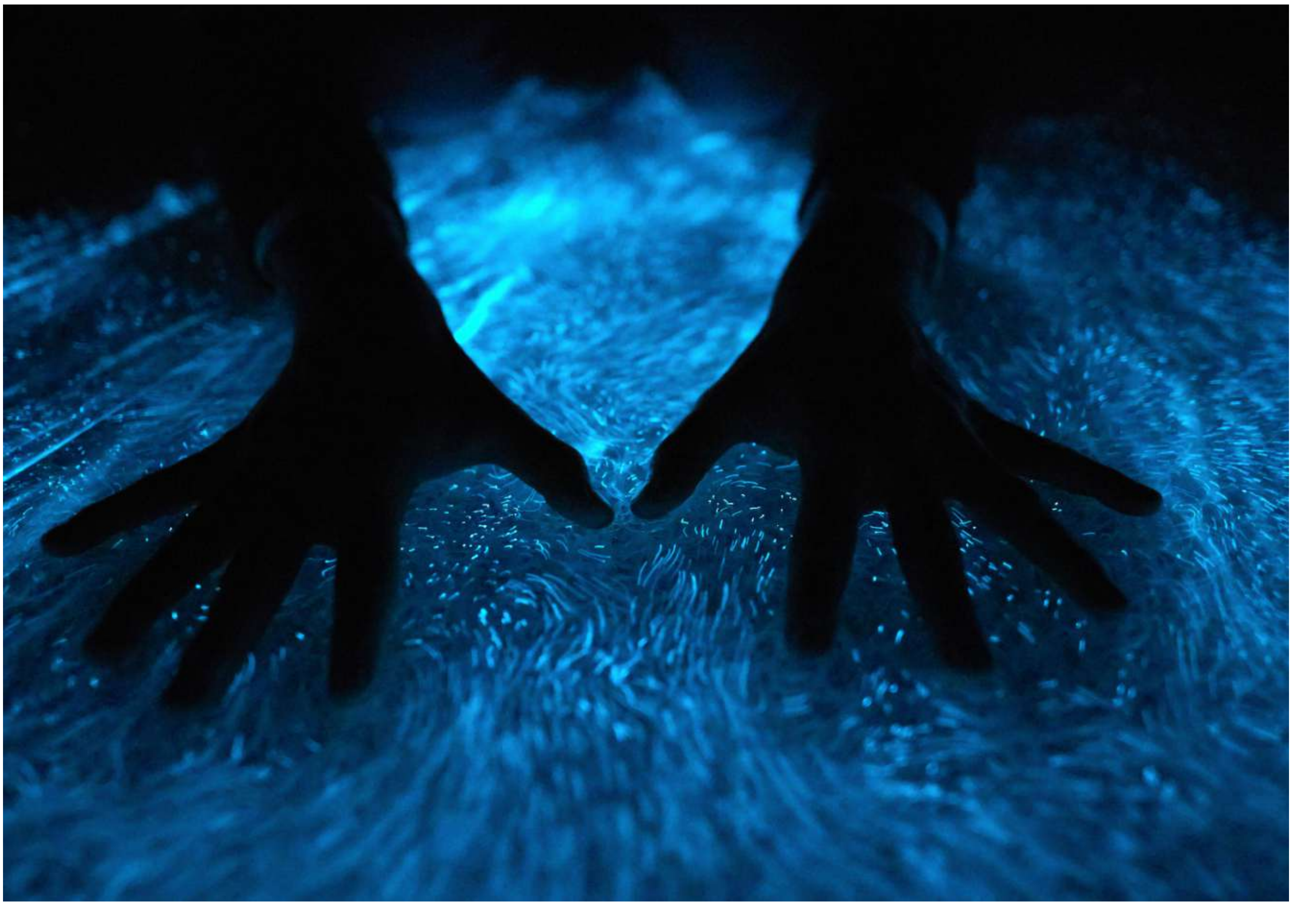


Fig: 35. Glowing nature - floor panels from light emitting algae

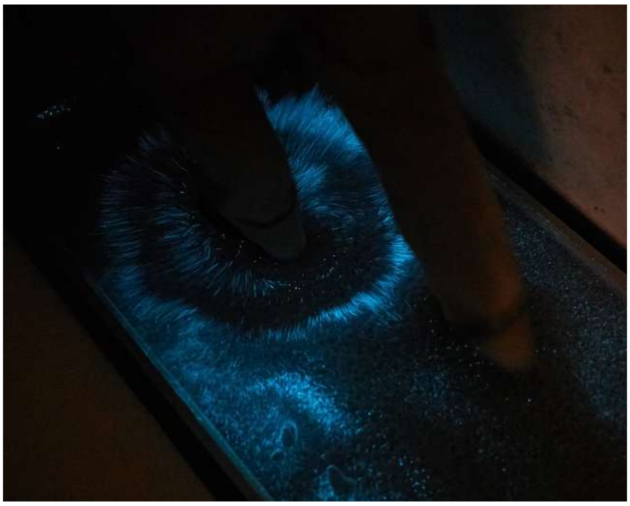


Fig: 36. Glowing nature - light activation through pressure of footsteps

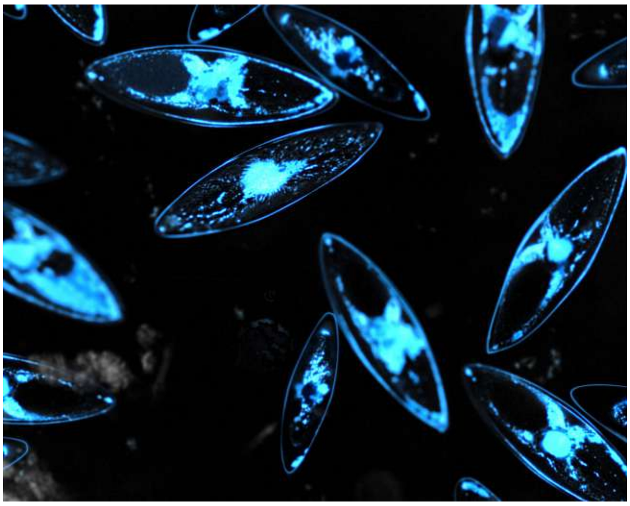


Fig: 37. Glowing nature - light emitting algae

The Studio Roosegaarde developed a "floor material" based on the most prominent light-emitting algae that can live for a long time. The pressure applied by footsteps activates the algae's bioluminescence and creates mesmerising changing environments. "GLOWING NATURE combines biology and technology to reflect on light and energy, and on nature's potential to provide the tools for a better future." (Studio Roosegard ,2017) An ongoing project envisioned by Daan Roosegaarde is the development of GLOWING Nature for public streetlights.

Fig: 38. Glowing nature - light activation through interaction

Vespers III

Another project based on biological processes is the Vespers III mask. The collection of Vesper masks consists of three separate series. The third element of the design changes colour due to the presence of microorganisms. Each mask in the Vespers III project is computationally designed and the result of a high-resolution 3D print made from photopolymers. Furthermore, the masks are coated with a cell-seeded hydrogel. The pigments develop based on the chemical signal generated by the respondents in the cell. These biohybrid materials are "formed by combining living and non-living materials such that the resulting composites take on the functional properties of both "(Soo,Smith, 2019,p.1).It was within this project that the "Hybrid Living Materials" (HLMs) framework was introduced. It should offer a framework for "computational design, additive manufacturing, and synthetic biology to achieve replicable fabrication and control of biohybrids" (Soo,Smith, 2019,p.1).

Fig: 39. Vespers III - habitats for microorganisms

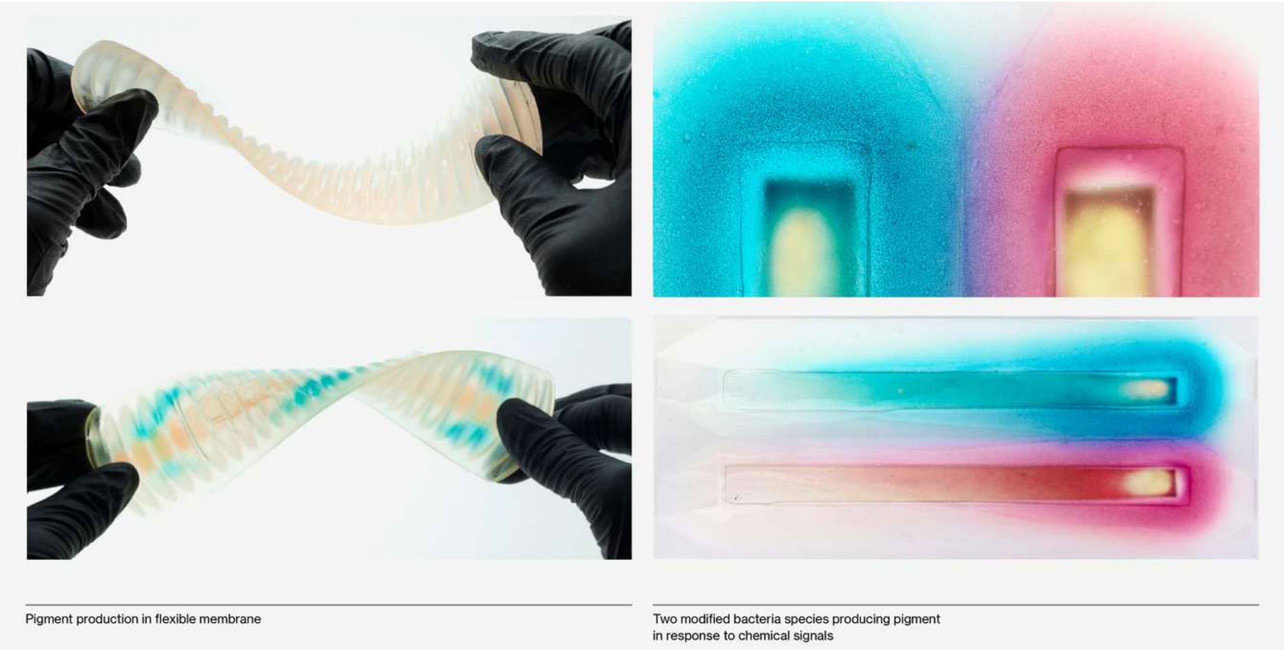


Fig: 40. Vespers III - habitats for microorganisms

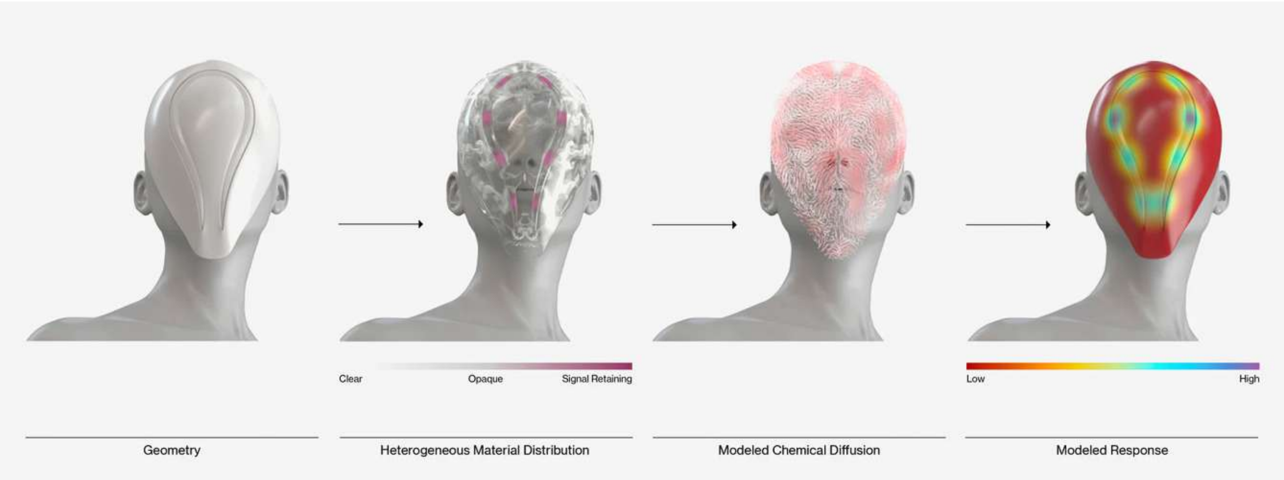


Fig: 41. Computational design process

While working at the Cambridge University, the architect Benjamin David and the plant biologist Fernan Federici developed a complex 3D structure from living biological cells that behaved like tiny computers. Using xylem cells that grow in the stems of plants, they generated complex 3D forms with a "biological algorithm". When the conditions are altered, the xylem cells that are beyond the glass plates create "bounding shapes", like the shape of a boot or a stadium. (Antonelli,Burckhardt,2020 p.160) As pointed out, "the resulting forms are striking,

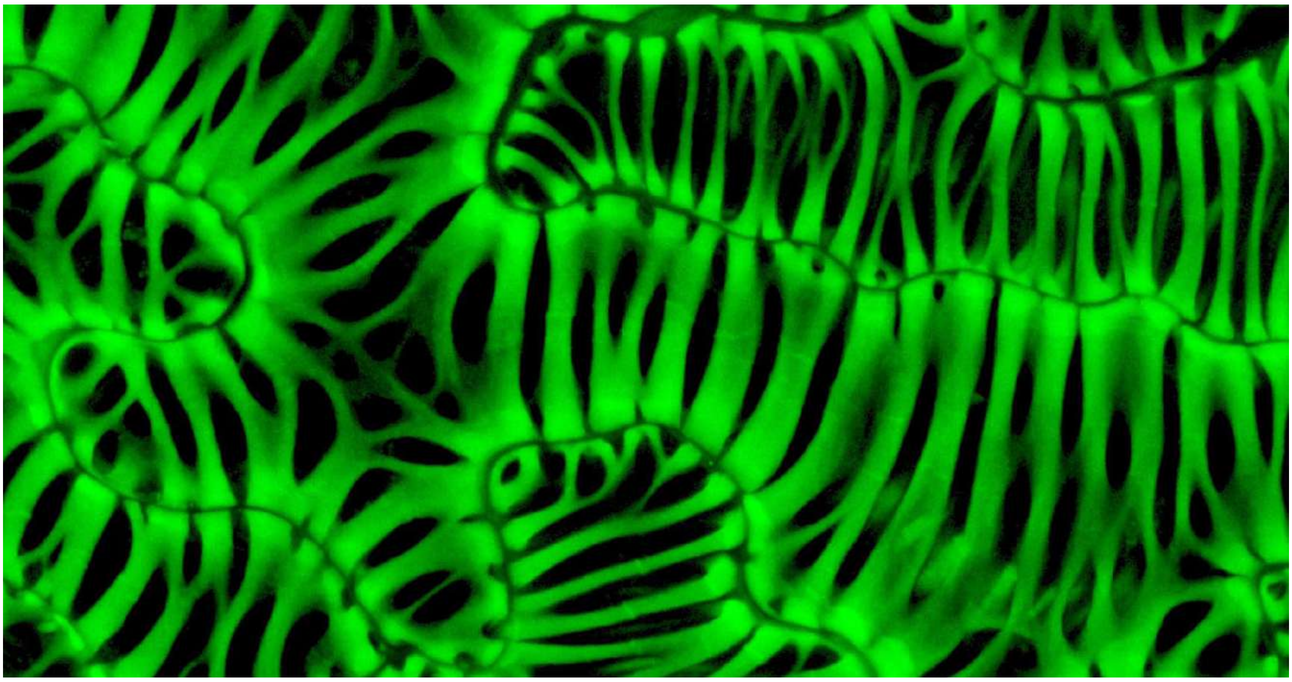


Fig: 42. Bio processing

efficient in their structure and distribution of material, and potentially useful in designing new architecture"(The Living,2021). The team emphasised that this new "cooperation" between a human designer and a plant cell present new designs that a human or a computer could never create on their own.

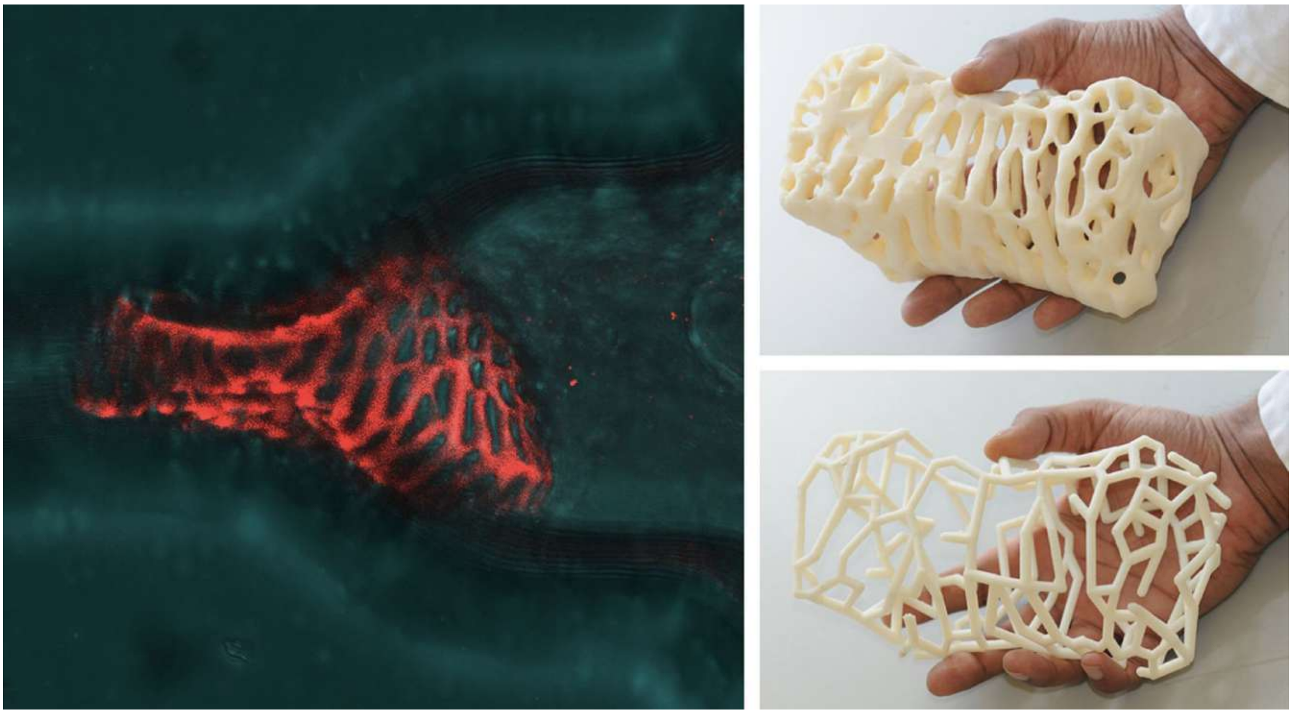


Fig: 43. Bio processing - generated 3D structure

Programmable materials

The third approach is the Programmable Material (PM) design that exhibits transformations in its form based on dynamic material behaviour. PM consists of one or more "active material" components. (see: Tibbits,2017,p. 128). An "active material" is a material whose properties change significantly when exposed to activation energy. Compositions of wood, carbon fibre, polymers, textiles, foams, and rubbers can be observed. Papadopoulou, Laucks, and Tibbits defined the three relevant characteristics of programmable materials: (1) their material composition – what they are composed of and how the materials are organised; (2) the activation energy that triggers the transformation; and (3) the transformation mechanics – the material's functional behaviour when subjected to an activation energy. (see: Tibbits,2017,p. 128) PMs allow the design of shape-changing elements that can be altered by different stimuli without the use of embedded classic actuators. The transformation is created as part of the dynamic material behaviour and takes over the functions of the actuator. The various new possibilities that come with designs based on shape-changing behaviour are still at an early stage of development. Projects that take advantage of new principles like self-assemble self-shape or reversible changes in shape can be seen in architectural research. Understanding these new, distinct principles and their potential in the field of architecture should be explored in further research. The following projects give an indication of the pioneering applications of shape-changing behaviour in architecture. Some are designed to open and close, whilst others self-shape their desired form or self-assemble.

Fig: 44. Shape-changing 4d printed programmable wood

Understanding these new, distinct principles and their potential in the field of architecture should be explored in further research. The following projects give an indication of the pioneering applications of shape-changing behaviour in architecture. Some are designed to open and close, whilst others self-shape their desired form or self-assemble.

Urbach Tower

The Urbach tower is a large-scale architectural project that takes advantage of a self-shaping process of curved wood components. Achim Menges and Jan Knippers researched the ability of wood to deform itself as the moisture content decreases. The different parts are manufactured in a flat state and automatically transform into the final form. This 14-metre-tall tower was designed and manufactured to self-shape the wooden parts programmatically, without additional mechanical forming processes(University of Stuttgart).

Fig: 45. Self-shaped wood tower

The project by Achim Menges and Steffen Reichert, who employed a no-tech strategy, is known as the concept of HygroScope. They experimented with a combination of inherent material behaviours and computational morphogenesis. The hygroscopic behaviour of wood enables the activation of the structure as changes in humidity occur.

Fig: 46. Hygroscope – meteorsensitive morphology

The self-assembling objects created by Skylar Tibbits display another principle that is based on PMs. The design of a shape-changing PM is a new endeavour that can be tackled with distinct methods. One promising manufacturing method to design PM and create transformable objects is the 4D printing process. Skylar Tibbits first introduced the term 4D printing in a TED talk in 2013.(Ajay Sharma and Ajay K. S. Singholi, 2019, p748)   The process is similar to 3D printing yet enhanced by the factor of time. Tibbits experimented with rigid plastics, as well as an active expandable polymer that transforms from one state to another by means of a

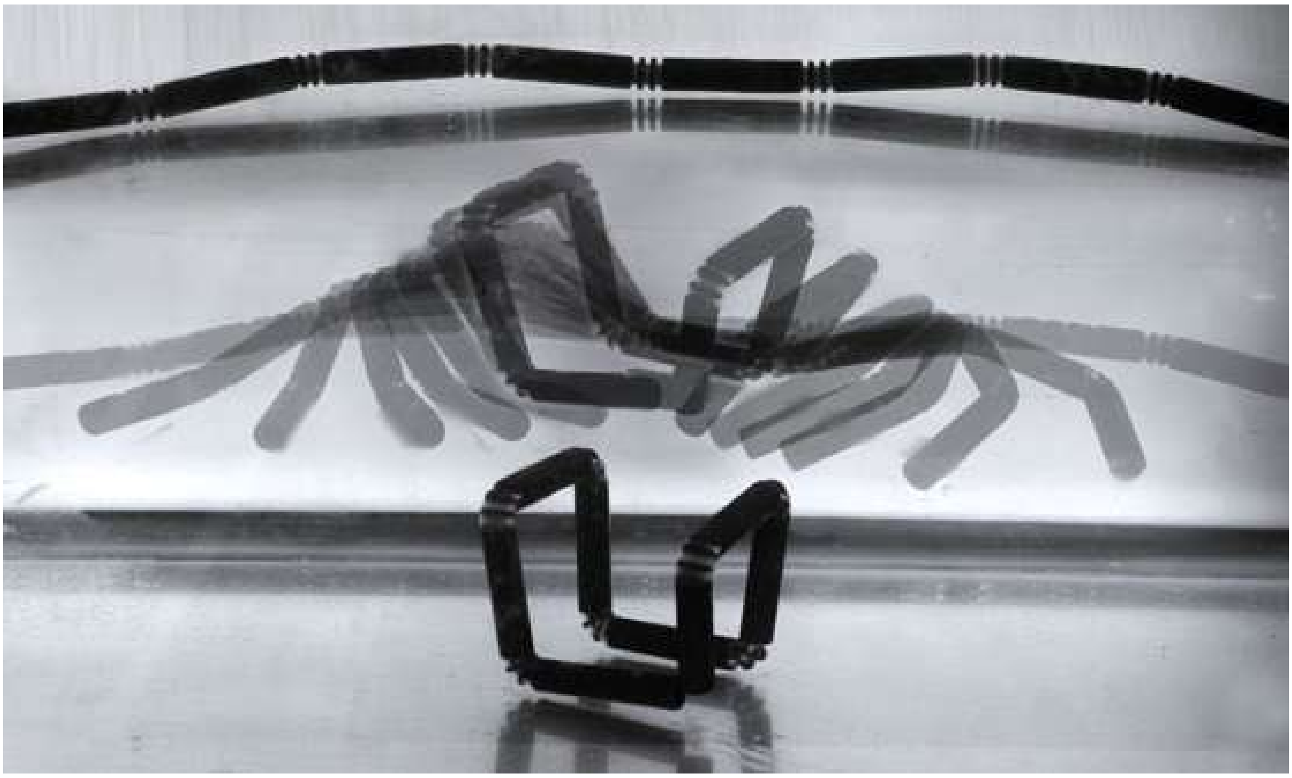
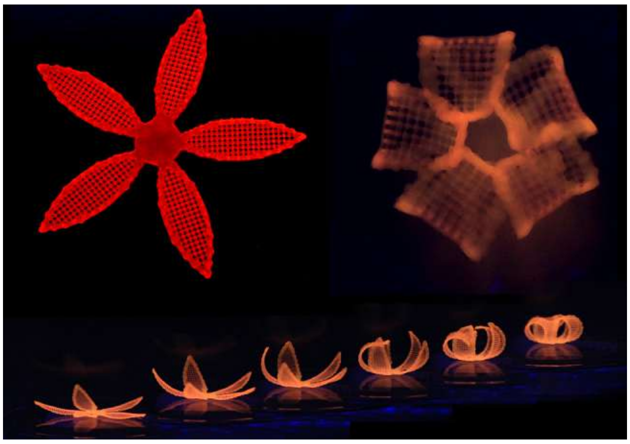


Fig: 47.   4D printed multi-material polymers particular stimulus. The materials for the 4D printing process are not limited to polymers. As pointed out by Ajay Sharma and Ajay K. S. Singholi, wood, fibre, and botanical cellulose are good alternatives for 4D printing. (2019,p.748) These different materials all display a dynamic material behaviour when exposed to different stimuli. Autodesk created a design platform called Cyborg back in 2013. It allowed design with programmable matter across distinct domains. Cyborg is a CAD tool invented for the modelling, simulation, and design optimisation of programmable matter, and it was possible to create specialised design platforms for different domains.(Sheppard,2013) The domains



ranged "from nanoparticle design to tissue engineering, to self-assembling human-scale manufacturing". "This new design platform, operating in the browser, includes cloud-native simulation for self-assembly and programmable materials as well as optimisation for multi-variable design constraints"(Sheppard, 2013). For an unknown reason, there is no further information about Cyborg that would be available on the official homepage. The possibility to visualise the variations in specific material behaviour within an object would be essential to design the multifunctional

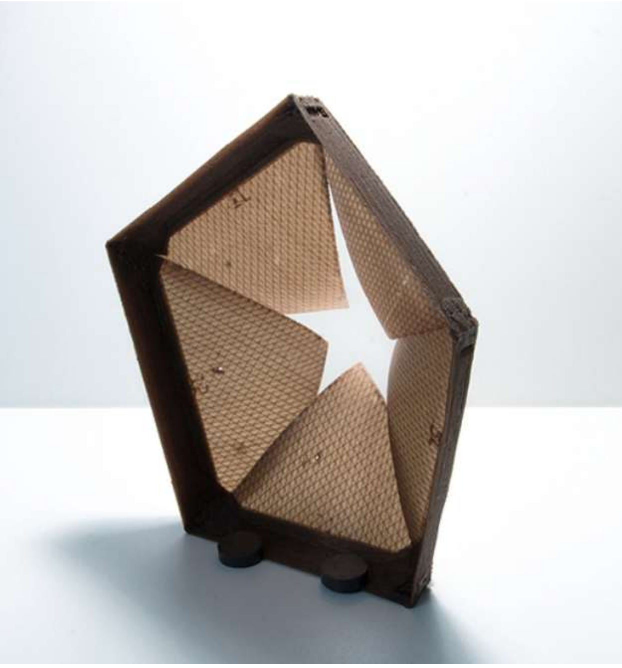


Fig: 48. 4D printed programmable wood

Fig: 50. 4D printed programmable textiles

Active matter research aims to embed observable natural matter changes into inanimate materials. Nowadays, these changes are, in certain ways, feasible. The following combination of distinct factors, as pointed out by Neri Oxman, are therefore crucial: "(1) computational design – the ability to design complex shapes with very simple forms; (2) additive manufacturing- the availability of sophisticated tools to design by adding materials instead of carving them out; (3) materials science engineering – the availability of materials with very high spatial resolution for manufacturing; and (4) synthetic biology – the ability to design with the units of life." . The main influences are advancements in biology, computer science, and material science. Developing projects place a certain emphasis on activating the dynamic material behaviour. Two main attempts can be distinguished: autonomous activation by natural phenomena or a controlled digital activation. The material changes range from colour changes in distinct bacteria and electroactive graphene, to shape-changing programmable material. The design of programmable materials based on the principles of material science makes shape-changing behaviour possible without any further electrotechnical components. The additive fabrication of multi-material objects designed with active and inactive materials ensures that the design of shape-changing materials is possible. The shape-changing process within programmable matter must be invented and designed according to the desired outcome. New principles can evolve as the design of deliberate shape change progresses. This development can be seen in self-assembly projects and self-shape towers, as well as others that cannot even be foreseen yet. One manufacturing method to design programmable materials is 4D printing. The additive fabrication allows multi-material composites to be manufactured. This presents a great freedom regarding the use and design of shape-changing material. A deliberate shape-change can be embedded into certain objects through the design. The intentional and planned use of the behaviour of dynamic materials enables the design of programmable materials that are predefined by a specific idea.

4D printed shape-changing materials

Programmable materials offer new possibilities for designing intelligent and transformable building elements. These developments can be observed in evolving design principles, ranging from self-shaping elements, to open and closing wood structures, and self-assembled objects. 3D printing is a manufacturing method that allows for various design possibilities and material combinations to explore future shape-changing construction elements. The material composites may be tailored to self-shape, self-assemble, expand, shrink, react to diverse triggers, open and close or have various states and behaviours in one basic form. Furthermore, composites may be autonomously or digitally active, which could permit further freedom with regard to the design and functions of future building elements. As pointed out by (Strauß and Knaack 2016), "additive manufacturing methods provide great freedom of form compared to traditional methods"(See:Yoon, p.76) . In order to explore the design possibilities of shape-changing multi-materials, additive manufacturing methods appear to be promising. However, the fabrication of multi-material elements is predominated by the multi-jet technology , and access to these technologies is limited. Therefore, this research aims to design 4D printed shape-changing multi-materials with a Standard FDM single extruder printer from the brand PRUSA MK3s + MMU2 (a multi-material top part) and an active SMP.

Hypothesis

H1: If we combine classic inactive filaments with the dynamic material behaviour of SMP, then it enables the production of shape-changing multi-material surfaces with a low budget 3D printer.
H2: If the SMP is combined with a conductive filament and intrinsic heating wires, then the activation of a shape-changing surface prototype is possible with an Arduino Uno.
Goals and questions:
This master thesis aims to design a programmable material based on a thermo-responsive shape memory polymer. The study engages with creating feasible material combination and the shape-changing behaviour of these composites to open up further design possibilities and prototypes with the Fused Filament Fabrication (FFF).

Is it possible to design a programmable shape-changing surface composite with a standard 3D printer?
1. Is it possible to print in 4D with a PRUSA MK3s+ and the MMU2s?
2. Is it possible to create shape-changing SMP composites from standard filaments?
3. What feasible materials are there for 4D-printed SMP composites with the MMU2s?
4. How should the shape memory behaviour of an SMP filament be activated?
5. Is it possible to activate an SME in SMP with a conductive filament and embedded heating wires?
6. How do the material composites affect the behaviour of the SMP?
7. Is it possible to design self-shaping composites which alter their surface from flat to upright?

Method

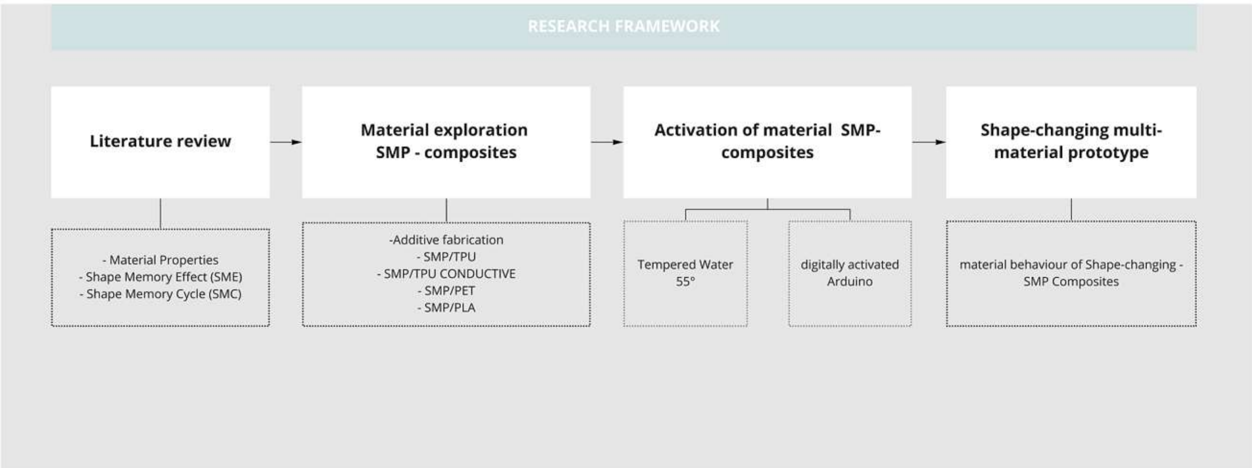


Fig: 47. Research Framework

The research conducted focuses on experimental material tests that enable the manufacturing, behaviour, and activation of multi-material SMP composites to be observed. For this quantitative research, photographs and videos were taken and specimens were evaluated. The approach and methods are based on a bottom-up material exploration. By doing research on a design process of simple prototypes and specimens, the feasibility of SMP composites for shape-changing surface panels is tested. The research process is divided into four distinct phases. (1) The first part includes a theoretical review of material science papers to understand the SME and the thermomechanical cycle of the SMP. Information from different platforms, including ResearchGate, Elsevier, is reviewed. (2) The second part evaluates the printability of single SMP specimens and the simple folding behaviours of single material prototypes to evaluate the shape-changing effect in single material prototypes. Furthermore, the possibility of creating a multi-material 4D print with the MMU2s and a possible material combination of commercially available TPU, PLA, and PET filaments are observed. Specimens from SMP-PLA, SMP-PET, and SMP-TPU are printed to explore possible material combinations and evaluate their printability and cohesion in view of their visual aspects. This section focuses on the additive manufacturing of distinct material combinations rather than on the possible shape-changing behaviour of these elements. (3) The third part includes an attempt to achieve a digitally activated SMP composite with embedded heating wires and an Arduino Uno (4). The last section aims to design a shape-changing-multi-material prototype. Simple shape-changing multi-material prototypes are designed to explore the material behaviour in the form of a manual deformation and the observable recovery of this material.

Literature Review of Shape Memory Polymers

The design of a multi-material shape-changing prototype is a complex process. Various factors must be kept in mind. Knowledge about the manufacturing process, the possible combination of materials and their distinct properties, the geometrical restriction during shape-change, the triggers chosen to activate a shape-change, and the dynamic material behaviour of SMP on the basis of the design of sophisticated multi-material prototypes should be considered. This section presents a general overview of the properties of Shape Memory Polymers. It includes a short explanation of the Shape Memory Effect (SME) and shows the programming of thermo-responsive SMPs with the Shape Memory Cycle (SMC).

Properties of Shape Memory Polymers

Shape memory polymers belong to the category of SMART materials and exhibit a particular material behaviour called the Shape Memory Effect (SME). Shape Memory Materials (SMMs) like Shape Memory Alloys (SMA) and Shape Memory Polymers (SMP) can recover their original shape even after the material is exposed to significant plastic deformation (W.M.Huang,2010,p.54). The SME was first discovered in the AuCd alloy as early as 1932 (Huang ,Wang,2010) . Chang and Read described the discovery of the SME as "one of the revolutionary steps in the field of active matter research" (Chang and Read, 1932,p.255). A characteristic of the SME is its classification by directionality. (Mu,Liu,2018) The shape memory effect can either appear in a one-way or a two-way manner. "(So far, two-way SME is reported only in shape memory alloys [29e31](Mu,Liu,2018)" .
Tailoring shape memory polymers is much easier than metals and alloys. Additionally, the costs of polymers are traditionally much lower(W.M.Huang,2010,p.55) Another interesting fact is that polymers can be designed to be biodegradable (Hornat and Urban,2020,p.2) . Moreover, as pointed out by Chris C. Hornat and Urban, "[s]hape memory is not unique to a specific polymer chemistry or microstructure; it is a consequence of molecular architecture, reversible mobility changes, conformational entropy, and programming [87](Hornat and Urban, p.2020, p.2)" The composition of the material enables the SME in SMPs. One segment is always hard or elastic, while the other part can be soft, ductile or stiff, depending on the stimulus applied. (W.M.Huang,2010, p.55) The first segment is called the elastic segment, whereas the second is the transition segment. Fig4(__) illustrates the SME in thermo-responsive SMPs. Shape Memory Polymers have a high recoverable strain, and they would usually have a wide shape recovery range. (W.M.Huang,2010,p.56) Therefore, it is possible to store more than one intermediate shape, which is called a multi-SME. (W.M.Huang,2010,p.559 Distinct environmental stimuli can trigger the SME. The triggers can be heat, light (UV and infrared light), magnetism (W.M.Huang,2010,p.1) , and chemical changes (moisture, solvent, and pH changes)(Leng,Lu,2011 p.55). SMP technologies provide seven different SMP with glass temperatures of 25, 35, 45, 55, 65, 75 and 90°. The only available SMP filament for a standard 3D printer has a glass transition temperature Tg of 55°C and is used for the material tests that follow. The glass transition temperature Tg is the temperature that indicates whether the polymer acts as a stable

element in the crystalline state or like a rubbery material above the glass transition temperature. The plastic properties of polymers can be dramatically different above and below the glass transition temperature.
As mentioned previously, the understanding of the SMC is crucial for designing shape-changing elements. The SMC is the process that indicates the transition from one original shape to a programmed intermediate shape and back to the original shape. The following figure demonstrates the three steps of programming shape-change in thermo-responsive SMP objects.

Shape memory effect (SME)

The design of a multi-material shape-changing prototype is a complex process. Various factors must be kept in mind. Knowledge about the manufacturing process, the possible combination of materials and their distinct properties, the geometrical restriction during shape-change, the triggers chosen to activate a shape-change, and the dynamic material behaviour of SMP on the basis of the design of sophisticated multi-material prototypes should be considered. This section presents a general overview of the properties of Shape Memory Polymers. It includes a short explanation of the Shape Memory Effect (SME) and shows the programming of thermo-responsive SMPs with the Shape Memory Cycle (SMC).
ongMua1LiwuLiua1

Shape memory polymers belong to the category of SMART materials and exhibit a particular material behaviour called the Shape Memory Effect (SME). Shape Memory Materials (SMMs) like Shape Memory Alloys (SMA) and Shape Memory Polymers (SMP) can recover their original shape even after the material is exposed to significant

SME in a thermo-responsive SMP

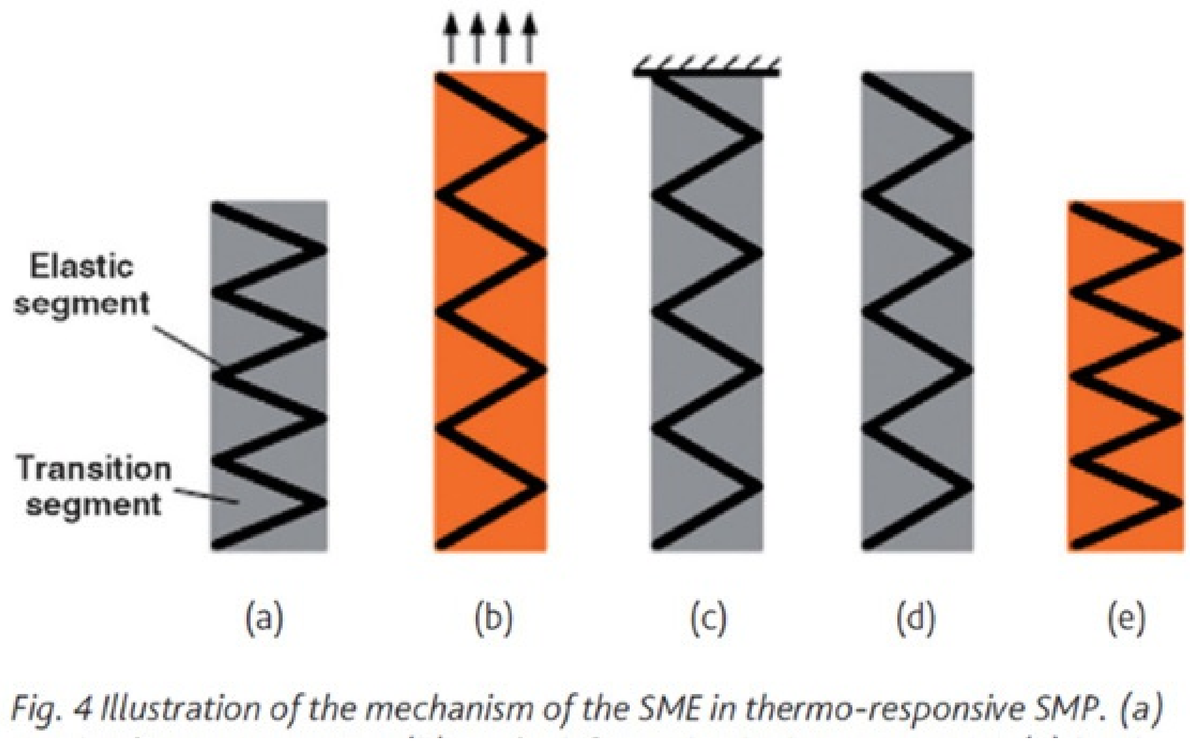


Fig: 48. SME in thermo-responsive SMP

As mentioned previously, the understanding of the SMC is crucial for designing shape-changing elements. The SMC is the process that indicates the transition from one original shape to a programmed intermediate shape and back to the original shape. The following figure demonstrates the three steps of programming shape-change in thermo-responsive SMP objects..

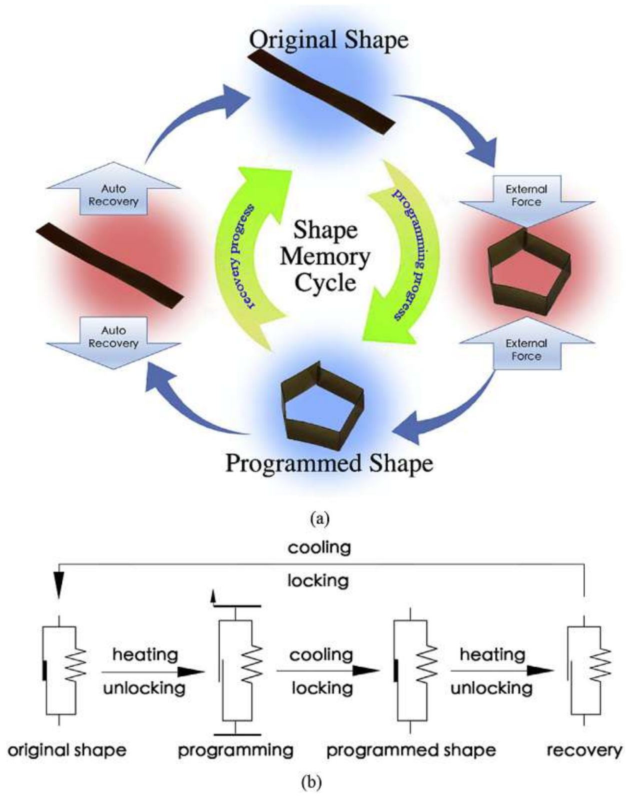


Fig: 49. Shape memory cycle

A detailed description of the SMC: Figure :
"As illustrated in Figure 1, the typical thermomechanical cycle of a thermo-responsive SMP consists of the following steps. (1) The SMP is formed into a shape (the original shape); (2) heat the SMP above its thermal transition temperature (Ttrans) and deform the SMP by applying an external force, cool well below Ttrans, and remove the constraint to obtain the temporary shape (storage); (3) heat the pre-deformed SMP above Ttrans, at which point the SMP recovers the original shape (shape recovery)."

Yoon describes the SMC as follows: "The general thermomechanical cycle of thermo-responsive shape memory polymers consists of three steps at a macroscopic level; (1) programming, (2) storage, and (3) recovery. " As the initial shape is decisive for further design decisions, special emphasis has to be placed on this field to print with SMP.

General Information Additive Fabrication PRUSA + MMU2s

The equipment that was used for this study was a PRUSA MK3s+ with an additional Multi-Material Kit that allows printing with five distinct filaments or colours. In the single mode, a print with details of up to 0.05 mm is possible. In multi-material mode, the MMU2s achieves a detailing of 0.10 mm. The printer uses a direct-drive mechanism that loads the filament with a single PTFE tube(PRUSA research) to one

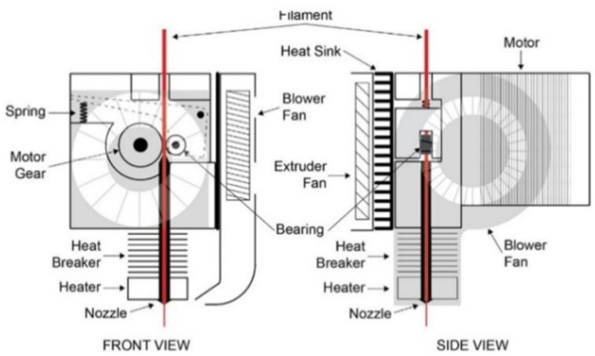


Fig: 50. Schematic representation of printing head (extruder)

extruder. (Fig__) For the following material tests, a heated print bed with a textured spring steel sheet with an area of 25x21x21 cm(PRUSA Research) was used. The print materials that are officially supported by PRUSA are ABS, ASA, PETG, PLA, PVA (a material soluble in water).

A limitation of the MMU2s is that generic flexible filaments like TPU and TPA are not officially supported with the MMU2s. The reason for that may be that the idler-body cannot distinguish between distinct materials and the shore hardness of filaments, thus, not all flexible filaments can be fed in reliably. For the material study four inactive materials were chosen: a generic PLA, recycled PETG, a PVA, and a TPU. ABS is excluded from the observation because it must be printed in a stable and enclosed environment.

The MK3s+ would not, in general, be shipped with a cubicle as it is a low budget printer. To compensate for this, the PETG was chosen, which offers the same properties as ABS and is easier to print. Another advantage is the lower ecological footprint as the used PETG filament consists of recycled materials from old PET bottles. Due to the hydrophilic behaviour of the PLA, TPU and SMP filament, it is crucial to store the filaments in a dry environment.

Unwanted water absorption may influence the quality of the print samples. For modelling the print samples, Rhino 7 was used. The program allows, the exportation of STL and 3MF data types, among others. These data types can be processed with the BETA Version of the PRUSA SLICER 2.3.0. (which was last checked on the 18th of April 2021). The model data is preferably exported as a 3MF data type as it allows differentiations to be made between multiple materials compared to the industry standard STL (Standard Triangulation/Tessellation Language) file format. A conversion of the STL file with its multiple parts to the desired multi-material part is a time-consuming process. The G-codes for the designed samples are generated by the PRUSA 2.3.0 Slicer.

The MK3s is a low budget printer, and some unexpected obstacles appeared during the calibration phase. For printing multi-material composites (MMCs), a fine-tuned calibration of the MMU2s is crucial. A significant limitation of the top part is the limited adjustments for
distinct levels of filament shore hardness (soft filaments like TPU). The pressure on the filament can only be regulated with two adjusting screws, and one screw controls the proper input of all filaments at the hot end. Finding the correct pressure of these screws is crucial for generating a reliable feed in the chosen materials and may not be suitable for all filament types. False adaption leads to loading and unloading issues that result in aborted print samples. In order to successfully print with flexible filaments, it is essential to find the proper pressure on the gears. When the pressure is too high, the filament begins to wrap around the gears, and when the friction is too low, the filament will not be fed appropriately. A false pressure on materials that have a higher shore hardness causes an abrasion on the filament,

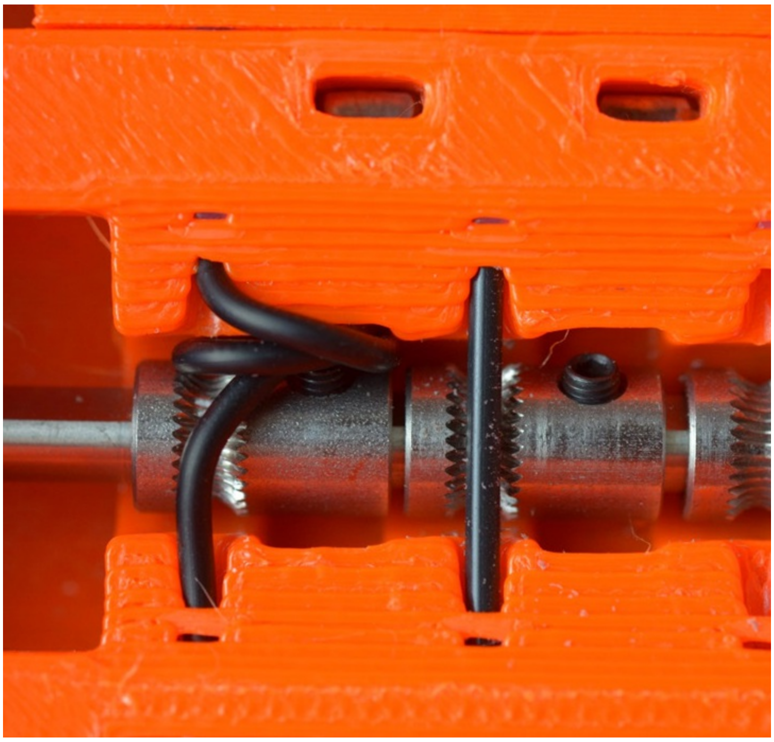


Fig: 51. Flexible TPU wraped around gears

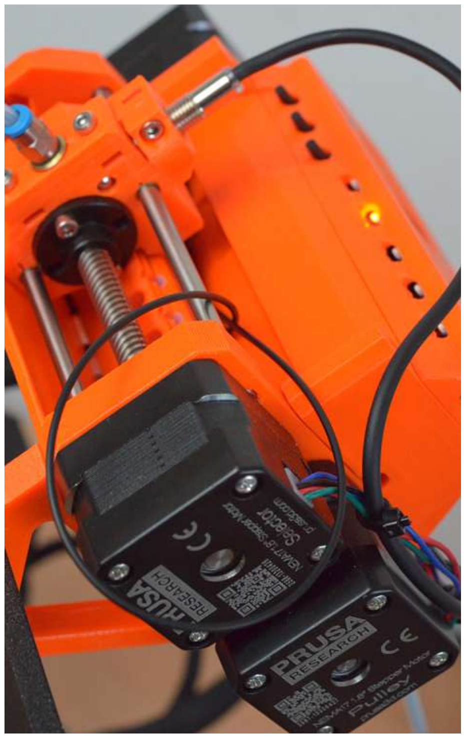


Fig: 52. Failed uloading flexible TPU filament

Fig: 53. Abrasion on PLA

The first phase of additive fabrication mainly consisted in locating the sources of loading and unloading errors. The first attempts to reliably load different materials failed due to a firmware error of the MMU2s. The collector header repeatedly lost track of the filament positions and loaded the filament from the wrong filament spots. The error was solved by a firmware update that was released on the 7th of January 2021, and the five filament spots could be used reliably. A further factor that influenced the loading and unloading process was the diameter of the filament. The PTF tubes that feed the filament into the idler

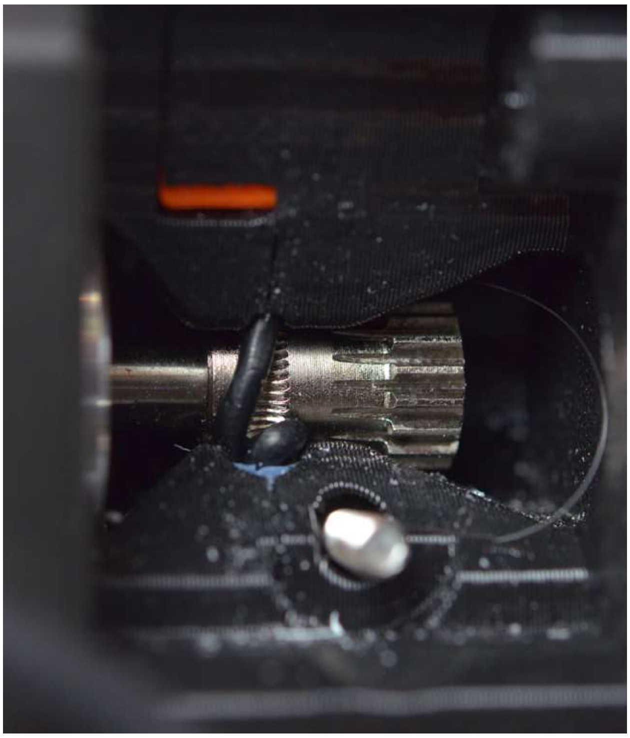


Fig: 54. Flexible TPU wraped around gears - feeding to the hot-end

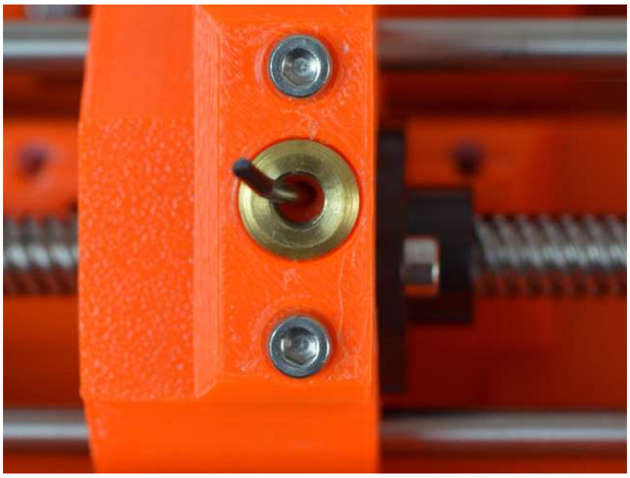


Fig: 55. False loaded filament

body are disproportionated. The friction of the tubes was too high with the tested conductive filament of NINJAFLEX, and the filament could not be loaded at first. It was recommended to shorten the PTF tubes to load slightly thicker filaments or flexible filaments. After replacing the long PTF, the filament could be loaded successfully.

The interplay between the proper pressure on the filament and the printer setting is a significant part of successfully conducting multi-material prints with the MMU2s. False adjustments lead to small filament remains in the collector header and at the hot end. The sensor detects the presence of a material and does not feed in the filament. This is especially crucial in connection with the constantly switching filament in one print process. Filaments are likely get stuck in the PTF tubes with false adjustments, which meant that the print must be stopped and the tubes must be cleaned out. Stopping prints within a print process caused the cohesion between distinct filaments to visibly worsen.

Fig: 56. Unclean tip of filament - wrong printing temperature

Fig: 57. Bulbous tip of filament

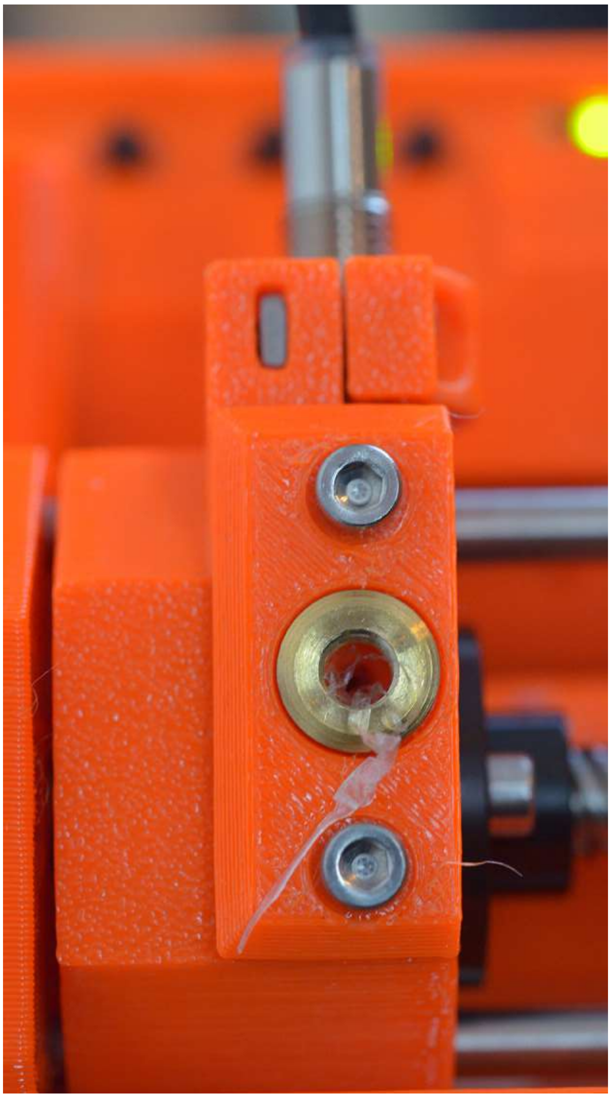


Fig: 58. Filament rest in the collector head

Switching between two filaments is a time-consuming process. After printing one layer with a specific filament, the filament is unloaded and the next filament must be loaded. This process must be kept in mind during the design of prototypes. (PrintingTime) Fig Furthermore, a wipe tower is generated during a multi-material print. As pointed out by Prusa, the wipe tower "ensures sharp color transitions and stable filament flow after a color change while aiming to waste as little filament as possible." The wipe tower grows with the actual print and, therefore, the wasted filament also grows. The SMP filament is compared to a generic PLA cost-intensive and slicing the models in a distinct order prevents undesirable material waste. Adapting a manufacturing strategy for designing fast and sustainable shape-changing prototypes should be researched further.

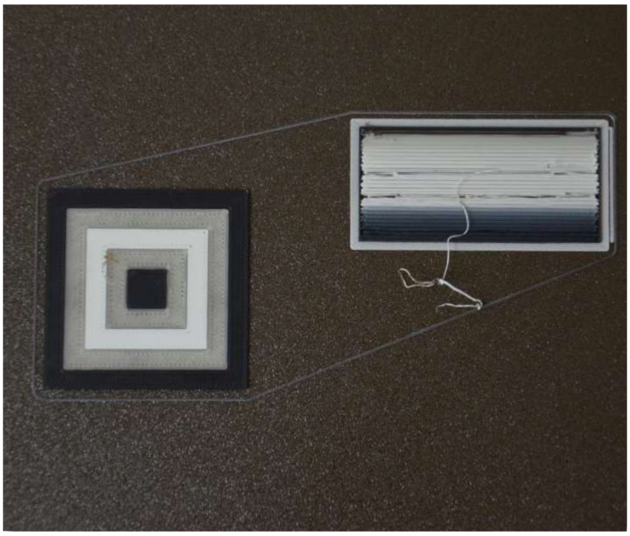


Fig: 60. Multi-material print PLA-black,SMP, PLA - white, SMP, PLA-black

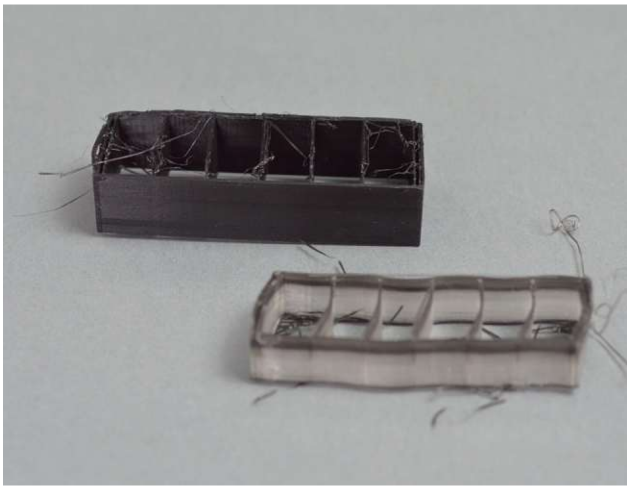


Fig: 59. Material waste - wipetower

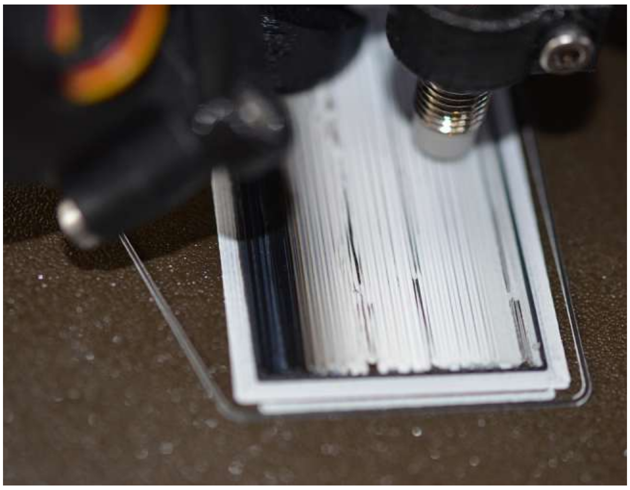


Fig: 61. Colour transistion between filament switching

All specimens are printed at a stable room temperature of ~ 22°C +/-1°C with low humidity of 35-42%. The active SMP filament from KO-BO is based on a thermoplastic urethane with a glass transition temperature (T¬g) of 55°C. The first approach to gain some insight into the shape-changing possibilities of SMP was the design of simple single material samples. For the observations I followed the taxonomy of Seokwoo Nam and Eujin Pei, who classified the shape-changing behaviour into three categories: a basic, a complex one, and a combination of shape-changes. The basic transformation involves just a single deformation. It includes bending, rolling, twisting, helixing, buckling, curving, topographical change expansion, and contraction. (Seokwoo Nam and Eujin Pei,2019,p.173) The experiments in this thesis are limited to simple folding

Fig: 62. Room temperature and humidity

Shape changing behaviour		Mechanical analysis
	Folding Raviv et al. [14] Tibbits [54] Ionov [20]	Folding deformation is caused by a stress mismatch between rigid and active materials, which is possible with various swelling ratios [10]
	Bending Gladman et al. [15] Wu et al. [54]. Zhang et al. [57]	Bending deformation is the swelling/shrinkage mismatch between both layers in response to activation stimuli, while sustaining the same strain at the interface between both layers, could result in different types of deformation [6]
	Rolling Ge et al. [13] Gladman et al. [15]	Rolling deformation is a normalized curvature that varies depending on both the expansion mismatch and the thickness, which is a nonlinear relationship between the rolling radius of one hand and the ratio of expansion and the sample thickness [4]
	Twisting Ge et al. [13] Wang et al. [53] Zhang et al. [57]	Twisting deformation printed the fibers with certain angles to induce twisting, and by adjusting the print angles of active fibers, the final twist angle would be changed [57]
	Helixing Zhang et al. [57] Ionov [20]	Helixing deformation is made by a uniaxial expanding/shrinking active layer for a nonzero angle between the main straining direction of the active layer and the main axis of the bilayer strip [21]
	Buckling Manen et al. [31] Sharon and Efrati [46]	Buckling deformation that compressive stresses above a certain critical value will induce out-of-plane buckling of the flat structure [31]
	Curving Tibbits [51]	Based on the light intensity gradient along the thickness of material, a stress gradient could be created, which results in spontaneous curving of the structure after release from the substrate [58]
	Topographical change Hu et al. [17] Tibbits et al. [52]	Mountain and valley features can be generated from concentric circles in the presence of an appropriate stimulus. Surface topography is the representation of local deviations of a surface from a flat plane. These features usually occur under compressive loading conditions [52]
	Expansion/contraction Bakarich et al. [3] Raviv et al. [42] Yu et al. [56]	"This mechanism is driven by a variety of expansion ratios between active and rigid materials, which consist of scalable, hydrophobic active materials and rigid materials [3]
	Waving Wu et al. [54]	Wave shape deformation could occur in bilayers with comparable stiffness and layer thickness through swelling/shrinkage mismatch in response to activation stimuli [6]
	Curling Tibbits et al. [52]	Curling deformation is enabled by a stress mismatch between rigid and active materials from their different swelling properties [52]

Fig: 63. shape changing behaviour

First, the printability and possible print quality of the SMP filament was tested. Small SMP specimens of size 5x5x0.04 cm were printed to adjust the print settings and quality with the PRUSA and MMU2s. A nozzle temperature of 210° C, a heat-bed temperature of 65°C, a 40mm/s print speed and a fan speed of 100% was used. The first SMP specimen showed lost layers and slightly lumpy prints. To adapt the print values, the four standard pre-sets of the PRUSA Slicer were tested: 0.1mm detail, 0.15mm quality, 0.20 mm speed, and 0.3mm draft to understand the reason for the undesirable print quality. The small errors could be attributed to a slightly uneven print bed. The calibration sample of the Prusa Knowledgebase was used for the bed levelling.(PRUSA Research) Nine bed mesh levelling cycles were carried out to achieve good print quality over the whole printing area. For the calibration, the used filament was switched to a cost-effective PLA.

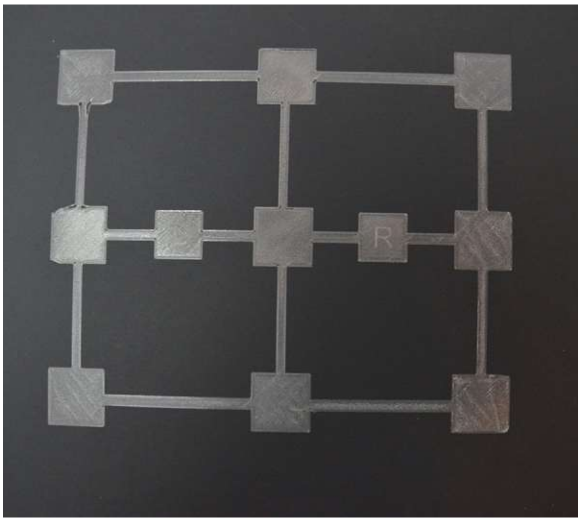


Fig: 65. Before bed mesh levelling

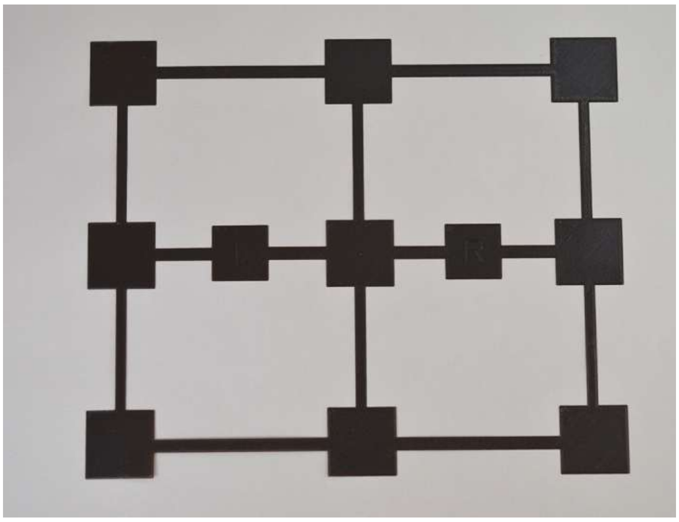


Fig: 66. After bed mesh levelling

Bed Calibration - Print Quality

Before bed Leveling	After bed Levelling	Key Values: Print Setting

Print Settings: Draft 0.3mm

Speed for print moves

Perimeters:	50	mm/s
Small perimeters:	30	mm/s or %
External perimeters:	35	mm/s or %
Infill:	85	mm/s
Solid infill:	80	mm/s or %
Top solid infill:	40	mm/s or %
Support material:	45	mm/s
Support material interface:	80%	mm/s or %
Bridges:	30	mm/s
Gap fill:	40	mm/s
Ironing:	15	mm/s

Print Settings: Speed 0.2 mm

Speed for print moves

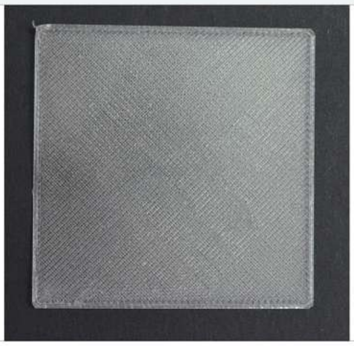
Perimeters:	60	mm/s
Small perimeters:	25	mm/s or %
External perimeters:	35	mm/s or %
Infill:	200	mm/s
Solid infill:	200	mm/s or %
Top solid infill:	50	mm/s or %
Support material:	50	mm/s
Support material interface:	80%	mm/s or %
Bridges:	30	mm/s
Gap fill:	40	mm/s
Ironing:	15	mm/s

Print Settings: Quality 0.15 mm

Speed for print moves

Perimeters:	45	mm/s
Small perimeters:	25	mm/s or %
External perimeters:	25	mm/s or %
Infill:	80	mm/s
Solid infill:	80	mm/s or %
Top solid infill:	40	mm/s or %
Support material:	50	mm/s
Support material interface:	80%	mm/s or %
Bridges:	30	mm/s
Gap fill:	40	mm/s
Ironing:	15	mm/s

Print Settings: Detail 0.1mm



Speed for print moves

Perimeters:	45	mm/s
Small perimeters:	25	mm/s or %
External perimeters:	25	mm/s or %
Infill:	80	mm/s
Solid infill:	80	mm/s or %
Top solid infill:	40	mm/s or %
Support material:	50	mm/s
Support material interface:	80%	mm/s or %
Bridges:	30	mm/s
Gap fill:	40	mm/s
Ironing:	15	mm/s

Fig: 67. Print quality SMP

Further test samples showed a good printability of the KO-BO filament with the MK3s. The adhesion on the print steel bed was considered to be good and desirable results in different print resolutions could be observed. The print bed be easily removed after cooling down. The early removal of the sample may cause an irreversible deformation in the print sample. For further tests the following print settings were used:

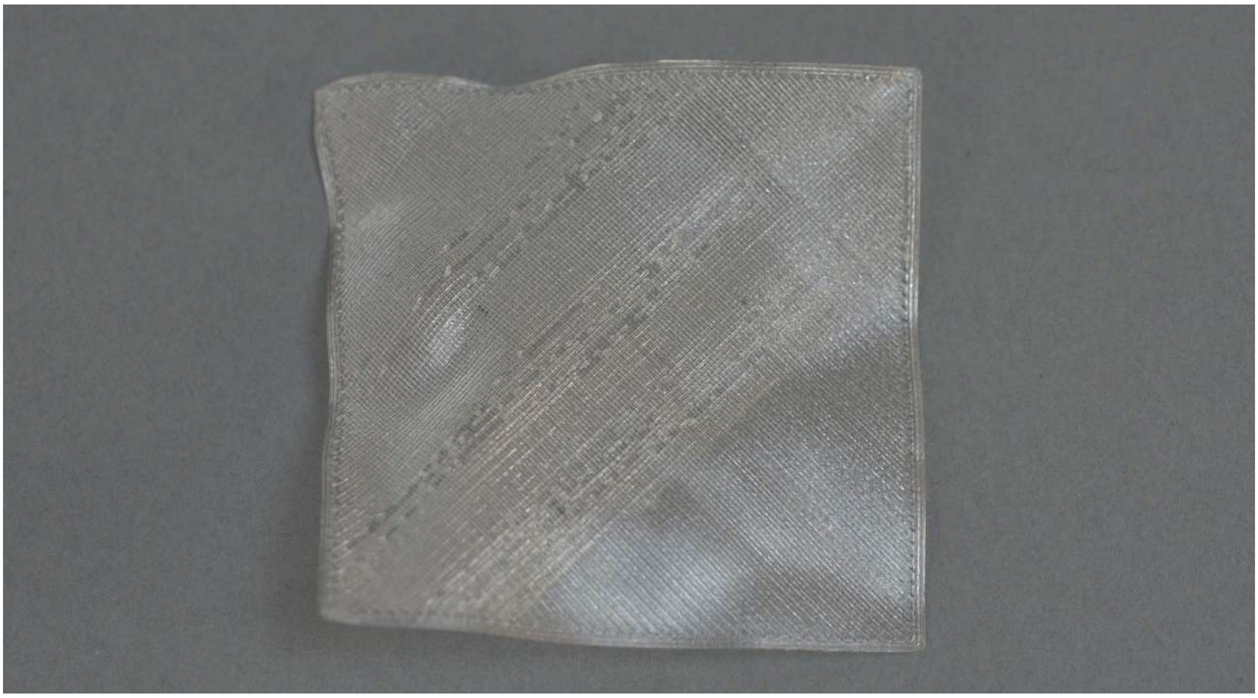


Fig: 68. Deformed specimens - early removal from the print bed

SMP KO-BO - PRINT SETTINGS			
PRIMARY PARAMETER	VALUE	PRIMARY PARAMETER	VALUE
Nozzle Temperature	210°C	Retraction Speed	35 mm/s
Bed Temperature	65 - 70°C	Retraction Distance	1 mm
Fan Speed	70 - 80 %	First Layer Thickness	0.2 mm
Print Speed	35-40 mm/s	First Layer Hight	0.1 - 0.2 mm

Fig: 69. Print settings SMP

Infill qualities

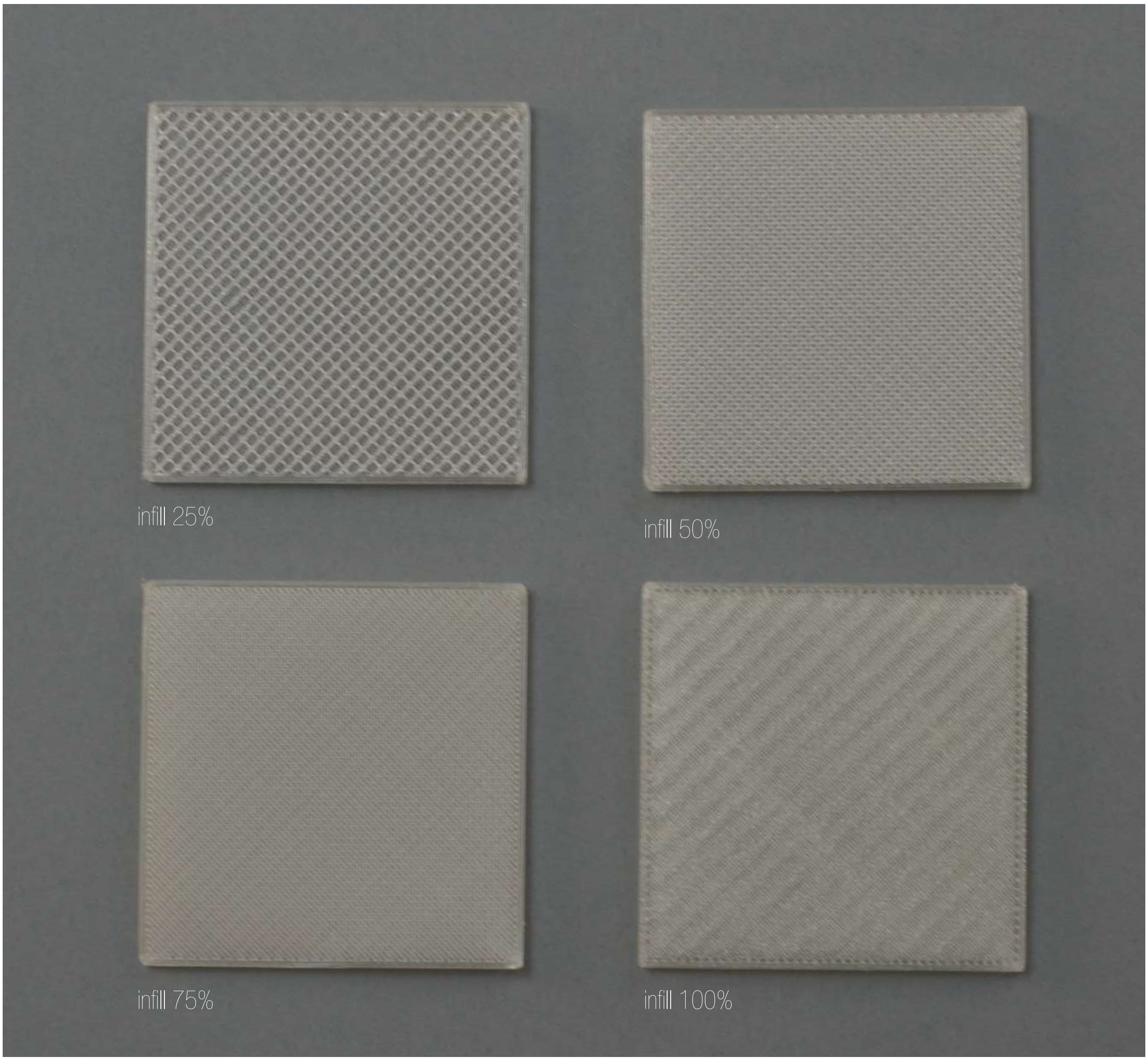


Fig: 70. Print quality - distinct infills

Experiments

Experiments - single material

Material deformation - programming a single material prototype

The first test was conducted with small 5x5x0.04cm specimens. A slightly too high temperature of 65.9C caused an irreversible deformation in the middle of the sample. This behaviour may be helpful for other programming strategies.

The subsequent experiments were conducted to observe the shape-changing behaviour of a one-way shape memory polymer concerning the manufacture of the model. The first print was designed in a flat state, the second in an upright state. As pointed out by Zhao, Jerry Qi and Xie, "[…] the training is included in the manufacturing process, while the shape change programming is a step applying force to input a temporary shape"(see:Yoon,2020,p.2) . During the design of the initial shape, it must be considered how the shape will transform. Its manufacturing process predefines the way in which the object is transformed. When printed flat, the unfolding process is programmed in the object and the sample can self-assemble. This behaviour is attributed to the one-way shape memory effect of SMP polymers and can be seen in test print that follows. This behaviour must be kept in mind for the design of multi-material shape-changing elements and in connection with other design decisions. In this work, the shape-changing observation is limited to simple folding behaviour as the focus is placed on the further possible material combinations instead of the diverse possible shape-changing behaviours. The whole investigation of diverse behaviours of multi-material shape-changing elements should be explored in further research.

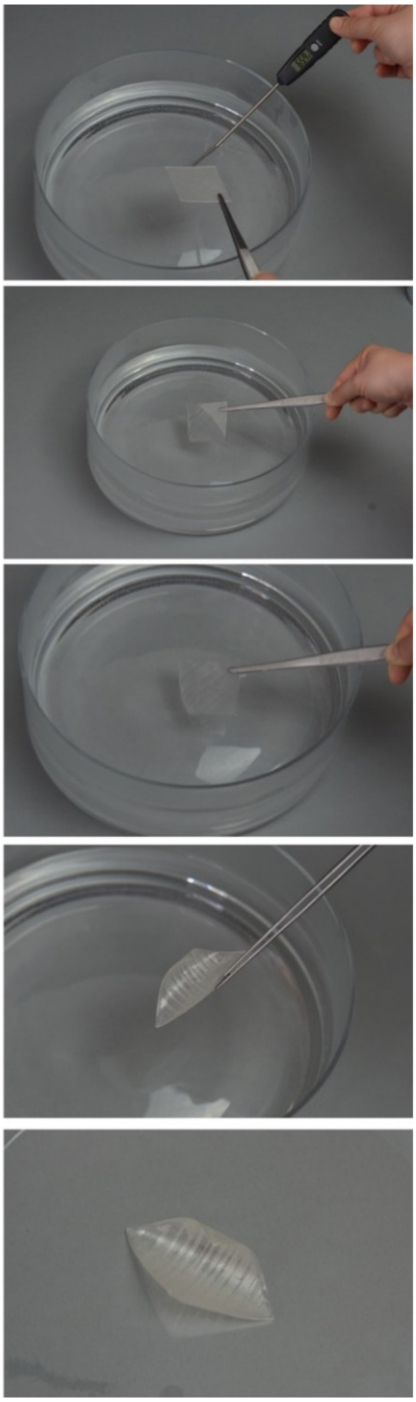


Fig: 70. Deformation heating above T_G 55

Programming shape-changing prototype - upright printed sample

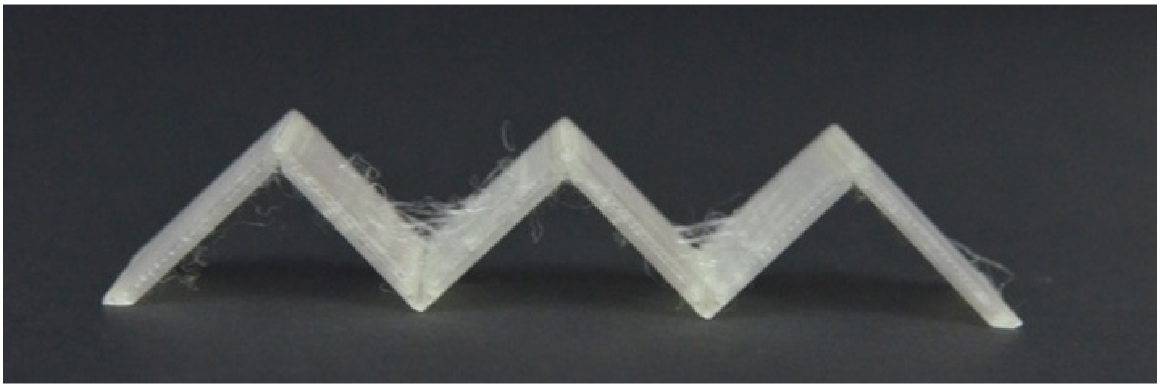


Fig: 71. First upright printed prototype with stringing

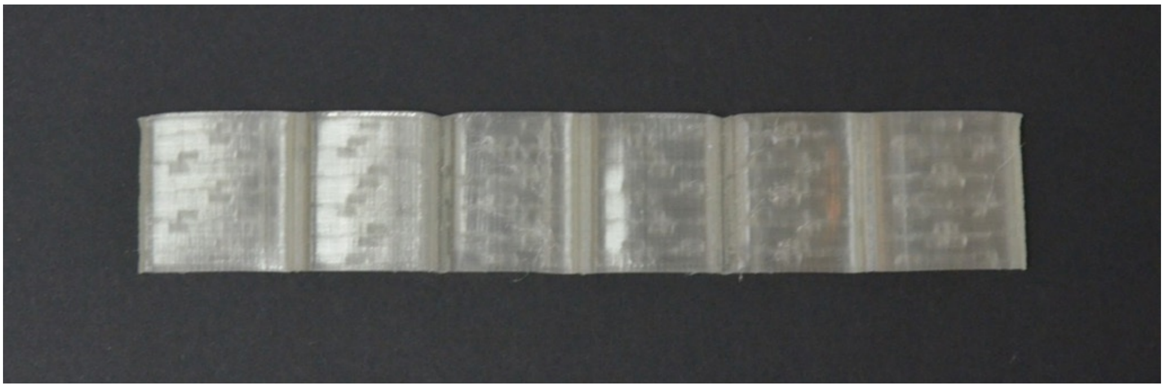


Fig: 72. First programmed prototype - flat state

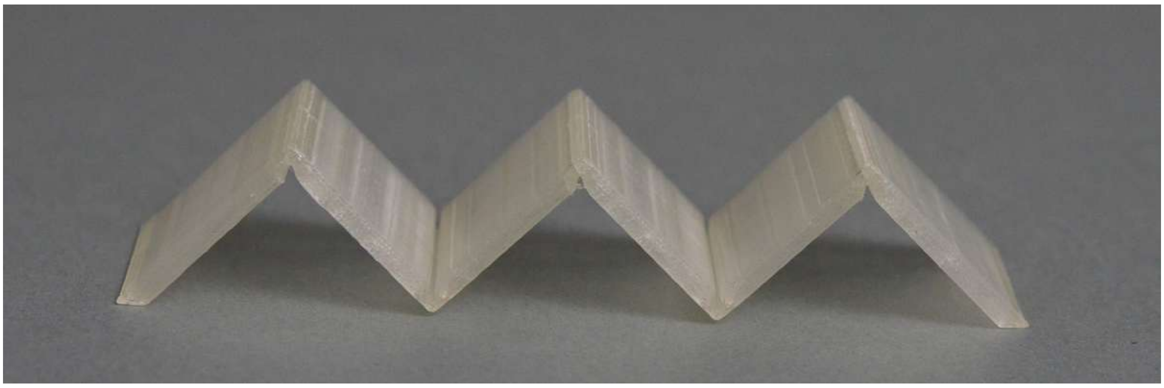


Fig: 73. Second prototype without stringing

Programming a shape-changing prototype - flat printed sample

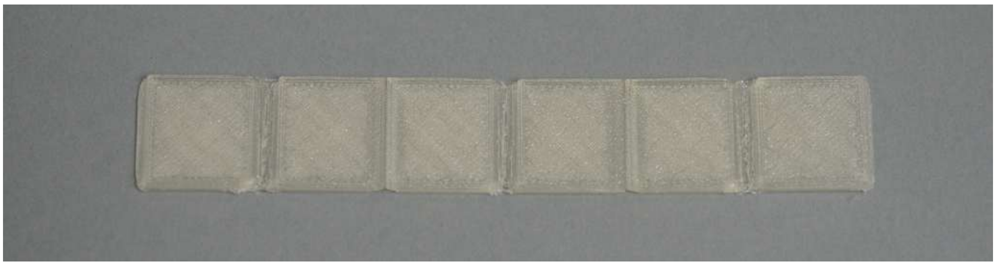


Fig: 74. Prototype printed in a flat state

Fig: 75. Programmed prototype to a upright state

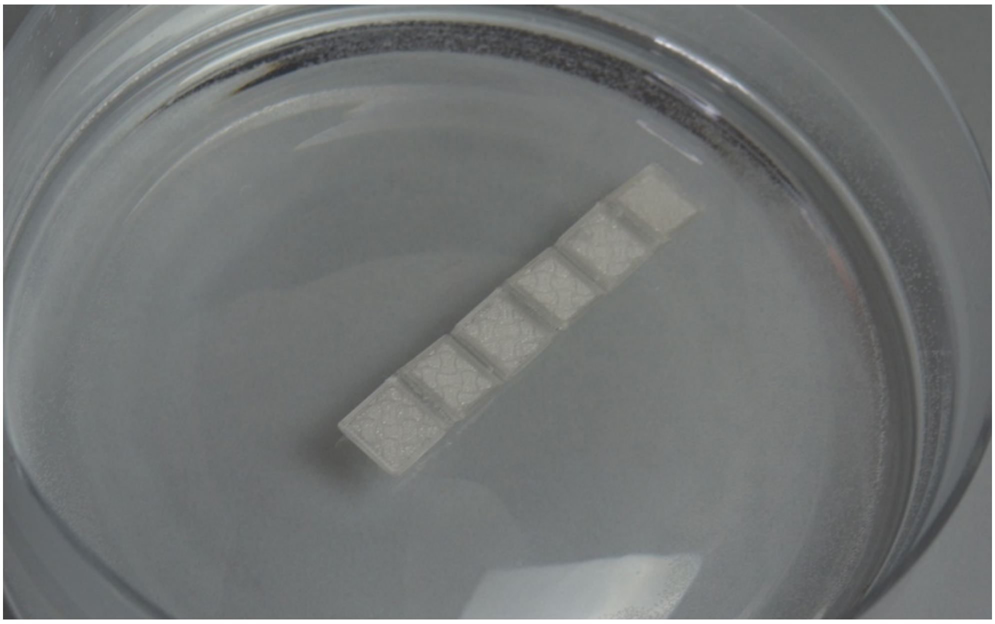


Fig: 76. Shape - recovery to a flat state

Experiments
multi-material

Mult-material shape-changing elements

The printing of multi-material parts is influenced by diverse factors, which includes the design of a given piece, the chosen 3D printer, the environmental conditions, the ability of the materials to connect on a chemical level, and the printer settings. The boundary between the distinct filaments creates a weak spot in multi-material prints. As pointed out by Lopes, Silva and Carneiro, "[…] in multi-material prints there is a new element in play, the interface formed between different materials at their geometrical boundary, which is dependent on the properties of the materials in-volved and on the printing conditions [18] "(Lopesa and Silvab,2018, p.46) .

Experiment: Recreation of the 4D Printed Cube

Multi-material 4D print: Cube

For the first multi-material test, a hands-on approach to recreate a version of Skylar Tibbits' self-folding cube was chosen. The initial test by Skylar Tibbits was conducted with material jetting technology that was based on liquid photopolymer printing. The recreation of the model has to be seen as a starting point to comprehend the possibilities and limitations of multi-material printing with the FDM method. The SMP filament was applied to the active regions of the self-folding cube and the commercially available PLA filament of Greentech (in black) was used for the inactive parts. During the first multi-material test run, the standard printing settings of the PRUSA Slicer were used (with a quality of 0.1mm). The nozzle temperature of the PLA was set to 215°C, and the bed temperature was turned up slightly to 65°. The cooling was turned off for the first layer and later the fan ran on 100%. The active SMP parts of the model were printed with a nozzle temperature of 210°C. The other settings can be obtained from the values in chapter 3.3.

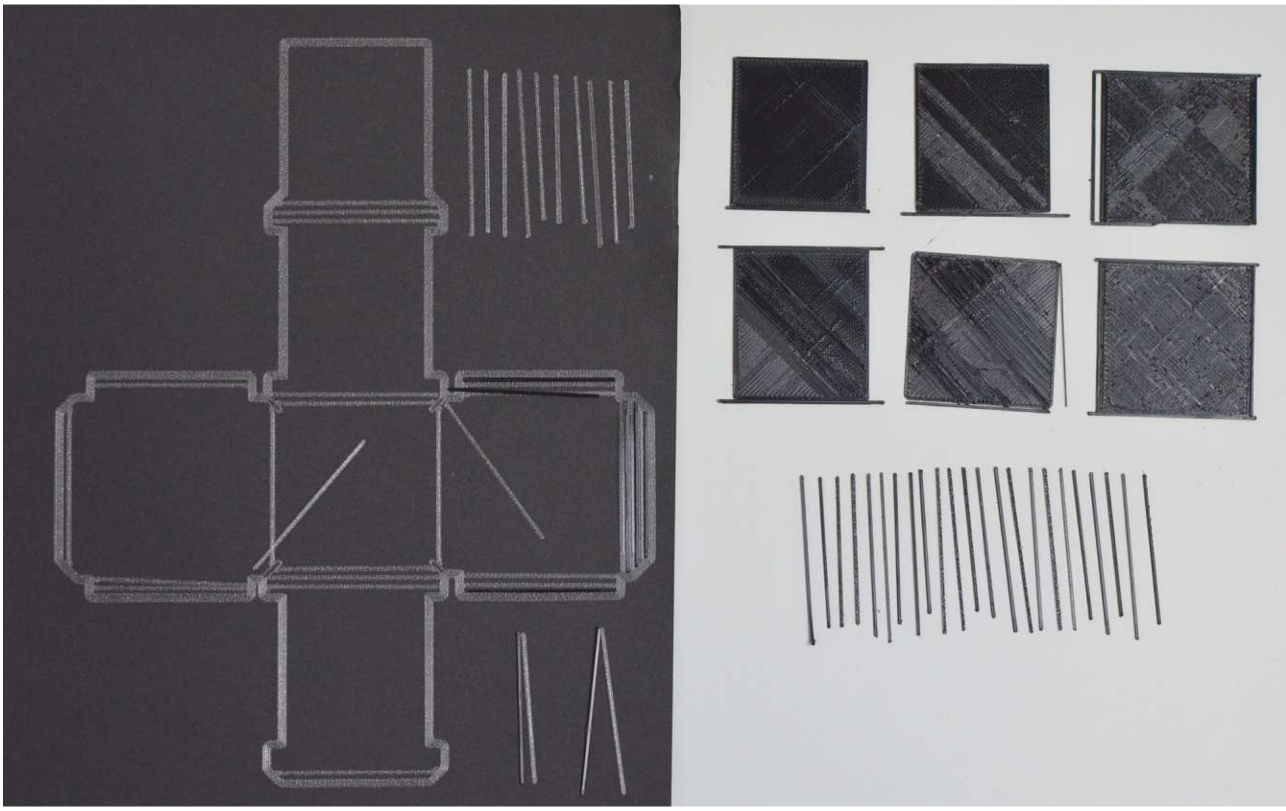


Fig: 77. Individual parts of first multi-material print

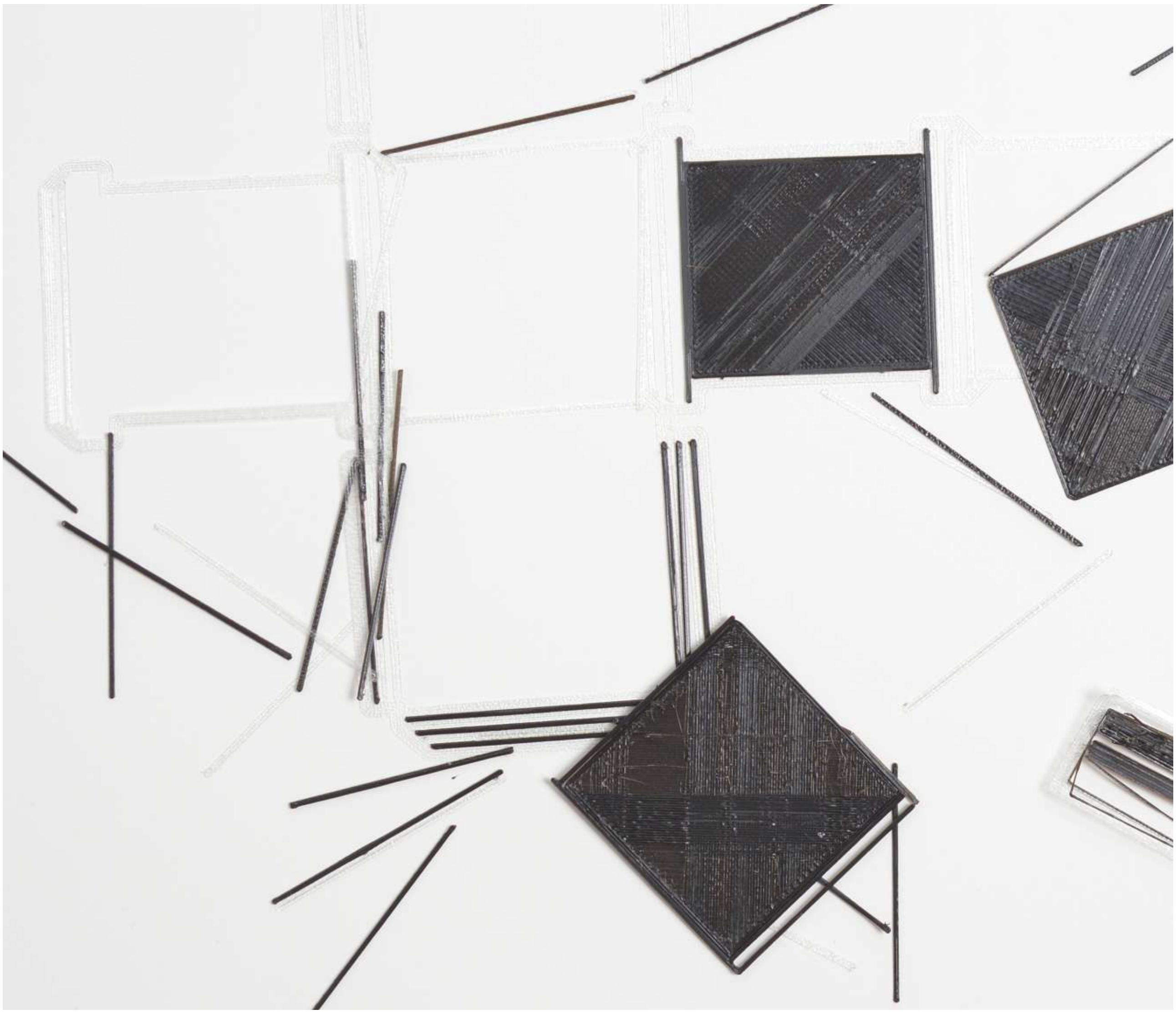


Fig: 78. Individual parts with insufficient print quality

The first multi-material print failed due to diverse reasons. The materials' cohesion showed undesirable results between the active SMP and the PLA Filament.

Print settings:

An attempt to overcome the failed connection between the materials was the adjustment of the printer settings. The previous undesirable result lead to a systematic observation of different print temperatures. Therefore, small 30x30x0.5 mm PLA/SMP specimens were tested. The values that were used can be seen in the following table.

Nr.	Product name	Nozzle Temperature	Bed Temperature	Print Speed	Sample Size	Fan Speed	Cohesion between Filaments
		in °C	in °C	mm/s	in mm	%	(+) (+/-) (-)
1.					lxwxh		
Material 1:	SMP - KO-BO	210	65°C	45	15x30x0.5	NO	(-)
Material 2:	PLA - Greentech	210	65°C	45	15x30x0.5	NO	
2.							
Material 1:	SMP - KO-BO	210	65°C	45	15x30x0.5	NO	(+/-)
Material 2:	PLA - Greentech	215	65°C	45	15x30x0.5	NO	
3.							
Material 1:	SMP - KO-BO	210	65°C	45	15x30x0.5	NO	(+/-)
Material 2:	PLA - Greentech	220	65°C	45	15x30x0.5	NO	
4.							
Material 1:	SMP - KO-BO	210	65°C	45	15x30x0.5	NO	(+/-)
Material 2:	PLA - Greentech	225	65°C	45	15x30x0.5	NO	
5.							
Material 1:	SMP - KO-BO	210	65°C	45	15x30x0.5	NO	(+/-)
Material 2:	PLA - Greentech	230	65°C	45	15x30x0.5	NO	

The values of the fourth material sample showed were comparable to the fifth sample. However, the surface quality produced better results in the specimens with print temperatures of 210/225°C. A second sample of the cube model was printed. The resulting print with adapted nozzle temperature showed only marginal improvements.

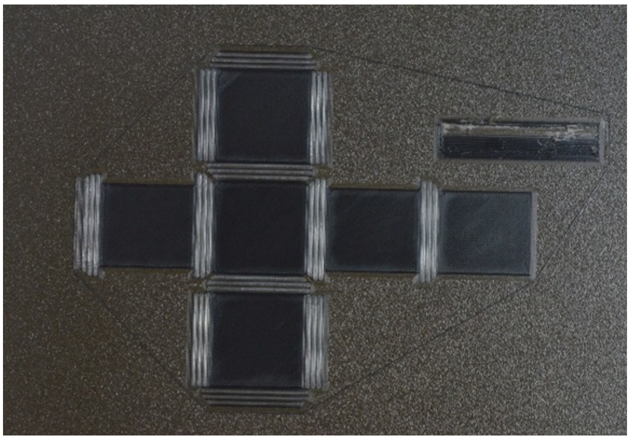


Fig: 80. Prototype: folding- cube second testprint on heat - bed

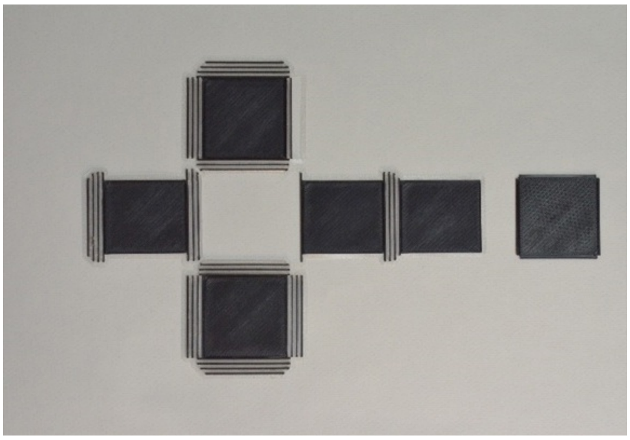


Fig: 81. Prototype: folding - cube second testprint off heat - bed

The undesirable result from the previous printing test required additional research into multi-material 3D printing. Lopes, Silva and Carneiro suggested applying a special design strategy to favour the physical interlock between different materials in multi-material prints. The boundary interface was identified as a weak spot in FDM multi-material printing(Lopesa and Silvab,2018, pp.45-52).
To overcome the poor cohesion of the print samples, a geometrical strategy was tested based on the PRUSA Knowledgebase. The user Rainer Schloßhan successfully tested a geometrical connection approach with a flexible TPU and PLA with the MMU2s (Schloßhan,2019). His multi-material hinged "Roll-Up Box"(PRUSA Research) model was subsequently used for the PLA and SMP combination to test the interlocking strategy. The model used was adapted to the above printer setting of the SMP and the nozzle temperature of the PLA was set to 225°C. The cooling fan was set to 100% after the third layer. The G-codes for the model were generated in the PRUSA Slicer 2.3.0.
Altogether four prototypes had to be printed. The MK3S+ repeatedly aborted during the first and second test run. Two thermal runaway errors occurred during the cross from the gridlocked pattern to the PLA surface. The abortion was attributed to the false cooling parameter in the printer settings. The fan caused a high fluctuation in the nozzle temperature between the SMP and the PLA filament

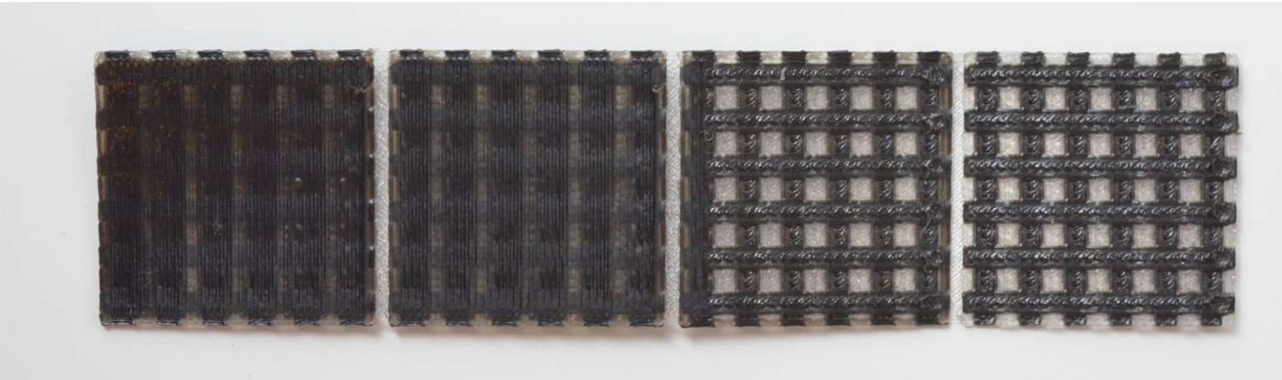


Fig: 82. First prototype aborted print sample

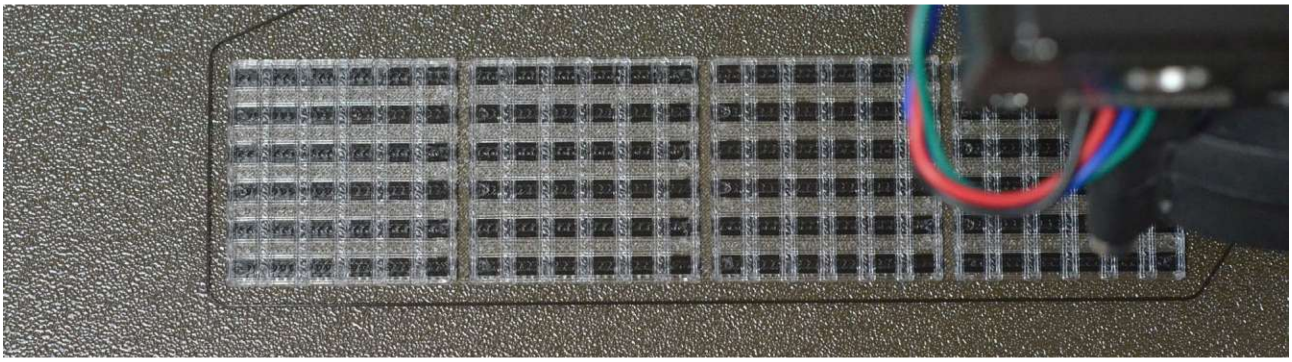


Fig: 83. Second prototype - aborted print sample

The first aborted print sample was used for a hands-on multi-material programming test with 55°C tempered water. Thus, a cube was manually formed. The shaping could be done easily and the recovery back to a flat state took place within 3 seconds. An observable effect was a twisting of the sample caused by the hydrophilic behaviour of the PLA. The area between the SMP and the more stable PLA was 0.04mm thin, and after four deformation cycles, the connection failed.
The recovery time was 8 seconds.

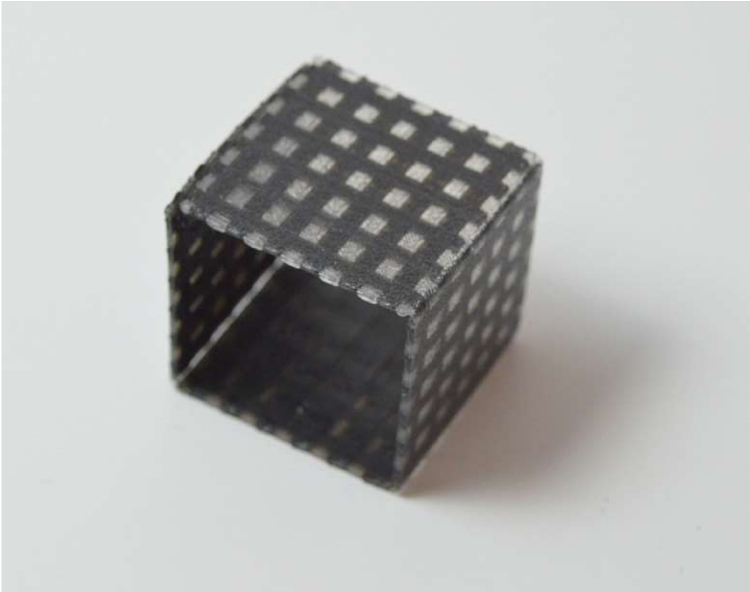


Fig: 84. Programmed abortet multi-material sample

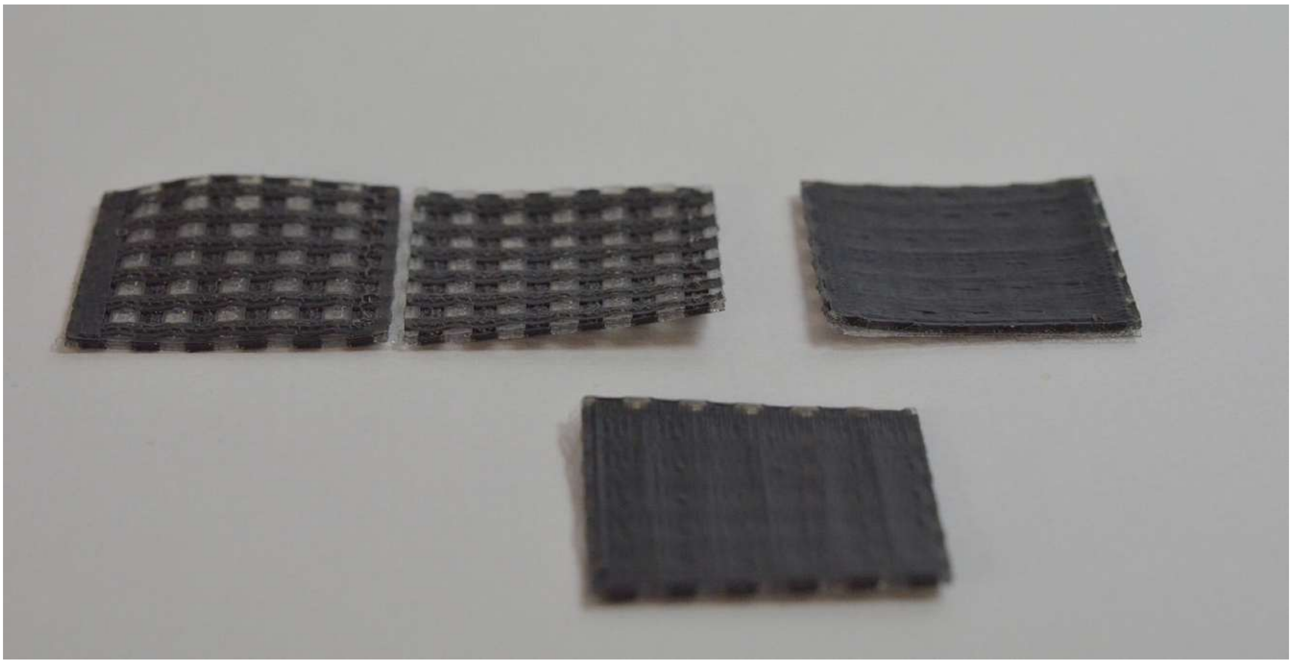


Fig: 85. Hydrophilic behaviour of PLA in a multi-material sample

The third model was printed successfully and showed desirable results in cohesion but not in quality. The retraction distance parameter was adjusted to 10mm in the fourth print. The last model displayed a clean outcome and the desirable cohesion between the filaments. (Fig___)

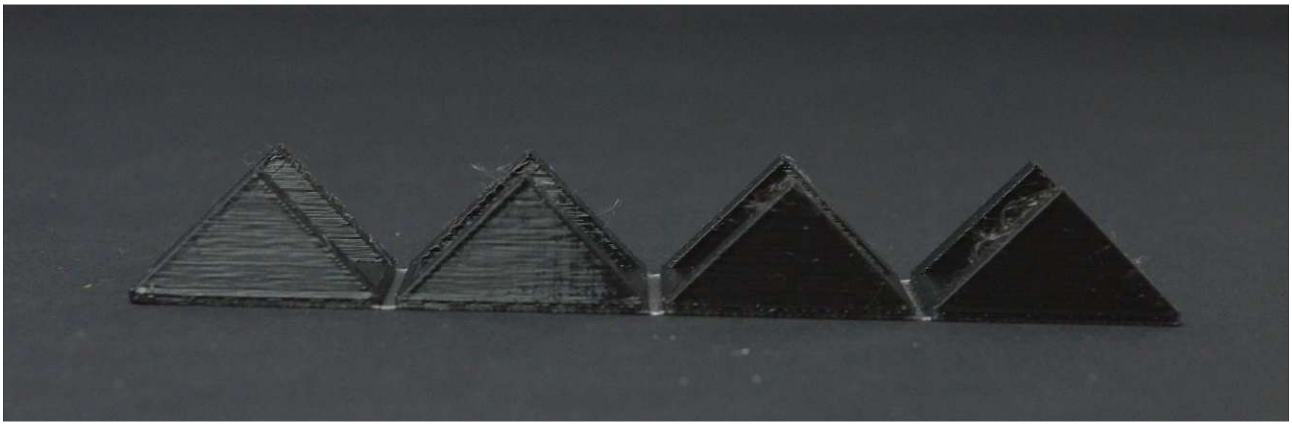


Fig: 86. First multi-material shape-changing prototype

Fig: 87. First multi-material shape-changing prototype - programmed cube

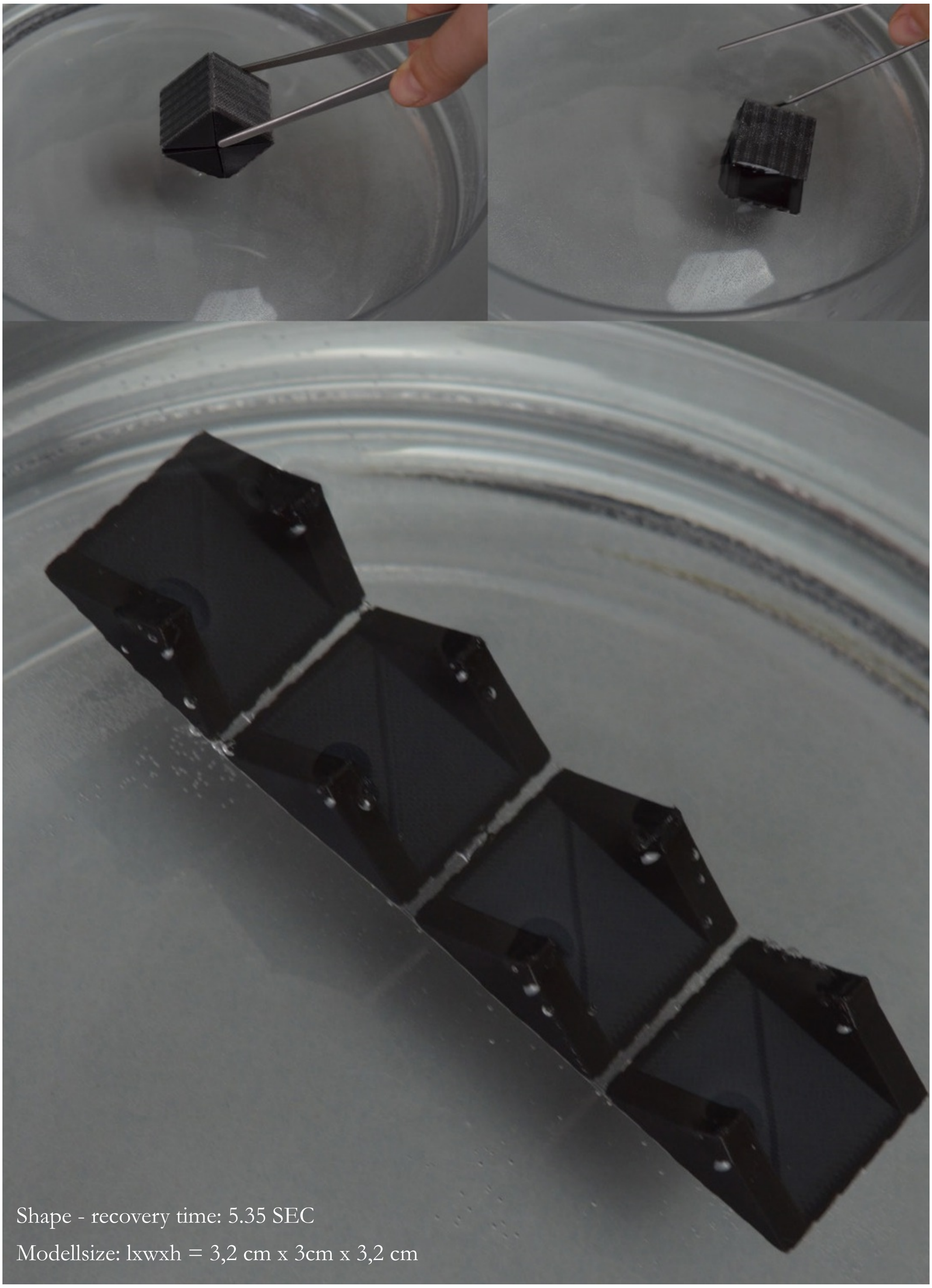


Fig: 88. Shape recovery of multi-material prototype - programmed cube

Cohesiontests - 4D printed multi - material composites

Multi-material composites

The desirable results of the printed test cube and the successful programming of the material-composite experiments led to an adapted strategy for systematically observing the cohesion of three distinct material combinations. The strategy to overcome the issues of the poor bonding of the layers is divided into two steps. The first step was (1) the fine-tuning of the printer settings adapted to the chosen specimens, and (2) for the second approach, three geometric patterns on the horizontal level are designed to test the cohesion of the interfaces. As pointed out before, the interface created between different materials at their geometrical boundary is the main obstacle to connecting two filaments. This strategy was chosen with the aim to create reliable interlocks to further understand possible shape-changing behaviour in multi-material prototypes.

The tested specimens were
- SMP(TPU) – PLA
- TPU – PET
- SMP(TPU) -TPU

Part 1 - Fine-tuning of the printing settings:

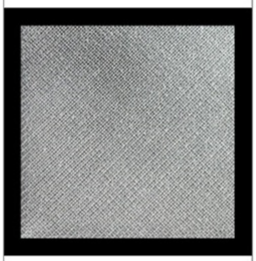
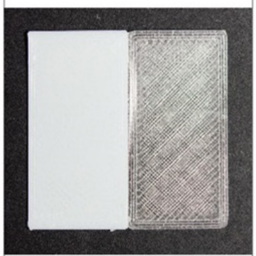
In the first phase the specification sheets of the chosen filaments were reviewed. PLA, PET, and TPU materials were compared to extract commonalities in the printer setting. Not all of the information from the suppliers were obtained. For the systematic observation, test samples of 30x30x0.05 mm were printed and classified according to their visual characteristics. Simple cohesion tests were completed that could be done manually, like simple tensile and bending tests. The temperature variable was increased by five degrees per specimens to observe an improvement of the material cohesion. The following tables display the values tested between SMP-PLA, SMP-PET, and an SMP-TPU filament. Common values were chosen in advance for print speed, retraction speed, filament flow, and fan speed to achieve good quality prints before adapting the right printing temperature.

The following cohesion tests are mainly conducted from the perspective of design and manufacture, they are tested within the framework of possibilities. The conducted tests aimed to gain a better understanding of the possible strategies for designing transformable multi-material parts for further shape-changing prototypes. In the next chapter the visual criteria indicate how the changes in the specimens were evaluated.

Part 1 - Fine-tuning of the printing settings:

Three evaluation criteria are introduced regarding the quality of the printed filament and the cohesion to compare the samples. The comparative values are divided into Surface quality, Material quality and Cohesion quality, as shown in Fig. (). The printing and surface qualities are designated with a (+) for good quality, a (+/-) would indicate quality with minor errors, (-) show an undesirable print quality. Material quality is evaluated according to the creasing and it shows if the material is brittle or melted.

Evaluation Criteria

Surface Quality			**Cohesion Quality**		
Visual Criteria Samples	Evaluation Values	Description	Visual Criteria Samples	Evaluation Values	Description
	Good (+)	clean surface no uneveness no lost layers		Good (+)	good cohesion between two filament specimens
	Average (+/-)	slightly unclean surface no uneveness lost layers		Average (+/-)	slight cohesion between two filament specimens easy to pull apart
	Undesirable (-)	poor surface uneveness lost layers lumpy burnt surface		Undesirable (-)	no cohesion between two filaments specimens

Material Quality		
Visual Criteria Samples	Evaluation Values	Description
	Brittle (Yes/No)	not properly melted, single threads observable
	Melted (Yes/No)	good cohesion between single threads

Fig: 89. Avaluation criteria - print samples

SMP/PLA - print settings

Nr.	Product name	Nozzle Temperature	Bed Temperature	Print Speed	Sample Size	Flowrate	Fan Speed	Retraction	Surface Quality	Layerbonding	Cohesion between Filaments
		in °C	in °C	mm/s	in mm lxwxh	R	%	mm/s	(+) (+/-) (-)		(+) (+/-) (-)
1.											
Material 1:	SMP - KO-BO	210	65°C	45	15x30x0.5	1,0	NO	35	(+)	melted	(-)
Material 2:	PLA - Greentech	210	65°C	45	15x30x0.5	1,0	NO	40	(+/-)	brittle	
2.											
Material 1:	SMP - KO-BO	210	65°C	45	15x30x0.5	1,0	NO	35	(+)	melted	(+/-)
Material 2:	PLA - Greentech	215	65°C	45	15x30x0.5	1,0	NO	40	(+/-)	brittle	
3.											
Material 1:	SMP - KO-BO	210	65°C	45	15x30x0.5	1,0	NO	35	(+)	melted	(+/-)
Material 2:	PLA - Greentech	220	65°C	45	15x30x0.5	1,0	NO	40	(+)	slightly brittle	
4.											
Material 1:	SMP - KO-BO	210	65°C	45	15x30x0.5	1,0	NO	35	(+)	melted	(+/-)
Material 2:	PLA - Greentech	225	65°C	45	15x30x0.5	1,0	NO	40	(+)	slightly brittle	
5.											
Material 1:	SMP - KO-BO	210	65°C	45	15x30x0.5	1,0	NO	35	(+)	melted	(+/-)
Material 2:	PLA - Greentech	230	65°C	45	15x30x0.5	1,0	NO	40	(+)	slightly brittle	

Fig: 90. Testvalues, PLA/SMP

SMP/PETG - print settings

Nr.	Product name	Nozzle Temperature	Bed Temperature	Print Speed	Sample Size	Flowrate	Fan Speed	Retraction	Surface Quality	Layerbonding	Cohesion between Filaments
		in °C	in °C	mm/s	in mm	R	%	mm/s	(+) (+/-) (-)		(+) (+/-) (-)
1.											
Material 1:	SMP - KO-BO	210	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	(+/-)
Material 2:	PETG - SEAGLASS	**235**	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	
2.											
Material 1:	SMP - KO-BO	210	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	(+/-)
Material 2:	PETG - SEAGLASS	**240**	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	
3.											
Material 1:	SMP - KO-BO	210	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	(+/-)
Material 2:	PETG - SEAGLASS	**245**	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	
4.											
Material 1:	SMP - KO-BO	210	70°C	30	15x30x0.5	1,1	70	35	(+)	melted	(+/-)
Material 2:	PETG - SEAGLASS	**250**	70°C	30	15x30x0.5	1,1	70	35	(+)	melted	
5.											
Material 1:	SMP - KO-BO	210	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	(+/-)
Material 2:	PETG - SEAGLASS	**255**	70°C	35	15x30x0.5	1,1	70	35	(+/-)	melted	

Fig: 92. Testvalues, SMP/PETG

Nr.	Product name	Nozzle Temperature	Bed Temperature	Print Speed	Sample Size	Flowrate	Fan Speed	Retraction	Surface Quality	Layerbonding	Cohesion between Filaments
		in °C	in °C	mm/s	in mm	R	%	mm/s	(+) (+/-) (-)		(+) (+/-) (-)
1.											
Material 1:	SMP - KO-BO	210	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	(-)
Material 2:	PolyFlex - TPU95	**210**	70°C	35	15x30x0.5	1,1	70	35	(-)	melted	
2.											
Material 1:	SMP - KO-BO	210	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	(-)
Material 2:	PolyFlex - TPU95	**215**	70°C	35	15x30x0.5	1,1	70	35	(-)	melted	
3.											
Material 1:	SMP - KO-BO	210	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	(+/-)
Material 2:	PolyFlex - TPU95	**220**	70°C	35	15x30x0.5	1,1	70	35	(+/-)	melted	
4.											
Material 1:	SMP - KO-BO	210	70°C	30	15x30x0.5	1,1	70	35	(+)	melted	(+)
Material 2:	PolyFlex - TPU95	**225**	70°C	30	15x30x0.5	1,1	70	35	(+)	melted	
5.											
Material 1:	SMP - KO-BO	210	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	(+)
Material 2:	PolyFlex - TPU95	**230**	70°C	35	15x30x0.5	1,1	70	35	(+)	melted	

Fig: 91. Testvalues, SMP/TPU

Result Experiments

The best result in the layer bonding could be achieved between the SMP and the flexible TPU filament of Polyplex. Both filaments are based on the same polymer structure with slightly different printing settings. The PETG of Reflow and the TPU showed sufficient layer bonding at the tensile test. At bending, the connection could easily be broken. Notwithstanding prior fine-tuning of the print temperatures and bed temperatures, the PLA results showed the lowest cohesion in the tested filaments. Furthermore, the PLA and its hydrophilic behaviour were not suitable for testing in tempered water, as experienced. The poor layer bonding of the PLA may also be partly attributed to the age of the filament as it was not tested with new material. The printability of diverse material combinations depends on various parameters: the room temperature, the humidity, the chemical composition, the printer settings, the filament brand. Therefore, the findings may not represent the best possible layer bonding between SMP and PLA, PET and TPUs with the MMU2s. Further research would be necessary to gain an overall understanding of how the materials bind together well, and it would be desirable to include a material scientist to explore the possible connection at the chemical level. Further experiments would have been beyond the scope of this master thesis and the following values are used for further test prints.

Print - settings

PET - PRINT SETTINGS			
PRIMARY PARAMETER	VALUE	PRIMARY PARAMETER	VALUE
Nozzle Temperature	250°C	Retraction Speed	35 mm/s
Bed Temperature	70 - 75 °C	Retraction Distance	10 mm
Fan Speed	70 %	First Layer Thickness	0.2 mm
Print Speed	40 mm/s	First Layer Hight	0.1 - 0.2 mm

Fig: 93. Print Settings - PET

TPU - PRINT SETTINGS			
PRIMARY PARAMETER	VALUE	PRIMARY PARAMETER	VALUE
Nozzle Temperature	225°C	Retraction Speed	20 mm/s
Bed Temperature	65 - 70°C	Retraction Distance	1 mm
Fan Speed	70 %	First Layer Thickness	0.2 mm
Print Speed	35 mm/s	First Layer Hight	0.1 - 0.2 mm

Fig: 94. Print Settings - TPU

This research was mainly conducted to explore possible materials combination to design shape-changing multi-material composites in order to expand the scope of material behaviours and application possibilities. Therefore, further interlock strategies were tested. The following were produced with a PETG and SMP, as they already showed minor layer bonding in thin specimens. The flexible TPU is excluded from these tests as the printability of SPM and TPU had already been confirmed. These cohesion tests propose a quick, intermediate step for solving the layer bonding issues for the further design of shape-changing multi-material samples.

For the geometrical approach, the testing strategy from the printer settings is pursued. The easy tensile and bending test allowed the observation of a proper connection within the printed composite. As pointed out before, the work must be seen in the framework of possibilities and not aim to explore the most robust connection between these specimens. The following tables show possible connection patterns for increasing the adhesion surface between the material composites

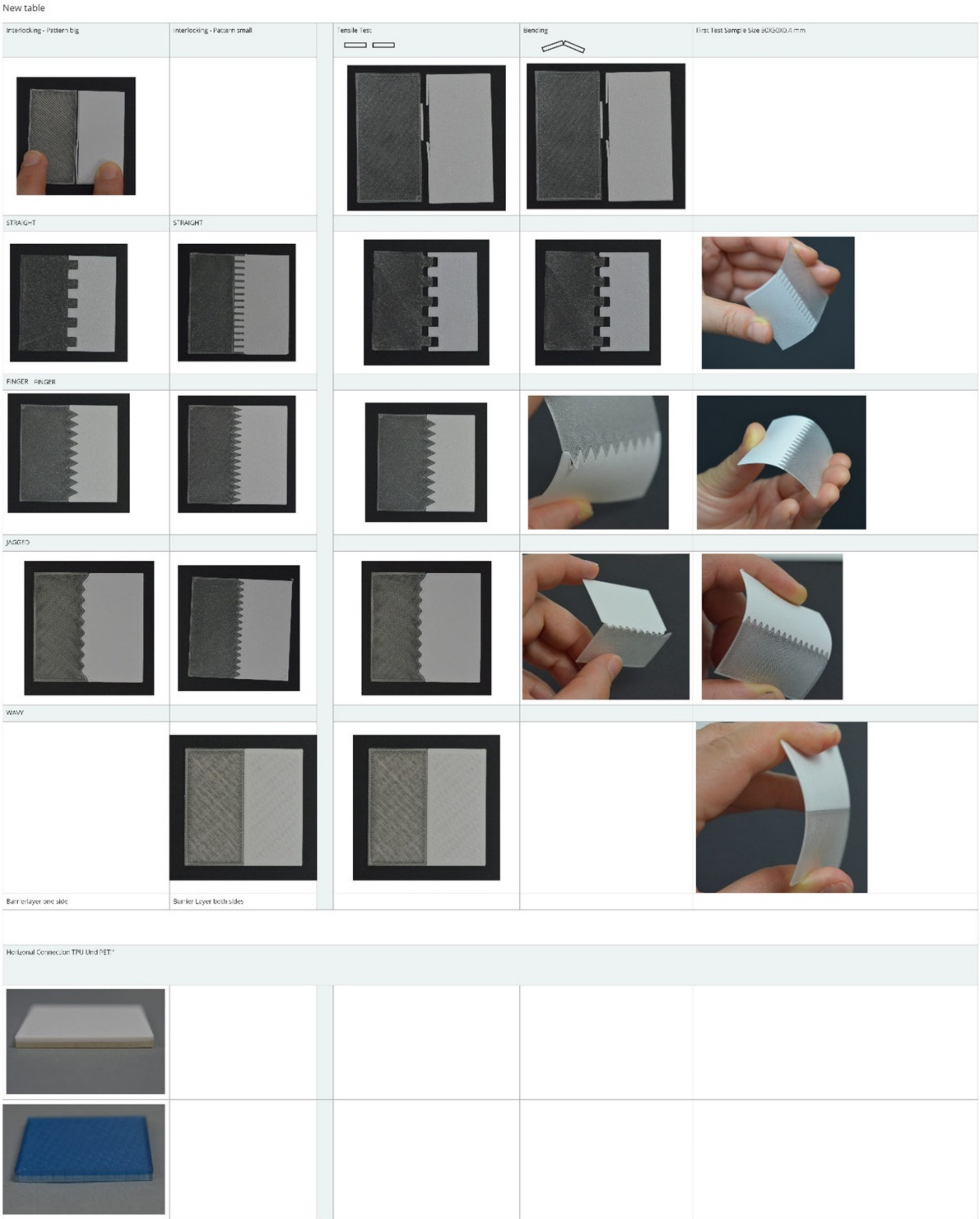


Fig: 95. Cohesion - test results

Patterns with a larger surface showed a trend of better connections between the SMP and the PETG. The tensile test demonstrated the improvement of the connection based on the geometric pattern. Patterns with larger surface boundaries showed better results than samples with smaller surface boundaries. Even though the tests showed marginally improved results for thin samples, the connection remained insufficient. To print a more reliable interface, an additional barrier layer with SMP Filament 0.02 mm was introduced to create feasible connections for thinner elements. This was tested with the obtuse straight PET/SMP sample and showed a satisfactory result within it. The last two samples exhibited horizontal printability. It may be that due to the more extensive surface area the filaments showed sufficient connections on the interface.
Folding cube with adapted print strategy:
Together with the adapted print strategy, the test cube from chapter 3.2 was recreated. An additional barrier layer on top and at the bottom of the model was added. The printer settings above were used. The adapted strategy enabled the production of a successful 4D multi-material model.

Recreation of the folding cube - test with adapted print strategy

Fig: 96. First multi-material shape-changing prototype - programmed cube

Folding cube with adapted print strategy:
With the adapted print strategy, the test cube from chapter 3.2 was recreated. An additional barrier layer on top and at the bottom of the model was added. The printer settings from above were used. The adapted strategy enabled the production of a successful 4D multi-material model.

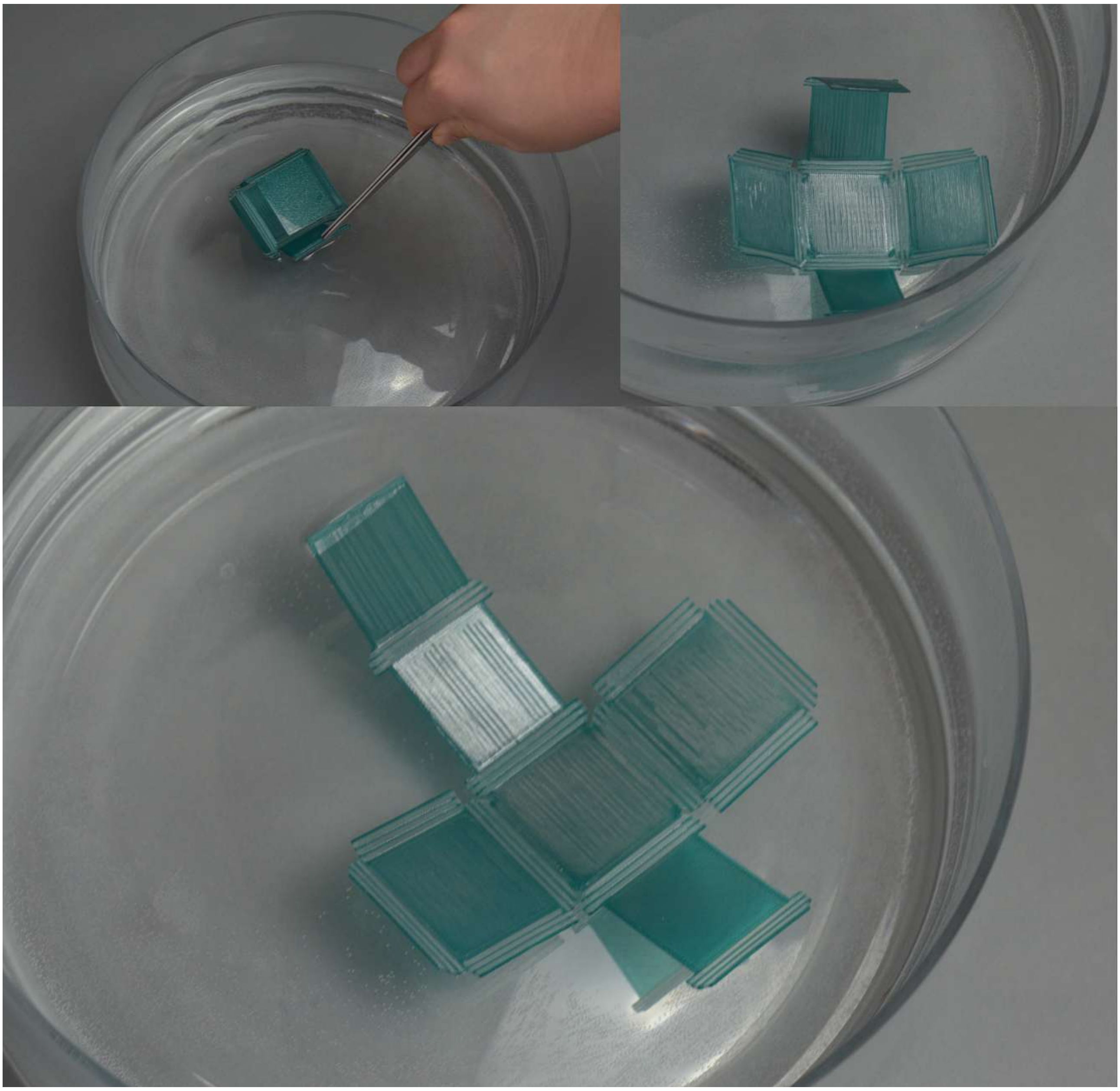


Fig: 97. Shape -recovery folding cube

Activation SME in SMP with embedded heating wires

To design a shape-changing material in architecture, the strategy to trigger a shape-changing effect in polymers has to be kept in mind. In this research project, the SMP is a thermo-responsive material and transforms at a Tg of 55°C. All previous shape-changing prototypes are actuated and programmed with 55°C tempered water due to limited access to a heating chamber.

The approach to activate the SMP with embedded wire was inspired by a shape-shifting architectural prototype from the Institute of Advanced Architecture Catalonia(IACC).
The first attempt involved the printing of conductive wires that lead to embedded heating wires.
The Flexible Conductive filament of NinjaFlex was printed repeatedly with diverse adjustments. The following problems occurred during the printing process. First, the gears of MMU2 could not reliably feed the filament into the nozzle. Secondly, during the printing too much material got stuck in the hot end, and the extruder was soiled. Furthermore, the remaining filament caused the extruding material to be mixed up. The mixed material polluted the sample.

The cleaning process during the wipe tower cycle did not clean out the rests of the conductive filament. Additionally, the conductive filament polluted the nozzle and the print bed and was hard to remove.

Printed multi-material samples soild with conductive TPU

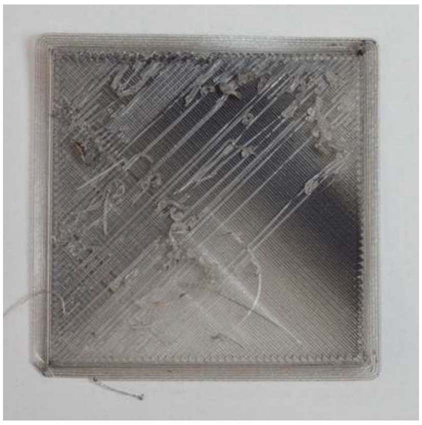


Fig: 98. Soiled print with conductive TPU

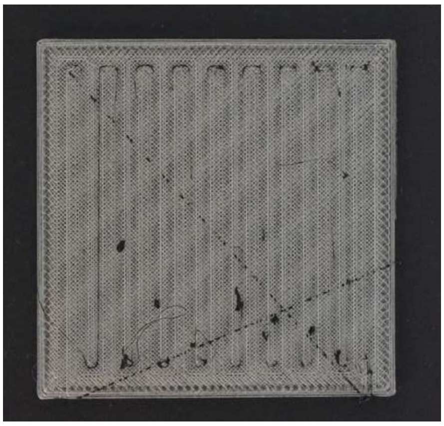


Fig: 99. No proper feeding of conductive filament

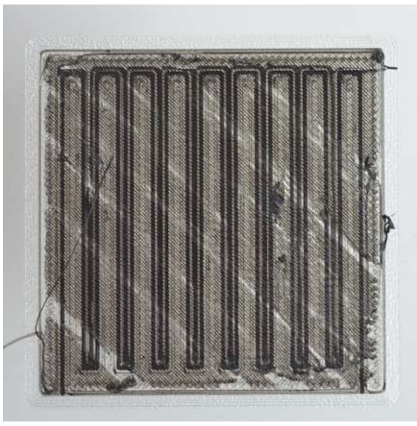


Fig: 100. Conductive filament and SMP composite

Fig: 101. Deformed SMP and conductive filament sample

Fig: 102. Conductive TPU sample

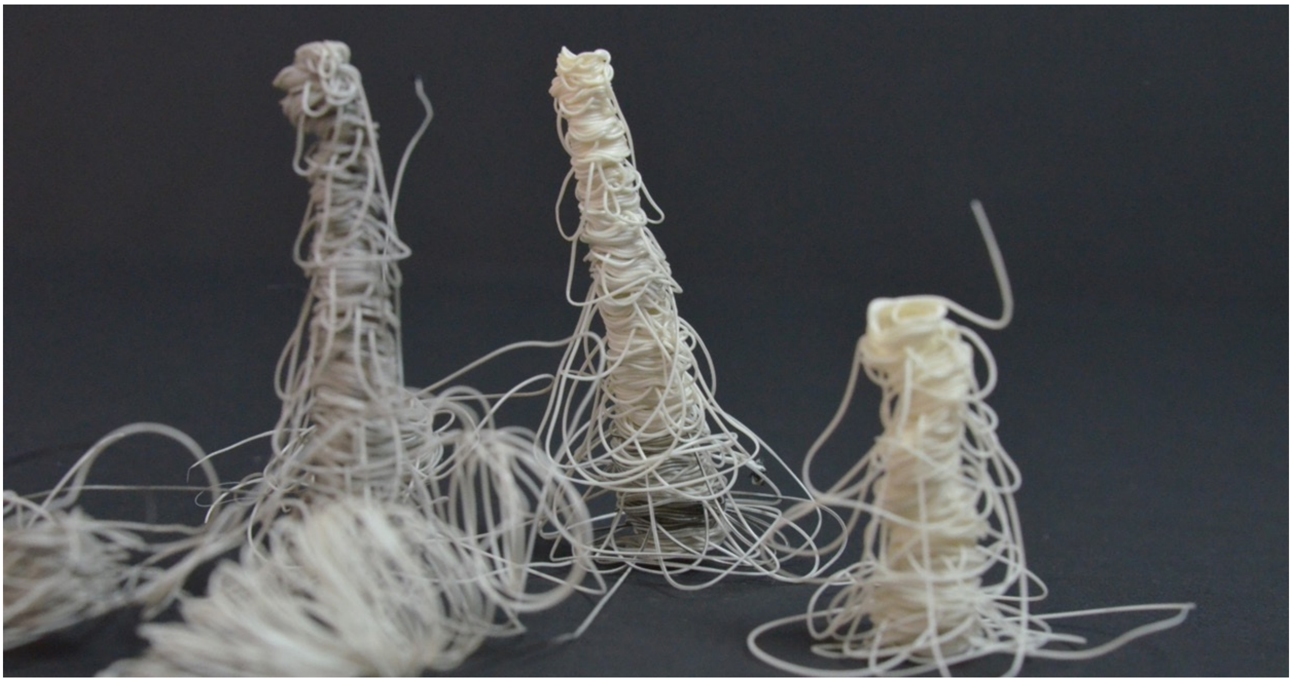


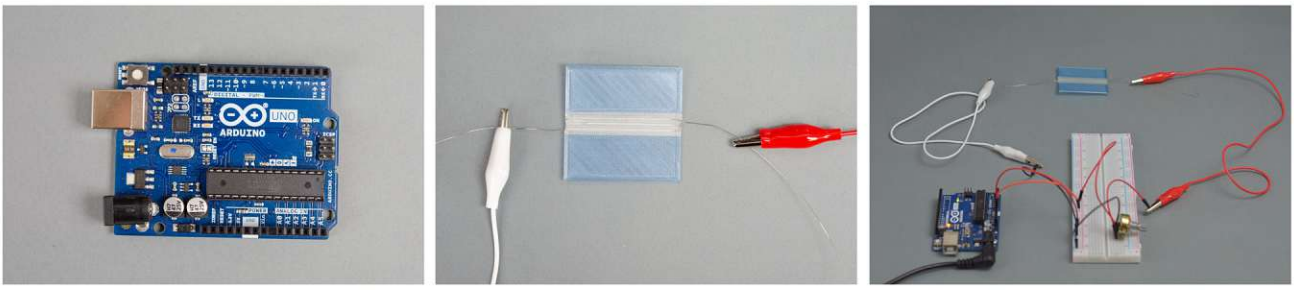
Fig: 103. Necessary cleaning filament, which was used to generate good prints

The attempt failed to print conductive NINJAFLEX filament with SMP and the MMu2s.

Description - tests

The conductive NINJAFLEX filament with SMP and the MMu2s failed to print during this attempt. For the intrinsic actuation with embedded heating wires, three specimens were produced: two single SMP sampled and one multi-material. The first sample had a size of 5x5x0.3 cm, the second is 5x5x0.2 cm, and the third is 5x5x0.1 cm. All samples had interwoven constantan wires integrated with a circumference of 0.3 mm. An Arduino Uno was used for the power supply to heat up the wires. The specimens were connected to the heating wire and were controlled with an analogue potentiometer.
The values were measured with a thermal imaging camera. The measurable temperature ranged from -20°C to +300°C, with a measuring accuracy of +/-2°C.

Set up for heating wire tests



Heating - tests

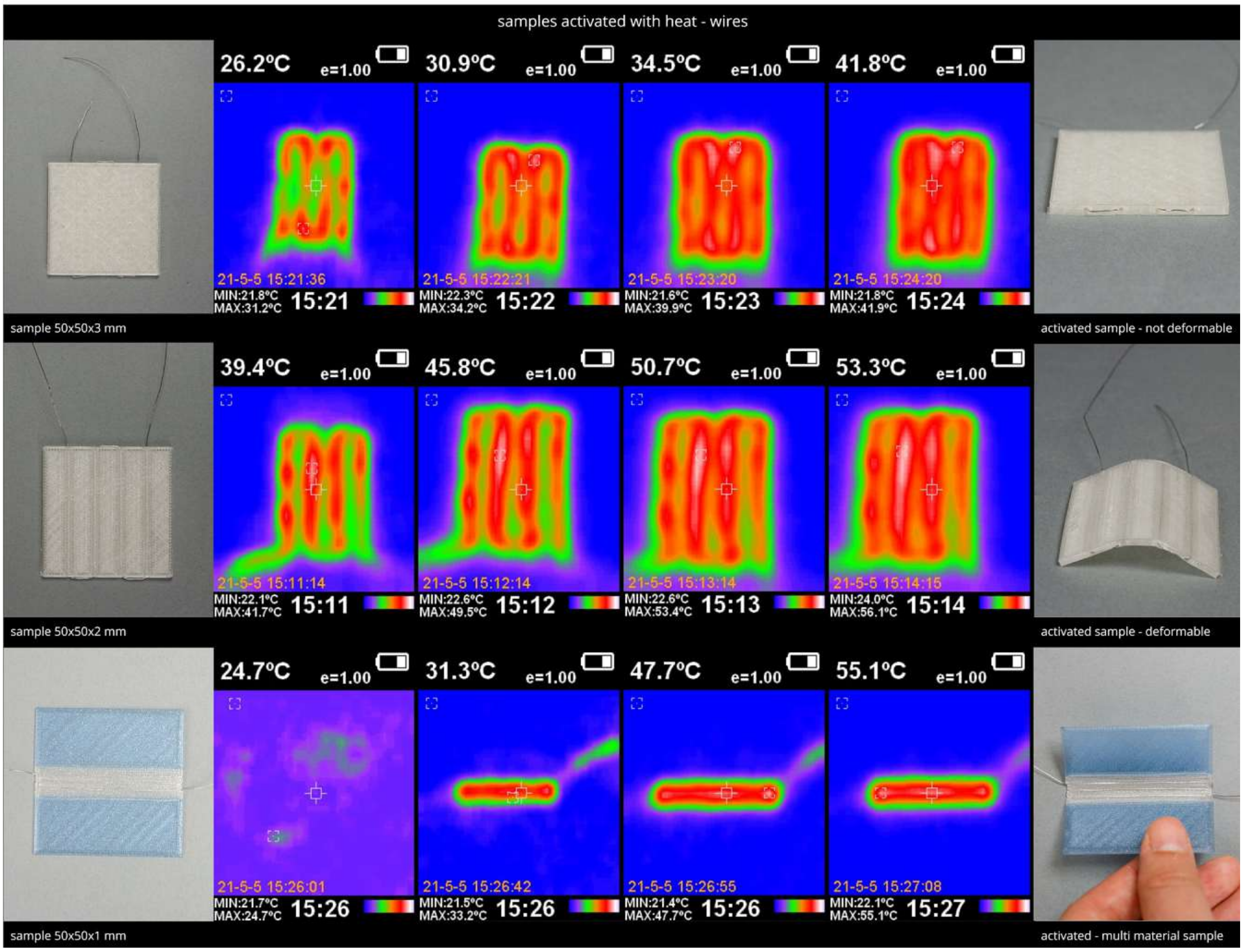


Fig: 105. Intrinsic activation with heating wires

Results - heating tests

The first sample could not be activated within 4 min. The second sample heated up properly within 3 min, and it could be transformed manually. The last sample, the PET_SMP composite with integrated constantan wires in the middle of the sample, showed the fastest activation of SMP.

3.5 Shape changing Multi-Material Composites

Overcoming the layer bonding issues was the main hurdle of further exploring possible shape-changing elements for architectural applications. Various factors must be considered for the design of shape-changing elements. The following diagram shows an overview of the design process.

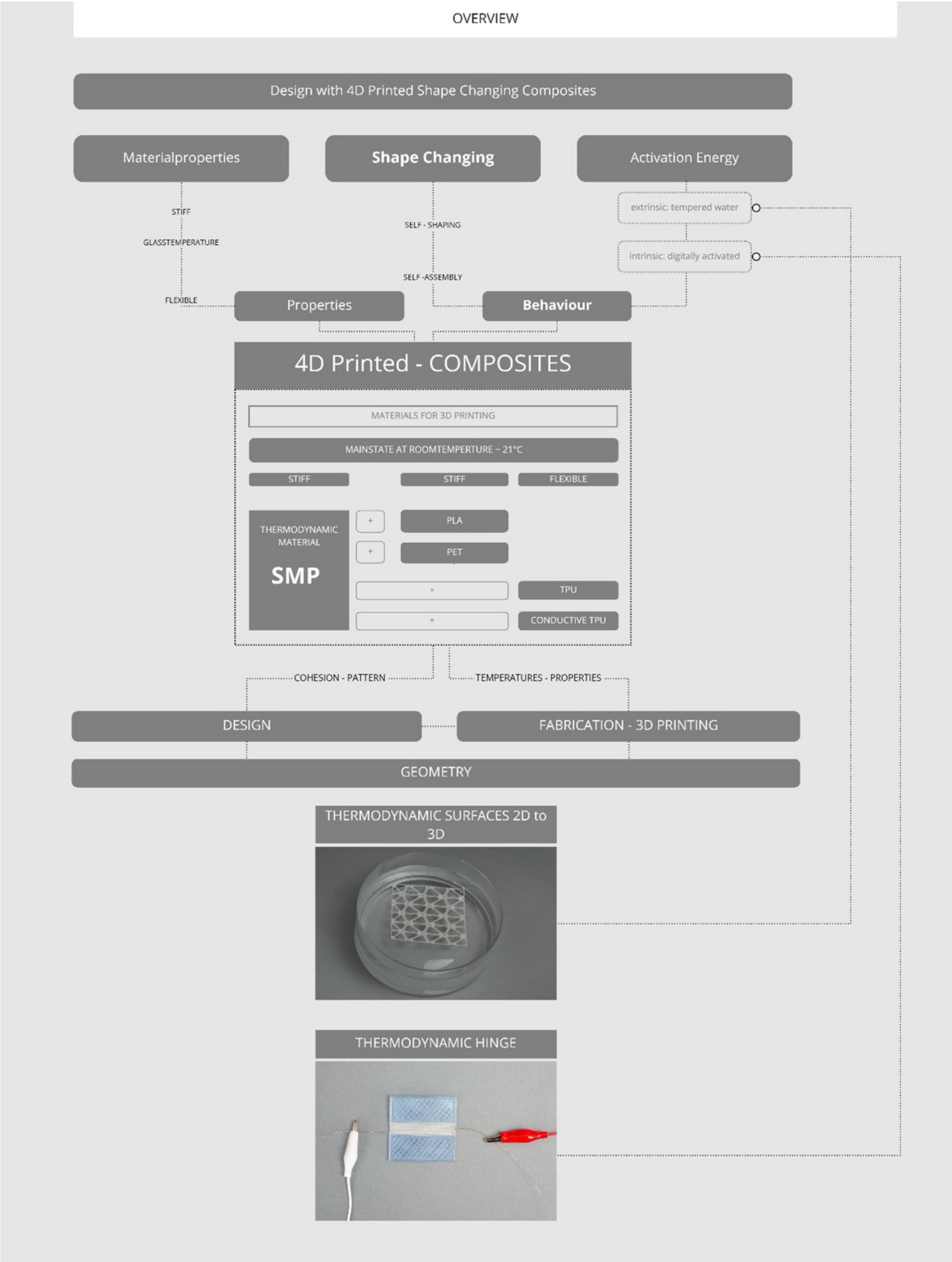


Fig: 106. Designframework

The following pictures display prototypes that were printed out to observe the possible material behaviour of the alterable composites. A solid SMP, an SMP/TPU composite, and an SMP /PET combination were printed for comparison. Each sample was manually deformed, and specific behaviour could be detected. The distinct behaviours can be seen in the following table

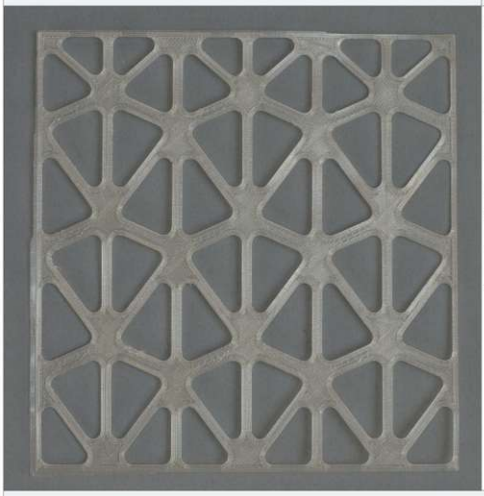
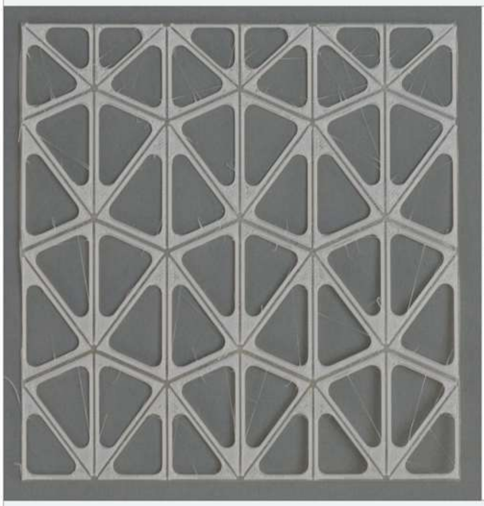
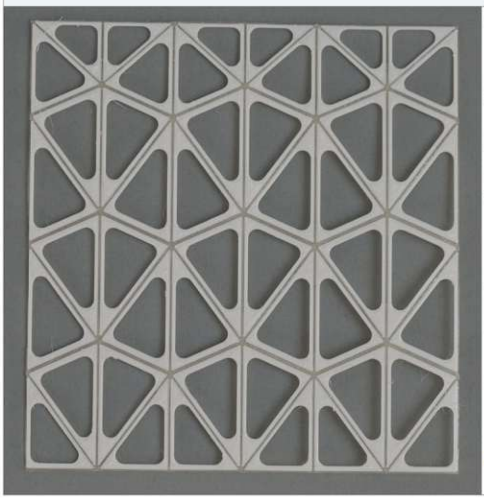
Prototype	Description - properties
	**SMP:** Single SMP Prototype Thickness: 1mm Material: single SMP Sample Size: 12,4 x 13 cm SMP properties: Shore Hardness: 77 Elasticity: 30 - 50 Glass transition: 55°C Loading: 400% water repellent
	**SMP - TPU Prototype:** TPU coated with a thin layer of SMP Thickness: 0.4 mm Material: SMP/TPU composite Sample Size: 12,4 x 13 cm TPU - Polyflex properties: Shore Hardness 95A Elasticity: 3 times original length Glass transition: 113°C Loading: 400%
	**SMP - PET Prototype** PET: stiff, water repellent, high resistance PET coated with a thin SMP layer Thickness: 0,6 mm Material: SMP/PET Sample size: 12,4 x13 cm PETG - Reflow: Glass transistion: 113°C high ability to handle stress resistance to: acids, oils, fats und alcohols. limit of application –20°C to+120 °C https://einfach3ddruck.de/petg-filament/

Fig: 107. Multi-material prototypes

Activation of the SMP/PET surface – sample:

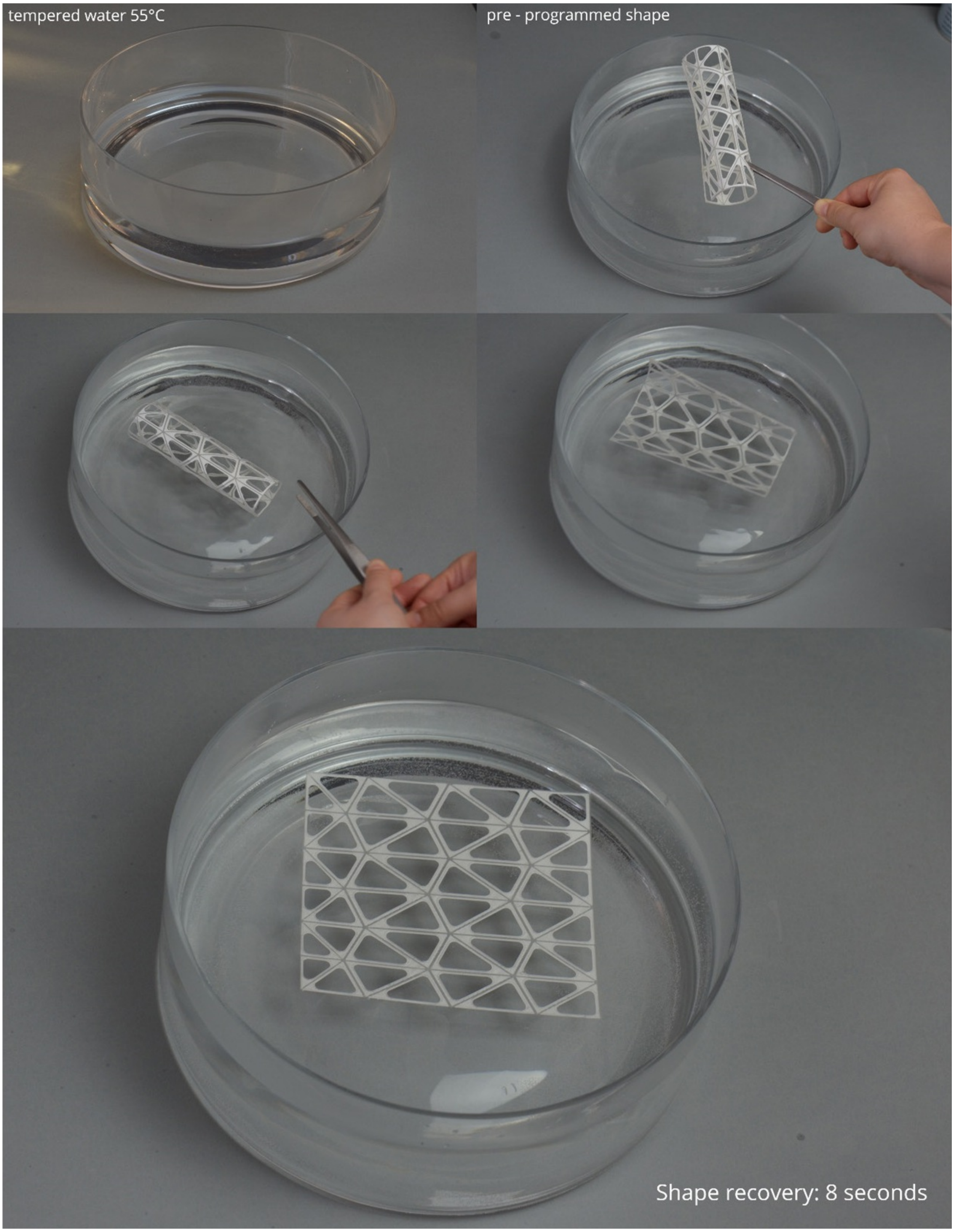


Fig: 108. Shape recovery of SMP/PET prototype

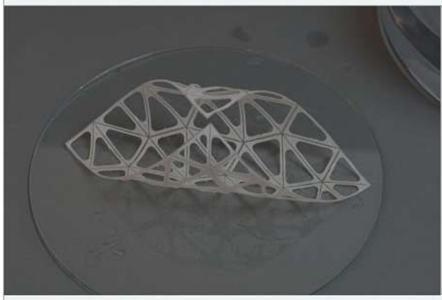
Prototype	Description - properties	Material behaviour and properties
	**SMP:** water repellent defromable above Tg 55 Single SMP Prototype Thickness: 1mm Material: SMP Sample Size: 12,4 x 13 cm	Fully deformable: free deformation of form possible Recovery time in 55°C tempered water: 5 **seconds** Deformation restriction: too much deformation force - irreversible changes possible Ability to withstand certain weight
	**SMP - TPU Prototype** TPU: flexible, rubbery texture TPU coated with a thin layer of SMP Thickness: 0.4 mm Material: SMP/TPU composite Sample size: 12,4 x 13cm	Flexible, Ability to Store a Shape and still behaviing flexible Recovery Time in 55°C tempered water: no data Certain deformation restriction due to the TPU Filament No ability to withstand weight - flexible
	**SMP - PET Prototype** PET: stiff, water repellent, high resistance PET coated with a thin SMP layer Thickness: 0,6 mm Material: SMP/PET Sample size: 12,4 x13 cm	Stable Form enhanced by the Restricted deformation to the active area: Coated with SMP Filament: Not fully deformable when exposed to heat, well-directed deformation possible. Ability to hold certain weight Recovery Time in 55°C tempered water: **8 seconds**

Fig: 109. Material behaviour - SMP composites

SMP behaviour:

The single SMP prototype was printed out to compare the distinct material behaviour between the single material prototypes and the flexible and stiff composite prototypes. The sample with a size of 12,4 cm x 13 cm and a thickness of 0.1 cm was heated up in a water container and manually deformed. The material properties included the rubbery behaviour above the glass transition temperature and a display of a wide range of possible deformations, see Fig. (). After cooling down below the Tg, the programmed shape was fixed, and the material behaved like a solid.

SMP - TPU behaviour within the composite

The second sample is an SMP and TPU composite (12,4 cm x13 cm). The prototype consists of a 0.2 mm flexible TPU layer and is coated with a thin 0.2 mm shape memory polymer film. The heated-up sample showed a slightly reduced deformability. An exceptional effect could be seen in this composite. The shape-changing behaviour simultaneously with a preserved flexibility was detected.

SMP -PET behaviour within the composite

The TPU-PET composite displayed the lowest range of transformation. The main geometry determines the possible deformation in this composite. The rectangle could be deformed along the diagonal and the opposite edges of the object. The SMP/PET composite allows a deformation in a predefined direction and is restricted to the primary geometric areas. If too much transformation force is applied, all samples show irreversible deformation of the original models.

The material behaviour research revealed the exceptional effect of a shape-changing behaviour simultaneously with a preserved flexibility in an SMP/TPU composite and a deformable PET composite with restricted deformation areas.

Conclusio:

"Matter architecture" is solidified in form by arranging materials that are under constant alteration and correlate with natural phenomena. Alterations can be triggered by humans or natural phenomena. This change may be seen in the form of transformable architecture, subtle rebuilding or at the smallest scale in architecture, specifically, in the material itself. The developments in modern material science show the dynamic material behaviour in static materials that evolve with the development of SMART materials. Apart from modern material science, synthetic biology advances design with living units like light-emitting algae. The development of new production methods like additive fabrication and robotic fabrication facilitates the design with dynamic material behaviour independently of their organic or inorganic origin. The predetermined composition of these materials enables new materials to be explored, ones which shape-change, grow and decay or self-heal. These changes can be triggered either by a computer-controlled source or by uncontrolled natural phenomena. The shape-changing process in programmable matter must be invented and designed according to the desired outcome. New principles evolve with the design of deliberated shape-change. These development can be seen in self-assembly projects and self-shape towers, and other initiatives that cannot even be foreseen yet. One way to design shape-changing materials is by using additive fabrication, which allows multi-material composites to be manufactured. Furthermore, the process of 4D printing enables the use of distinct active material like wood hydrogel or shape memory polymers, among others. For this particular bottom-up material exploration, an active SMP polymer was used. The experimental study presents a strategy to explore shape-changing surface prototypes with a low budget FDM printer and commercially available filaments. The conducted research showed the feasibility of creating a 4D print with the PRUSA MK3s and the MMU2s. The limitations of the PRUSA were found to be the extensive printing times and the unreliable feeding of distinct filaments. The unpredictable behaviour of the MMU2s that was detected was due to certain limitations in the adjustment settings. It was proven that a finely calibrated printer would make it possible to explore shape-changing artefacts to gain further understanding in the field of programmable materials. Based on the data elicitation, the printability of certain filament combinations turned out to be rather complicated. The conductive filament could not be printed within a multi-material print. The manufacture of shape-changing composite elements could be achieved with the proposed printing strategy; however, the approach would require improvements to be made. Specific material behaviour that was desirable within the SMP/TPU and SMP/PET prototype could be observed. The tested approach used to achieve a shape-change in tempered water showed a fast recovery speed. However, the programming strategy must be reconsidered in connection with a potential risk of injury. The research further confirmed the possible activation of the SME in SMP composites with embedded heating wires and an Arduino microcontroller. However, the design of electric wires within a shape-changing multi-material with a conductive filament could not be achieved. The intrinsic activation allowed the deformation of small prototypes, but it is limited to a certain thickness and the power supply that was obtained. Furthermore, the restriction to a one-way SMP showed that a complete movement cycle has not been fully explored yet.

Further potentials:

Many design combinations with diverse materials have been left for the future. However, it would have been beyond the scope of this master thesis. Future work in shape-changing 4d printed multi-materials requires a deeper understanding of the possible behaviour of distinct material combinations. It could be interesting to observe PET/SMP combination with restriction areas within a shape-changing model. A design framework must be adapted to explorer distinct material behaviours. Furthermore, there is a need for proper simulation and planning tools. Another aspect is the activation strategies of thermo-responsive SMP that could be researched within the scope of digital and autonomous activation. The pre-programming may be tackled from a different perspective to activate the SMP composites within the manufacturing of the printing process. A further task would be the overcoming of the one-way SME effect. An activation with diverse tension within a flexible prototype could be researched. Adapted design strategies may be the groundwork for further upscaling SMP multi-material prints with robotic fabrication for large scale membrane prototypes.
Concerning the result of this thesis the possibility to explore shape-changing elements from the design perspective, new design principles and mechanisms may be integrated into design decision. The limitation showed mainly within the manufacturing method. To explore future upscaled prototypes and test the limits of the SMP material on a large scale, a switching to robotic fabrication is necessary. For exploring diverse design principles within intelligent artefact prototypes, the FDM strategy may be suitable with adapted print strategies.

Abbreviation

SMP	Shape Memory Polymer
TPU	Thermoplastic polyurethane
PETG	Polyethylene terephthalate glycol
PLA	Polylactide
TG	Glass transistion temperature
SMC	Shape memory cycle
SME	Shape memory effect

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