Dynamic Casting: Using Deployable Fabric Formwork

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The utilization of fabrics as formwork can facilitate a certain degree of flexibility in design, particularly when combined with deployable structures. Regarding this statement, the aim of this study is to explore the potential of a fabric formwork with deployable structure principles to prevent rigidity in the casting process. The deployable approach combined with fabric contributes to the study by allowing various configurations and reusability. A design-led methodology is adapted during this exploration based upon five phases: (1) crease pattern selection, (2) digital pattern creation, (3) deployable fabric formwork construction, (4) casting the concrete and (5) comparing the physical model to computational model. Various models and mediums are used to examine the form behaviors along with the material relationship to highlight the collaboration between tools and craft to achieve a common goal. Therefore, the utilization of digital mediums is expected to improve the understanding of such a complex system as a dynamic mold fed by interdependent parameters. The results comparing the digital simulations and the several attempts to create the casting products displayed similar, if not identical, attributes. The differences between these models depend on the properties of the selected materials for both the deployable skeleton and the fabric.

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Dinamik Kalıp:
Konuşlandırılabilen Kumaş Kalıp Kullanarak Döküm

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Kumaşların kalıp olarak kullanılması, özellikle konuşlandırılabilir yapılarla birleştirildiğinde tasarımda esneklik sağlayabilir. Bu ifadeyle ilgili olarak, bu çalışmanın amacı, döküm sürecinde sabitliği önlemek için konuşlandırılabilir yapı prensiplerine uygun kumaş kalıpların potansiyellerini araştırmaktır. Kumaş ile birleştirilen konuşlandırılabilir yaklaşım, çeşitli konfigürasyonlara ve yeniden kullanılabilirliğe izin vererek çalışmaya katkıda bulunmuştur. Bu araştırmada beş aşamaya dayanan tasarım odaklı bir metodoloji uyarlanmıştır: (1) katlama şablonu seçimi, (2) katlanma şablonunun dijital ortamda üretimi, (3) konuşlandırılabilir kumaş kalıp yapımı, (4) betonun dökülmesi ve (5) karşılaştırma. Üretilen fiziksel, hesaplamalı ve dijital modellerin form davranışlarının yanı sıra malzeme ilişkisinin de incelenmesi için çeşitli model ve dijital ortamlar kullanılmıştır. Ortak bir hedefe ulaşmak için araçlar ve zanaat arasındaki iş birliğini vurgulamak amacıyla form davranışlarının yanı sıra malzeme ilişkisini incelemek için çeşitli modeller ve ortamlar kullanılmıştır. Bu nedenle, dijital ortamların kullanımı, birbirine bağlı parametrelerle beslenen dinamik kalıp gibi karmaşık bir sistemin anlaşılmasında yardımcı olmuştur. Dijital simülasyonları ve döküm ürünlerini oluşturmaya yönelik çeşitli çalışmaların karşılaştırıldığı sonuçlar, birebir aynı olmasa da benzer nitelikler sergilemiştir. Modeller arasındaki farklar hem konuşlandırılabilir iskelet hem de kumaş için seçilen malzemelerin özellikleriyle bağdaştırılmıştır.

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Anahtar Kelimeler: Döküm, Konuşlandırılabilir Kalıp Sistemi, Kumaş Kalıp, Kumaş Şekillendirme, Katlama

1. INTRODUCTION

The concept of craft obtains many meanings, such as an activity involving a special skill at making things with your hands (Oxford Dictionary, 2024). It is the combination of different operations to form the same products repeatedly. The inclusion of the hands is one of the prominent features encountered during the explanation of craft, whether digital or traditional. McCullough (1996) mentions the supportive and opposed relationship between technology and craft in his book, “Abstracting Craft: The Practiced Digital Hand”. Although the technology and tools advanced through the years, the use of the hand for the craftsman did not diminish but evolved into different motions that rely more on fast and small notions. The change shows how the skill and dedication of the craftsman can adapt to the technological advancements of the tools. Since the meaning of craft implies the inclusion of skill in putting something together, partnerships with technology are better than autonomous technology (McCullough, 1996). This project aims to follow this partnership with tools to benefit from the different utilization of hands in the digital environment and physical realm to perform holistic research on the casting process.

Casting using concrete or cement has been a commonly applied method in various fields of architecture and engineering since its invention. The use of rigid and planar mold structures utilizing timber or steel for the formwork during the casting process has created a norm in these fields for the concrete elements to have simple, prismatic, and uniform cross-sections (Hawkins et al. (2016). These applications lack flexibility and limit the creativity of designers while increasing production costs, duration, the material usage, and waste since these rigid molding systems are not reusable (Elmas & Alaçam, 2018). Although it is suitable for various cases, the usage of different materials as molds can enhance the flexibility and material-based design approach by making the parameters of the molding material a crucial point of the design. The usage of fabric formwork has increased due to the enhancements in synthetic production technologies and concrete pumping (Ghaib & Górski, 2001) since the early 2000s. The application of the fabric formwork allows a variety of forms with the help of the changing parameters of the fabric and poured mixture, thus preventing the system from being rigid.

Concrete casting is a dynamic process with the liquid nature of the initial phase of the mixture. The mixture adapts and follows the shape of the formwork. The use of the planar mold systems fails to reflect the properties of the compound and makes the process rigid. Regarding the issue of rigidity, it is necessary for the molding system to be supported by a structure that enables the desired form to be imparted to the fabric. While many studies focus on the flexibility of the fabric formwork through a state of form and structure generation (Kostova et. al, 2019; Popescu et al., 2021), there are few studies concentrating on the dynamic nature of fabric formwork in terms of generating variations of form through a sole reusable mold system (Akçay Kavakoğlu,2020; Baghi et.al, 2022). The proposed system of Akçay Kavakoğlu (2020)took advantage of the fabric's deformation resistance, thus preventing the need for additional materials in the production of each new product and enabling the use of the same fabric mold in the generation of multiple products. In light of these pioneering studies, more research is aimed at exploring the possible methods to enhance the flexibility of mold systems in terms of material usage, reusability, and sustainability. Deployable support systems have huge potential for incorporating dynamic molds and fabric formwork.

Deployable structures are defined as those that are capable of undergoing a change in appearance, whereby they enable transition from a larger configuration to a smaller one, typically through the process of folding. During this process, the parameters, such as geometry, material properties, and mechanical considerations, play a pivotal role in the design (Rivas-Adrover, 2015). Deployable systems are lightweight, reusable, and, most importantly, flexible structures due to their changing and evolving nature (Rivas-Adrover, 2015). Consequently, these characteristics have potential to enhance the flexibility of the fabric formwork as aforementioned. Regarding these, this study aims to elaborate dynamic mold system through a deployable fabric formwork application. Tang and Pedreschi (2015) conducted several experiments with a deployable and reconfigurable fabric formwork system to produce concrete grid shells. These applications proved feasible and flexible by reusing the same deployable mold for the rapid creation of products with different sizes, compared to the rigid formworks (Tang & Pedreschi, 2015). To that end, exploring the related literature is essential to understanding the existing practices and applications in the field of fabric formwork and dynamic mold systems.

2. LITERATURE REVIEW

This paper initially focuses on breaking the rigidity in formwork applications while casting. Therefore, the literature review emphasizes the successful and efficient approaches to fabric usage as formwork, which emerged in the late 1800s (Hawkins et al. (2016). Veenendaal et al. (2011) provide a definition for fabric formwork as a non-rigid membrane system affected by environmental parameters and fabric type that supports fresh concrete and earth. In the planar formwork systems for concrete casting, the relationship between the mold and the mixture becomes inactive. The properties of the mix cannot affect the result of the hardened object. In the case of fabric formworks, the weight and the plasticity of the mixture are the defining features of the final shape (West, 2017). The tension created by the combination of flexible fabric with concrete, a static and rigid material that works under pressure, has potential research opportunities in terms of creativity. (Elmas & Alaçam, 2018). This new relationship allows the formwork to be more responsive to the unique properties of the casting mixture. These responsive structures results with high plasticity in construction also in terms aesthetics (West, 2017).

Beside these, fabrics offer sustainable ease in transportation and production, in addition to the robust fabrication process (Hawkins et al. 2016; Li et al., 2022). Easy transportation allows the fabric formwork system to be built off-site by professionals and sent to the construction area to be utilized without excessive knowledge (Hawkins et al. 2016). The characteristics of the fabric have been studied widely in terms of resistance and reusability, especially for providing non-sticky molds and clean concrete surfaces that emerge from the permeable surface of the fabric's ability to prevent air bubbles and increase durability (Wagiri et al., 2023; Veenendaal et al., 2011). These properties make such materials highly durable and enable the reuse and recycling of the fabrics. The production footprint can be reduced by reusing the same fabrics (Le Quéré et al., 2018).

The literature displays studies on creating forms from various materials with the help of fabric molds. O'Green and Harris (2023) created prototypes that move from the conventional planar formworks to a more flexible approach using geotextile fabric to produce nonstructural clay objects. The experiments comparing the fabric and planar formworks showed that the clay mixture hardened faster than the traditional approaches. The fabric formwork displayed smoother surfaces with fewer cracks than the conventional examples. Although the study presented in this paper benefits from the material properties to shape the fabric as mold, the emphasis is on the drying time, cracking, and shrinkage of the clay, which improved the parameters positively, rather than the rigidity issue of the planar formworks. The flexibility in the casting process of fabric formwork is studied with a wide range of materials, such as living organisms. Elbasdi and Alaçam (2019) worked on mycelium's ability to grow in a fabric formwork and aimed to create a free-form mycelium geometry. Unlike the drying process of concrete, mycelium can remain open to manipulation for a prolonged period (Elbasdi & Alaçam, 2019). Although this approach demonstrates the opportunities of the fabric formwork, this study focuses more on the concrete and cement casting process. The opportunities of the fabric formwork in terms of plasticity using concrete are displayed by Wagiri et al. (2023). In their paper, several attempts are presented using polyester with flexible properties to examine the relationship between the wet concrete and the fabric. The study demonstrates end products made from different tessellation patterns. As in the previous example, this study highlights the influence of the concrete parameters in changing the output of the casting process. Additionally, the changing patterns emphasize the level of adaptability of the fabric formwork to the changing parameters of the mold. Surface manipulations like pushing, pulling, etc., create varied expressive results (West, 2017) that enhance the interactive value.

These surface manipulations open a gate at incorporating deployable structures which can further encourage the mixture's adaptability to the mold. Kinetic structures provide complex behaviors that enhance the flexibility of the architectural elements. The implementation of new environments and tools is indispensable to display these behaviors efficiently. The concept of origami is a suitable technique that helps the architects understand such complex systems (Gönenç Sorguç et al., 2009). The folding process can easily be executed with these approaches and combined with the fabrics to diminish rigidity in casting.

Akçay Kavakoğlu (2020) proposes a different dynamic molding system combining folding fabrics with origami understanding called Fabrigami. Unlike origami, which is based on folding, fabrigami needs more hinge operations and anchor points (Akçay Kavakoğlu, 2020). This approach creates a system that works like deployable structures that further improve the flexibility of the molding. The paper also highlights the importance of the feedback loops between the digital environments and the physical products for material reduction and sustainability purposes. The result of this technique can be both predicted and uncertain (Akçay Kavakoğlu, 2020) at the same time. In order to minimize production costs, time, and waste caused by uncertainty, digital simulations help predict the behavior of the materials by taking real-world parameters into account. The results of the simulations operate as both output and input in this system, thus helping to create a holistic study (Elmas, Alaçam, 2018) that contributes to the collaboration between hand and computational tools. Therefore, a comparison between digital and physical products is needed to establish a complementary relationship based on feedback to evaluate the accuracy of the models during each step of the design phase.

3. METHODOLOGY

The literature indicates that the studies utilizing fabric formwork have proven benefits for casting activities in terms of flexibility, sustainability and reusability. Consequently, the objective of this research is to utilize diverse casting patterns and elucidate the interrelationship between the digital environment and the physical casting process to understand the complex nature of the dynamic fold combined with fabric. Based upon Akçay Kavakoğlu's (2020) dynamic mold system proposal, the methodology of the study is constructed accordingly and represented below (Figure 1) and stated as follows: The initial phase of the study is designated as the pattern selection stage. In this stage of the study, a crease pattern for the creation of a foldable origami pattern is selected, and the parameters that render the pattern suitable for the casting process are elucidated. The second stage of the study outlines the process of creating the crease pattern in a digital environment and the subsequent simulations. The Rhino7 and Grasshopper environments are employed for these applications. Once the pattern has been created, the adjustments are made to perform a folding simulation. The Crane plug-in for Grasshopper is used, as the extension is specifically designed for folding simulations. As the objective of the study is to develop a dynamic formwork system utilizing fabric, the model was further adapted to be used with the Kangaroo plug-in. The extension was selected due to its ability to perform cloth simulations according to the loads, which are similar to a casting process. The fabric mold studies of contemporary fabric pioneer West are conducted primarily through making and prototyping, which allowed for the detailed evaluation of structural forms and formwork that utilized a variety of fabric types and methods (Manelius, 2012). Consequently, the third stage is the assembly of the physical model, which should reflect the behavior of its digital counterpart. This section presents the material selection for the deployable system and the fabric parameters. This stage also encompasses the casting process. The section consists of a series of casting experiments, in which the parameters of the mixture, fabric, etc. are varied to examine the differences between the end products. Once the final products have been created, they are scanned using photogrammetry method. These approaches permit a comparison between the digital and the physical models in terms of accuracy. In the final stage of the process, the future studies are discussed, and several designs are established, including panel combinations and microstructure examples.

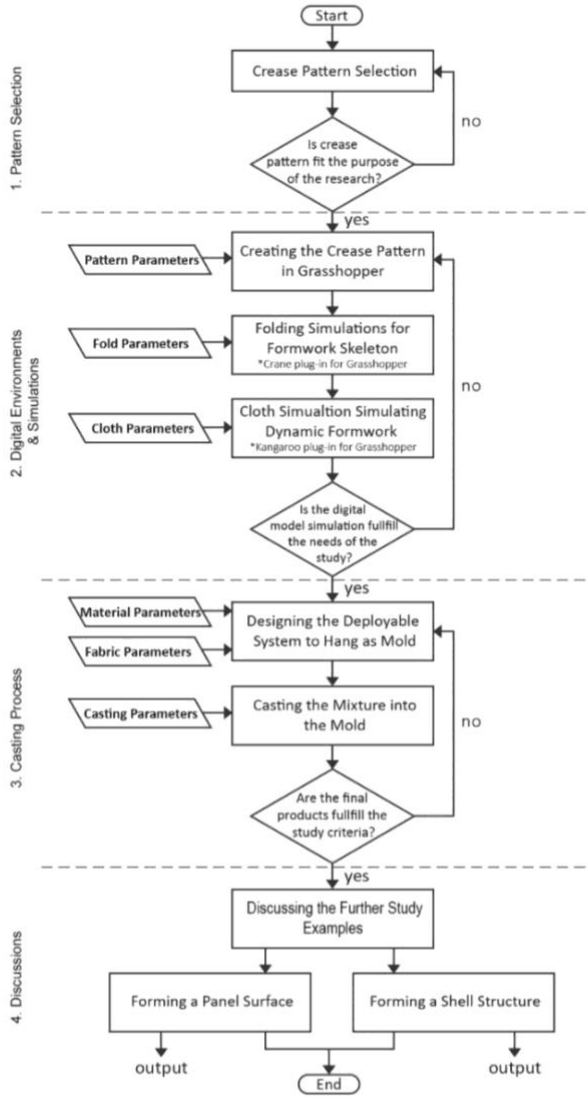

Figure 1: Methodology of the Study.

3.1 Design Process

3.1.1 Crease Pattern Selection

The reusability of the system without experiencing disruption or breakdown is one of the most important parameters for the selection. The motion of opening and closing with folding eliminates the risk of system failure and allows the system to be used in long-term operations (Çavuş & Gönenç Sorguç, 2023). The folding pattern selection is made according to the potential depth creation for supporting the casting mixture without any additional elements. In terms of aesthetics, the dynamic qualities of the pattern surfaces are aimed to be maximized. Therefore, during the folding process, the vertical movement of the pressure points on opposite sides is aimed to be achieved and the solid void relationship of the product's surface is highlighted, as observed in **Figure 2**.

2D representation of crease pattern shown in **Figure 3** which is found suitable based on the given criteria. This type of pattern is created by rotating a single unit from the bottom right corner point three times. The resulting rotation composes a pattern that consists of two squares, one of which is reduced by half towards the center, and lines going from its center to all corners and midpoints of all edges. Through this process, seventeen pressure points are created from the intersections of the folding lines. These movement axes of these pressure points provide the intended depth and interior movement according to the mountain and valley line analysis **(Figure 4)**.

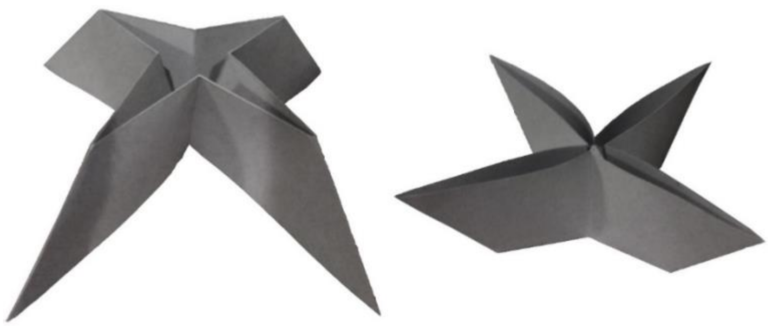

Figure 2: Folded pattern using paper and cardboard. (Photograph by the authors)

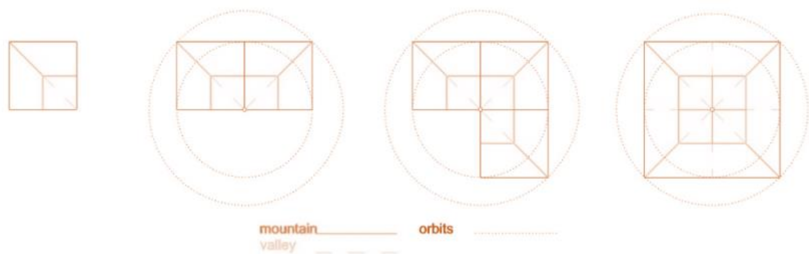

Figure 3: Formation steps of the crease pattern.

3.1.2 Digital Creation of the Pattern

The visual programming medium (Grasshopper) is used for generating the computational model of the selected crease pattern. In the previous section, the formation steps of the selected pattern are explained using a deductive method. In contrast, the computational process follows an inductive procedure that originates from a 20x20 square. The square is copied and scaled by 0.5 to the center and each square is divided into eight equal segments covering the corner and middle points. Each point is connected with the center in a straight line to achieve the crease pattern. The produced lines are grouped according to their folding behavior to work as input valley, mountain, or boundary lines for the folding stage.

The folding is achieved using a Grasshopper add-on Crane. For the first step, a 20x20 mesh square is created from the boundary as a base for the pattern. The Crane folding solver obtains the data for the folding mesh and the crease lines to perform the folding simulation. Therefore, each face of the mesh is individually defined to allow their movement. These surfaces are created by including all crease lines as cutting elements. Once the original mesh is divided into sixteen pieces and welded, the crease lines are grouped according to their folding directions as Mountain and Valley Lines. In the figure below (**Figure 4**), the Mountain lines are represented with continuous lines, and the valley lines with dashed ones. Mountain lines make the adjacent surfaces move in the negative Z-axis, while the Valley lines allow the movement in the axis (**Figure 5**).

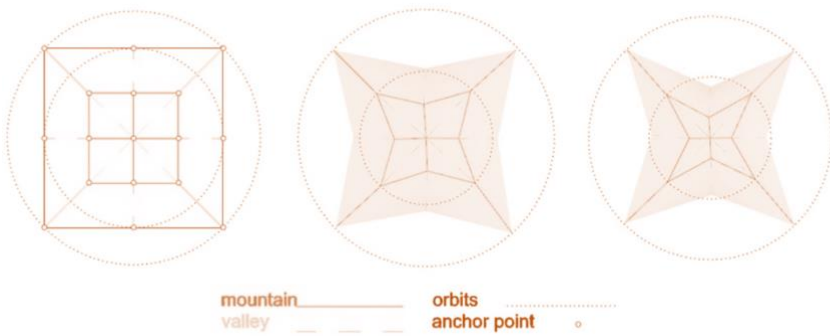

Figure 4: The pressure points of the crease pattern and folding behaviour.

One of the constraints of the Crane tool is that it works with speed while folding the structure rather than direct angles. So, the folding angle is determined by the speed of folding during the amount of time which the simulation is running. Therefore, it is possible to measure the level of folding from these inputs according to the set speed.

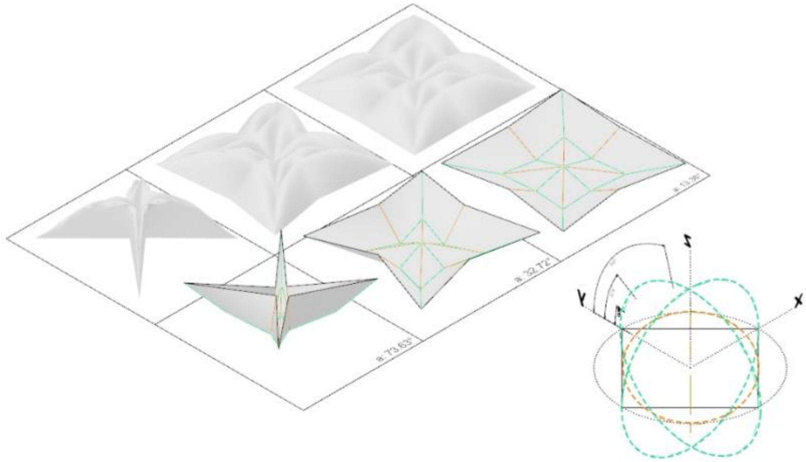

Figure 5: The folding angles of the simulations and the cloth simulations.

In the next stage, since the study focuses on the fabric formwork, the fabric behavior under the mixture load is aimed to be simulated with the help of the Kangaroo plug-in. To achieve the digital models in **Figure 5**, the vertice amount of each folded mesh face is increased using the Weaverbird add-on. The load of the mixture is applied to each vertex, and the length factors are identified approximately as the fabric stretching value. Before the simulation, vertex points intersecting with the crease lines are used as anchor points since the deployable skeleton will limit the stretching of the fabric in those regions.

3.1.3 Deployable Fabric Formwork Construction

In the previous section, the pressure points of the pattern are analyzed to understand the folding dynamics of the system. In the formwork stage, these pressure points are used as the base for constructing the deployable system. Seventeen points are grouped according to the number of lines that are connected to each point (**Figure 6**). After that, the required connection types are analyzed, and the material search is started. The material selection is based on the flexibility of the material and the ability to fold and stay in the desired position (**Figure 7**).

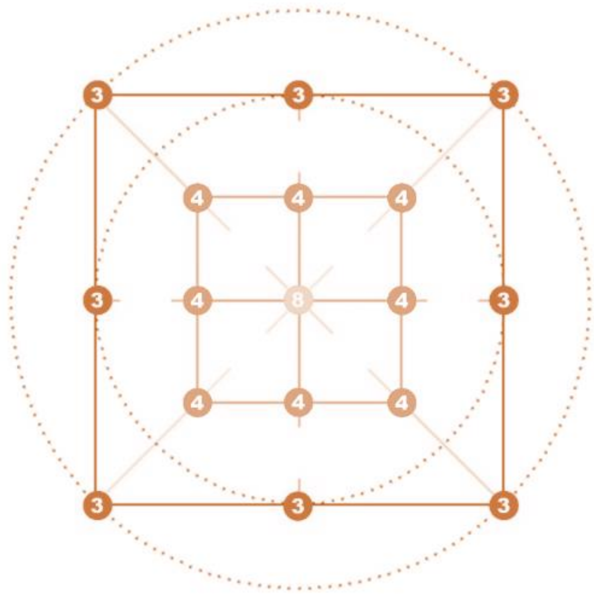

Figure 6: Grouping of the pressure points based on the amount of connections.

Based on the defined criteria, a 1:1 prototype of one of the pressure points is designed consisting of the two exact elements. In the first stage, plastic straws and rods are experimented with. The cylindrical straw is cut into 5 centimeters, and 5-millimeter rods are inserted from both sides. During this process, these rods are prevented from touching, and a 1 cm gap was left in the middle of the straw to allow folding in XZ axis. The rods, whose locations were determined, were fixed to the correct places with the help of paper tape to explore the folding behavior. It is examined that the usage of straw presents the desired folding movement with the folding force but returns to its initial form after the force concludes. Therefore, an additional element is introduced to make the unit remain stable, which is wire. The wire changes its form with the applied force and provides the crucial strength to keep the straw constant at the desired angle. The material properties of the plastic straw allowed the system to be flexible in various directions apart from its main folding axis. Another advantage of this technique is that the straw has a structure that can be easily pierced. Holes are created in the middle of each element, and identical elements are connected through the holes, as shown in the second step of **Figure 8**. This approach allowed the joints to perform folding behavior in two directions, benefiting from the material properties of the straw. By pursuing this process, a pressure point connecting four lines is created and replicated for the whole pattern except for the center of the pattern. A similar procedure was followed in the second group of pressure points but only used to connect three rods. The remaining excess connection was left empty to make it easier to remove the mold during the casting stage. The connection on the middle point is left to unravel while preparing the fabric joints. The step-by-step explanation is presented below (**Figure 8**).

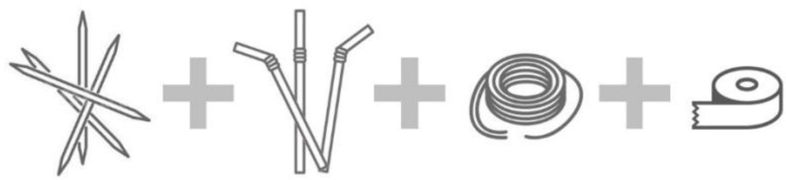

Figure 7: Deployable system materials.

The selection of the plastic allows the system to be folded several times without any deformation. The system can also reuse the waste straw to create this molding unit. The advantage of using the tape is the easy fixing of the mistakes or deformations without breaking the whole system. The usage of accessible materials makes this system easy to build and replicate when faster production is required. As a whole, each of these elements has a level of flexibility that allows this system to be easily deployed.

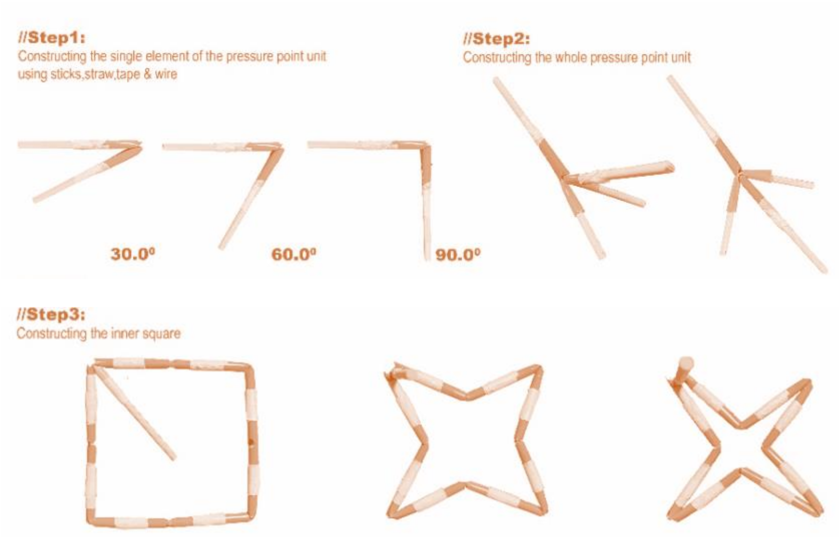

Figure 8: Construction steps of the deployable skeleton structure.
(Photograph by the authors).

In the later stage, the flexibility of the system is aimed to be protected. So, the application of the fabric surface needs to allow movement and not be tightly fixed. Since the structure deals with the use of fabric, sewing is considered an appropriate technique to combine the skeleton and the fabric (**Figure 9**). The skeleton is placed on the fabric, and the location of the sticks is traced with a little offset to allow flexibility. Small flaps are produced for each stick to get in these locations, allowing the fabric to work together with the deployable system. On the center point, it is necessary to create a connection detail for eight rods. Since the straw technique used at other points only allowed four sticks to join, a new solution is considered for that region. The endpoints of each stick are sewn onto the center of the fabric. This way, the eight rods worked together to ensure the correct operation of the folding system (**Figure 10**).

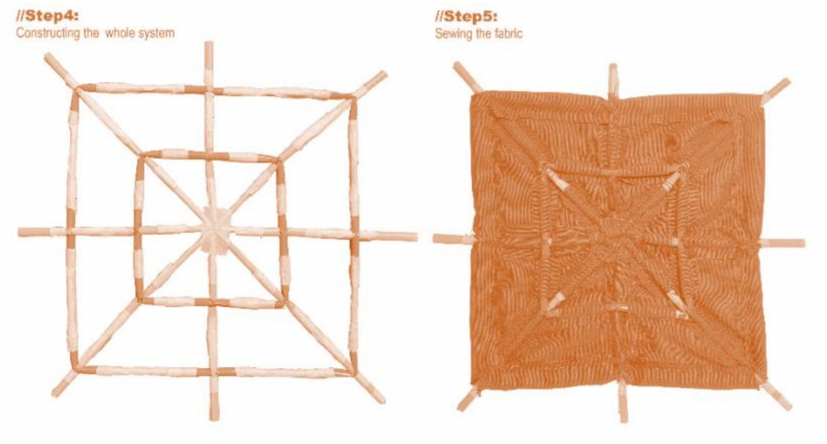

Figure 9: Construction steps of the deployable skeleton structure and sewing. (Photograph by the authors)

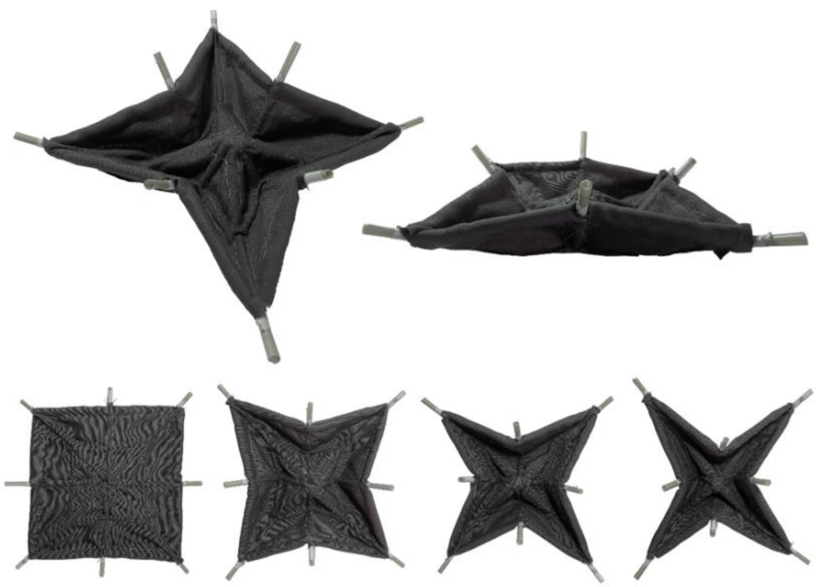

Figure 10: Deployable system with a fabric surface. (Photograph by the authors)

Gravity-induced parameters play a major role in determining the final shape of the output product. Utilizing fabric for the mold surface helps create a dynamic system. This dynamic system differs from traditional formwork approaches by changing its form in relation to the parameters of environment, mixture, and mold components. The aim is to improve the surface deformation caused by gravity in the final product by stretching the selected fabric. Several attempts have been made to determine the fabric type that fits this purpose. Hawkins et al. (2016) mention that woven fabrics are preferred for formwork examinations to benefit from their availability, cost, surface qualities, and durability since the study aims to reuse the same fabric for multiple creations. The first test is conducted with the duck fabric, which consists of cotton and polyester. This material is selected since it can support the weight of the casting material due to its thickness and leak less liquid after the material is cast. Although these features prevent wrinkling, one disadvantage is that this type of fabric has a slight stretch value, and the effects of the gravity-related are minimal. Thus, it defeats the purpose of using fabric as a mold. Therefore, as a second attempt, the same structure is recreated using the combed cotton fabric. This fabric type can stretch more than the duck fabric due to its thinner surface properties and perform surface deformations more clearly than the previous selection. Therefore, wrinkling behavior is ignored in this study since it is difficult to predict in material simulations.

The folding behavior under gravity is aimed to be reflected in the digital environment. Figure 11 represents the digital folding sequence using the Kangaroo plugin. This plugin allows the user to reflect the loads of the physical environment to the computational model but fails to include data on gravity and material. Therefore, the mathematical calculations regarding the load of the mixture under gravity or fabric's stretching values, instead, a realistic representation is achieved. The surface of the computational model is divided into points, and the points corresponding to the deployable skeleton are entered as the anchor points. On the other hand, a load is assigned to the remaining points to represent the load of gravity.

Figure 11: Digital folding process of the deployable system.

The last stage before casting is the production of a hanging system for the deployable structure to operate and maximize the stretching using gravity. The deployable system is located inside of a rectangular skeleton. Operational axes covering different lines are created in two layers of this box. When the deployable system is placed inside the box, the points will operate in the corresponding axes, shown in the diagram below (**Figure 12**). Each marked point is tied to the related axes to achieve this relationship (**Figure 13**). The formwork system is tightly connected to the axis on the upper layer with the help of a rope so as not to hinder the movement of the cube. The ropes are connected to the four pressure points at the corners of the folding pattern and help the system fold when the ropes are pulled to the center (**Figure 14**). The folding angles of the physical mold are prepared in accordance with the digital simulations.

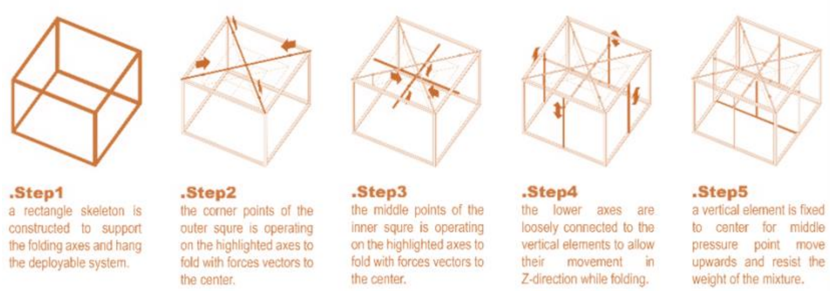

Figure 12: Steps of the hanging system design.

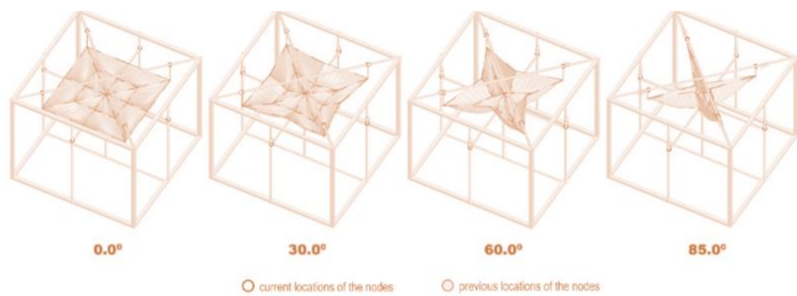

Figure 13: Digital folding hanging deployable system.

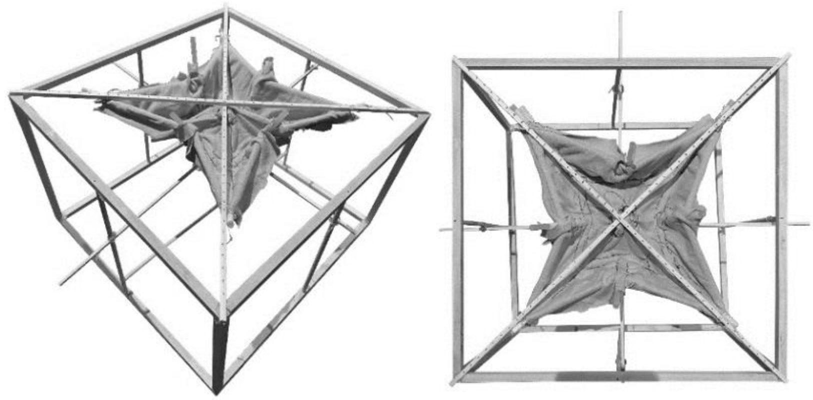

Figure 14: Constructed deployable mould system (Photographed by the authors)

3.2 Casting Process

The previous section mentioned the deployable structure configuration using two different fabrics. In this section, a casting process is conducted using these structures to analyze their behavior further and obtain physical outputs. In the first experiment, the system with duck fabric is selected, and the casting is performed without hanging the system. The first attempt serves as an experiment at understanding the casting process. Although it is not fit for the criteria of this study, a cling wrap is utilized only for the first trial, since the focus is the understand the requirements of the casting process. Cling wrap is applied to the surface of the deployable structure after the desired folding angle is achieved and protect the fabric from any deformation of the liquid material.

White cement is selected as the casting material. In the first experiment, a mixture of 650g white cement and 0.5l water (1.3/1.0 ratio) was used (**Figure 15**). The cling wrap helped the cured cement to be removed easily from the mold without any fractures. Due to the smooth surface of the wrapped surface, the texture of the fabric did not affect the cement surface and remained smooth, the same as the bottom part of the cast form. Also, the cling wrap helped the mold remain reusable without any deflections. The water leakage and absorption were prevented, since the fabric's surface did not touch the mixture. Thus, the fabric is not deformed, and the mixture ratio was not affected during the hardening. On the other hand, these properties made the solidification process longer, blocking the porous properties of the fabric. The mixture had to stay in the mold for 22 hours. One of the issues that did not meet the required conditions was the holes on the surface of the finished product caused by not shaking the mixture to remove air bubbles after it was cast. Additionally, the usage of thick duck fabric caused sharp wrinkles and less stretching from the desired shape.

Figure 15: Casted products photos and details of the first attempt.
(Photograph by the authors)

The second experiment is conducted with the same mixture ratio, but the technique and fabric are changed (**Figure 16**). As of this experiment the use of cling wrap has been eliminated. This experiment aimed to create a product using the combed cotton fabric without the need for a wrap. Still, a protective layer using potash soap is applied to the fabric's surface to allow easy removal of the finished product (**Figure 17**). The water in the mixture is able to get absorbed and leak due to the direct contact between the mixture and the fabric, thus the drying time is shortened from 22 to 13 hours. Although the same mixture ratio is used, the fabric absorbs and leaks water after the mixture is poured. Therefore, the adjacent surfaces become less humid during the first 5 minutes of the pouring process. The soap works while removing the product from the mold efficiently. In this experiment, the cement obtained the surface characteristics of the fabric and the soap and had a texture different from the bottom surface. Due to the color of the soap, the finished product had a slightly colored surface. After the model was removed, the mold was ready to be used again once its cleaned, thus proving reusability without any additional surfaces. The number of surface holes is reduced in this experiment by shaking the casted mixture. The combed cotton fabric proved more suitable for this study than duck fabric since it is possible to provide the desired shape with its high stretch value and continued in the other experiments.

Figure 16: Casted products photos and details of the second attempt. (Photograph by the authors)

Figure 17: The fabric surface before (with soap) and after the casting process. (Photograph by the authors)

The following three experiments are conducted with the same techniques as the previous attempts (combed cotton fabric, soap) (**Figure 18**). The same fabric of the second experiment is reused in each subsequent attempt and no extra fabric was needed. The mixture ratio is changed to 1.5/1.0 with 750g white cement to allow more stretching by benefiting from the load. For each experiment, the mixture stayed in the mold for the same amount of time, 13 hours. In each following example, the center points aimed to have a deeper configuration to examine certain levels of asymmetry. After these experiments, it was seen that the water leakage caused the paper tapes to be deformed and allowed the sticks to move. Thus, by creating uneven surfaces, the middle protrusion causes a thin cement layer that can be cracked during mold removal.

Figure 18: Casted products photos and details of the third, fourth and fifth attempts. (Photograph by the authors)

The connections in the pressure points are fixed, and the last experiment is conducted with the same fabric. For this experiment, the center point is left less pressured to allow more stretching in the middle. The same proportion and techniques were used as in the previous experiment (combed cotton fabric, soap, 1.5/1.0 ratio). Since the sixth attempt is the last experiment performed for this study, the mixture stayed in the mold for 22 hours to examine the effects of the time parameter by leaving the concrete in the mold for an extended period. In terms of surface quality, the last experiment gave the best results, and the fabric is still usable if additional experiments are needed (**Figure 19**).

Figure 19: Casted products photos and details of the sixth attempt. (Photograph by the authors)

4. FINDINGS

There is a total of 6 casting attempts during the course of the study, which is visualized in the chart below **(Table 1.)**.

Table 1: Matrix of all the products.

	Mixture Ratio	Fabric Type	Time in the Mold	Technique	Additional Layer	Results Top View / Perspective View / Surface Detail
Prototype 1	650g White Cement 0.5lt Water	Duck Fabric	22h	Without Hanging	Cling Wrap	
Prototype 2	650g White Cement 0.5lt Water	Combed Cotton Fabric	13h	With Hanging	Potash Soup	
Prototype 3	750g White Cement 0.5lt Water	Combed Cotton Fabric	13h	With Hanging	Potash Soup	
Prototype 4	750g White Cement 0.5lt Water	Combed Cotton Fabric	13h	With Hanging	Potash Soup	
Prototype 5	750g White Cement 0.5lt Water	Combed Cotton Fabric	13h	With Hanging	Potash Soup	
Prototype 6	750g White Cement 0.5lt Water	Combed Cotton Fabric	22h	With Hanging	Potash Soup	

4.1 Comparing the Physical Model to Computational Model

Hawkins et al. (2016) suggest that after the form-finding stages, an assessment between model geometries manually or using technologies such as 3D scanning and photogrammetry should be made. The table above displayed the properties of the models and created a criterion focusing on material usage, type, time, and texture to select the optimal variant for the computational comparison. For this stage, the second and sixth prototypes are considered suitable since they are successful examples in texture, shape, fabric stretching, and minimal deformation in the surface. The chosen models are photographed and scanned in the Agisoft Metashape program. This tool assembled a point cloud from colliding points of the model photos. From this point cloud, it is possible to create a mesh model containing the surface qualities of the physical model, including the textures. Also, the program visualizes the point elevations in the point cloud (**Figure 20**). Although the program did not provide any numerical data, it is possible to visualize the height and depth differences of the models through gradient colors and compare them. The point-cloud elevation demonstrates the symmetricity of the output products with a display of asymmetry by the sixth prototype. This geometry arises from the stability failure during the casting phase due to the change in mixture weight. Hence, the symmetrical distribution of the point elevations of the second prototype shows system stability. It is seen that the middle recession has a greater depth in the second prototype than in the sixth prototype due to the hanging system remaining stable under the mixture weight. Since the tension in the center is reduced, the fabric stretching is increased.

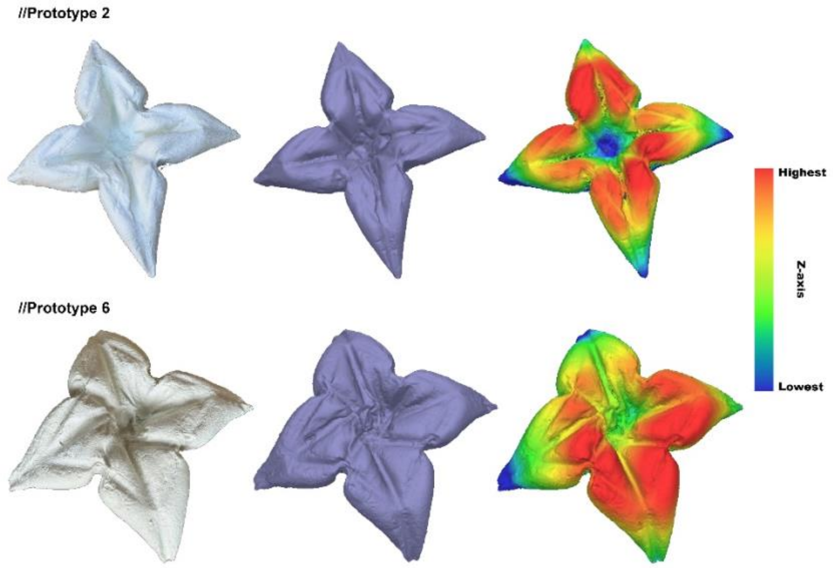

Figure 20: Metashape models using Photogrammetry technique. (Mesh-Textured, Mesh-Solid, Point Cloud-Elevation)

The scanned models are exported to the Rhino7 environment to be examined with the digital model. The figure below (**Figure 21**) shows the sections of each model passing the center. This comparison showed that the sections of the physical model differ from the physical model due to the corresponding skeleton elements not being tied to the hanging system and manipulated from the mixture load. Although the sections provide different results, the models deliver volumetric similarities. Additionally, the outlines of the top views are analyzed for each product, and the sixth prototype is examined to be a more accurate example to the digital model than the second model in terms of volume and area (**Figure 22**). This value difference is caused by material usage. In the second prototype, 650g of cement is used, and in the sixth prototype, 750g is used with the same amount of water. The resulting mixture for the sixth product provided a similar load value used in the algorithm, thus obtaining a closer volume to the digital model.

Figure 21: Sections of the digital model, prototype 2 and prototype 6 and section deflections.

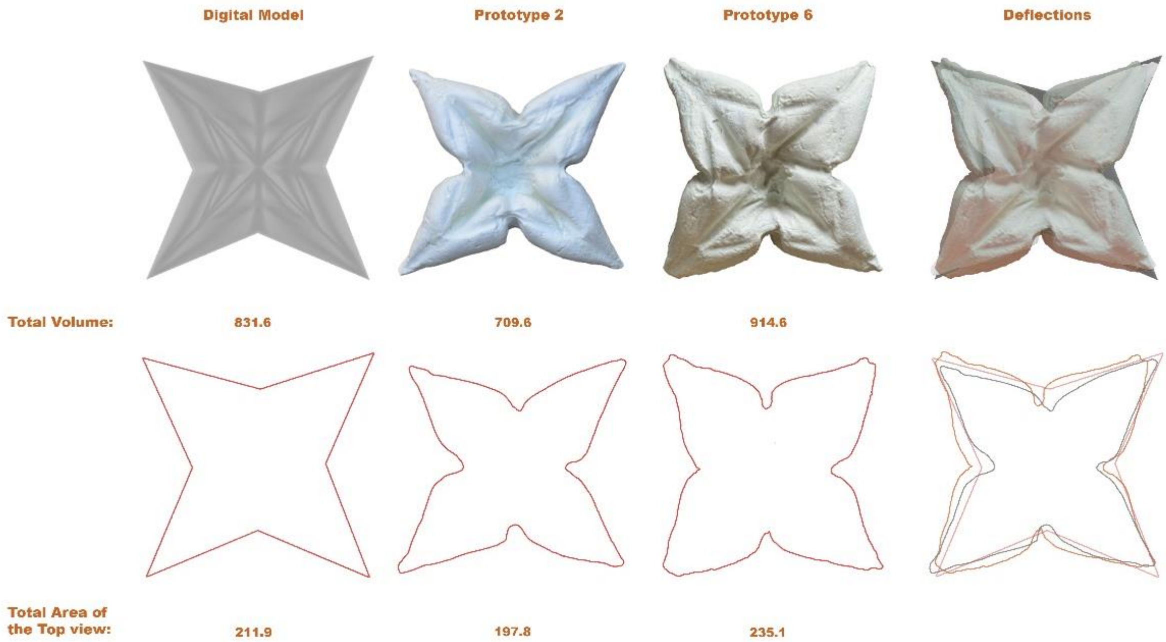

Figure 22: Volume and area comparison between the digital model, Prototype 2 and 6 and deflections between models.

4.2. Exploring the Modular Potential of the Products

After the experimentation period with physical models is concluded, the architectural potentials of the mold units are explored in this section. In this study, fabric formwork is used only for producing a single unit, but the modular nature of the system allows the mold to operate together with numerous units. The modularity of the formwork design holds the potential to create architectural systems, such as wall panels, shading elements, and shell structures. Concrete shell structures are material efficient structural systems, and the usage of fabric formwork eliminates the disadvantages caused by traditional mold examples like cost and structural limits (Tang & Pedreschi, 2015). Within the scope of this study, a preliminary study was presented on the methods of connecting the produced elements to work as an interdependent system.

Three examples are created for the modular system by placing the units into 2D grid and diamond pattern formations. As seen in **Figure 23** the first configuration failed to perform meaningful connections by providing weaker connection points. Therefore, an angular approach is proposed using the same grid pattern, and a third configuration is obtained (**Figure 23**). It is examined that the connection methods of the second and third configurations offer a stronger connection that holds the potential to build a deployable mold system consisting of several units. The presented usage of such a system with multiple units offers many form variations by adding new parameters to the system, such as the number of units in the system and folding angles of each individual unit, thus improving the flexibility of the fabric formwork.

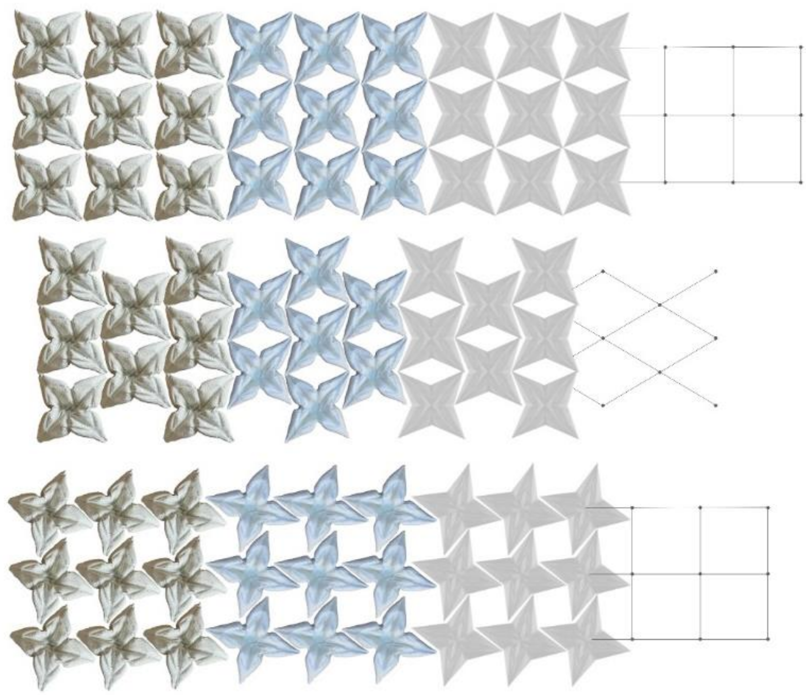

Figure 23: Deployable panel patterns grid, digital pattern, patterns using the physical model. (grid pattern, diamond pattern, grid pattern with angled units).

6. CONCLUSION

This study examines a casting process utilizing a fabric formwork, with the objective of capitalizing on the flexibility and stretching abilities of the fabric. The deployable structure is integrated with the fabric to create a dynamic mold with adjustable parameters, thereby enhancing flexibility. As a preliminary step, a crease pattern is selected as a foundation. The pattern is subjected to analysis, after which a deployable structure is created for purpose of shaping the fabric in accordance with the desired outcome. This research comprises a series of casting attempts utilizing a range of techniques, mixtures, and materials. In addition to these experiments, Grasshopper simulations are conducted using plugins such as Crane and Kangaroo for folding and simulating cloth behavior. These models are employed to assess the precision of the physical models produced based on specific parameters. Finally, this paper discusses potential applications for these cement units.

In terms of a craft standpoint, the usage of the proposed formwork enhances the inclusion of the hand in the process. While the hand applies a direct intervention by manipulating the mold to the desired direction, it also has the opportunity to affect the mold indirectly by making interventions and additions to the whole casting process (Forren, 2019). While the direct manipulations of mold form, such as geometry selection and deployment angles directly influence the product, the indirect factors that determine the final geometry are influenced by the designer. Applying the mixture transforms the system into a kinetic formation until the concrete reaches its drying point. The system moves and changes with the indirect factors defined by the designers, such as the weight of the mixture according to the mixture ratio, application speed of the mixture, and demolding time.

This project highlights the interconnected relationship between digital mediums and the craft adapted to technological improvements. In the light of the advancements, the role of the hand is not diminished during the craft process but evolved into the development of new methodologies. The utilization of digital mediums helped the craftsman understand complex systems with several parameters, in the case of the study, the dynamic mold.

In this research, the folding units are considered and examined as individual elements. The structural system composed of these elements does not consider the behavior of a continuous system containing a certain number of units. Future research can examine creating a dynamic fabric formwork of a structure possessing more than one unit. Therefore, the system is capable of functioning collectively and being influenced by alterations in each unit. This will provide a greater range of variations and examples of new microstructure. In this paper, the hinges and connection points are assembled from readily available materials, such as straws, tapes, sticks, and wire. Further research could be conducted to enhance the design of these elements within computational environments. Additionally, the manufacturing process could be optimized through the incorporation of digital tools such as 3D printing, thereby improving the accuracy of the final product. Consequently, the precision between the physical and digital models can be enhanced. Finally, the hanging system is designed to allow asymmetric forms for the casting, despite the project's focus on symmetric results. It is recommended that further studies be conducted to investigate the potential for extending the range of form variations. It is examined that the usage of multiple units to form a flexible mold system holds architectural potential. The system can be utilized in the creation of shading elements, with the openings between each unit reducing with folding according to the direct sunlight values based on the orientation of the building. These patterns can also be used as a wall or ceiling decoration. Future studies are also aimed at examining the possibilities in concrete shell construction using the modular mold system and comparing the efficiency of the deployable fabric formwork to the rigid mold systems.

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Conflict of Interest Statement

The manuscript is entitled "Dynamic Casting: Using Deployable Fabric Formwork" has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere.

Author Contribution

Barış Uzyıldırım: Literature Research, Digital Creation Process, Performing Digital Simulations, Formwork Construction, Performing the Casting Experiments, Writing the Manuscript Draft (50%). Ayşegül Akçay Kavakoğlu: Literature Research, Preparation of the Study Methodology, Contribution to Design, Simulation and Casting Process, Contribution to the Final Manuscript (30%).
Leman Figen Gül: Preparation of the Study Methodology, Contribution to Design, Simulation and Casting Process, Contribution to the Final Manuscript (20%)

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