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FORM DRIVEN, ADAPTIVE, AND REUSABLE TUNNEL FORMWORK FOR CUSTOMIZED MASS HOUSING

A THESIS SUBMITTED TO

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

OF

MIDDLE EAST TECHNICAL UNIVERSITY

BY

AYŞE ZEYNEP ÖZİŞ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR

THE DEGREE OF MASTER OF ARCHITECTURE

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Approval of the thesis:

FORM DRIVEN ADAPTIVE, AND REUSABLE TUNNEL FORMWORK FOR CUSTOMIZED MASS HOUSING

submitted by **AYŞE ZEYNEP ÖZİŞ** in partial fulfillment of the requirements for the degree of **Master of Science in Architecture, Middle East Technical University** by,

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ABSTRACT

FORM DRIVEN, ADAPTIVE, AND REUSABLE TUNNEL FORMWORK FOR CUSTOMIZED MASS HOUSING

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The recent developments with Industry 4.0 have been added new agendas and methodologies in the manufacturing and designing process. Although data-driven architecture became more common in practice, forms are still determining with fabrication limitations.

While these developments are changing the architectural environment, increasing population and need for accommodation are causing standardized design production, resulting in stereotyped living areas. Although conventional typologies have been changing, most of the mass housing projects remain their resemblances, and buildings are producing with the same methods.

With this thesis, novel tunnel formwork in building construction without compromising sustainability and low costs wanted to be achieved. This experiment aims to evolve tunnel formwork to have flexible and reusable features. With these features, improvement of formal qualities of mass housing is targeted.

Several experiments have been realized to obtain flexible and adjustable formwork, and results indicate that producing customized mass with adaptive and reusable tunnel formwork is promising. While form-driven features are offering precision and accuracy, reusability offers sustainability. Also, results show that these methods can evolve for larger structures to change stereotyped mass structure designs and evolve the architectural environment.

Keywords: Adaptive Formwork, Flexible Formwork, Customized Mass Housing, Tunnel Formwork, Form Driven Manufacturing

ÖZ

TOPLU KONUT TASARIMLARININ ÖZELLEŞTİRİLEBİLMESİ İÇİN FORMA DAYALI KONTROL EDİLEBİLEN, AYARLANABİLİR VE TEKRAR KULLANILABİLİR TÜNEL KALIP SİSTEMLERİ

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Endüstri 4.0 ile yeni gündemlerin ve metodolojilerin geliştiği günümüzde, üretim ve tasarım süreci oldukça değişikliğe maruz kaldı. Veri tabanlı ve form tabanlı tasarımlar mimari pratiğe eklenmesine rağmen form üretimi hala üretim metotlarının limitleri ile belirlenmeye devam ediyor.

Aynı zamanda, mimari meslek pratiği ve üretim süreçleri bu değişikliklere uyum sağlasa dahi, şehirlerdeki yükselen popülasyon ve konut ihtiyacı hız ve ekonomi isteğine yol açıyor ve bu durum dolaylı olarak standartlaşmış bir toplu konut üretimleri ile karşılaşmamıza neden oluyor. Birbirine benzer ve çevresiyle uyumsuz bu yapılar, genellikle aynı yöntemlerle üretiliyor ve yaşam alanlarının aynılaşmasına neden oluyor.

Bu tez çalışasında, tünel kalıp sistemlerine yeni bir yaklaşım sergilenmesi suretiyle; sürdürülebilirlik, ekonomi gibi majör konulardan taviz verilmeden bir tünel kalıp sistemi önerisinde bulunuluyor. Bu kalıp sistemi ile toplu konut projelerinde sıklıkla kullanılan tünel kalıp sistemlerinin dönüşümü sağlanarak, esneklik, tekrar kullanılabilirlik ve farklı tasarımlara göre ayarlanabilir bir özellik kazanmasını hedefliyor. Böylece, toplu konut projelerinin iyileşmesi, gelişmesi ve farklı tasarım alternatiflerine açık hale gelmesi amaçlanıyor.

Bu esnek ve ayarlanabilir tünel kalıp sistemini geliştirmek için kalıp sistemleri geliştirildi ve bu kalıplarla beton tasarımlar üretildi. Sonuçlardan yola çıkılarak, önerilen sistem özelleştirilebilir tasarımlar için ayarlanabilir ve yeniden kullanılabilir bir kalıp sistemi olarak umut vadettiği söylenebilir. Bu sistem, hassasiyet ve doğru sonuçlar önermekle birlikte, tekrar kullanım özelliği sayesinde sürdürebilirlik kapasitesine sahip. Sonuçlar ayrıca bu sistemin daha büyük ölçeklere uyarlanma kapasitesine sahip ve standartlaşmış tasarım sorununu çözmek açısından gelişime açık olduğunu gösteriyor.

Anahtar Kelimeler: Ayarlanabilir Kalıp Sistemleri, Esnek Kalıp Sistemleri, Özelleşmiş Toplu Konut Tasarımı, Tünel Kalıp Sistemleri, Forma Dayalı Üretim

To my patient and loving family…

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ABBREVIATIONS

3D	Three Dimensional
AM	Additive Manufacturing
CAD	Computer-Aided Drafting
CAM	Computer-Aided Manufacturing
In-Situ	In the original place, instead of being moved to another place
M5 Bolt	Metric 5 Socket Head Cap Screw: Width Across Flats is 5mm
MDF	Medium-density fibreboard. Wax, resin, binder, and wood are forming into panels by applying high temperature and pressure. Dense and durable material.
NURBS	Nonuniform rational B-splines
PVC	Polyvinyl chloride (colloquial: polyvinyl, vinyl; abbreviated: PVC) is the world's third-most widely produced synthetic plastic polymer (after polyethylene and polypropylene)
RTV2	Two-component Room Temperature Vulcanizing silicone rubber formulations
TOKİ	Toplu Konut İdaresi (Collective Housing Administration)

CHAPTER 1

INTRODUCTION AND BACKGROUND

"By slow degrees, the building sites will become industrialized, and the incorporation of machines into the building industry will lead to the introduction of standard components; house designs will change, a new economy will be established; the standard components will ensure unity of detail and unity of detail is an indispensable condition of architectural beauty… Our towns will lose the look of chaos which disfigures them today. Order will reign and the network of new roads, from an architectural point of view, will provide us with splendid views. Thanks to the machine, thanks to standard components, thanks to selectivity, a new style will assert itself."

-Le Corbusier, l'Esprit Nouveau

The evolution of technology has changed everything all around us. Today's technology, which is known as "Industry 4.0" has so many challenges. All the terms like "Artificial Intelligence, 3D printing, Machine Learning, Robotics" became widespread terms and took their places in our daily life.

While data-driven architecture is becoming common in practice, several possible uses of materials, forms, and performances are determined mainly by fabrication processes. Architecture still discusses scale, structure, system, form, design, detail, and material in this content. Architectural practice should catch Industry 4.0 and the coming 5th one in the design zone and be visible in producing it (Sorguc, Özgenel, & Kruşa, 2018).

Recreation of community and culture changed with the presence of machines and technological developments. CAD & CAM give designers a chance of more flexible and meaningful form making. With computation, architects have the ability to explore complex and more sophisticated designs. However, change in construction methods remained relatively slow, and the gap between what is designed and what is built is still a challenge.

Despite all the new technologies, production and construction are generally in orthogonal shapes with planar elements. Since the formwork itself is more complex than the final built form in many artifacts. Construction and buildings have become more and more complex, yet the requirement for a cheaper and more sustainable way of construction is always a crucial matter in today's industry.

As a common way of building, tunnel formwork and its abilities are acknowledged. Various examples can be seen, from unique customized designs to mass housing since *tunnel formwork* can provide economical solutions for the continuously increasing population in urban areas, which brings various disputable issues to the table. Also, due to its reusability feature, tunnel formworks offer sustainability because this construction method produces less waste material when compared with other formwork methods.

"The right to have a decent house" for everyone emphasizes the controversial subject of mass housing which manifests itself in dull building typologies. Although many of those mass housings are affordable, their forms, choice of materials, and details are almost the same without giving away any hint of site, context, etc., making them arguable architecture. One of the reasons for such mediocre solutions is doubtlessly the relatively low cost of construction. The other is the method of construction for which the use of concrete and tunnel formworks are common.

This thesis addresses the use of novel tunnel formworks in the realm of new technologies in building construction without giving up sustainability and achieving low construction costs. In this vein, the potentials of reusable and flexible formworks, tunnel formwork and their use in mass housing, and their adaptable and flexible features are to be explored.

1.1 Problem Statement

The need for fast housing created the “Mass Housing” term, which is a way of a standardized process of *building the same block*. That caused *stereotyped living areas* and resembled one to other buildings and a standardized architecture. While many conventional typologies are changing, most of the mass housing projects have remained the same. In order to improve the formal qualities of mass housing, from mass production to mass customized architectural production, to develop novel approaches for formwork but also adaptive and flexible ones offer many new potentials.

Today customization of large structures such as in mass housings (TOKİ examples in Turkey) is expensive, difficult to achieve with conventional technologies, and their sustainability is questionable. A part of these problems is related to material and form. Since concrete is still popular, giving form to this shapeless material will be one of the essential research topics like developing new versatile formworks that can be used vertically and horizontally on-site or in factories being adaptable and flexible.

Here it is believed that such research will contribute to achieving specialized and non-standard living places without compromising the quality, detail, and affordability. When the limits encountered in the construction of flexible designs are eliminated, it is possible to see more customized living spaces and an industry that has caught up with the era to create more innovations.

1.2 Aim and Objectives of the Research

This thesis aims to provide a flexible vertical/horizontal and reusable tunnel formwork for mass customizations. Especially in mass housing, speed and affordability are quite important, and that is why updating and transforming tunnel formwork systems are aimed. Economical and sustainable design in the production environment is targeted. The objectives of this thesis can be listed as:

- Proposing an adaptable/flexible/reusable formwork system that can be used in customized mass housing.
- To reduce the cost of construction related to the cost of formwork
- To reduce material and energy used in the construction of formworks for sustainability
- Providing integrated, flexible formwork which can stand gravity forces and making a less complicated system for smooth surfaces.

In order to achieve these objectives in this research, questions that will be answered can be listed as below:

- What are the main limitations of tunnel formwork methods to provide smooth surfaces?
- Which materials can provide both durability and flexibility for smooth surfaces while offering reusability at the same time?
- How the problems solved due to lateral forces resulted from concrete's agglomeration in the vertical settlement.
- How can digital parametric tools be integrated into form-driven flexible tunnel formwork systems?

1.3 Scope

This thesis consists of six chapters. In this chapter, the problem statement and research objectives are introduced. The Second chapter presents the literature review, which expresses the background of this research and earlier studies. The third chapter describes the material and method of research and accompanied experiments and productions. The Fourth chapter continues with the results of experiments. In the fifth chapter, the discussion of the research and recommendations and further research possibilities as a consequence of the findings will be presented. The last chapter concludes the thesis with a summary, conclusion, study limitations, and possible future works.

Table 1: Summary of the thesis and chapters is shown, as a manual of the scope

Thesis Structure				
Chapter 1 Background	Chapter 2 Literature Review	Chapter 3 Research and Design	Chapter 4 Results and Discussion	Chapter 5 Conclusion
• Architecture and Industry 4.0 Artificial Intelligence, 3D printing, Machine Learning, Robotics • Developed CAD & CAM design options Production options is not developed as well as the design tools. • Formwork Formwork is complicated than design itself. It is rigid, stable and distant • The potential of Tunnel Formwork • Mass Housing Speed production, urgent need for housing, designed spaces PROBLEM STATEMENT AIM AND OBJECTIVES SCOPE	• History of Concrete and Mass Housing Customized Mass Housing and Concrete's adaptation and relationship with complex shapes especially in larger structures. • Formwork and Complex shape relationship • Digital Fabrication Methods Formwork and AM differences. Fabric formwork and experimental 3D printed, textile used, and robotic arm used formwork studies • Flexible and Adjustable Formwork Setups	• Phase I Understanding form and Formwork • Phase II Digital Design and Controlling with numeric valued results • Phase III Concrete production with Flexible Formwork setup Vertical Concrete Production I Vertical Concrete Production II Horizontal Concrete Production	• Results Digital design to formwork Adjustments Concrete production results Formwork study results • Discussion Implications of the thesis Limitations Weakness Recommendations and practical actions for future.	• Summary of the Thesis • General Conclusions • Limitations • Possible Future Studies

CHAPTER 2

LITERATURE REVIEW

This chapter presents a research background and literature review about historical events, previous researches, and technical details. Firstly, concrete, mass housing, customization will be discussed, and historical developments of material and technologies will be summarized.

Secondly, alternative building methods and technologies will be discussed. The advantages of formwork and differentiation of methods will be presented. Also, in this part, experimental digital fabrication methods will be discussed.

Lastly, flexible formwork researches will be examined. Identifying problematic parts of previous researches and analyzing their experiments and integrated workflows are scrutinized as an essential part of this study.

2.1 History of Concrete and Mass Housing

Concrete is a fundamental and important material for the architectural and structural world. Its liquid features make it special, and that is why it can take any form with high precision and accuracy. Most importantly, concrete is one of the economical materials for many artifacts. According to the U.S. Geological Survey report, it was the most used material in the world in 2018, and about 10 billion cement is manufacturing every year. (*U.S. Geological Survey: Mineral Commodity Summaries*, 2019)

Concrete has unique features because it is liquid at the beginning. Due to its liquidity, it offers flexibility. When it dries, it becomes rugged and durable, which is essential, especially in architecture. In practice, this flexibility has certain consequences in all manufacturing methods but especially in formwork. Complexity, waste, and cost are the main problems. This caused the domination of flatforms and rigid formworks in the architectural environment. Curved geometries are mostly ignored because of the results that are mentioned above. High costs and a large amount of waste creation have not helped either. (R. Schipper, 2015). Complexity, concrete, and formwork relationship will be discussed deeper in further sections.

Compared with steel, concrete has less carbon footprint (Crow, 2008). Also, due to its composite material nature, concrete's features may differ. It is possible to make it stronger, which reduces CO_2 emission levels and may become a more sustainable material (Crow, 2008). Growing population and city life brought climate change to a significant level. Although there are certain problems in urbanization regarding sustainability and climate problems, concrete is still the best option to maintain this growth because the population is increasing and the need for rapid housing continues (Hawkins et al., 2016).

Figure 1: Mass Housing Areas in Moscow (Photographs taken from Archdaily.com)

Developing industry, transformed working conditions, urbanization, and increasing poverty level started the housing reform movement. In this vein, concrete has changed architecture. After the 2nd industrial revolution, appreciation of organizational culture and the need for efficiency in production welcome by societies. These advancements manifest themselves in mass housing concepts which also have ideological roots behind them.

In those years, functionalism and rationalism were rising as pioneer movements. Industrial production, rational plans, and structures were the terms spread as a part of rational thought. Function, form, and processes were discussed in the realm of functionalism (Melvin & Şahin, 2007). House planning was used as an experiment, and modernist houses came out as an expression of equality. The best advantage of making mass housing is cheap and fast alternatives (Borden et al., 2012).

In *Turkey*, the situation was not too different. After World War II, politics in Turkey changed, and the rapid transformation of the built environment started. Because of war, housing projects could not be improved, and the lack of a sufficient number of housings caused social problems. While urbanization was promoted, Life was expensive, and people were in need of affordable spaces. Raising prices and lack of construction material have hindered the 'novel idea' of low-cost housing, which could not be realized at that time (Baturayoğlu Yöney & Salman, 2010). This led to the idea of *social house standards*. This term has been proposed in the Second Reconstruction Congress organized by the Ministry of Reconstruction and Resettlement. The main idea was the optimization of resources and balancing of housing construction to ensure social justice and economic development. Also, standardization and optimization were believed to be achieved with this procedure.

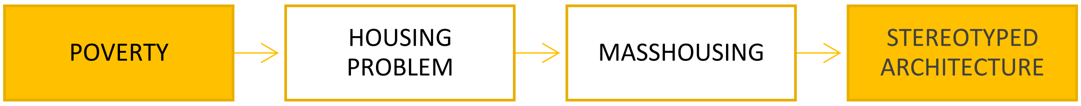
This belief led to *planned urbanization* in the 1980s. Healthy and durable building production was aimed, and the demolition of squatter areas was targeted. In 2002, TOKİ was established for this purpose (TOKİ, 2019).

TOKİ did almost the same project in every area of Turkey, where there are different climates, soils, and cultural characteristics. Also, these buildings do not have any clue of customization for residents, and many novel technologies in construction and innovations in building materials, energy systems, etc., are not integrated with most of them.

Figure 2: TOKİ Buildings (Photographs taken from TOKİ website)

All in all, TOKİ and mass housing were built for poverty, and it claims to be cheap and accessible, especially for poverty. In today's situation, these buildings have become stereotyped and impersonal.

Table 2: Poverty and slum housing have caused housing problems, and mass housing was suggested as a cheap and accessible living. This resulted in stereotyped architecture, which does not have identity and quality.



2.2 Customized Mass

Customization for users and the environment is an important issue since this problem is the origin of the architecture itself. Many architects discussed this issue in different ways. Venturi relates this problem with searching for meaning (Venturi, 1977), Le Corbusier relates form with a new aesthetic and function. In *Unite d'Habitation*, Le Corbusier fundamentally tried to explain mass housing and its relationship with individuals and society. This understanding led to the idea of adaptation of form and the shaping of the individual, society, and environment by the form itself. Also, his manifest and understanding of forms have added a new aesthetic and function to the architecture.

Figure 3: Le Corbusier / Unite d'Habitation is a significant example of Mass Housing Customization. (Photographs taken from Archdaily.com)

Later, Frei Otto, Felix Candela, Pier Luigi Nervi, Eero Saarinen, and other pioneers designed various shells and their own architectural statements. Their works brought a new perspective for shell designs and construction techniques, especially for customized mass designs. While doing that, the brand-new aesthetic perception and complex forms are also forced the formwork technologies. However, customization with formwork, especially in smooth surface designs, is still an issue independent of the size and function. Generally, producing formwork is more complicated than the form itself.

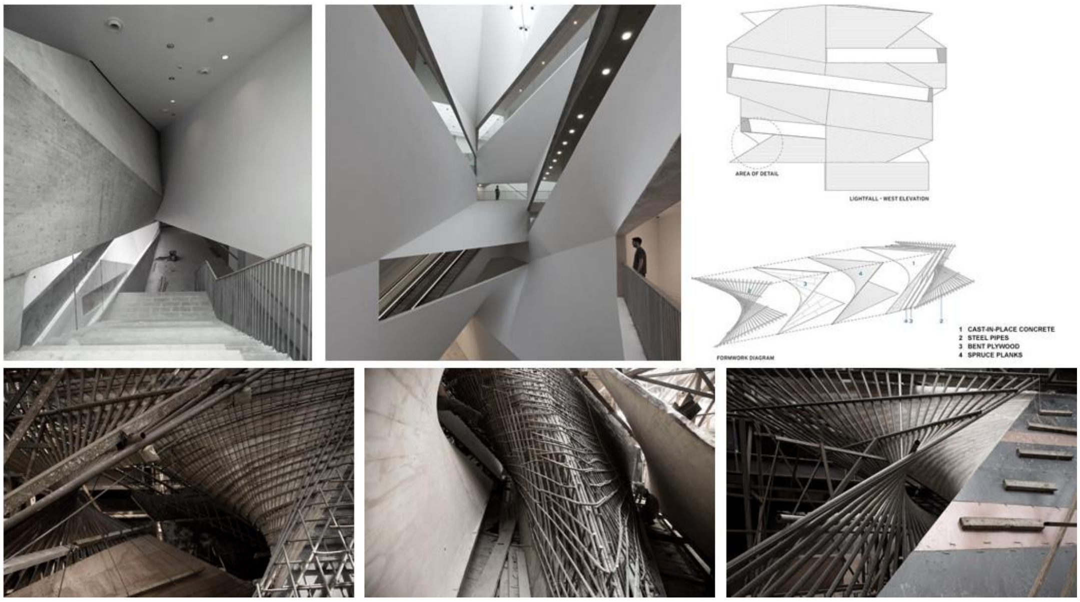


Figure 4: Tel Aviv Museum of Modern Art Photographs, Formworks, and Construction Concept Drawing. At the drawing, it is seen that formwork is complicated parts of constructions. (Photographs are taken from Preston Scott Cohen Inc. Website)

2.2.1 Formwork and Concrete Relationship

Simplifying formwork job is the main problem of this study because from small to large scale objects or structures, formwork is almost everywhere. The relationship that formwork creates with concrete is interesting since concrete is liquid material for which the formwork supports it temporarily to gain its final form.

There are several methods and different production techniques for architectural formwork. All have various features in order to cost, time, material, safety, sustainability, and quality. In Table 3, general categorization for formwork types can be seen.

Table 3: Formwork Types and Specialties (Engineering, 2016)

Simple and Conventional Formwork	System Formwork	Tunnel Formwork	Bridge & Large Structure Formwork
• Also known as "Traditional Timber Formwork" • Accessible • Not technological • Not convenient for flexible designs • Not long-lasting • Not available for large structures • The result has not smooth and flat surface • No needs for skilled labor force • Relitively cheap for local productions	• Technological and sustainable. Formwork can use several times. • Durable. Falsework material is composite and light material • Overall formwork system is light • Easy to construct • Universal • Same modules or similar modules can produce walls, columns and slabs. • Skilled labor force is needed. • Not as cheap as basic type of forwork but useful for larger constructions.	• Both walls and structures provide together • Metal formwork systems are used, and they are fast and secure • Since tunnel formwork is constructing with crab, it requires not too much work-power • The risk of failure is in minimum level • Formwork structures are easily adjustable for projects. Especially for high buildings • System is practical • Rigid system, and it is hard to generate flexible and parametrically designed projects • Cost of formwork system increases formwork cost per m^2 if project is small sized • Skilled labor force is needed compared to traditional systems • Higher equipment costs due to the crane need for each block	• Larger constructions • Unique for structure • Parts can reusable • Adjustable for another bridge or larger structures • Skilled labor force is needed. • Higher equipment costs due to the crane neccessity.

It is possible to differentiate formwork types cost-wise. For small and local structures, conventional formwork is cheap and accessible. This formwork is also known as "Timber Formwork." It is both accessible and useful for local and small size buildings. On the other hand, it requires labor, effort, and more energy. This method limits flexibility to produce smooth and complex concrete designs. Moreover, the main formwork material is wooden, and thus it is not long-lasting, avoiding its use multiple times. The conventional method is practical and cheap for small-scale concrete designs, but it is not useful when the scale and complexity increase.

Another formwork type is system formwork, and it suggests more practicality and more usability due to its plastic surface as a primary formwork material. As a result of these features, system formwork is useful for mass housing and larger-scale buildings. It may seem to be more expensive when compared with conventional formworks; however, the given details about system formwork in Table 3 show the advantages of this formwork type.

The requirement of practicality and speed in the construction of mass housing makes tunnel formwork a good candidate in such practices. Tunnel formwork forms walls and structural elements at the same time and saves time. Also, concrete dries and hardens in a day thanks to its heating system, and it becomes possible to level up faster. In this formwork method, a serious cost saving occurs because it builds in a short time, and the need for work power is relatively low.

Many factors affect the construction cost, like ready-mix concrete, cost of concrete, work power, and formwork. Among those, formwork seriously changes the overall cost ("How to Achieve Economy in the Cost of Formwork Construction?," 2019). Hence it is important to choose the proper type of formwork in relation to the targeted building types.

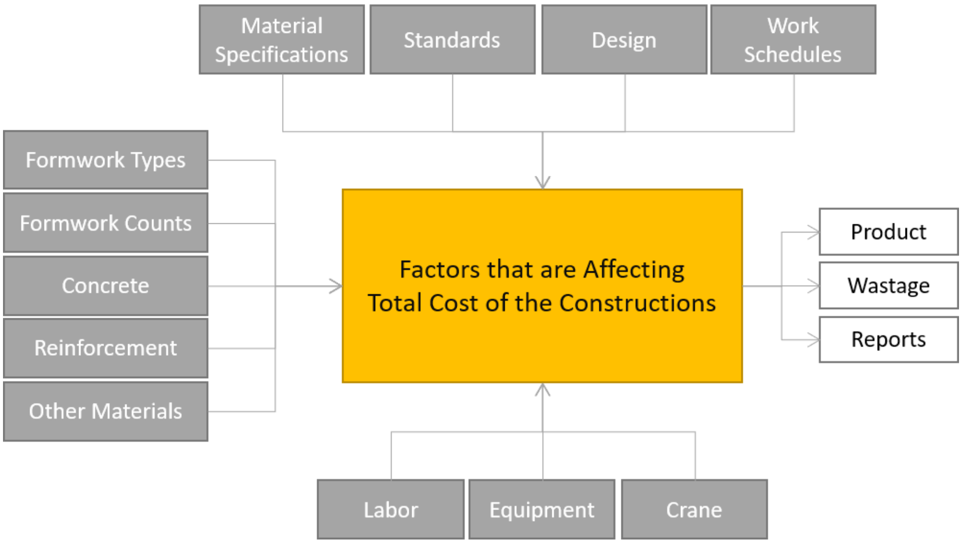
2.2.2 Formwork and Cost Relationship

The initial cost of construction is affected by different aspects and factors, as it is discussed in the previous section. Discussing these issues is essential because design and production are directly connected with cost, and generally, this problem restricts what is intended in the design.

At the beginning of the 90s, the formwork was responsible for around the %35-60 concrete structure costs (Hanna, Willenbrock, & Sanvido, 1992). However, this expenditure decreased at the end of the 2010s, and formwork became responsible for around %10 of total construction costs. This is mainly related to the technological developments of the construction industry and gained reusability feature of formwork (Lee & Ham, 2018). Also, in concrete structure costs, %45 of labor and %55 is material expanse (Türken, Yılmaz, & Erkan, 2011).

Construction may be unpredicted in cost vise because it has various entries and depends on a serious number of elements. Even the weather can change the course and cause a change in costs. However, it is possible to anticipate and foresee some details. In Table 4, the points that affect initial cost can be seen.

Table 4: Construction total cost is affected from the items shown below, table drawn by the author.



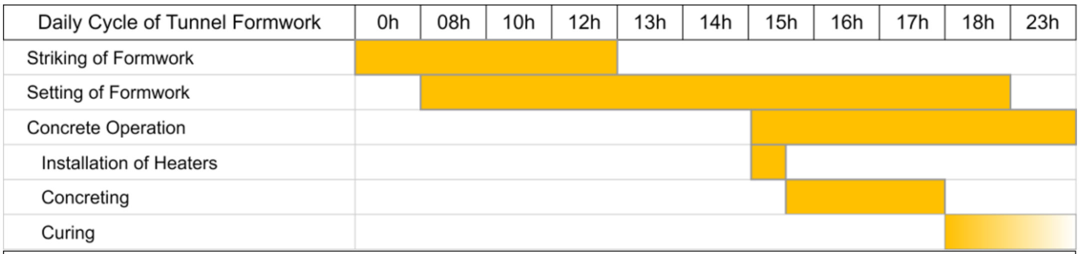
It is expected that the cost will increase in direct proportion with the number of floors. However, with tunnel formwork, this situation is the opposite. Tunnel formwork suggests a speed production method and reusability because it decreases daily spending on labor and operational costs. Tunnel formwork also reduces the construction time, which also affects overall cost positively.

Its reusable feature offers both practical and economical solutions for repetitive constructions with multiple floors (Hangarge, Waghmare, & Patil, 2017). Especially for mass housing, tunnel formwork has huge advantages because walls, columns, and beam casting produce simultaneously with it. The finishing quality that tunnel formwork offers is also better than the other formworks, which also reduces workload (Ilerisoy & Tuna, 2013). Eventually, with many more advantages like these, it decreases the overall costs and construction time.

Table 5: Tunnel formwork and conventional method comparison through detailed subjects. Drawn by the author based on the information (Chaudhary, 2017)

	Tunnel Formwork	Conventional Formwork
Floor Construct Duration	1 day to maximum 3 day	Minimum 2-3 weeks
Speed	Very High	Normal
Labor Type	Skilled	No need for skilled labor
Labor Need	5 to 12 person	Depends on the size and time necessity
Reusability	+500	Max. 15-25
Labor Cost	Higher	Minimum Wage
Additional Machinery	Crane	No need
Finishing Quality	High quality finishing	Finishing is required
Safety	Requires less safety precautions	Requires more safety preventions
Waste	Low Waste	High waste
Scrap Value	High	No scrap value
Cost Comparison	45% less	-
Time Comparison	50% less	-

Table 6: Tunnel Formwork daily cycle and some critical details for construction area per floor, the table is drawn by the author based on (MESA - TRTF, 2010)



Tunnel Formwork application which has a 450 - 500 m^2 construction area per floor.

- Formwork area : ½ floor 650m2 approx.
- Platform area : Full set for one floor
- Temperature : Approx. 20 °C in day and Approx. 5 °C at night
- Working Hours : from 06h to 18h
- Working crew : Assembly Crew (5-6 persons)
  Tunnel Formwork Crew (12 persons)
  Plumbing Crew (4 persons)
  Concrete Crew (5 persons) – might be the same people from the tunnel formwork crew

Table 5 describes the main differences between conventional and tunnel formwork methods. Especially, speed and floor construction duration change both cost and overall construction time dramatically. In Table 6, formwork phases have been described, and the schedule has been given. As it is seen, formwork arrangement and concrete operations are the most important and time-consuming phases.

As a result, construction and cost relationships depend on various factors and elements. Especially for mass housing, it suggests a cheaper and quick concrete production process and saves time. All these results make tunnel formwork quite advantageous for repetitive and larger-scale structures.

2.2.3 Formwork and Complex Concrete Forms

Since the beginning of the ’80s, the material and production processes and digital design tools have improved. However, while digital design modeling, additive manufacturing, robotics are developing, formwork, which is the most used material for concrete, stayed behind this development for several reasons (Asprone et al., 2018). Especially for the construction industry and architecture, complex forms maintain analog processes and require intensive labor limiting the exploration of complex forms, which require special efforts and results in high costs compared with the “*regular*” forms (R. Schipper et al., 2015).

Additionally, the complexity of architecture may bring the question of the “ornament” issue here. Architecture society has already been discussing this matter for a long time, and the “*complexity”* issue that comes with these parametric and digital tools only brought more questions into here. Rosenbauer says that “*Engineering when it uses materials up to their functional limits approaches the economy of nature and thereby creates forms as beautiful as the forms of nature*” (Rosenbauer, 1947). Especially, parametrically produced complex designs require state-of-the-art technologies and advanced engineering solutions to be realized.

Nevertheless, it seems like the new material research and studies are increasing, and trends have already signaled digitalization and automation in building design and construction. Both academic and industrial experts note that Digital Fabrication in construction is expanding especially in digital concrete fabrication (Wangler, Roussel, Bos, Salet, & Flatt, 2019).

William J. Mitchell, in the article "Constructing Complexity in the Digital Age," expresses those innovative applications in manufacturing technology which includes computer-aided design allowing to exceed all the limits that have been posed a long time ago. Moreover, with these developments, complexity issues in all levels, from materials to forms, from design to construction, can be handled, making it possible to react more sensitively to human requirements in construction contexts (Mitchell, 2004).

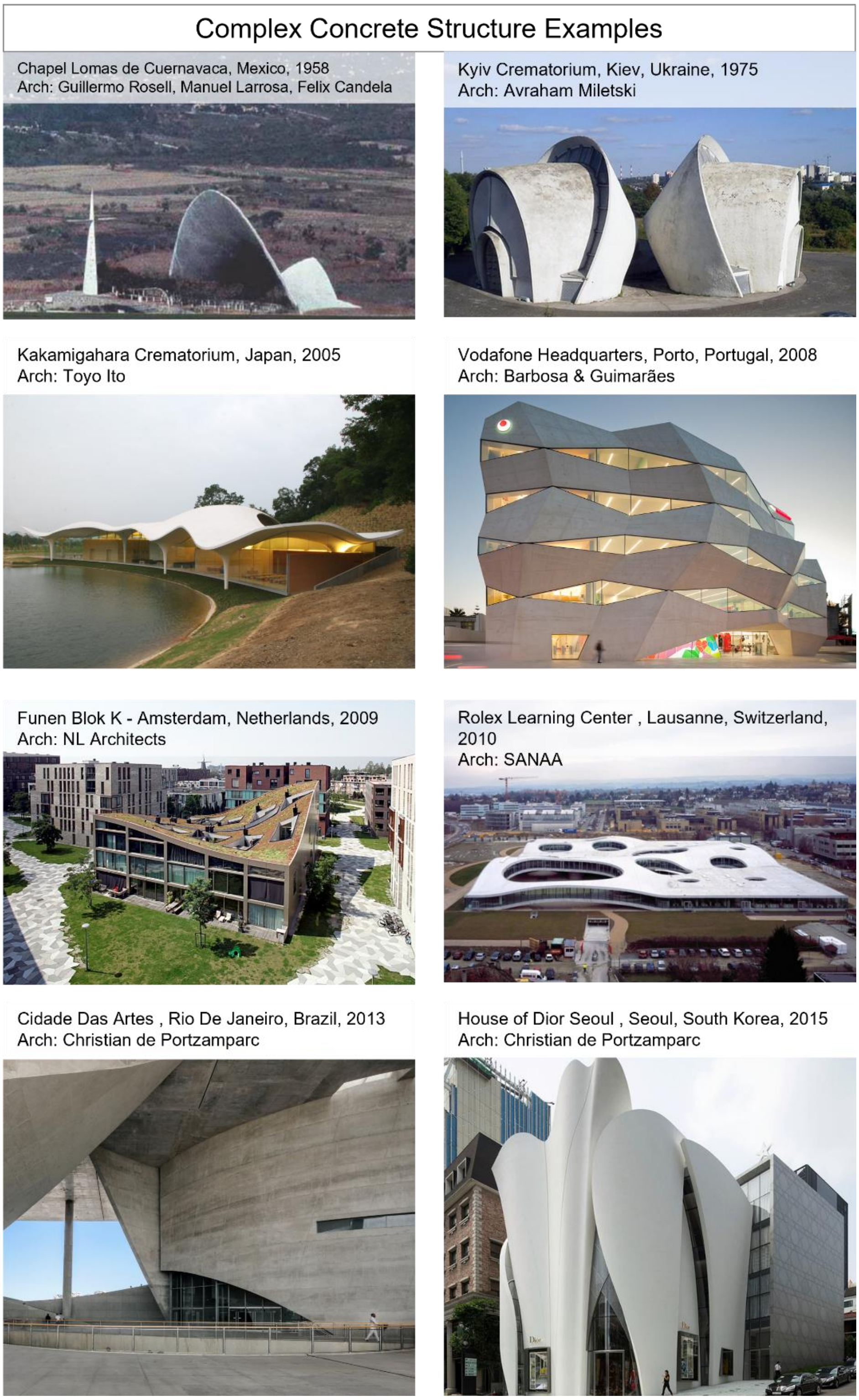
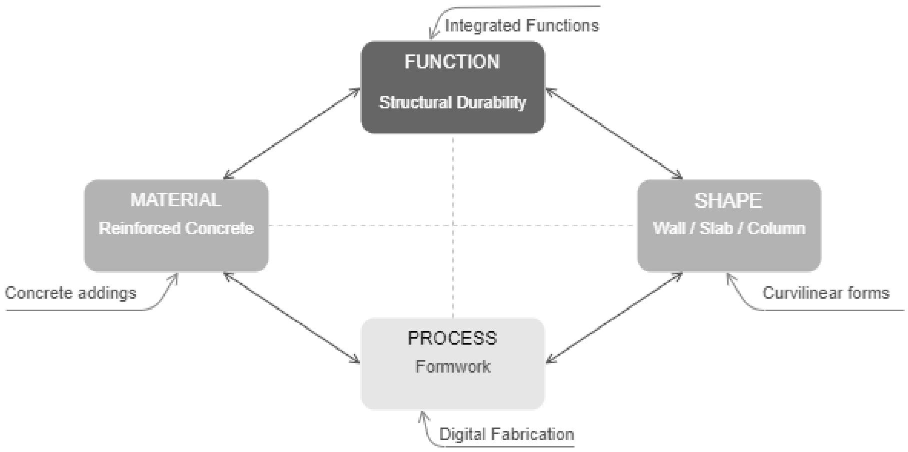


Figure 5: Some buildings which have complex designs. Produced mostly with precast method piece by piece and assembled in the construction site. (Table produced by the author and images taken from Archdaily website.)

When digital fabrication methods are compared with conventional methods, it is usually believed that digital fabrication techniques have higher costs, resulting in mostly small-scale implementations like pavilions, components, housings, or prototypes. Structural engineers are searching for designing more efficient forms in terms of materials, but “custom formwork” restricts form freedom due to their high costs. Yet, more investigation is required for more sustainable curvilinear and complex design productions to get material efficiency for formwork (Wangler et al., 2019).

Table 7: These subjects are deeply interlinked. Curvilinear forms influence several details and change both functionality and overall process (Mitchell, 2004) (Redrawn by author)



Freeform architecture mostly consists of curved forms, and here at this point, formwork becomes a severe issue. In the research of “Flexible mold for double curved precast concrete elements,” Roel Schipper has identified the theoretical concept of flexible formwork projects and proposed a flexible and reusable system. In this research, the connection between the digital model and physical implementation is the primary concern starting from the very initial phases of the design processes. (R. Schipper & Vambersky, 2010).

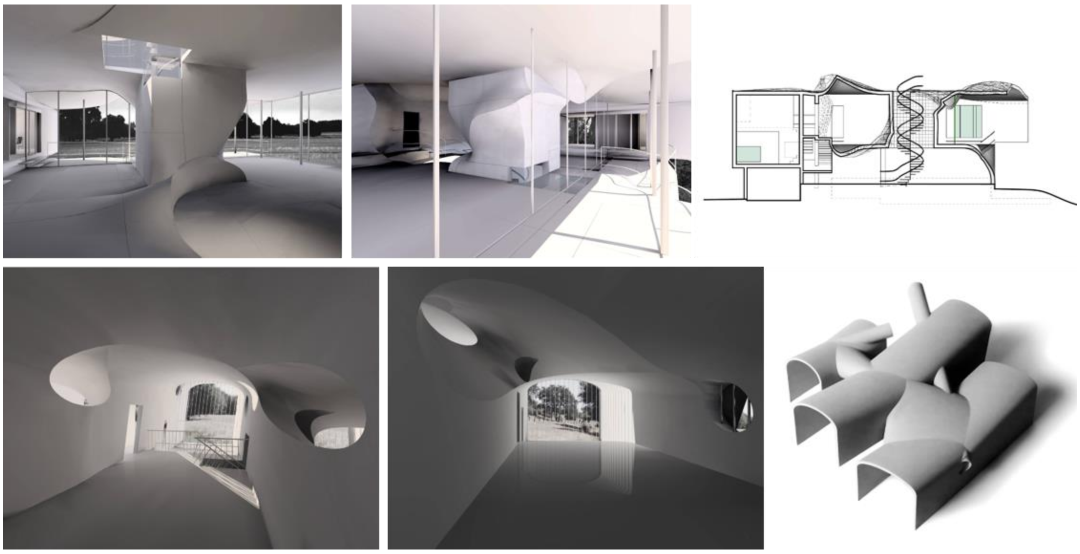
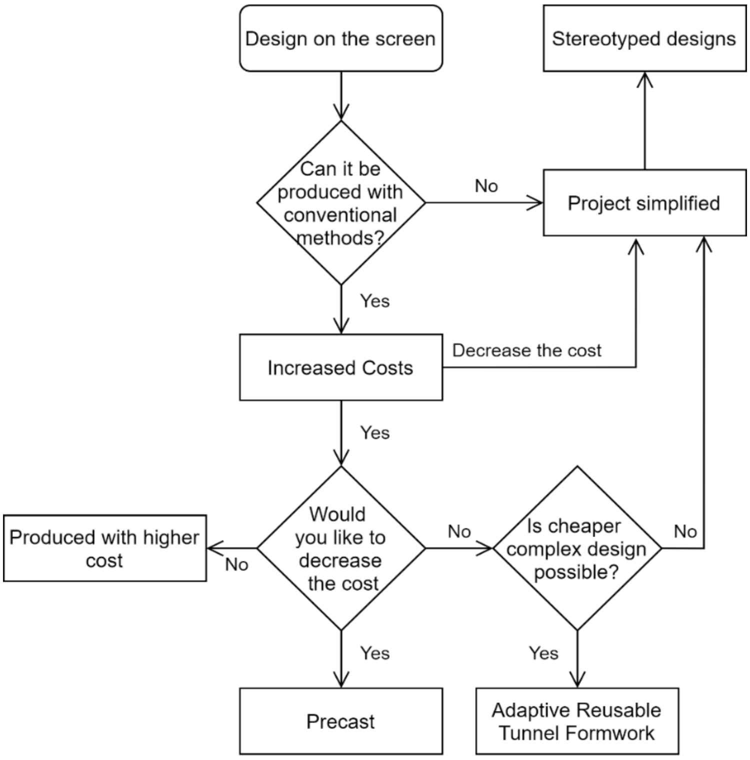


Figure 6: Preston Scott Cohen’s house designs 3D renders. Torus House (Top), Wu House (Bottom). Curvature-formed walls cannot produce with traditional production methods. (Images taken from Preston Scott Cohen Inc. Website)

Modern architecture developed a new design culture, and in terms of structural and materiality, non-standard surfaces are wanted. These wishes require some integrations in fabrication technologies and construction techniques. Geometrically complex design production is difficult and expensive (Agustí-Juan, Müller, Hack, Wangler, & Habert, 2017).

Here, the main goal is not just to produce complex or curved forms. Instead, creating designed and specialized masses are matter. Therefore, the appropriate and suitable design that the designer sees on screen and producing it better and more accessible is required for both the design and construction industry.

Table 8: Generally, design is restricted with various elements, and these restrictions cause a simplification for designs. When costs are increased, manufacturers tend to simplify things.



2.2.4 Complex Geometry vs. Reinforcement

Concrete requires reinforcement implementation to have the structural ability because the concrete does not have tensile strength. Reinforcement gives this feature to the concrete. Thus, reinforcement and concrete together offer structural mass component which has high durability and strength.

Conventional reinforcement methods are not suitable for complex designs and digital fabrication methods. Adjustments in the manufacturing process are necessary. However, in the current situation, it is not applicable. Conventional reinforcement methods need to be revised especially for larger-scale concrete component production, which has complex geometric features. Although some complex form and reinforcement systems researches have been done, these researches are generally unique for the design and not adjustable for different scales and designs (Asprone et al., 2018).

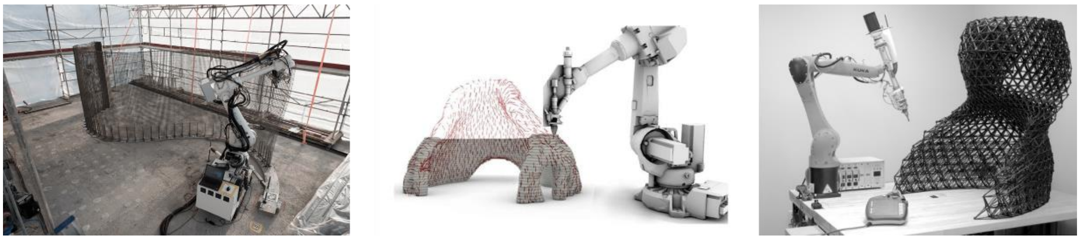
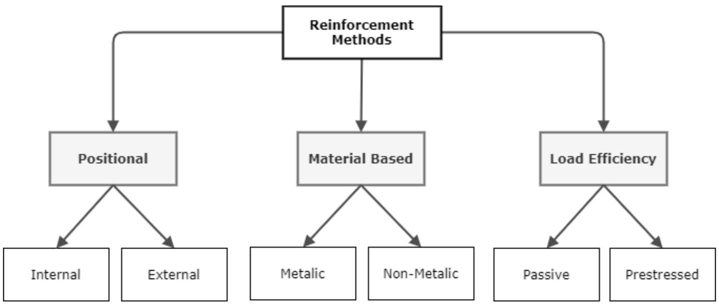


Figure 7: Robotic reinforcement application examples.

It is also possible to categorize the conventional reinforcement types. Positional reinforcement methods are internal and external, and the internal method is the most known and used technique. It is inexpensive, easy to use on-site, and durable. External, on the other hand, is arranged for the digital fabrication methods, which is wanted to use concrete without interfering with reinforcement during the digital fabrication process.

Table 9: Reinforcement categories chart. Table is drawn by the author based on the information in (Merli, Preziosi, Acampora, Lucchetti, & Petrucci, 2019)



Recently material research with reinforcement and concrete has increased. Fiber or, in other words, non-metallic reinforcement increases the tensile capacity of concrete while preserving its fluid feature. Although these material-based researches are promising, it is not possible to adjust these methods into larger-scale structural components without conventional reinforcement implementation (Wangler et al., 2019). Non-metallic reinforcement methods cannot use alone for concrete structural components in today's situation. Generally, it increases the existing structure's strength, especially for repair projects (Asprone et al., 2018).

Figure 8: Fiber reinforcement methods with concrete.

Load-based reinforcement techniques are divided into two categories. The first one is *passive reinforcement* which is mostly seen in traditional constructions. The second type is the *prestress (active) reinforcement* that is generally using for prefabricated concrete components. (Asprone et al., 2018).

Consequently, reinforced concrete is the most popular material as structural material and has different implementations to have more economical and sustainable solutions. Yet, conventional methods are not adequate for digital fabrication methods and complex designs. Suggested reinforcement involved digital fabrication methods that could not adapt for larger-scale structures.

2.2.5 Precast vs. In-Situ Concrete Production

The building industry mainly uses traditional/conventional construction methods, limiting or making it harder to build complex surface topologies. Hence, most of such building components are either precast or prefabricated and brought to the site and assembled.

Today, precast production is widely used for complex and relatively more conventional designs and gives high-quality results. However, as the complexity in the forms increases, the number of repetitive parts or diversity in the forms increases, which eventually increases the number of formworks. It is possible to achieve high-quality part production with precast concrete panels but again increased non-repetitive formwork usage, increasing the project's total cost. It has not become a versatile and eco-friendly solution technique yet as is expected. In this regard, It is important to have reusable formwork technology for both flexibility and diversity in form (Chan & Crolla, 2019)

Despite its quality and geometric flexibility, this approach has limitations too. Since the final product is on a large scale, it creates transportation problems. Until it is located in its final position, it is exposed to several assembly steps. Using precast building components may pose some problems. One of them is the scale of the precast parts. The size of such parts is limited by the size of the transportation. Also, during transportation, these parts are prone to be damaged by cracks or other severe failures, which may drastically increase the final cost.

Transportation is not the only problem in precast production. Assembling is another issue that is sensitive to workmanship during mounting requiring high precision and care to avoid damage risk.

Although the precast method is widely used for non-conventional designs and complex forms, it has problematic aspects, especially when it is compared with in-situ productions. Since in-situ production is not allowing for complex form production, manufacturers are heading for precast. Nonetheless, the possibility of complex form fabrication on-site might be better to decrease the failure, assembly, and damage risks.

2.3 Digital Fabrication Methods

This part represents a brief explanation of some digital fabrication methods and the features of these methods. Also, there will be a discussion about the advantages and disadvantages of these methods. Eventually, it will be examined in comparison with conventional formworks.

2.3.1 Additive Concrete Manufacturing and Formwork Comparison

It is clear that 3D printing technologies have evolved and affected almost every industry. Healthcare, fashion, design, casting, aviation, etc., all influenced by it, and architecture is not an exception. Additive Manufacturing (AM) evolved from rapid production and prototyping needs. With AM complex geometries, unique forms seem to be possible to create. However, it has its own limitations and features. Although it is well accepted in many fields and its use opens up many new possibilities, as in architecture, there is still a need effort to use them efficiently.

Recent studies and examples show the potentials of AM forcing to reconsider the act of concrete construction, especially the role and efficiencies of formworks. AM technologies necessitate revisiting structural systems, materials, type of reinforcements, the scale of components, even printing direction affecting the load-bearing capacity (Feng, Meng, Chen, & Ye, 2019), and many more. Concrete, with its fluidity, is one of the best and viable candidates to be used in construction by AM, as it is seen in almost all the recent implementations. The pros and cons of AM are given in Table 9.

Table 10: Negative and Positive Features of Additive Concrete Manufacturing. Table is drawn by the author.

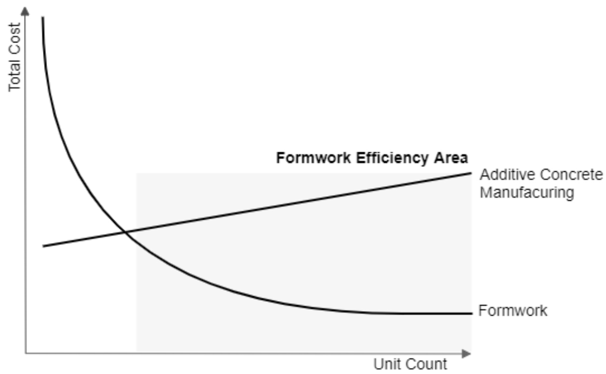
Negative and Positive Sides of Additive Concrete Manufacturing
Negative
• Requires temporary support material • Concrete's liquid specialty is not compatible with AM's nature • Pumpability is limited and fluid feature may disrupted while pouring • Layer by layer process presents slow process for larger structures • AM's transportation problem • Scale problem. Its own structure should be larger than the design. • Finishing quality is problematic • Emerging technology, details need to solve
Positive
• Fast for small scale constructions • Circular forms are easier to produce. • No need for work power • Economical for small structures

In addition to those, the size of the 3D printers that should be bigger than its product is another challenge in relation to the scale of the components ("Additive Manufacturing: Overcoming Current Limitations | International Pivot," 2018). Their size gives rise to some problems of transportation and problems in installation on the site. Also, due to its layer-by-layer process, pumping became a huge problem that needs attention because of the concrete freezing problem.

Formworks in this context have more flexibility in scale, which can be used from skyscrapers to small-scale ones. Despite the problems summarized above, it is believed that AM will reduce the cost of construction in the near future and eliminate several construction details (Holt, Edwards, Keyte, Moghaddam, & Townsend, 2019). This eventually affects the tectonics of the buildings and revises the whole construction process.

Figure 9: Additive concrete manufacturing process photographs.

Table 11: The table shows the cost change due to the unit count. In formwork, when unit count increases, the cost will fall. On the other hand, AM is not suitable for a large number of productions. The table is drawn by the author.



To sum up, today AM on-site and prefabricating major building parts is still experimental and requires more research and experiments. Rather than using them as the substitutes of the conventional/traditional technologies, how building design and construction can be evolved, the new means, how structural systems will evolve and more, should be explored.

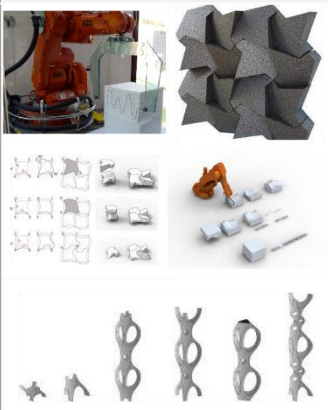
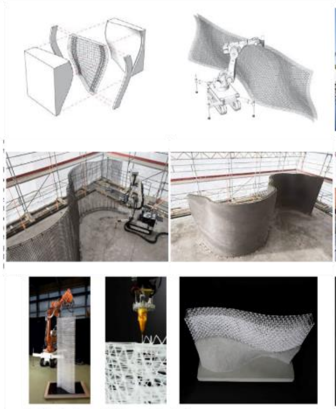
2.3.2 Experimental Formwork Studies

This section covers experimental formwork methods. Robotic formwork, fabric formwork, and adjustable formwork methods will be examined, and examples will be presented.

Robotic formwork studies in recent years have increased, and precision and flexibility with formwork concrete production are aimed. With this method, machines create some formwork that is digitally designed and fabricate the formwork. There are several studies for different methods that have been done.

Among several studies, *Mesh Mould,* developed for complex and non-standard concrete structures, is acknowledged as an important implementation. It is suitable for larger structures and complex forms together with its *reinforcement"* ability. Mesh Mould, conducted by ETH Zurich, proposes a robotic fabrication system that makes it possible to differentiate the architecture *structural design*. (Hack, Viktor L., Gramazio, & Kohler, 2014).

Table 12: Robotic formwork studies and details, table drawn by the author.

	ROBOTIC FORMWORK STUDIES		
WHAT	Robotic Fabrication of Modular Formwork	Mesh Mould	Robotic Formwork in the Mars Pavilion
WHO	Graz University of Technology 2013	ETH Zurich Gramazio Kohler Research 2014	Form Found Design 2018
FEATURES	• Formwork created with robotic arm • Can be used for both for load-bearing element and other parts • Small pieces created with robotic arms	• Reinforcement and formwork folded together • Differentiate structural design • Multiple sensing design • No human needed for structural process • Column and wall can produce	• Formwork created with robotic arm • Structural elements can be created • Freeform is possible • Unique formwork that cannot use for another design • Human involved process
NEGATIVE	• Slow process • Time and Cost is high • Human involved process	• Slow process • Time and Cost is high	• Until concrete freeze and get dry robotic arms cannot use • Slow process
PHOTOGRAPHS			

Other important research studies are “Robotic Fabrication of Modular Formwork” and “Robotic Formwork in the Mars Pavilion,” which present new approaches in formwork studies for structural, architectural forms. Each project turns digital input to develop complex concrete formwork structures robotically. While creating complex and organic forms with formwork, formworks have no reusable features, and the overall process is relatively slow, and the costs are high.

Robotically fabricated formwork still has some problems that need to be solved. Costs and time for construction are two important subjects that require attention. Although this ongoing research is promising, they are an emerging technology, and the adaptation for other designs and forms is not easy. Especially for larger structures, the robotically fabricated formworks are not easy to adjust and adapt.

Table 13: Features of experimental formwork studies, table drawn by the author.

Tensile, Fabric and Unroll Formwork	Robotic Formwork
• Formwork consist of tensile material, fabric or unroll surface • Suitable for walls, column or beams. • Not possible to use created formwork for different shape • Slow process • Small scale structure • Possible to produce rigid or organic shapes.	• Formwork is created with robotic arms. • Suitable for beam or column structures. • Possible to create different structures • Small scale structure creation • Slow process • Possible to produce rigid or organic shapes.

Fabric and fabric type materials have widespread use for different designs, and it is used for concrete structures through history for custom designs. From Roman times to Industrial Revolution, it is possible to see the traces of fabric. Later, developing technologies enabled the production of different textile products, and this situation led to the creation of emerging fabric formwork studies.

Today, this technique primarily consists of structural membranes as a main facing material for concrete casting. With fabric formwork, customized surfaces come up with a decent quality as a result. Researches proved that for non-standard shapes, fabric formwork consumes up to 40% less concrete which offers energy saving (Jones & Hammond, 2008). Also, it is possible to create all parts of buildings such as columns, beams, or walls with fabric formwork. It allows doubly curved geometries without structural failure risks, and that is why it is possible to use them for larger structures. The fabric used as a formwork must resist the tensile strength of concrete and carry all the load and pressures. Also, the fabric should be elastic enough to sustain the intended form.

Table 14: Hanil Visitor Center and Guest House Fabric Formwork Details and Information

Hanil Visitors Center & Guest House BCHO Architects & C.A.S.T (2009)	• Waste concretes recycled and used • Eastern wall of the project produced with fabric formwork and the other façades made with gabion method. • Fabric formwork precast façade have structural property

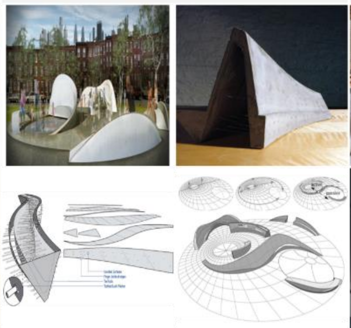
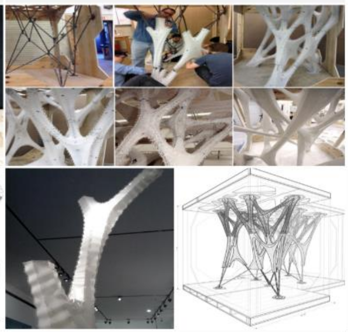
The ability of fabric formworks to different forms enables designers to explore complex forms in building components like it is seen in façade elements. The same fabric formwork can be employed recursively by re-designing the form to be molded.

Table 15: All form and all-purpose fabric formwork studies of C.A.S.T / Mark West

WHAT	**Fabric Formed Concrete** C.A.S.T / Mark West
FEATURES	• Developed structural elements with fabric formwork • Reduced dead weight of concrete and used less material (material and weight saving up to %40) • Suggests economical structural sustainable manufacturing • Shape of structure designed due to the loading condition (Tension & Compression position effected the design) • Their motto is *concrete in all form*

While such fabric formworks may increase workload, it offers new potentials in adaptive formwork for complex forms production. Using one formwork system more than once can offer sustainability, economic, and practical use, which is critical for the construction industry. Fabric formwork research shows their potential to obtain complex and organic forms and novel solutions for conventional building elements.

Table 16: Tensile, Fabric, and Unroll formwork example chart and their features. The table is drawn by the author.

	TENSILE, FABRIC AND UNROLL FORMWORK STUDIES		
WHAT	P-Wall	FluidScape	TensileEffects
WHO	MatSys 2009	Kansas City University 2013	American University of Shorjah Washington University 2014
FEATURES	• Shaped fabric creates formwork itself • Form parametrically controlled • Formwork can be used multiple times for different designs • Computation for complex physical forces negotiated • Organic shape creation	• Complex concrete formwork for public park • Digitally generated dynamic and flexible structure • Precise and smooth surface • CNC fabrication / unrolled face idea • Formwork can be used multiple times for same design	• Material efficiency in computational design fabrication • Computationally designed concrete structure production • Formwork suggestion for structural configuration • Optimal structure configuration arrangement
NEGATIVE	• Small scale / brick type concrete form creation	• Formwork is not adaptable • Unique shape creation	• Arranged formwork can use only once and for same design
PHOTOGRAPHS			

In *P-Wall,* mass production with fabric adjustable formwork is achieved with small-scale units resulting in tiling, parametrically designed with no load-bearing capacity (Kudless, 2011). This is important research because it is well understood that fabric can form organic shapes and complex forms with P-Wall. Now, it is possible to produce repetitive and differentiated forms with the same formwork. However, this technique is still not long-lasting and durable enough to use this formwork for larger-scale forms. Although adaptiveness and reusability are achieved, this research cannot adjust for larger-scale designs.

Later, with *Fluid Scape*, unroll formwork experienced and smooth and precise form produced (Howe, 2013). This formwork is reusable for the same design, and it offers a *structural* concrete form. Although this research offers reusability, it is not adjustable for different designs.

With *Tensile Effect*, structural configuration with material efficiency in computational design fabrication was studied in 2014, and optimal structure composition is explored (Kenneth, Yogiaman, & Tessmer, 2014). The main goal of this research is to achieve material efficiency for structural designs. In the design part, the optimal structural configuration is wanted to achieve, and computationally designed concrete structures have been produced. However, due to the nature of developed formwork, it is impossible to use it multiple times because it must be removed by tearing. Although this research is important to understand for digitally configured formwork, it requires improvements in the context of reusability, flexibility, and adaptiveness features.

In conclusion, with these methods, designers have faced new problems that they did. Digitally designed complex forms are possible to be produced with fabric, unroll, or tensile methods. However, they all have their own problems, and mostly, it is well learned that these methods do not offer durability for multiple usages. Achieving complex forms with formwork may not be sufficient enough, and these methods do not provide adaptiveness, flexibility, and reusability.

2.4 Critical Review for Literature Review

Recent studies show that there is a considerable effort in developing new formworks easing the construction of building components and improving (pre)cast and in situ applications. Newly emerging technologies and parametric design enabling control of form digitally and physically offer remarkable potentials. Moreover, today, formwork is still an important issue in construction, and novel formwork designs will contribute a lot to construction practice and building design.

Consequently, this research focuses on designing new flexible vertical formworks for concrete, which is capable of adapting different forms in recursive use.

Table 17: Literature Review summary to research table, drawn by the author.

Critical Review for Literature Review

Mass Housing and Concrete	Digital Fabrication Methods
▪ History of Concrete and Mass Housing ▪ Mass Customization and Customized Mass ▪ Formwork and concrete relationship ▪ Formwork and complex concrete shape ▪ Precast vs In-Situ Concrete Production	▪ Additive concrete manufacturing and formwork differences ▪ Experimental formwork studies ▪ Fabric, Tensile and Unroll formwork ▪ Robotic formwork

⇩

Research

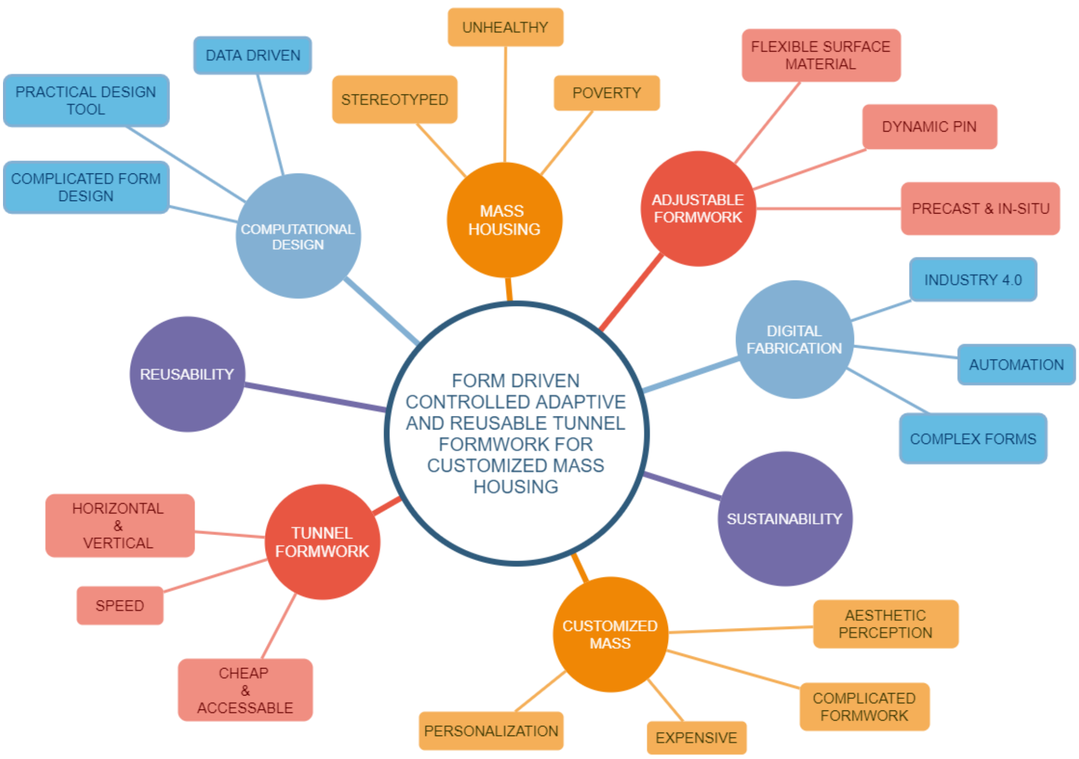
Flexible Formwork Setups
▪ Reusable formwork designs through history ▪ Plastic surface material for flexible and re-usable formworks ▪ Kerfed surface material for flexible formwork

CHAPTER 3

RESEARCH DESIGN

This part of the study is designed to be composed of three stages. In the first stage, the form, formwork, and tunnel formwork behaviors are explored. In the second stage, the proposed system's computational design and formwork configurations will be explored. In the third stage, the physical concrete mass production will be examined and explored.

Table 18: Keyword chart for today's situation that this research matters, drawn by the author



The primary motivation of this research is adapting complex concrete production in an adaptive and flexible formwork system. In that way, it is possible to produce customized mass in a better way without compromising sustainability and quality. Another Motivation is to achieve flexible formwork in two directions for both **horizontal and vertical** use. Positioning formworks vertically requires special care regarding the effect of gravity during the form attaining of the concrete and regarding the quasi-static hydrostatic forces exerted by the concrete to the formworks. Due to the problems briefly presented above, flexible/adjustable formworks are employed horizontally in many implementations.

For customized mass designs, reducing waste material is targeted as well. As it is mentioned above, customized formworks create excessive waste that cannot use for different purposes. With the adaptation feature, the waste material problem may solve, and reusable formwork may be achieved.

Tunnel formwork offers structural units of buildings, and it also offers thickness differentiation related to the unit's structural features. While this thesis aims to achieve tunnel formwork having flexible and adjustable features, it is also aimed to preserve the essential features of tunnel formwork.

Table 19 shows the research design stages to achieve an adaptive, flexible, and reusable formwork system. Stage I is the understanding of form and formwork, and it also includes previous flexible formwork research details. Stage II describes the digital design of flexible formwork and data-driven setup. In stage III, concrete mass and adaptive and flexible formwork experiments are to be examined.

Table 19: Research methodology steps for formwork research, drawn by the author.

Stage I	Stage II	Stage III
▪ Understanding form and formwork ▪ Understanding Spline and NURBS ▪ Understanding Tunnel formwork system and setup ▪ Formwork Trials with possible surface and pin material.	▪ Design of Flexible Formwork Setup ▪ Technical drawings ▪ 3D Models ▪ Structural Analysis with possible concrete loads ▪ Computational design for flexible formwork setup ▪ Parametrically obtained pin depth configuration	▪ Concrete Production with formwork setup ▪ Formwork Setup ▪ Formwork re-design and update ▪ Data driven ▪ Concrete Production ▪ Vertical I Concrete Component Production ▪ Vertical II Concrete Component Production ▪ Horizontal Concrete Component Production

3.1 Stage I: Understanding Form and Formwork

This stage of the study is focused on form and formwork relations as details of the tunnel formworks. Besides the examples in the literature, initial experimentations in the present research context are explained to further the explorations of the thesis.

As it is already acknowledged, conventional formwork methods from small to large scale are common in many industries, such as in construction. It is safe, quick, and practical. Moreover, they are relatively low cost when used multiple times or recursively in all scales. However, customization of formworks, or developing formworks for complex building parts, is a critical issue. Customization is increasing cost, time, labor effort and limiting reusability. Thus it becomes unfeasible. Moreover, an increasing amount of waisted material is against all the efforts to provide more sustainable solutions. Hence formwork that allows flexibility is essential for almost all industries, and construction is not an exception, as discussed previously.

3.1.1 Form and Formwork Research

In the ’60s, Renzo Piano studied light-weight structures with plastic materials such as fiberglass, polyethylene, and polyurethane foam and faced formwork challenges. From this experiment, he envisioned a “*deformable mould*” in order to decrease manufacturing limitations of free-form designs (Piano, 1969). His detailed *experimental shell structure* idea still inspires many other researchers even today.

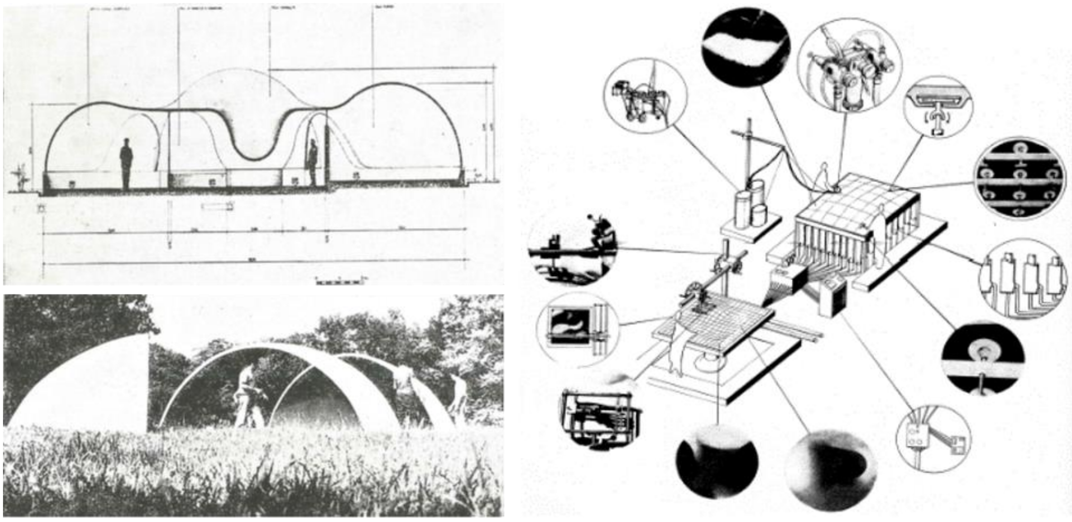


Figure 10: Piano's Works. Morphological study for a pavilion in glass-fiber reinforced (Left Up). Pavilion made out of circular double-curved plastic (Left Bottom). Renzo Piano's Flexi Mold Sketches (Right). (Images taken from the article R Schipper, 2013)

Piano’s work is significant because he tried to understand both form and formwork together and develop a formwork system that suggests complex form production. Later, more form and formwork studies were generated for curved forms based on this research.

Constructing curved forms in CAD programs is mostly achieved by NURBS. Describing any curved form with a number of control points and their interpolations with different weights offers not only flexibility for both surfaces and but also allowing designers to interact easily with models ("NURBS Curves and Surfaces," 2006).

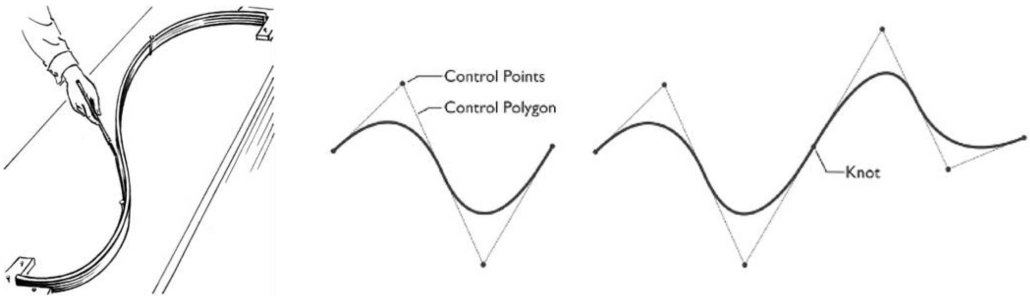


Figure 11: Before CAD and other computer developments, curvature forms were mostly drawing by freehand because of the straightness of rulers. Although for larger drawings, flexible wood strips were used, which are called splines. The elasticity value was determined by the behavior of the element that is used. Later, in 1946 mathematicians wanted to formulize the spline behavior and started to study spline shape. Because the computers had involved the designing process, the formalization of splines had huge importance, and Piere Bezier named the Bezier curve due to his published works (Cabrinha, 2005).

Being able to control different geometries computationally and the idea behind NURBS is inspiring for the flexible/adjustable formworks in surface molding. In Schipper's and his team's research, it is tried to explore the limitation of NURBS and its behavior (R. Schipper et al., 2015). These geometry actions are important to understand because it directly affects the formwork itself. Figure 11 shows the number of actuators and shape behavior and their relationship with formwork. A number of actuators and their locations affect the surface. It is well understood that formwork pin placements and counts are as important as the formwork surface design and material.

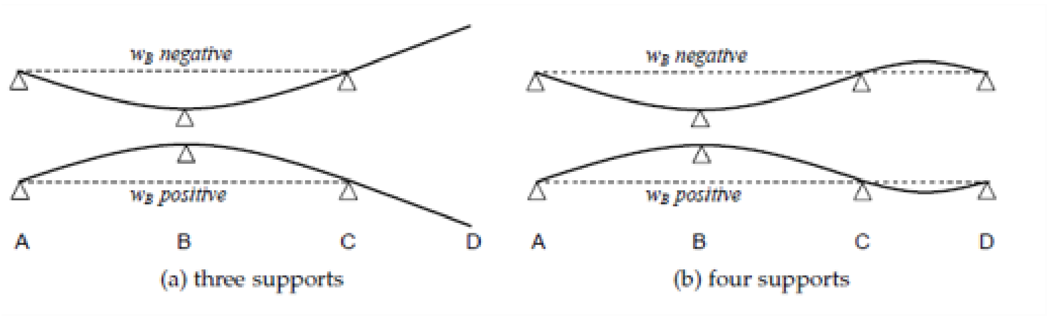


Figure 12: NURBS shape differentiation with different number actuators. Pin positions have a huge effect on formwork. Image is taken from (H. R. Schipper, 2015)

Also, in Figure 12, Schipper's Kine Mould research drawings can be seen and the result of formwork surface material through the pressure to pins when concrete pressure occurs. The material flexibility and stiffness affect the form, and it may result in an unbalanced surface design.

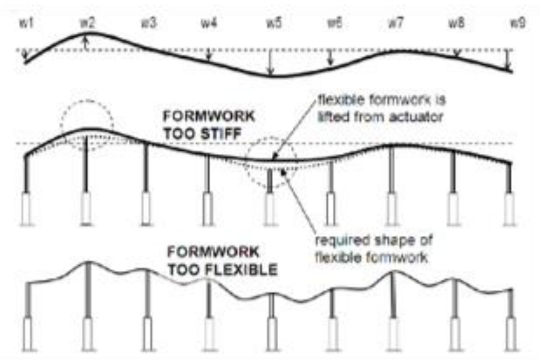


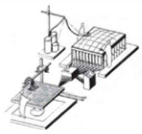
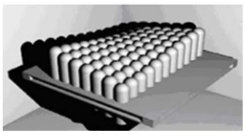
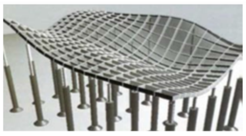
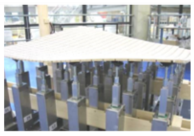
Figure 13: The most critical element is the surface material in this set-up because its stiffness affects the form itself. Image taken from (H. R. Schipper, 2015).

3.1.2 Adjustable Formwork Studies

In this section, the details about previous studies about flexible and adjustable formwork will be examined. It is seen that the success of the flexible/adjustable formworks is dependent on the materials and detailing, such as elasticity of the surfaces of the formwork, points of actuation to control geometry and their details, etc. Hence various materials in different sizes are explored in fabricating the formwork to test their performance.

Most of the current research in this field focuses on horizontal flexible/adaptable formworks. The idea behind those examples is to use actuator pins and flexible surfaces to control the surface topology and curvature, as shown in the examples below.

Table 20: Early ideas for flexible formwork setups. Images taken from (R. Schipper & Janssen, 2011)

			
Rezzo Piano's Early Flexible Formwork Concept Drawing (1966)	Hans Janssen Strip Mould: pin mould flexible formwork idea (2004)	Lars Spuybroek's flexible formwork device design (2004)	Huyge's and Schoofs' Precast Double Curved Concrete Panels Study (2009)
• Vision and first practical results of an innovative production flexible formwork method for double-curved designs. • Manipulated a flexible surface by a grid actuators to arrange the form of a predefined curved shape	• Three-dimensional curved surfaces without repetition • Prototype of a strip-mould surface supported by a pin-bed • Produced several curved concrete elements with this device.	• An elastic material surface between actuators • Concrete can have smooth surface	• Proper choice of elasticity and intermediate layer • Choose right material specifications • Adjustment method successfully achieved • Full-Automated system with pneumatic pistons.

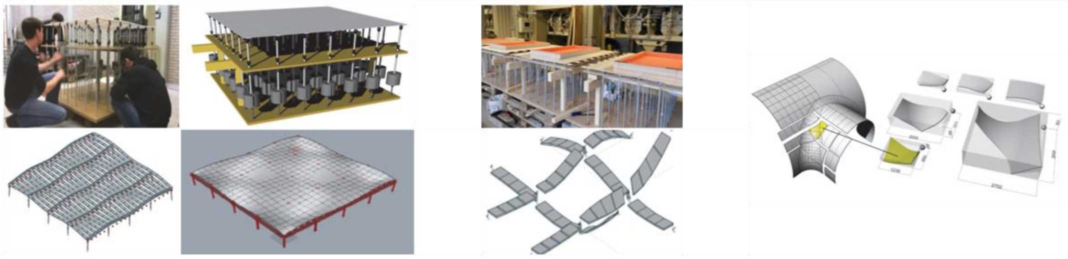
Inspiring from the Piano's drawings, in 2004, two similar research have been developed. Hans Janssen examined the pin behavior and developed an interlaced and kinetic system. Lars Spuybroek developed a pin system with pistons and also added an elastic surface to produce concrete mass. Later, in 2009 pneumatic pin system was developed, and the formwork mechanism was automized. The details have been given in Table 20 about these four studies.

Table 21: Kine-Mould Study. Reconfigurable flexible formwork study for precast concrete production made by Schipper in Delft University of Technology

- Casting concrete in a flat shape on a single-sided formwork
- Horizontal only design
- Inspired from Renzo Piano's drawing and starting from the previous successful outcomes
- Precast composition for modelling design and assembly of a larger scale
- Wanted to change the situation executed as shotcrete (sprayed concrete) on *CNC-milled mould made* of *either foam* or *timber* with a **reconfigurable flexible mould** system
- Smooth and aesthetic surface with good structural performance
- Visible uneven areas in the surface
- Slow process

Kine-Mould - Manufacturing technology for curved architectural elements in concrete

Delft University of Technology
2015

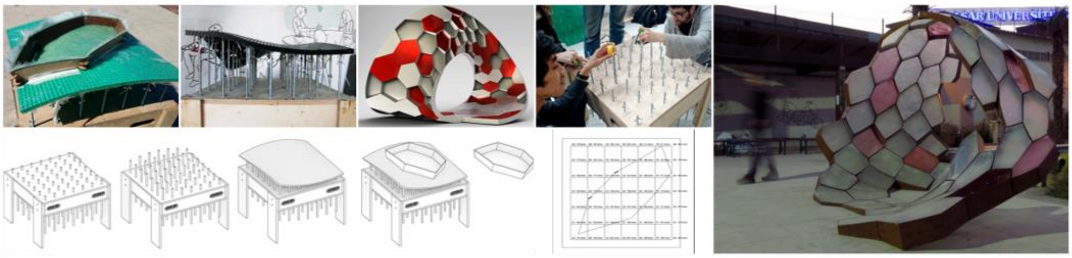


Later, Schipper developed a reconfigurable flexible precast formwork system at Delft University in 2015 and wanted to achieve single-sided concrete casting. With the precast and shotcrete method, concrete parts have been produced. With this reconfigurable flexible formwork study, small concrete parts have been created, and later, they all assembly to create a smooth surface. Although Kine-Mould presents an *aesthetic* surface production, it also offers a relatively slow and only horizontal production process.

Then, in 2016, FlexiMold research was realized, which has quite a similar system to Kino-Mould. Differ from Kine-Mould, with this method, hexagonal plastic shapes produced. Also, borders have been closed with wooden parts, and plastic surfaces merged with these wooden pieces. In the end, wooden *walls* assembled with each other, and a designed pavilion was created. Despite the fact that this system offers adaptive and flexible formwork, it also presents a slow form-making process and a substantially human-involved production method.

Table 22: FlexiMold flexible formwork research. Similar to the Kine-Mould project differ from the used surface and used material.

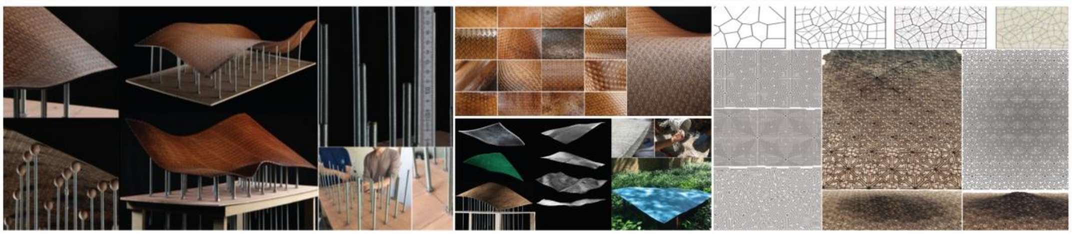
• Hybrid device controlled both numeric information and humans • Overall design is designed and produced by students • Procedure has serious difficulties and problems • Conjunctions and details are not efficient and not successfully solved • Human involved process • Pin controlled surface material is fiberglass • Horizontal only design and not doubly curved production • Slow and inefficient process	**FlexiMold – Flexible Formwork Device and Built Object** Yaşar University & Delft University 2016



Last but not least, in 2018, a similar system with different formwork surface material was suggested for flexible formwork. Kerfed material which presents fabric-like features, has been used as a formwork surface material. Also, since the surface material is more rigid and durable, it stands the mass pressure. However, it is hard to adjust this system for a larger scale, and also it is hard to obtain larger kerfed formwork surface material.

Table 23: Kalantar and Borhani researched kerfed surface material and its effects on flexible formwork. Table created by the author.

• Non-linear design fabrication struggle is that starting point • Hybrid device controlled both numeric information and humans • Conjunctions and details are not efficient and not successfully solved • Pin controlled surface material is kerfed material that becomes flexible feature • Balance between rigidity and flexibility is the main goal • Kerfed preferences may change through design wishes. It maybe more rigid or more flexible • Decreasing cost and waste material for freeform architecture is aimed • Horizontal only design and not doubly curved production • Slow and inefficient process	**Deformable Formwork –** Parameterizing Deformation Behavior of a Non-Stretchable Membrane via Kerfing Texas A&M University 2018



Various techniques have been used as adaptable formwork for complex forms and structures. However, in general, the found solutions could not be as practical and sufficient as is desired. It is important to determine the negative aspects and identify the missing points of these studies. All these works were carried out in *horizontal position* and *precast* setup.

Although these formwork setups yield promising results, the final products are on a small scale and suitable for only precast concrete, and fit for highly customized specific projects rather than mass customization or recursive use.

However, due to the sophisticated control of the formwork liaison with the digital model in construction sites, their use is rather difficult. Besides, it requires more research on how to control the solidification of the concrete in such form-shifting/flexible formworks.

Another important issue is the settlement of the formwork. In most precast implementations, such flexible formworks are used horizontally to overcome problems like the non-uniformities due to agglomeration in thickness and the dead weight of the concrete itself exerting considerable lateral forces in the case of vertical settlements.

The integration of tunnel formwork to flexible formwork promises to eliminate the matters mentioned above. As it is already acknowledged, tunnel formworks are versatile systems that are commonly used in mass housings. The ease of construction with this method and the possibility of completing construction make them very attractive quickly. This system also has the potentials for modifications and adjustability. The next chapter will describe the proposals of initial prototype experiments based on the tunnel formwork systems.

3.1.3 Proposal of Initial Prototype

This exploration aims to observe the potentials of flexible/adjustable formworks closely. In this vein, a horizontal formwork is designed and made incorporating the experience of previous studies carried out horizontally used formworks.

The initial horizontally used setup shows that the freezing time of the concrete is one of the critical problems like in other formworks. Another important problem is the pins used to actuate the flexible surfaces of the formwork.

Table 24 shows the negative and positive results of the first flexible formwork experiment. As a surface material, silicon rubber has been used, and it presented both durability and flexibility. However, this material also requires formwork of the shape itself, and solidification of silicone requires more than 24 hours, and this causes a slow overall process.

Table 24: Early adjustable and flexible formwork with silicone rubber surface material. Pin bolt placed before the silicone freezes, developed by the author.

Silicone Rubber Surface
Pin Bolt and Stamp

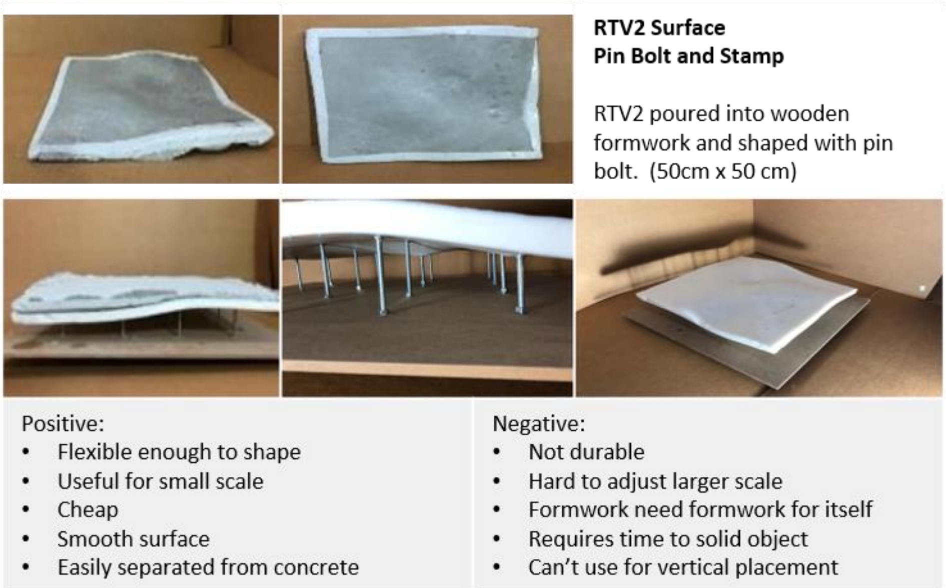
Silicon rubber poured into 3D printed formwork and shaped with pin bolt.

Positive:	Negative:
• Flexible enough to shape • Durable • Useful for small scale	• Expensive • Hard to adjust larger scale • Formwork need formwork for itself • Requires time to solid object

Information gathered in previous studies facilitates the development of another prototype with RTV2 surface material having a similar system but on a larger scale. As Table 25 shows the detail of this experiment, it can be seen that a smooth surface for concrete mass is obtained, and it is an easy-to-use setup for small scale.

Although it offers flexibility, it is not suitable for vertical settlements because it is too flexible to stand gravitational/hydrostatic forces. Thus, it may be useful for small-scale concrete mass production in the horizontal settlement. However, it needs to be developed further with refining the choice of materials, especially for formwork surfaces.

Table 25: RTV2 used as a surface material for adjustable and flexible formwork. This material is similar to silicone rubber. While this material offers more flexibility, unfortunately, it presents fewer durable features. Pin bolt placed before the RTV2 freezes, System developed and photographed by the author.



The experiences of two prototypes developed in the course of thesis studies helped the author identify the problems necessary to be solved, possible risks, and detailing problems, showing their potentials.

These two prototypes then led to the revisions, and a revised system allowing to be used recursively is developed. At this stage, research is further detailed on materials to be used in the formwork regarding the properties of concrete like freezing, reinforcing, etc.

Table 26: The outcomes of research and formwork study. Table is drawn by the author.

Stage I Outcomes		
ADJUSTABLE FORMWORK	TUNNEL FORMWORK	SURFACE MATERIAL
• Horizontal settlement research not dealing with gravity • Different flexible surface material • Precast • Manuel pin movement • Useful for curved designs	• Easy to setup with the help of crab • Fast and practical. All floors, walls, columns and beams can be produced in one go. • Has huge potential for adjustable and flexible surface arrangement • Thickness can be arranged • Less labor necessity • Both horizontal and vertical settlement	• The surface material production process is not practical • Makes no economy both in cost and time • Surface material is durable in horizontal settlement but not in verticality • RTV2 surface cannot stand itself • Pin distance are not arrangeable

3.2 Stage II: Digital Design and Computational Control

In this part, a detailed explanation is presented for the intended flexible/adjustable formwork. Details can be seen in the drawing in Figure 14. This drawing and flexible tunnel formwork system are set up based on current tunnel formwork drawings and systems (Figure 15).

Figure 14: Tunnel formwork details and photographs, images taken from PERI website.

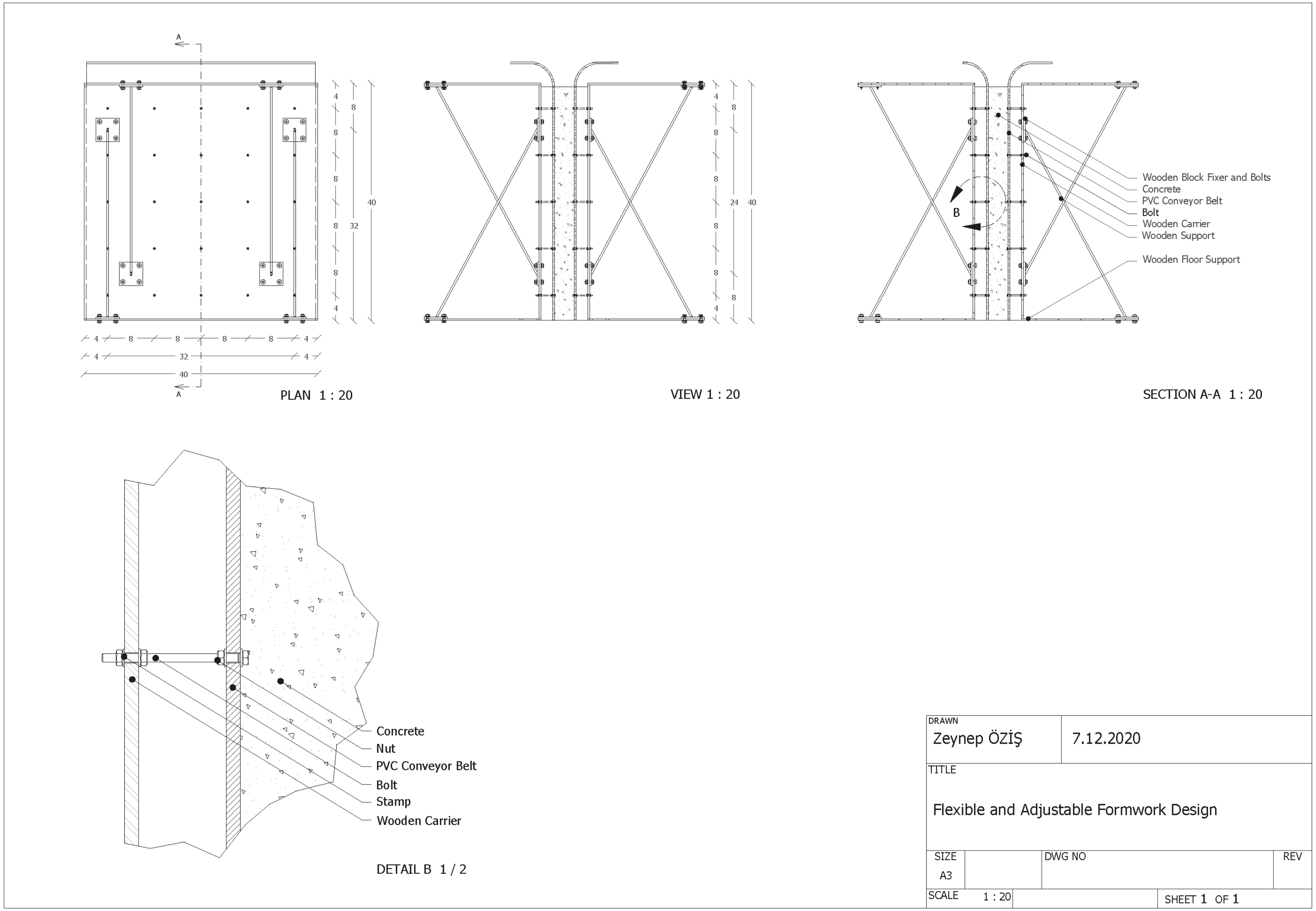
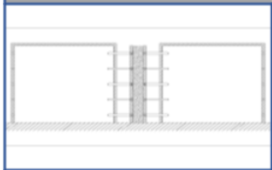
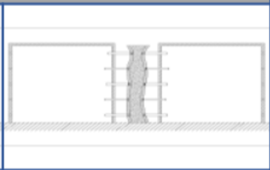
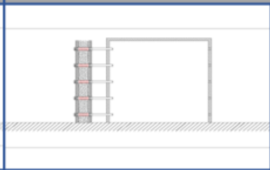
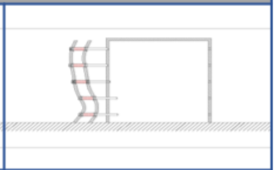
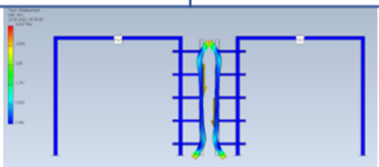
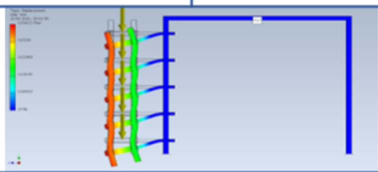


Figure 15: Adjustable and Flexible Formwork Drawing, drawn by the author

The structural performance of the proposed formwork with its two modes is analyzed as shown in Table 27. In the first column of the table, a single-pinned doubly curved system is illustrated. Its analysis shows that although it is an easy-to-use and low-cost system, proposed pins and material are not strong enough to withstand the load and concrete pressure.

In the second column, a modified system can be seen. The table shows that surface material could not stand the concrete pressure and material forced to change position. This means it may need some supporting material for these points. It also shows that the first system offers better stability for a flexible formwork system.

Table 27: Load-carrying analysis of possible placement trials, designed by the author.

Fixed by single pin bidirectional doubly curved vertical adjustable and flexible formwork		Fixed with one-way single pin doubly curved vertical adjustable and flexible formwork	
			
			

Later, in order to understand the shape and possible material behavior 3D model was drawn. The risks and potential problems are understood with these analyses, and details of the overall system are observed better. Before producing a real-scaled formwork system, these models and analyses are helpful in problem determination to understand pin movement.

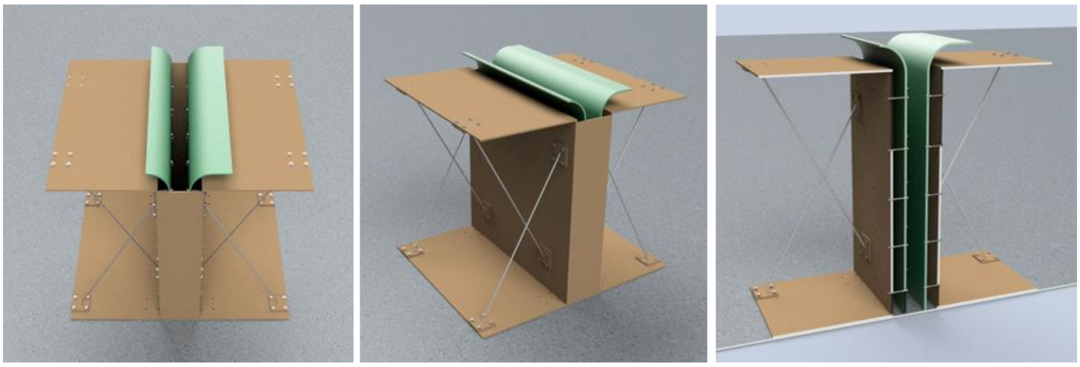


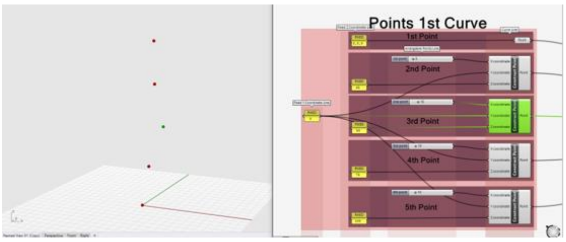
Figure 16: 3D render for adjustable flexible formwork, designed by the author.

3.2.1 Computational Design and Control

This section describes the computational design background of the formwork. Having a parametrically designed form is important for this study because parametric design offers differentiation and adjustability at the design level. In this formwork study, both in the computational design and production stage, adjustability is critical. In parametrically produced forms, it is possible to arrange features such as scale, size, design, etc. This enables to experiment on different parameters and to be able to develop new design alternatives.

Table 28 expresses the sample parametric design process which is specified for the formwork system. Lines (NURBS) were placed inside a 100cm square, and their actuator points were determined as pinpoints to develop the design of the formwork surface. In order to have a systematic design process, Y and Z coordinates of points are fixed with specified positions, and X values are subjected to some limitations. These limitations helped the determine surface material limits and test them in the real formwork, for which details are given in the following chapters. Further details about points X, Y, and Z positions are given in Table 29. Initially, these points define a formwork surface and provide pin distances for the formwork.

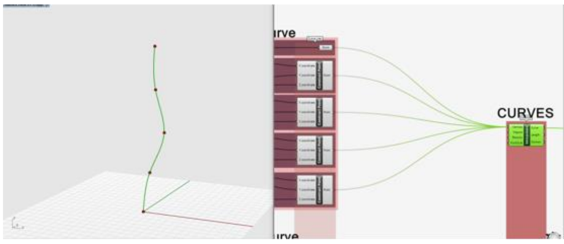
Table 28: Grasshopper computational form generating process, produced by the author.



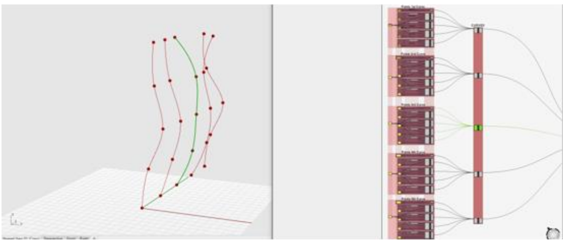
5 adjustable point created.

These points Y and Z coordination are fixed

X coordinates are set as adjustable

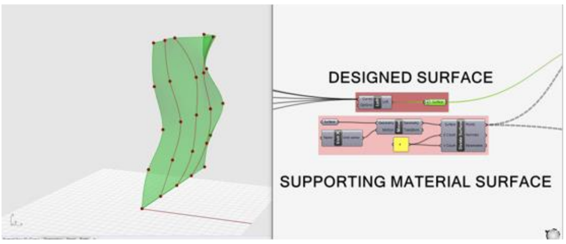


5 points interpolated as curve



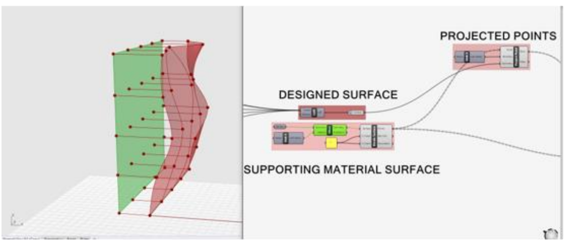
5 more curves are created with the same principle.

Y and Z coordinates fixed and only X coordinate set as adjustable.

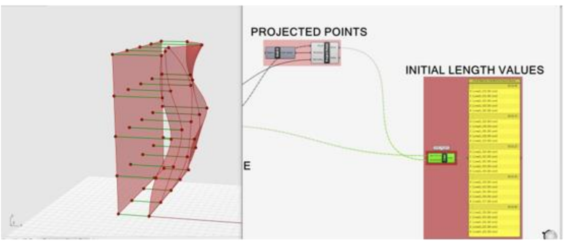


5 curves created surface.

Flat supporter surface created from the base of main curved surface



Surface is divided in order to determine the points location



Length gives the distance that should be arranged in real formwork system

This grasshopper system was established to create form. Also, the system sets the limits for the production stage. Since a system without restrictions cannot be proposed, it is wanted to set the movement constraints. A prior to the physical implementation of the proposed form, experiencing it and determining the limitations are the other advantages of this formwork system. Thus, before producing the form itself, formwork and form can be experienced. From the designing to the production stage, precision and accuracy can be obtained. Table 29 shows the positions of fixed points and the range of movable pins.

Table 29: The points which create surface placements details. Y and Z coordinates are fixed for optimum positions. For X, the value range is given, drawn by the author.

SURFACE

Curve 1 (C000)

	Point 001	Point 002	Point 003	Point 004	Point 005
X	0	0 ≤ X≤ 50	0 ≤ X≤ 50	0 ≤ X≤ 50	0 ≤ X≤ 50
Y	0	0	0	0	0
Z	0	25	50	75	100

Curve 2 (C100)

	Point 001	Point 102	Point 103	Point 104	Point 105
X	0	0 ≤ X≤ 50	0 ≤ X≤ 50	0 ≤ X≤ 50	0 ≤ X≤ 50
Y	25	25	25	25	25
Z	0	25	50	75	100

Curve 3 (C200)

	Point 201	Point 202	Point 203	Point 204	Point 205
X	0	0 ≤ X≤ 50	0 ≤ X≤ 50	0 ≤ X≤ 50	0 ≤ X≤ 50
Y	50	50	50	50	50
Z	0	25	50	75	100

Curve 4 (C300)

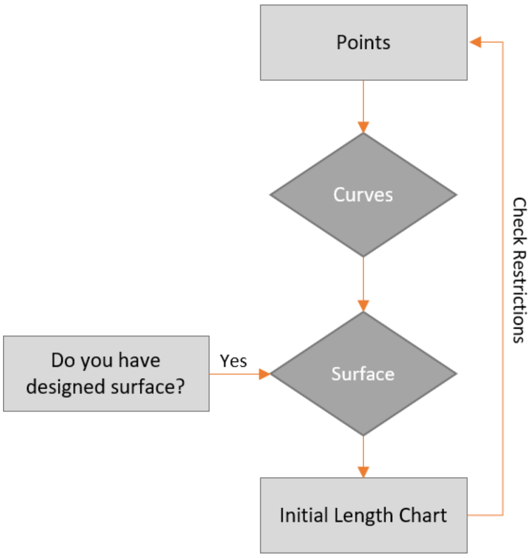
	Point 301	Point 302	Point 303	Point 304	Point 305
X	0	0 ≤ X≤ 50	0 ≤ X≤ 50	0 ≤ X≤ 50	0 ≤ X≤ 50
Y	75	75	75	75	75
Z	0	25	50	75	100

Curve 5 (C400)

	Point 401	Point 402	Point 403	Point 404	Point 405
X	0	0 ≤ X≤ 50	0 ≤ X≤ 50	0 ≤ X≤ 50	0 ≤ X≤ 50
Y	100	100	100	100	100
Z	0	25	50	75	100

Table 30 illustrates the Grasshopper form generating process from point to surface. This parametric system allows designing in this interface but also allows pre-designed integration too. As long as the designed surface can turn into NURBS form, design can be integrated into the formwork designing process regardless of which CAD program it is produced.

Table 30: Grasshopper form-making process and restrictions chart, the table is drawn by the author.



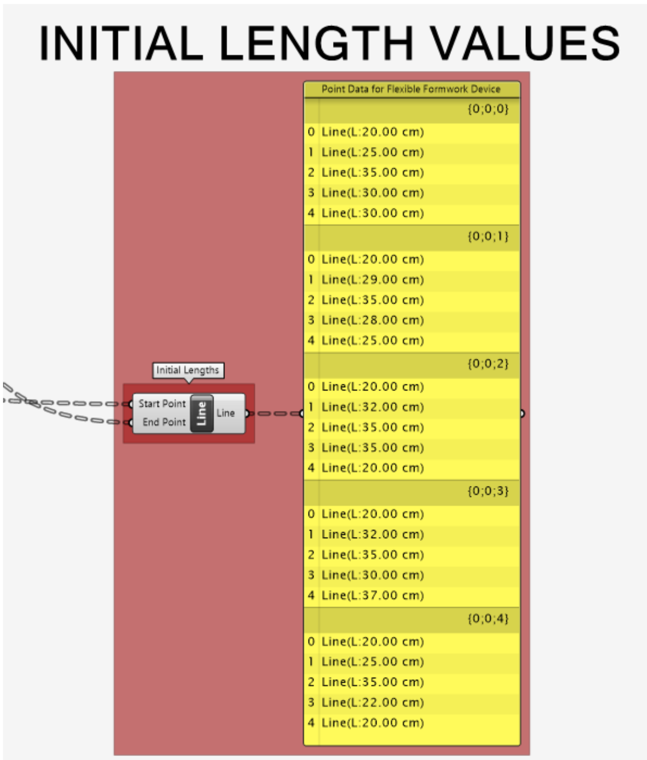


Figure 17: Mathematical outcome of the distance of supporter surface and curved surfaces. The figure expresses the example values. It can change according to shape, designed by the author

Figure 17 shows the initial length values, representing the distance between the supporter surface and the flexible formwork surface. From this knowledge, the pin distance in real formwork will arrange accordingly. Also, when required, Y and Z positions can be arranged related to the formwork size and additional designed form requirements. Although this setup sets limitations, it does not restrict the design freedom with its changing paradigms.

The last step is the development of a double curvature system. It is important to point out that this system allows *different designs for each side*, not suggest just a *mirrored image*. The distance between the two designed walls also can be modified relating to the required thickness. Also, while arranging concrete mass thickness, the following issues should be considered before implementation.

- The designed surface and purpose of use should be considered while determining the thickness. Reinforcement and other structural elements can cause significant thickness changes.
- The height of the design should be considered for both formwork and concrete mass' stability because it has effects on thickness.
- Flexible surface material which allows adjustability can be affected by the thickness. Because of the thickness change in concrete's lateral pressure, surface material may not withstand this pressure and load.

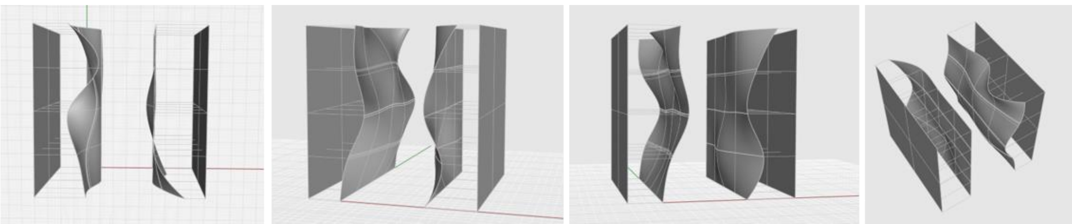


Figure 18: Double-sided formwork with sample curved design 3D model generated with the grasshopper, designed by the author.

As a result, this stage helped determine the possible problems that may occur in the production stage. Details have been solved before the formwork and concrete mass has been produced. Also, in this stage, realized analysis helped to understand the behavior of flexible surfaces and pins.

Table 31: Understandings from the digital design research and structural analysis of adaptive formwork, drawn by the author.

Stage II Outcomes		
FORMWORK 3D MODEL AND DRAWINGS	⇨	FORMWORK PARAMETRICAL DESIGN
• Double-curved design • Inspired from tunnel formwork drawings and detailed accordingly • Some detail material determination • Concrete pressure analysis. Double-pinned system is promising. • Ground joints require support behind the surface material		• This design allows pre-designed surface interpretation. • Thickness can be arranged according to design and structural necessities • Pin distance automatically obtain from digital design • Pin positions can arrange • Generated surface is the formwork surface. The concrete component surface will be the reverse

3.3 Stage III: Concrete Production with Form Driven Adaptive and Reusable Formwork Setup

In this section, the model of formwork setup and production of concrete mass processes will be discussed. The execution of the formwork and its production process are the primary interests of this process. The material selection, initial design of formwork, and concrete production process will be explained.

3.3.1 Formwork Setup

The first and most critical stage is the proper choice of the surface material for the system. To do so, a small setup has been developed, as explained in the previous section. After several material research and trials, it is decided that the *PVC conveyor belt* is the most suitable material for a flexible surface. This material is quite flexible and durable for pressure because it consists of a combination of plastic and fabric. While its plastic surface provides flexibility and durability, fabric supports it without affecting its elasticity. Also, this material's thickness and the number of layers can be arranged. Thus, it is both promising for small and larger-scale productions in the context of flexibility and durability. Also, because the surface material's finish is plastic and has a smooth feature, it is quite easy to separate formwork from concrete.

Determining system and material behavior limitations are essential since they define the precision of the process and guides to be followed. The proposed system consists of 9 pins which are placed 10 cm apart in a 50x50 cm sized wooden support material. As mentioned above, after several experiments, as a surface material, two-layered PVC conveyor belts have been chosen with 2mm thickness. Basically, this setup moves with pull-pull movement, and through these moves, the surface gains parabolic and smooth features. Nut, bolt, and washer helped to fix pin to the surface, and since they create a small new surface, they support pins in the movement process and also support through concrete pressure.

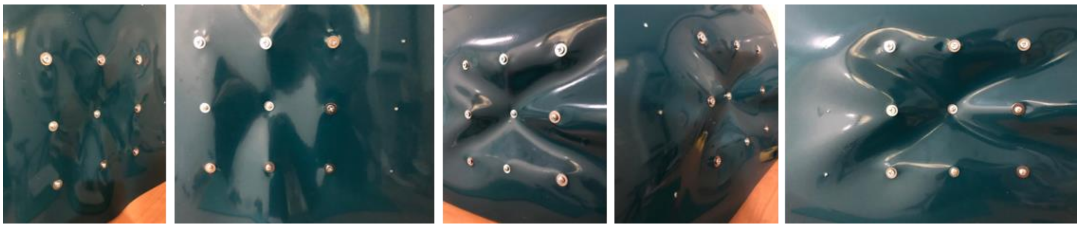
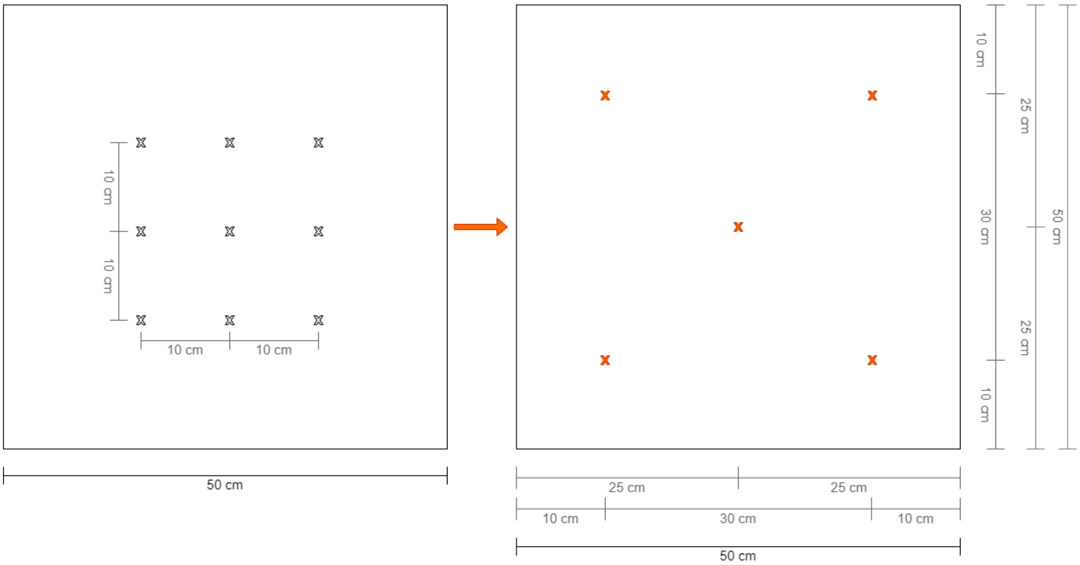


Figure 19: Material behavior experiment with pin bolts. 50x50 cm setup with nine bolts. Determination of the flexibility of the material. In the example, the distance between the pins is 10 cm. M5 / 100 mm bolt has been used. (Produced and photographed by the author.)

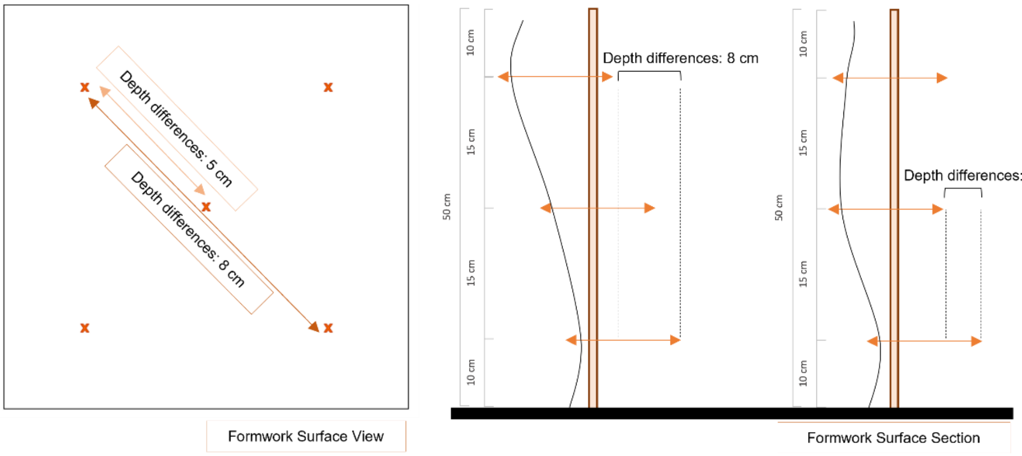
Figure 19 shows the pin settlement and the limits of the surface with pin movements. However, in this settlement, pins are too close to each other, and surface material could not show enough flexibility. In order to obtain a more flexible feature with the surface material, the number of pins is reduced, and pin positions are replaced. The change in the pin positions can be seen in Table 32. With this configuration, the distance between the pins becomes farther. Thus surface gains more flexibility.

Table 32: Surface pin settlement evolution through experiences drawn by the author.



With this positioning, surface limitations have been decided by having the minimum and maximum depth distances. These five pins were placed 30 cm apart, and the maximum depth distance differences between the two closest pins were tested as 5 cm. The depth distances between the two pins at the farthest point can be up to 8 cm. These values could not be obtained in the previous layout. Thus, reducing the number of pins to 5 has become quite beneficial in terms of the flexibility of surface material.

Table 33: Pin positioning and depth details. Unscaled representation, table drawn by the author.



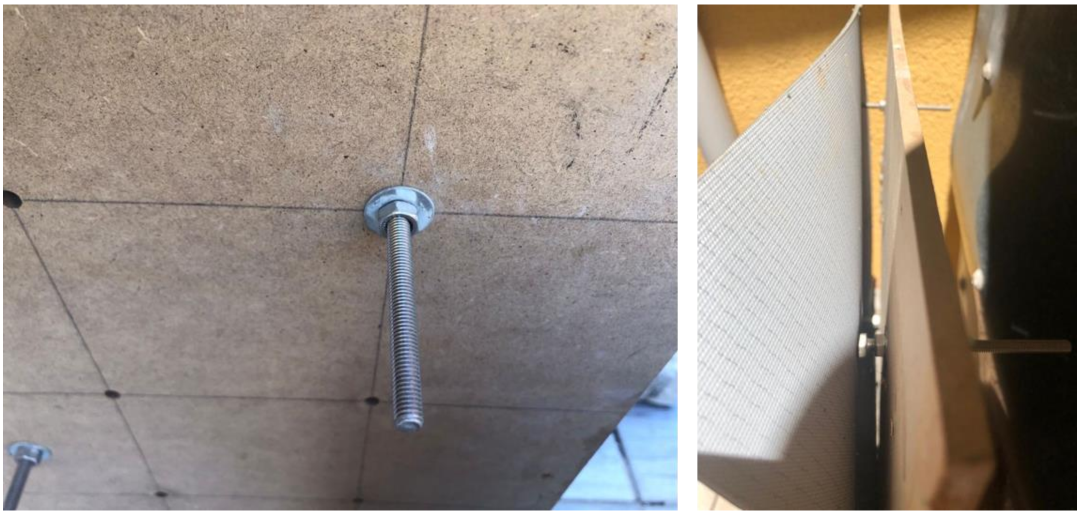


Figure 20: Pin system details. Bolt, nut, and washer combination on the support surface.

After pin position decisions, formwork installation has been realized. 15mm MDF has been used for support because it presents stability and structural stiffness in thin thicknesses. Surface material fixed the support with pins, and in order to have a closed volume, supports fixed with each other with MDF too. All MDF surfaces are fixed with clamps.

Figure 21: Details and arrangements for concrete production with the formwork, developed and photographed by the author.

Thus, a closed and doubly curved flexible formwork system was provided. Pin positions and concrete component production process will be explained in the next chapter in detail.

3.3.2 Production of Concrete Components

This section explains the concrete production process and experiences of overall adaptive and reusable formwork study. With vertical and horizontal placement, the material behavior and pros and cons of the formwork are described.

As the first step, as explained in the previous section, a setup has been assembled with five pins, and it is expected to observe possible deteriorations, especially in the vertical settlement. Before starting the concrete component production phase, the concrete mixture range has been researched, and the mixture provided accordingly. The suggested range of concrete is a mixture consisting of 75% aggregate, 10% cement, and 15% water to have a *conventional* concrete mixture. Even though this is the average mixture value, there is no strict mixing ratio or rule. Also, it is possible to add some chemicals or additives to achieve desired stiffness and/or flexibility in concrete, but this ratio should not be over 2% ("Betonsa | Hazır Beton," 2018). In this study, chemicals or any additives have not been used.

Also, before concrete mixture preparation, the joint level of formwork and surface material with the ground is fixed, leveled evenly, and brought into the settlement explained in the previous section. Thus, formwork gained more stability and durability for concrete pressure. As it is explained previously, support surfaces are fixed with each other with the help of clamps.

3.3.2.1 Vertical Concrete Production I

Firstly, based on the generated parametric model, pin distances and depths are calculated, and the system is configured accordingly. Since this formwork provides doubly curved components for mass production, the formwork surface doubly curved feature has two sides, and pin distances are given in Table 34 and Table 35. The distance between supports is arranged as 15 cm, and the average thickness of the designed mass is taken as 10 cm.

Table 34: Vertical Formwork I Grasshopper design and X positions (pin distances) for the points, table drawn by the author.

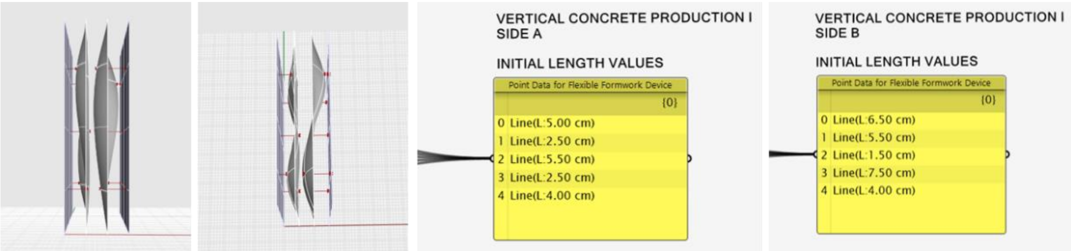


Table 35: Vertical formwork production I. Pin position and distance details Side A and Side B, drawn by the author.

Vertical Concrete Production / Trial I / Side A					Vertical Concrete Production / Trial I / Side B				
Formwork Pin Location				Pin Distance	Formwork Pin Location				Pin Distance
	Y	Z	X			Y	Z	X	
Point 001	40	10	5,0 cm	5 cm	Point 001	40	10	6,5 cm	3,5 cm
Point 002	40	40	2,5 cm	2,5 cm	Point 002	40	40	5,5 cm	4,5 cm
Point 003	25	25	5,5 cm	4,5 cm	Point 003	25	25	1,5 cm	8,5 cm
Point 004	10	10	2,5 cm	7,5 cm	Point 004	10	10	7,5 cm	2,5 cm
Point 005	10	40	4 cm	6 cm	Point 005	10	40	4 cm	6 cm
Concrete Material					Volume				
Pozzolanic Cement					7 lt				
Water					10,5 lt				
Aggregate					22 lt				

The surface is generated according to the parametric model, and the limitations explained in the previous section are also considered. Pin positions are placed to control points in the parametric model, and the pin depths are calculated from the outcomes given in Table 35. Y and Z represent the pins' position on the formwork surface.

As a pin, a 10 cm long bolt is used. Figure 23 shows the distances that are obtained from the computational model. Consequently, the distances between support and formwork surface are provided as length values from the same computational model. In order to have the values in Figure 23, a subtraction is required. For instance, Table 35 for Side A Point 004 X value is 2,5 cm, and pin distances are calculated as 7,5 cm.

Figure 22: Pin distances are shown. These values match the vertical concrete production I / Side A, developed and photographed by the author.

Concrete mixture values also can be seen in the Vertical Formwork Production I table (Table 35), and the mixture is prepared under recommended ranges. After fixing the joints and ground, concrete is poured, and formwork is left to dry. In the concrete mixture, pozzolanic cement has been used. Since the mixture is more fluid than it should be, the curing process took eight days. However, the result is a success. The shape of the component appeared to be as there was no problem in dismantling, and the concrete was removed in one piece. No flexion has been observed at pins, and no break or crack has occurred in the formwork system. Even though the concrete mixture was more liquid than it should be, no noteworthy overflow was experienced.

Figure 23: Concrete and formwork separation. Surface and concrete are easily separated without any break or shape deformation, produced, and developed by the author.

Figure 24: Vertical Concrete Component Production, first vertical concrete component production, produced and photographed by the author

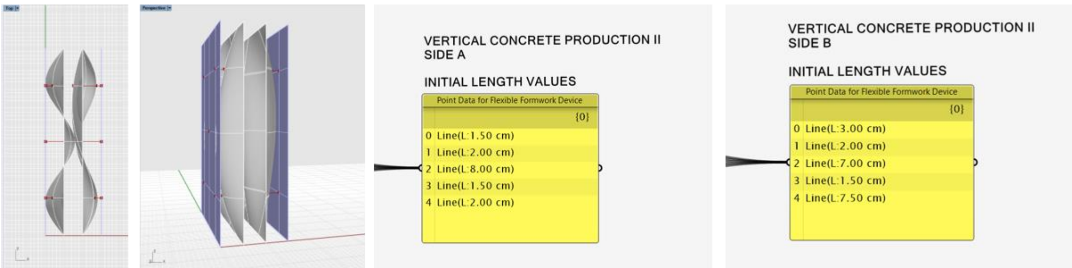
Figure 25: Photographs of vertical concrete component production I result, produced, and photographed by the author

3.3.2.2 Vertical Concrete Component Production II

After the first component production, the second vertical concrete component production is realized using the same formwork. Form generated processes are the same as the previous concrete component production process.

Distances have been obtained from the parametric model. Pin positions are set in the previously determined positions. Because the first vertical concrete component production process resulted successfully, the pin depth values are pushed to the limitation in this production. Without going beyond the specified limits of surface and pins given in Table 36, the pins were pushed as far as they could be placed. In this situation, middle pins for both surfaces are touched. The values are given in Table 37.

Table 36: Vertical Formwork II Computational Design and the X positions for the points, table drawn by the author.



The values are obtained from the parametric model, and the distance between two support surfaces has been arranged as the previous one. Also, the joint with the ground is fixed as in the previous one.

Table 37: Vertical concrete production II coordinate details and pin positions, drawn by the author.

Vertical Concrete Production / Trial II / Side A					Vertical Concrete Production / Trial II / Side B				
Formwork Pin Location				Pin Distance	Formwork Pin Location				Pin Distance
	Y	Z	X			Y	Z	X	
Point 001	40	10	2 cm	8 cm	Point 001	40	10	2 cm	8 cm
Point 002	40	40	2 cm	8 cm	Point 002	40	40	7,5 cm	2,5 cm
Point 003	25	25	8 cm	2 cm	Point 003	25	25	8 cm	2 cm
Point 004	10	10	1,5 cm	8,5 cm	Point 004	10	10	3 cm	7 cm
Point 005	10	40	1,5 cm	8,5 cm	Point 005	10	40	1,5 cm	8,5 cm
Concrete Material					**Volume**				
Pozzolanic Cement					13,5 lt				
Water					9 lt				
Aggregate					30 lt				

Figure 26: Second vertical concrete production process, developed and photographed by the author.

The concrete mixture details can be seen in Table 37. The composition of the concrete is again within the allowable ranges. Based on the experience of the first experimentation, a less fluid concrete mixture is prepared. The amount of water is decreased, and the cement and aggregate amount increased. The concrete curing process took two days. No overflowing is experienced. Although the formwork was used a second time, separating concrete from the formwork surface was effortless.

Figure 27: Second vertical concrete component production photographs, produced and photographed by the author

3.3.2.3 Horizontal Concrete Component Production

After vertical production, horizontal settlement is attempted to observe the behavior of formwork without changing the concrete mixture parameters. Since tunnel formwork covers both vertical and horizontal concrete production, it is required to experiment both settlements with this adaptive and reusable tunnel formwork.

In the horizontal settlement, pin behavior is important because, different from the previously made flexible formwork studies, this proposed system directly sits on the pins. The system needs to stand the concrete pressure, and pins need to carry all pressure.

The overall system needs to be revised in case of potential breakage or cracks due to the loads. It should also be noted that a single-sided concrete component can be produced in the horizontal settlement due to the configuration and working principles of the formwork. Pin positions and distances as well as concrete mixture details can be seen in Figure 29 and Table 38.

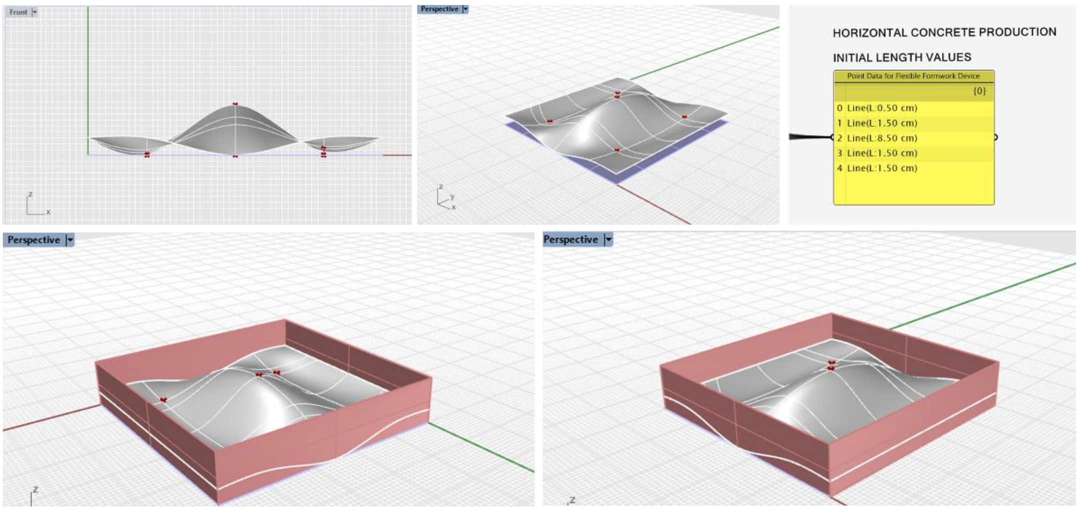


Figure 28: Horizontal formwork 3D Model from Grasshopper and Rhinoceros, drawn by the author

Table 38: Horizontal concrete production details. Pin coordinates and concrete mixture ratios, drawn by the author.

Horizontal Concrete Production				
Formwork Pin Location				Pin Distance
	X	Y	Z	
Point 001	10	10	0,5 cm	9,5 cm
Point 002	10	40	1,5 cm	8,5 cm
Point 003	25	25	8,5 cm	1,5 cm
Point 004	40	10	1,5 cm	8,5 cm
Point 005	40	40	1,5 cm	8,5 cm
Concrete Material			**Volume**	
Cement			13,5 lt	
Water			9 lt	
Aggregate			30 lt	

Like previous experiences, the computational model developed in grasshopper is used to determine the formwork's final configuration, such as the number of pins, distances among them, their locations, etc. Since the general setup is essentially designed for vertical use, in horizontal position system required extra arrangement. As it can be seen in Figure 30, a frame is built around the formwork to border concrete.

The concrete thickness is accepted as 10 cm on average. Although the formwork was used for the third time, any problems or difficulties were not experienced in concrete and formwork separation. Moreover, no harm on pins or severe surface deformations is experienced. It can be said that the proposed system functions quite well despite some problems observed in the final product.

Figure 29: Horizontal concrete component production with recursive and re-usable formwork. Framed with flat wooden supports for a concrete pour, developed and photographed by the author.

Figure 30: Horizontal concrete component production with adaptive and reusable tunnel formwork, produced and photographed by the author.

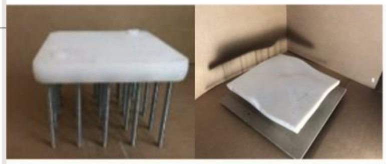
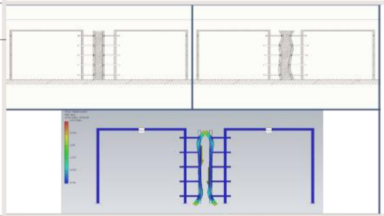
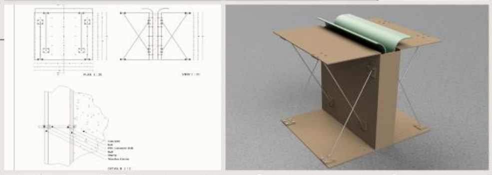
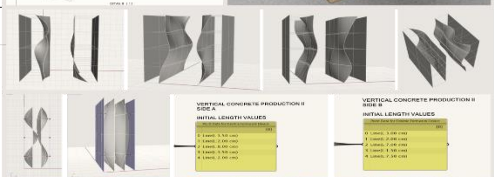
Close-up observations show some small shape deformations. In Figure 31, it can be clearly seen a whirlpool effect on the surface, which should not exist. This shape formed because of the concrete pressure on the surface.

Table 39: Concrete component production outcomes and understandings

Stage III Outcomes		
VERTICAL I	VERTICAL II	HORIZONTAL
8 Days concrete curing	2 days concrete curing	
Mixture was fluid	Mixture was in optimum ratio	
Shape produced successfully	Shape produced with some deformations	
No breakage experienced. Solid mass produced		
No significant flexion observed in pins		
Produced concrete mass and formwork separated easily		
Smooth surface is obtained		
No noteworthy overflow is experienced		

As a result, a system that receives feedback from the parametric model and translation into physical components has been developed. Concrete components have been produced vertically and horizontally with adaptive and reusable formwork.

Table 40: Summary of research. The table represents the formwork system evolution, the table drawn by the author.

Summary of Research Stages		
General Result		
	**Early Formwork Trials** • Pin positions cannot be replaced • Formwork requires formwork for itself • System cannot carry itself in vertical settlement • Expensive • Too much time is wasted when drying the formwork surface	
	Analysis of Formwork • Inspired from tunnel formwork settlement • Ground and top positions require extra support • With concrete pressure and the gravitational force pins do not create any displacement	
	Drawings and 3D Models of Formwork • From tunnel formwork drawings and analysis 3D model and technical drawings have been generated • Material and technic details of the system composition are decided.	
	Computational Formwork Design • Parametric model has been generated • Later the size of the parametric model has been arranged for produced formwork • Customized concrete component design has been generated	
	Vertical Concrete Component I • Pin depth values provided from computational design • Concrete component produced with developed formwork • Component produced successfully	
• Concrete component produced with flexible formwork vertically and horizontally • Pin depths are gathered from computational model • Formwork reused several times • Data of pin depths are obtained from computational model	**Vertical Concrete Component II** • Pin depth values provided from computational design • Pin depth positions pushed to the limits • Component produced with minor deformations	
	Horizontal Concrete Component • Horizontally placed parametric model have been generated • Formwork updated for horizontal settlement • Pin depth values provided from computational design • Due to the concrete pressure a whirlpool effect is occurred on surface	

CHAPTER 4

RESULTS AND DISCUSSION

This section covers the outcomes of experiments. Then, implications of the results will be discussed. Limitations, improvements, and some recommendations for adaptive and reusable formwork will be provided.

Both discussion and results will be carried on in the frame of *customized mass, adaptive formwork, and reusability* since they are the main objectives of this thesis.

This section covers the initial outcomes for overall experiments and analysis according to these findings. Later, in the discussion, the meanings of these results will be discovered. Then, implications of these results to the objectives and aims will be discussed. Limitations, improvements, and some recommendations for adaptive and reusable formwork will be mentioned.

Table 41: Result and Discussion framework, the table is drawn by the author.

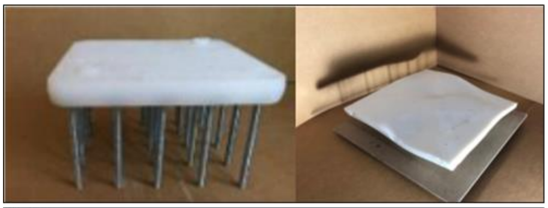
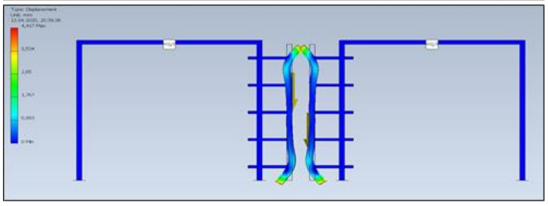
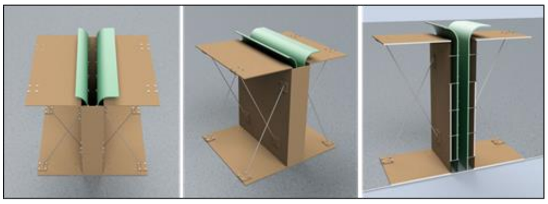
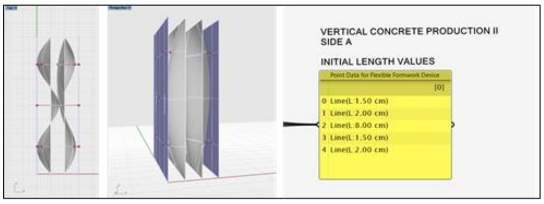
FORM DRIVEN ADAPTIVE AND REUSABLE TUNNEL FORMWORK FOR CUSTOMIZED MASS HOUSING
CUSTOMIZED MASS
FORMWORK
REUSABILITY

4.1 Results

Results are given in three sections. First, early drawings of formwork, 3D model analysis, and parametric setup will be discussed. Later, the integration of the parametric model into the concrete component production and manufacturing processes will be examined. Achievements and failures of the developed setup and the components will be analyzed.

Finally, reusable and adaptive formwork results will be reviewed according to experiences. This stage will be related to the adaptiveness of the system into design variations as well as the precision of the final concrete component. The reusability and sustainability of the formwork will be reviewed.

Table 42: Adjustable and reusable formwork evaluation and development process and the concrete component productions. The table is drawn by the author.

	Early Formwork Trials
	Analysis of Formwork
	Drawings and 3D Models of Formwork
	Computational Formwork Design
	Vertical Concrete Component I
	Vertical Concrete Component II
	Horizontal Concrete Component

4.1.1 Flexible Formwork Setup

This section covers the general outcomes and early understanding of flexible formwork designing and production processes. Firstly, the outcomes of previously realized flexible formwork outcomes will be analyzed. The understandings are listed below:

- The surface is the main focus of almost every study, and its durability, material, flexibility, and behavior affect all systems. All researches focused on the surface material and its configuration with the overall system.
- Computational design paradigms offer practicality for the complex form design process. However, conventional manufacturing methods are not sustaining and supporting this designing process.
- Doubly curved mass production is expensive and challenging to produce.
- Realized studies are mainly generated with small-scale production methods and provide a precast assembly method.
- The concrete freezing process requires time, and during the curing process, the formwork cannot use for another form production. Unfortunately, this causes time loss and increases overall costs.
- Only horizontal production methods have been experimented with these formworks because of gravitational forces.

Figure 31: Early flexible formwork experiences, produced and photographed by the author.

These observations are inspired to conduct a new alternative for tunnel formwork and flexible formworks, and with these understandings, two flexible formwork systems have been generated. Although these formworks have not resulted as intended, they helped configure the pin movement and surface material behavior. The outcomes of these two flexible formworks are listed below:

- Both formwork and surface material require formwork, which creates conflict and suggests an inconvenient production method.
- In order to have flexible movement, pin systems have been configured, and, in both systems, pins were embedded into the surface material. This situation caused a pin positioning that could not be changed.
- Although silicon rubber offers durability and flexibility, it is expensive and hard to adjust for larger-scale productions.
- RTV2 is too flexible for this system which cannot stand gravitational forces to carry itself. Whit this material, horizontal concrete mass has been produced. However, the vertical settlement could not be produced.

Also, after these experiments and knowledge, 3D models, drawings, and structural analysis have been held, and possible formwork decisions have been proposed. Here, tunnel formwork design and previous adjustable formwork setups are combined. Functional and flexible tunnel formwork systems are proposed.

Firstly, one pin-two surface system developed, and its 3D model and structural analysis have been explored. The results are listed below, and the details can be seen in Figures 33 and 34:

- While providing doubly curved mass production, this system does not allow a separate design for each side.
- Also, this setup does not allow to arrange thickness
- Figure 34 clearly shows that this arrangement cannot withstand gravitational forces and faces significant displacement, especially in edges.

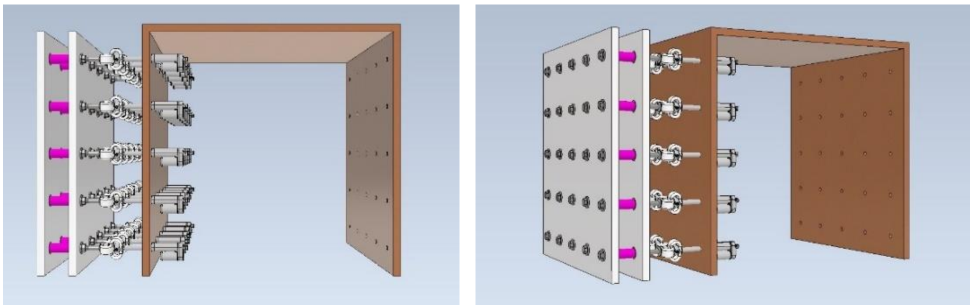


Figure 32: The first designed adjustable formwork 3D model, produced by the author

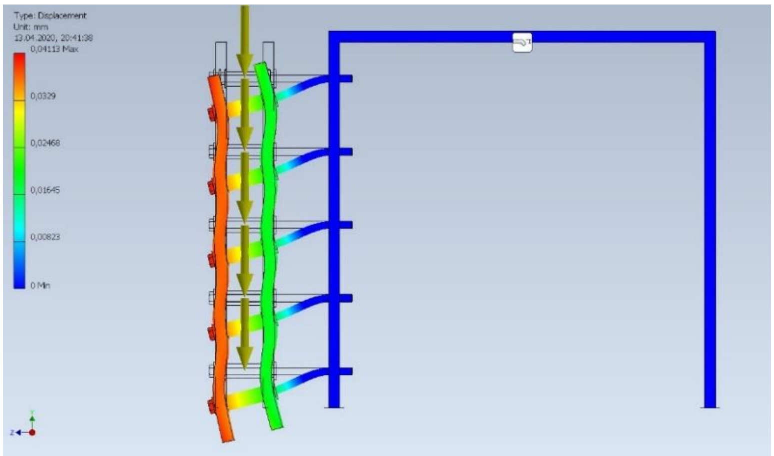


Figure 33: With gravitational forces and concrete pressure, the system cannot stand the load, and displacement is observed, the 3D analysis produced by the author.

Later, this setup is evolved based on the conventional tunnel formwork system, and for vertical settlement, the same analysis was performed (Figure 35). This analysis shows that surface can stand the lateral pressure of concrete, and also it can stand gravitational forces.

Ground and top positions need further considerations for displacement. In the analysis, the displacement measured almost 2 mm. Generally, in this kind of analysis, the representation of displacements is exaggerating to observe the material behavior better. Although these displacement values are not at high levels, it still requires adjustments for top and ground positions. Thus, this analysis has been considered before producing an adjustable formwork setup, and the overall system is arranged accordingly.

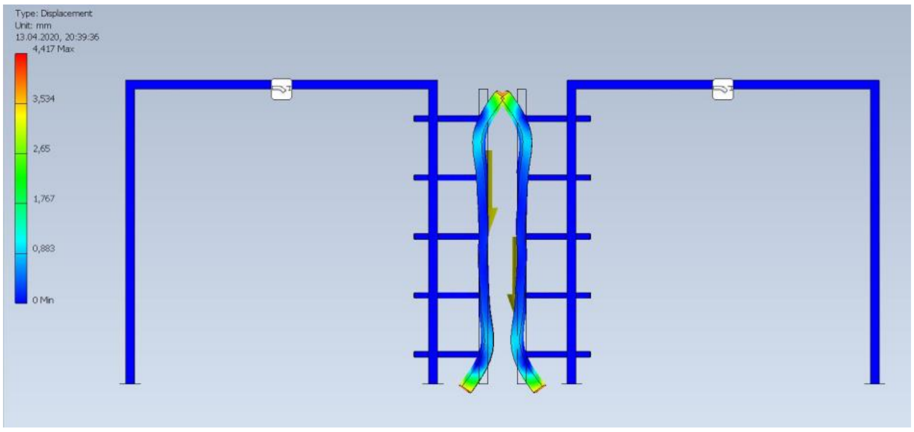
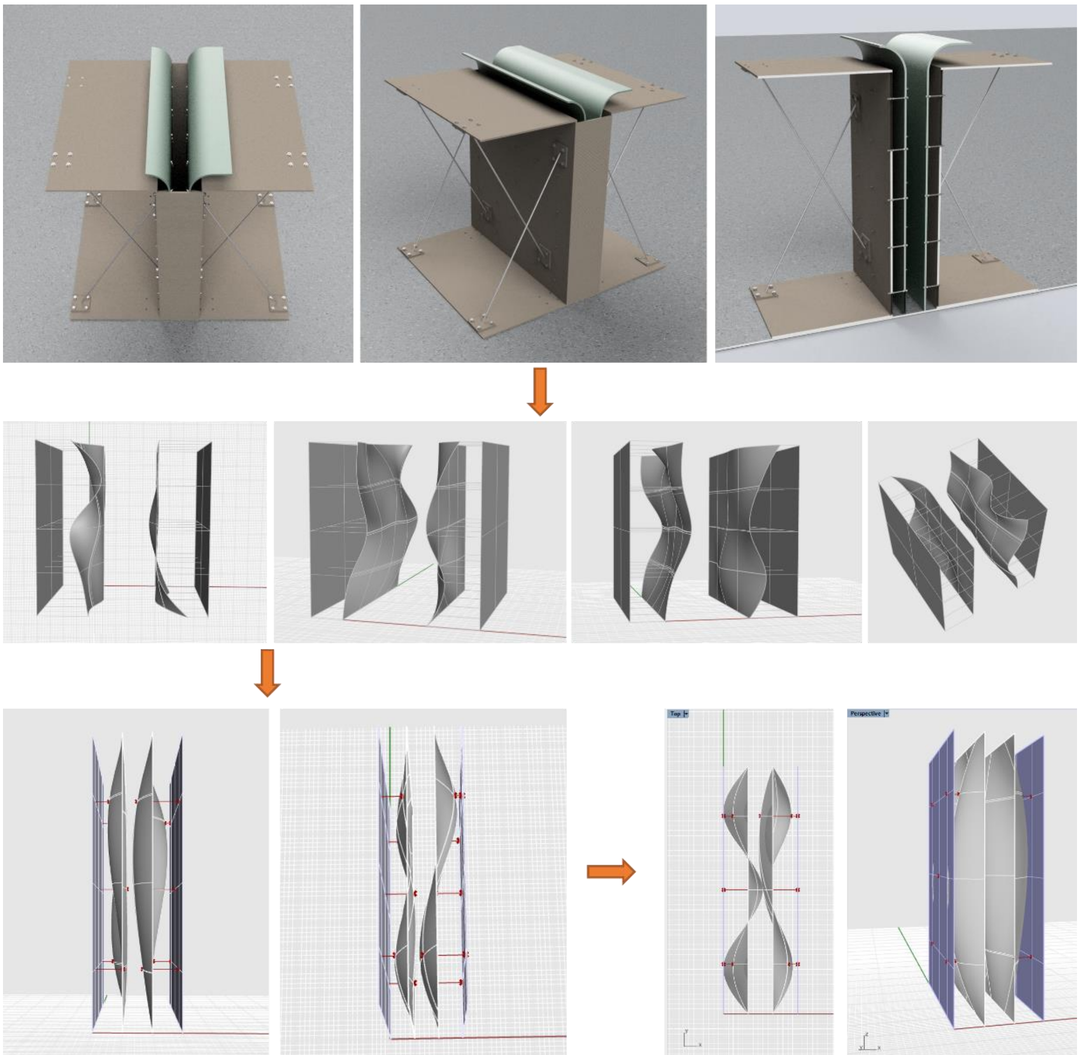


Figure 34: Evolved adaptive and reusable tunnel formwork load analysis, produced by the author.

After these analyses, 3D flexible formwork drawings have been produced, and the system developed according to initial adaptive and reusable formworks. The evolution of formwork design is shown in Table 43. First, the larger scale tunnel formwork inspired flexible formwork drawings produced. Then, a parametrical model is developed. Lastly, the producible adaptive formwork's computational configurations have been generated.

Table 43: Formwork model evolution process. Table and images produced by the author.



4.1.2 Customized Components: From Computational Design to Adaptive Formwork and Concrete Components

After formwork design is settled, a parametric model in grasshopper for formwork design has been developed as the last design step. This model provides the pin distances from computationally designed formwork design. It is also possible to provide the concrete components pre-designed representation. Thus, a system that provides data flow from the computational model was created. The advantage of the parametric model is listed below:

- It is possible to change scale and dimensions, which means that design becomes configurable from small to large scale.
- Coordinate-based points suggest re-configurable locations, and it allows to change design aspects, and when dimensions are changed, it is possible to arrange pin positions accordingly.
- The thickness between two flexible surfaces is arrangeable, allowing adjusting mass thickness due to the changed requirements such as reinforcement, wall thickness, etc.

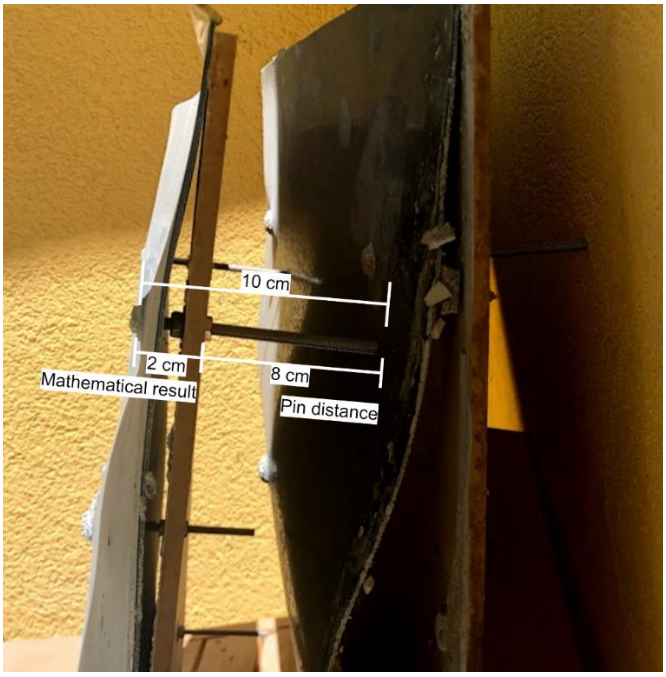
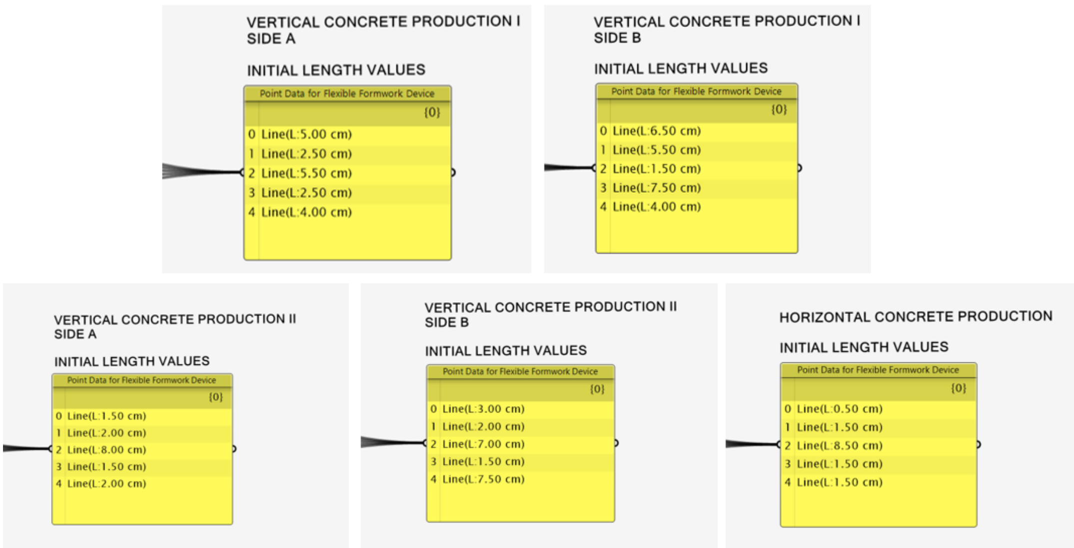


Figure 35: Pin distance and Grasshopper Mathematical result differences, produced and photographed by the author

- The parametric model allows pre-designed surface adaptation for the formwork. Thanks to determined limitations, a pre-designed surface can be tested and arranged accordingly before the concrete component production stage has begun.
- Designed Grasshopper components suggest adaptation to changing paradigms.
- Obtained mathematical results are not the distances that belong to the pin distance of formwork. Because pin distance is relevant to the pin itself, extraction from the pin distance from the model is necessary. In this design and formwork setup, the distance between support and formwork surface is given.

Table 44: These values are not showing the pin distances. It should be considered that pin distances are obtained by subtracting these values from the pin length, table designed by the author



As it said earlier, it is suggested that the surface material with more thickness should be used for larger structures. In the design stage, this should be considered with pin positions and limitations that affect the placement of the supporting surface. As a result, from the provided computational model, data-driven adaptive formwork has been generated. Formwork can be arranged and adapted for customized concrete component production from the obtained depth values and pin positions.

4.1.3 Adaptive Formwork: Concrete Component Production with Flexible and Reusable Formwork

This section explains the experiences of concrete component production with the provided formwork method. The positive and negative implications are outlined, and the system's overall evaluation and functionality will be discussed.

Suggested formwork has strengths, especially for curved customized concrete productions, and it is quite useful for larger and faster structures. The thickness adjustability of surface material makes overall formwork suggestions useful for different scales and designs.

As a result, two vertical and one horizontal concrete mass has been produced without any damage or significant problem. Since all previous adjustable formwork studies in the literature were realized in the horizontal position, vertical adaptive formwork can be considered a success in many ways.

Even though the main goal was to achieve the vertical settlement, it was also critical to accomplish the horizontal concrete production. This system is prone to damage its own structure, for which concrete pressure directly affects the pins and the surface forces exerted on. Despite the possibility of failure of surface material and pins due to applied pressure, the result was successful, and the designed surface was produced as intended.

Some general results about produced components are as follows:

- The thickness of mass for each mass is approximately 10 cm. However, in some pin positions, concrete thickness decreased by almost 1 cm. Vertical concrete blocks can stand by themselves. Average volumes for each concrete block are around 0.025m^{3,} and each block weighs around 85 kg.

- In the vertical concrete pouring and freezing process, no serious overflow was observed, which is one of the critical issues during the process. The surface withstood the concrete pressure and did not allow any leakage. In horizontal placement, corners and edges are sealed with plastic insulation tape. Insulation material did not stand the pressure when the concrete was poured, and the plastic position was displaced. Nevertheless, the surface and pins withstood all, and no leakage was observed due to the concrete pressure. On the other hand, the displaced material created undesirable marks and shapes on the concrete surface

Figure 36: Horizontal plastic seal material details on the concrete surface produced and photographed by the author

- After three complete customized concrete component productions, the formwork surfaces are still in re-usable conditions, and the overall system has no problem for possible future concrete production.

Figure 37: Designed and produced concrete masses, produced and photographed by the author

As a general result, it is possible to claim that designed and produced adaptive formwork setup allows multiple uses without creating serious problems. Nevertheless, the system still needs to be elaborated on due to the problems listed below.

- The formwork joints, which are corners, edges, and ground details, require more attention. Revisions like more support systems or durable bedding material can test.
- Although formwork’s flexible surface did not cause any problem, more tests with different scales are required. The system also needs to be used many more times recursively to assess its performance.
- The surface material, the conveyor belt, has differentiated thickness options. However, in this experiment, only 2 mm thickness has been used. From these experiments, it can be presumed that thicker materials may offer better behavior for larger-scale concrete productions, and more tests are required to verify the role of thickness in the performance.
- In the second vertical concrete component, middle points (Point 003) for each side were positioned in the excess depths, and when the formwork system became closed volume, middle pins were touching each other. Even in this situation, there is no problematic displacement observed. However, the concrete mass production with thicker concrete width may exhibit different

behaviors due to the concrete pressure. Because of the lack of data on thicker-width concrete experiments, these results do not indicate the initial pin behavior.

- Also, pin behavior may change in larger-scale productions as well. Because no experiments have been done on larger scale concrete mass production, pin behavior and overall system may create displacement, and the durability level may decrease.

At this point, precision is one of the critical points that need to be discussed. With these experiments, some minor faults have been observed in detail.

- Although there are no significant differences between the model and the produced component, some shape deformation still exists. Due to concrete pressure, the final product has some minor deviations in shape.
- Deformations are formed due to the pressure that is suppressed from concrete to surface material. The number of pins was not enough to compensate for pressed concrete pressure in this settlement. Deformations on the concrete component can be seen in Figure 39.

Figure 38: When surface material has insufficient tension and strain, it shows stretching due to pressure. (Produced and photographed by the author)

- This experience shows that surface material needs more tension and stiffness not to create unwanted shapes and deformations through pressure. Increasing the number of pins might also increase the durability and prevent these kinds of unwanted shapes. With more experimentations and differentiated pin position tests, better results can be obtained.
- Thicker material like 3 mm or 4 mm may suggest more precision. On the other hand, thicker material offers less flexibility, and this surface material preference may affect its adaptation feature.
- Also, because the surface has been configurated with vertical curves in computational design, the form shows different behavior than the produced concrete component. In order to have a more precise form and close to reality, parametric design should update. The differences are shown in Figure 40.

Figure 39: Designed component and produced concrete component differences. Designed mass created with vertical curves, so the form directly indicates the vertical curvature feature. (Produced and photographed by the author.)

Overall, the system works satisfactorily despite the displacements that are occurred in local fragments of concrete components. In general, adaptive and reusable formwork has promising results in contexts of accuracy and precision. Depending on the computational design, arranging the surface material thickness and/or changing the number of pins may provide more accuracy and precision.

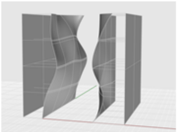
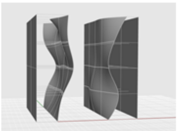
The reusability feature provides a sustainable feature to performed adaptive formwork. Below, can be found the inferences about sustainability from this study.

- As the experiment shows, the formwork system can be used several times adapting to different surface topologies, which reduce the waste material out of the formwork both in its production and its use and thus improve its sustainability
- Thanks to the parametric model, it is also possible to calculate the volume of the component. This calculation provides to determine the amount of the material. Thus, efficiency is ensured not only in terms of formwork but also in terms of material.

- Experiments show that adaptive and reusable formworks can provide time efficiency, especially for larger-scale concrete structures, compared with other customized mass form productions.

It can be claimed that such formworks can be adapted for large-scale productions, reducing the cost and embedded energy in the formworks.

Table 45: Intentions and Constrains, Problems, Failures, and Results. (Table is drawn by the author)

Intended	Constrains / Problems / Failures / Results							
		Surface	**Pin**	**Concrete Mixture / Time**	**Gravitational Forces**	**Concrete Pressure**	**Accuracy and Precision**	**Overflow**
	**Vertical Concrete Component I**	Formwork Surface: No problem, tearing is observed Concrete Component Surface: No serious deformations observed	No serious displacement is observed No breakage is experienced Pin depth values are in limitations	• 7 Lt Cement, • 10,5 Lt Water, • 22 Lt Aggregate 8 Days concrete curing	Formwork: Caused no significant problem on the system Concrete Component: Caused no breakage on concrete component	Formwork: No problem or breakage is occurred in formwork system.	Complete accuracy could not be provided Parametric model need revision	
 	**Vertical Concrete Component II**	Formwork Surface: No problem, tearing is observed Concrete Component Surface: Minor deformations is observed	Minor displacement is observed No breakage is experienced Pin depth values are pushed to the limits	• 13,5 Lt Cement, • 9 Lt Water, • 30 Lt Aggregate 2 Days concrete curing	Formwork: Caused a minor displacement on pins Concrete Component: Caused no breakage on concrete component	Formwork: No problem or breakage is occurred in formwork system. Caused some shape deformations of formwork surface	Accuracy and precision could not be provided Number of pin need revision	No overflow is experienced due to the formwork surface deformations, gravitational forces and concrete pressure
	Horizontal Concrete Component	Formwork Surface: No problem, tearing observed Concrete Component Surface: Minor deformations is observed / A whirlpool effect is occurred	No serious displacement is observed No breakage is experienced Pin depth values are in limitations	• 13,5 Lt Cement, • 9 Lt Water, • 30 Lt Aggregate 2 says concrete curing	*In horizontal concrete settlement gravitational forces and concrete pressure suppressed together* Formwork: Caused no significant problem on the system. Caused temporary shape deformations on surface material Concrete Component: Caused shape deformations on the component surface		Precision could not be provided completely Surface material requires more support	

To summarize, this research mostly achieved its objectives and created customized concrete masses with adaptive and reusable formwork. It is likely to adjust this setup for the tunnel formwork method for larger-scale productions and suggest sustainable and waste-free complex form creation.

Table 46: Summary for results, drawn by the author

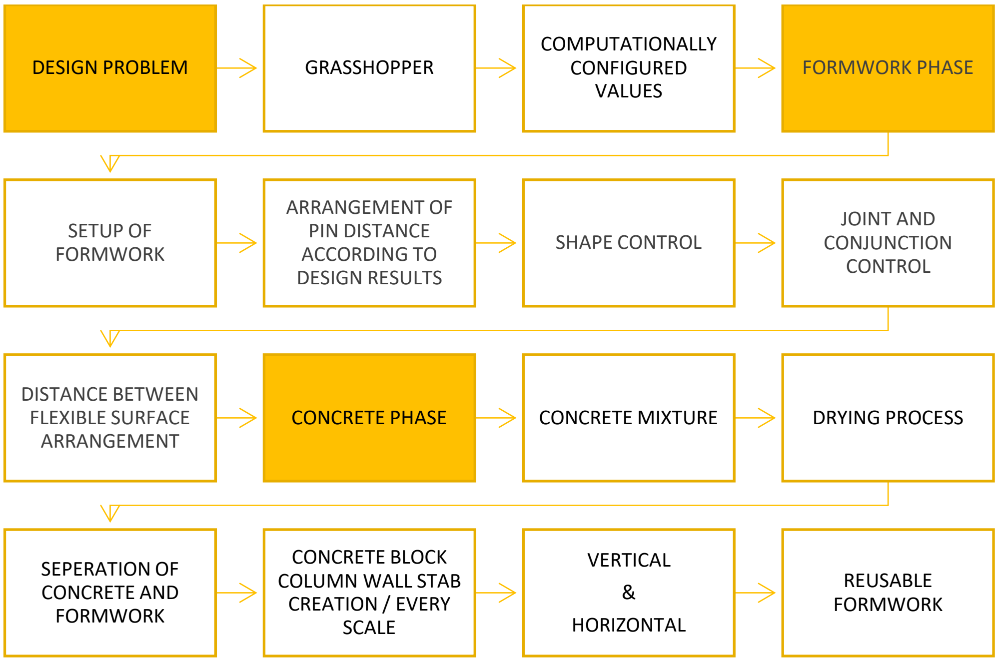
	CUSTOMIZED MASS	FORMWORK	REUSABILITY
FORM DRIVEN ADAPTIVE AND REUSABLE TUNNEL FORMWORK FOR CUSTOMIZED MASS HOUSING	• Changing the stereotyped situation • Providing the healthy and designed spaces • Cheap and accessible • Not only for mass housing but also for individuals can change the living spaces • Personalization and customization	• Flexible surface material • Dynamic pin • tunnel formwork adjustment • Precast vs In-Situ • Speed • Cheep and accessible • Easy manufacturing • Horizontal and vertical	• Sustainability • Reduced material • Less waste concrete material and no formwork waste • Time and cost reduction • Efficient material consumption • Multiple time use • In-Situ production • No transportation and assembly problem

4.2 Discussion

This chapter covers the discussion by evaluating the aim and objectives of the data-driven controllable adaptive formwork experiments. Providing vertical, flexible, and reusable formwork for customized mass was the main goal of this thesis. An economical and sustainable solution without compromising design freedom is wanted to achieve. After the results, it is possible to claim that this formwork promises some innovations for customized mass productions.

The system suggests an adaptation for changing digital design tools and paradigms and suggests a new method for customization. From point to the surface and from design to production, it is wanted to frame a new method with adaptiveness. It was aimed to give a new perspective to conventional and known concrete production methods. The cost of construction that is related to formwork is wanted to be reduced. With experimented formwork, minimization of material loss, efficient time management, and reducing overall construction costs are likely to be achieved in large-scale productions. It is possible to increase the speeds of customized concrete mass production without compromising the quality. Also, unlike precast production, it offers in-situ and eliminates the transportation and assembly risks. In the current situation, customized designs can only be produced with unique formwork that can only produce one design or flexible formwork methods that offer only horizontal production methods for small-scale forms.

Table 47: Design to construction steps, table drawn by the author.



- Precast causes a slow production process. On the other hand, flexible tunnel formwork offers faster production methods, especially for larger-scale concrete productions.
- The analysis supports that this adaptive formwork can stand gravitational forces.
- Adaptive formwork offers a less complicated production method for complex form-making. Also, according to the analysis acknowledged in the previous

section, this production method minimizes the manufacturing steps and reduces the failure risks.

- Because most of the steps are automized, the need for labor is reduced, and failure possibility has been decreased.
- Reusable formwork offers repeated use, and because of the unnecessity of having new and unique formwork, costs related to formwork will be reduced. Furthermore, as it is already said that waste material is reduced too. Overall adaptive and reusable formwork offers both sustainability and economical customized concrete mass manufacturing.

Suggested tunnel formwork system offers not only customization for mass housing but also to have customized masses. From small to large scale, suggested formwork can adapt for differentiated concrete mass and differentiated purpose. Initially, this study is not limited to the mass housing concrete structures. Although it can adapt for a different scale, the main motivation is to suggest customized mass housing with adaptive formwork to have accessible and customized mass living areas. *Designed space for everyone* in Industry 4.0 era should be available. Thus, with the evolution of this tunnel formwork, stereotyped and impersonal housing is possible to change in the future.

Form discussion is significant for architecture. Especially in housing, *evaluating the masses* that people live in, *increasing the quality of life, and reveal undiscovered opportunities in the nature of architecture itself*. It is valuable to evolve the conventional method instead of suggesting a brand-new production method.

Complex Structures with Different Purposes and Scales

Selvika, HavØysund, Norway, 2012,
Arch: Reiulf Ramstad Arkitekter / Landscape Architecture

Kouhsar Villa, Kordan, Iran, 2013,
Arch: NextOffice – Alireza Taghaboni / Single House

Pool House, New Delhi, India, 2014
Arch: 42mm Architecture / Single House Project

Elbphilharmonie, Hamburg, Germany, 2016,
Arch: Herzog & de Meuron / Theater

Apartments on Ave. Maréchal Fayolle, Paris, France, 2018,
Arch: SANAA / Housing Complex Project

Uredd Rest Area , Inndyr, Norway, 2018,
Arch: Haugen - Zohar Arkitekter / Landscape Structure

Figure 40: Complex concrete architectural examples that have different purposes and scales. (The table has been drawn by the author; images are taken from the Archdaily website.)

4.2.1 Limitations and Weaknesses

The major challenge of this study is the development of a flexible and reusable formwork that can stand both gravitational and lateral forces in the vertical settlement. Especially surface material is the key point of this formwork. From these experiments, it is understood that surface material behavior through concrete pressure needs to be improved. In order to create more accurate results, more experiments and tests are required.

More experiments should be realized in order to generalize the limits and behaviors in different scales. Changing the number of pins, positions, and surface material thickness, with different design and scale configurations is necessary. This research frames the future studies and set a new perspective for tunnel formworks to have adaptive and reusable feature.

Additionally, the conjunction points and surface material’s positioning with the ground need to improve especially for larger-scale concrete component productions. Due to the time limitations and space/material constraints, larger-scale experiments could not be realized.

Also, more alternated pin tests and more thickness-modified surface material experiments should be performed to eliminate surface deformations due to the concrete pressure.

As a result, more experiments are required to eliminate these limitations and weaknesses. Pin, surface, and concrete pressure behaviors need to be observed, and these weaknesses should be solved.

CHAPTER 5

CONCLUSION

This thesis aims to explore the possibility of customized concrete mass component production with flexible and adjustable formwork by using tunnel formwork systems. This suggestion may be the solution since the waste-free formwork methods are not discovered, and non-standard designs are built with huge costs and problems. **Adaptive Tunnel Formwork** suggests decreasing human mistakes and construction budgets.

The suggested formwork system offers customization for mass housing and provides customization for **all scaled concrete components**. From small to large scale, suggested formwork can adapt for different forms and purposes. Initially, this study is not limited to the mass housing concrete structures. Although it can adapt for a different scale, the main motivation is to provide a customized mass housing with this tunnel formwork evaluation. *Designed space for everyone* in Industry 4.0 era should be available this stereotyped and impersonal housing situation re-arrange.

With this study, evolving the known methods, integrating the novel computational technologies, and minimizing the human factor to reduce failure possibility is targeted. Today, formwork is more complicated than the form itself, and with adaptive and reusable formwork, simplification the manufacturing steps and minimizing the construction costs for customized mass components are aimed.

Building customized mass without compromising cost and **sustainability** is a huge design issue and needs higher integration techniques between form, material, and manufacturing. This study suggests not only customized mass housing but also for all proportions of structures.

Tunnel formwork is a well-known system that has been using for a long time in the construction industry. Evolving known systems without compromising production speed, durability, and costs makes adaptive and reusable tunnel formwork more practical. Since mass housing construction needs to be built fast and durable without having a huge economic outcome, customization in the recent situation is not suitable for this type of buildings. This thesis targets not to change these advantages of tunnel formwork and to have a customized mass housing.

As a result, computationally configured data guides the adaptive formwork surface. With the reusable and adaptive feature, an evaluated version of tunnel formwork is developed. Also, designing and manufacturing steps are co-processing in almost every step of the production process. Customized concrete components with various scaled and designs can be realized with this simplified formwork.

5.1 Future Work

Future research can maintain in five main aspects. According to the experiences from experiments, these five areas need to be revised.

Firstly, and most importantly, larger-scale adaptive and reusable tunnel formwork needs to be experienced. The system's overall behavior and its durability need to be tested. In order to provide this system for mass housing, differentiated sized tests and experiments are necessary.

Later, pin position variations should be tested to have a more accurate and more precise mass surface. As mentioned in the results, some detailed deformations were observed, and in order to solve this problem, more surface and pin combination research should be performed. An increased number of pins might also increase accuracy, and while doing that, it may affect the flexibility of surface material. So, in order to have better results, pin and surface behaviors and more alternatives need to be tested.

Table 48: Possible future studies, drawn by the author

FUTURE STUDIES:

- Larger Structural Production
  - Real size or larger scale concrete production with adjustable formwork
  - Structural analysis of designed structure / mass
  - Precision analysis of produced structure
- Adaptive Pin Position Study
  - Arrangeable and changeable pin order and location
  - Grid system
  - Create more precision and accurate result
- Bidirectional Production
  - Horizontal and Vertical placement at the same time
  - Corner conjunctions and flexibility arrangement
  - Ground and formwork details
- Pin Automation
  - Data driven pin automation
  - Standardized pin distance and movement with pneumatic pin pistols
- Maintenance
  - Maintenance routine must be determined
  - Surface material and pin durability should be tested
  - The number of successful repetition should be determined

With this thesis research, horizontal and vertical experiments have been tested. As a future project, *bidirectional production*, which can be considered as both horizontal and vertical production at the same time, needs to be tested. Tunnel formwork offers a system that can be produced both vertical and horizontal settlement concrete production simultaneously. This feature can be integrating into this adaptive and reusable formwork system.

Also, for pin movement, automation systems can be tested. The automation that takes its values and pins' depth distances directly from the computational model might be a novel approach for data-driven manufacturing methods. Automation eliminates major steps and human involvement in the production process.

Lastly, the maintenance and repair of the overall formwork system can be tested. Generalization and formalization of the maintenance of the system and determining the schedule for this process has great importance because, after several usages, many problems and malfunctions can begin to appear, and this risk should be tested and calculated.

Form-driven adaptive and reusable tunnel formwork offers a promising result. It presents more research subjects for the future. Especially, the vertical settlement on a larger scale should be more tested. Producing customized mass and adapting the benefits of tunnel formwork concrete fabrication method has both challenges and potentials. Further research is required to establish based on evaluation of these future studies that are mentioned above.

Table 49: Summary and Conclusions of Chapters

	HEADINGS	SUMMARY	OUTCOMES
CHAPTER I Introduction and Background	• Problem Statement • Aim and Objective of the Research	• With Industry 4.0, data-driven architecture has begun more common in practice. • With computation, architects can explore complex and sophisticated designs.	• Need of fast housing created mass housing requirements. • Flexible vertical/horizontal and reusable tunnel formwork for mass customization wanted to develop.
	• Scope	• Tunnel formwork provides economical and sustainable solutions for increasing populations.	• Economical and sustainable design in the production is targeted with the evaluation of tunnel formwork
CHAPTER II Literature Review	• History of Concrete and Mass Housing • Customized Mass	• Concrete is fundamental element for architecture. • Mass housing became widespread, and urbanization is promoted.	• Social house standards have been led to planned urbanization. • Novel technologies in construction and innovations in building materials, energy systems are not integrated
	• Formwork and Concrete Relationship	• Structural formworks differentiated through the requirements and size of the structures.	• Customization with formwork, is still an issue independent from the size and function and formwork is more complicated than the form itself
	• Formwork and Complex Concrete Shape • Precast vs In-Situ Concrete Production • Digital Fabrication Methods • Additive Concrete Manufacturing and Formwork Comparison • Experimental Formwork Studies	• Complex concrete forms produced with different methods. • Digital fabrication methods such as robotics, AM and fabric has been integrated to formwork studies.	• Customized mass designs generally produced with precast method.
	• Critical Review for Literature Review	• Newly emerging technologies and parametric design enabling control of form digitally and physically offer remarkable potentials.	• Formwork is still an important issue in construction, and novel formwork designs will contribute a lot to construction practice and building design.

CHAPTER III Research Design	• Phase I: Understanding Form and Formwork
	  • Understanding Formwork
	  • Flexible Formwork Studies
	• Phase II: Digital Design and Numeric Valued Control
	  • Digital Design of Adjustable Flexible Tunnel Formwork Suggestion
	  • Computational Design and Control
		• Various techniques have been used as adaptable formwork for complex forms and structures.
		• All these works were carried out in *horizontal position* and *precast* setup.
		• Early formwork experiments have been tested for adaptive and reusable formwork and materials have been experimented.
		• Analysis and drawings have been developed for adaptive and reusable formwork.
		• Grasshopper model of formwork has been generated and details are given.
			• In most precast implementation, flexible formworks are used horizontally to overcome problems like the non-uniformities due to agglomeration in thickness and the dead weight of the concrete itself exerting considerable lateral forces in the case of vertical settlements.
			• From the experienced early formwork study, surface material should be more adaptive.
			• Suggested formwork system needs to develop for vertical settlement.

	• Phase III: Concrete Production with Flexible Formwork
	  • Formwork Setup
	  • Concrete Production
	  • Vertical Concrete Production I
	  • Vertical Concrete Production II
	  • Horizontal Concrete Production
		• Adaptive and reusable formwork is produced.
		• Digital designs of mass' have been generated and pin data have been obtained.
			• 3D model and grasshopper setup established to control design and set limitations.
			• Three concrete mass successfully produced without any serious breakage and displacement.

CHAPTER IV Results and Discussion	• From Digital Design to Formwork Adjustments	• From digital design to real concrete production data flow and experiences explained. • Early formwork study results discussed	• Analysis and early experiments showed that manufacturing steps and used materials should be evolved for vertical concrete production and have adaptiveness and reusability. • Obtained pin distance need to integrate better with physical formwork.

	• Concrete Production with Recursive Re-usable Formwork
	  • Vertical Concrete Production I Results
	  • Vertical Concrete Production II Results
	  • Horizontal Concrete Production Results
		• Created concrete mass quality and details are discussed
		• Positive and negative impacts of the tested adaptive and reusable formwork have been examined
			• Although produced concrete mass do not have serious problems, in details some deformations have been observed.
			• Precision between design and production is not fully achieved.

	• Discussion • Limitations and Weaknesses	• This chapter covers the discussion by evaluating the aim and objectives from the data-driven controllable adaptive formwork experiments • Limitations and problems have been explained	• From these experiments, it is learned that this research is promising for larger-scale concrete mass designs. • Due to the only small-scale experiments, more test are required.
CHAPTER V Conclusion	• Conclusion • Future studies	• Summary of thesis and the overall results have been reviewed • The possible further studies and research are listed	• Form driven, adaptive and reusable formwork evaluation of tunnel formwork is promising for mass housing customization

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