Integrating Computational Fabrication Methods with Architectural Education

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Today, technology is developing rapidly. It changes architectural design and building techniques. To these changes up education system should be updated and be integrated with the novel technology. Tomorrow's professionals only be educated with this way. To make novel technology a part of architectural education, computational fabrication laboratories should be established and be integrated with architectural curriculum. They have the potential to transform architectural education processes. Within this context, this study tries to integrate computational fabrication methods with architectural education. The aim of the study is to share the process and results of a series of exercises applied to the use of computational fabrication tools and methods at the undergraduate level of architectural education. The study deals with exercise processes in a multidimensional scope. In this framework, constructivist learning processes, the concept of metacognition, the flipped classroom model and portfolio evaluation method played a role in the creation and evaluation of the exercise processes. Integrating computational fabrication laboratories with educational processes brings the student to play an active role in the exercise process. This approach is defined as constructivist learning process. In this way, it is ensured that the students can construct their own thinking and understanding processes. While the verb "teaching" is in question in conventional or objectivist education processes, the verb "learning" comes to the fore in constructivist processes. The instructor does not give the information directly but directs the student to reach the information. Flipped classroom model and portfolio evaluation are used as the methods of this study. The background of the exercises is supported by constructivist learning processes and metacognition concept. Within the exercise processes computational fabrication processes such as CNC laser machining and robotic milling were experienced. Within this study four exercises were performed to make the students experience computational fabrication methods: Unfolding, Tessellation, Sectioning, Folding and Moulding. To evaluate the exercise series success portfolio evaluation method was used. The answers in the portfolio to the questions of "What is the aim of this study?" and "What did you learn from this study?" are compared with the aim and learning outcomes of the exercises. As a result of this study, it is seen that the students' knowledge on file-to-factory process is increased. They learned how to make ready a parametric model for computational fabrication. Based on student portfolios, it has been determined that students have begun to realize the potentials of computational fabrication tools. The students learned how to use computer aided manufacturing software, and even they could manage to define toolpaths on their own. This shows that, undergraduate architectural education level is not early to teach students computational fabrication tools and software.

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Sayısal Fabrikasyon Yöntemlerini Mimarlık Eğitimi ile Bütünleştirmek

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Günümüzde teknoloji büyük bir hızla gelişmektedir. Teknolojinin mimarlık alanındaki yansımaları tasarım ve üretim süreçleri bağlamında kendini göstermektedir. Geleceğin mimarlarının bu teknolojiyi kullanabilmeleri ve katkı sağlayabilmeleri ise ancak mimarlık eğitimi süreçlerinin güncellenmesiyle olacaktır. Sayısal tasarım ve fabrikasyon laboratuvarları eğitim sürecinin bir parçası haline gelmelidir. Bu bağlamda çalışmanın amacı sayısal fabrikasyon yöntemlerinin mimarlık eğitimi ile bütünleştirilmesine yönelik uygulanan bir dizi egzersizin sürecini ve sonuçlarını paylaşmaktır. Uygulanan egzersizler çok yönlü bir yapıya sahiptir. Egzersizlerin kurgulanma sürecinde konstrüktivist öğrenme süreçleri, üstbiliş kavramlarının yanı sıra ters-yüz edilmiş sınıf modeli, portfolyo değerlendirmesi gibi yöntemler kullanılmıştır. Öğrencinin ders sürecinde aktif rol oynadığı konstrüktivist öğrenme süreci egzersiz kurgusunun temelini oluşturmaktadır. Bu aşamada öğretme eyleminin yerini öğrenme eylemi almaktadır. Çalışma kapsamında dört adet egzersiz uygulaması yapılmıştır: Cisim açılımı, teselasyon, dilimleme, katlama ve dökme. Egzersiz süreçlerinin başarısını ölçmek için portfolyo değerlendirme yöntemi ile elde edilen veriler kullanılmıştır. Bu bağlamda öğrencilerin portfolyolarında “Sizce bu çalışmanın amacı nedir?” ve “Bu çalışmadan ne öğrendiniz?” sorularına verdikleri cevaplar ile egzersizlerin amacı ve öğrenim çıktıları arasında karşılaştırmalar yapılmıştır. Çalışmanın sonucunda öğrencilerin parametrik model oluşturma, bu modeli sayısal üretim süreci için hazır hale getirme ve sayısal üretim dosyasının hazırlanması konularında bilgi sahibi oldukları gözlenmiştir. Öğrenciler sayısal fabrikasyon yöntemleri ve araçlarının sahip oldukları potansiyellerin farkına varmaya başlamışlardır. Öğrenciler sayısal üretime ve simülasyona yönelik bilgisayar programlarını kullanabilmeyi başarmışlardır. Bu durum, lisans düzeyinde sayısal fabrikasyon yöntemlerinin başarılı bir şekilde yürütülebileceğini göstermektedir.

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1. INTRODUCTION

Becoming computational design and fabrication a part of architecture reveals the need of an architectural education process that includes fabrication processes and laboratory studies. Bob Sheil (2014) emphasises that the information exchange between design and fabrication is now in a fast flow and designing and making processes can be carried out simultaneously. The importance of computational design and fabrication laboratories in architectural education is increasing to be able to experience designing and making. At the end of the 1990s, new types of computational design laboratories began to be established in leading architectural schools (Celani, 2012). Considering today's schools that integrate computational design and fabrication with architectural education, it is seen that these processes are generally handled at the graduate education level. For example, Neil Gershenfeld's famous lesson "How to Make Almost Anything" is only open for master students (Gershenfeld, 2008). The same thing can be said for Institute of Advanced Architecture of Catalunya (IAAC)'s education system, too. Bob Sheil (2014) emphasizes that a new relationship has been defined between learning, technology, research, industry and practice, and in this context, the biggest dilemma of today's architectural education is the necessity of defining the designer's expertise within the scope of this developing technology. As digital fabrication laboratories become integrated with architectural education, they have the potential to transform architectural education processes (Celani, 2012). Although, "digital fabrication" has a more common usage in the literature, "computational fabrication" term is preferred in the study. Because computational fabrication emphasises making by computing, which is the focus of the study.

The aim of the study is to share the process and results of a series of exercises applied for the use of computational fabrication tools and processes at the undergraduate level of architectural education. The study deals with exercise processes in a multidimensional scope. In this framework, constructivist learning processes, the concept of metacognition, the flipped classroom model and portfolio evaluation method played a role in the creation and evaluation of the exercise processes. These concepts will be briefly explained.

Integration of computational fabrication laboratories with educational processes brings the student to play an active role in the exercise process. This approach is the core of the exercises processes and is defined as constructivist learning process. In this way, it is ensured that the students can construct their own thinking and understanding processes. While the verb "teaching" is in question in conventional or objectivist education processes, the verb "learning" comes to the fore in constructivist processes. The instructor does not give the information directly but directs the student to reach the information.

Wilson (1996), defines constructivist learning environment as a learning process which students work together, support each other, and supported by various resources and tools. Since this process is based on experience and learning by making, students create their own learning processes. In the constructivist education approach, first “knowing how” is experienced then “knowing that” is occurred (Schoenfeld, 1987). In this approach, metacognition is a frequently emphasized concept. Metacognition means learning how to learn, internalizing the learning process, being aware of the learning process. Schoenfeld (1987) describes metacognition as thinking on your own thinking process. Metacognition requires to ask some questions in the learning process: “Can you describe exactly what you are doing?”, “Why are you doing it this way?”, “What are the benefits of doing this?” (Schoenfeld, 1987). These types of questions deepen the learning process by making the people to fully explain what they are doing.

From the date of the constructivist learning approach presented (Piaget, 1971; Papert & Harel, 1991; Mahooney, 2004) till today, technological developments have occurred and even the definitions of generations have changed. Z generation, who are currently studying at universities, represents the generation born after 2000, also called the "net generation", "digital natives" (Erten, 2019; Twenge, et al., 2010; Oblinger ve Oblinger, 2005; Prensky, 2001). This generation finds it fun to watch digital contents. For this reason, visual contents and social media has been made a part of course items. Video lectures have become popular with universities such as MIT and Princeton broadcasting their lectures digitally (Ronchetti, 2010). These new types of lecture processes have revealed the concept of “Connectivism”

(Siemens, 2005). Video lectures flip the course process as doing the lesson at home and the homework at class. That is why the model is called as “flipped classroom model”. Flipped classroom model is performed in this study to teach the students the parametric modelling part of the exercise process. YouTube videos were prepared and shared with students each week.

Constructivist learning strategies involve individual learning process. In this context, it would be appropriate to use an evaluation system in which individual performance can be measured, which may have different effects for each student. For this reason, portfolio evaluation method was used to measure the students’ progress. Portfolio shows the students developments, abilities, and efforts (Hamm&Adams, 1991; Hypki, 1994). Portfolios reflect the learning performance and prove the situations achieved by the student (Popescu-Mitroia et al., 2015). Portfolio measures what a student can do rather than what they know. This adapts to the process-oriented nature of constructivist learning strategies. The portfolio evaluation method allows students to see their progress from the beginning to the end of the course period. Thus, it is possible to see the meaning of the workshops from the perspective of the student and to understand whether the exercises reach their goals and objectives.

To sum up the introduction, flipped classroom model and portfolio evaluation are used as the methods of this study. The background of the exercises is supported by constructivist learning processes and metacognition concept. Within the exercise processes computational fabrication processes such as CNC laser machining and robotic milling were experienced. Iwamoto’s (2009) and Kolarevic’s (2003) classifications on computational fabrication methods have used as a guide in terms of defining exercises.

2. EXERCISES ON COMPUTATIONAL FABRICATION

The exercises focusing on the computational fabrication processes were performed within the scope of a series of exercises designed to learn computational thinking (Figure 1). Among these exercise processes, the geometry-oriented one was applied in the third semester, the material-oriented one was applied in the fourth semester, the computational fabrication-oriented one was applied in the fifth semester, and the 1:1 scale fabrication-oriented one was applied within the scope of the elective courses related to the students of the sixth semester architecture department. Each exercise series begins with shape grammar (Stiny, 1980; Stiny, 2006; Knight, 2012; Tching et al., 2017) exercise. The shape grammar exercise is a transition exercise between conventional and computational design processes. Because it is a warming-up exercise its details are not explained.

The exercise series were performed with 65 students in total. Eight of them was completed the computational fabrication-oriented exercises which this study focuses on.

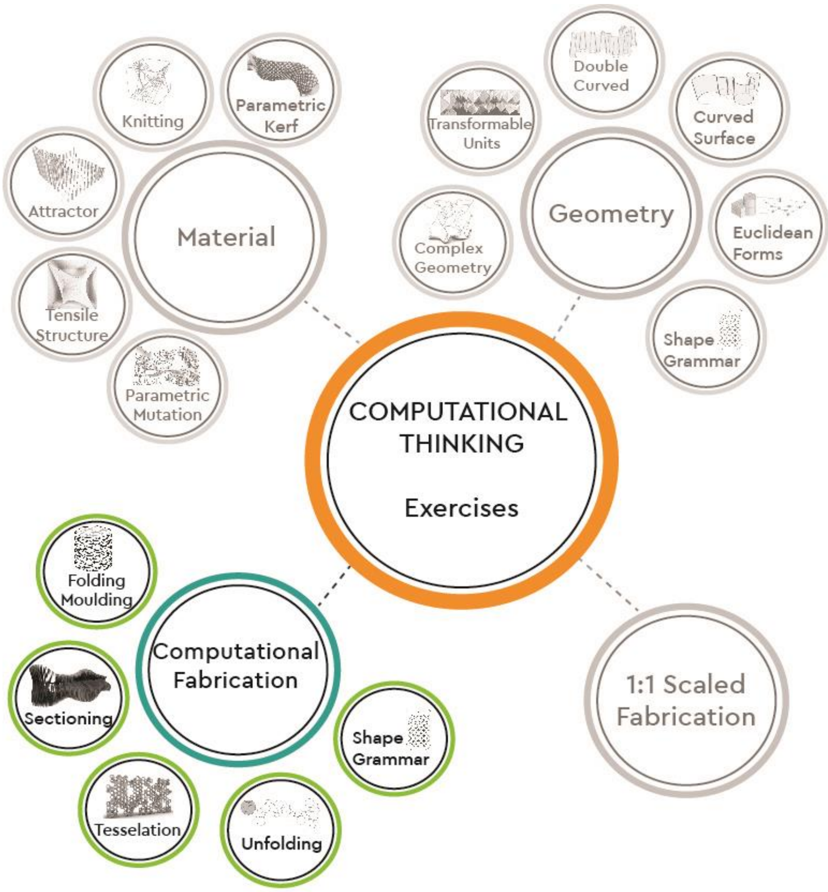

Figure 1: The overview of performed exercises

The exercises on computational fabrication methods were defined with the refence of the classification made by Iwamoto (2009). Some of this classification titles were renamed or combined according to the exercise process. Iwamoto (2009) classified computational fabrication techniques as sectioning, tessellation, folding, contouring, and forming:

Sectioning provides the same surface perception by lining up a series of profiles that follow the geometry of the surface, rather than constructing an entire surface. Thus, both the surface itself and its structure would be constructed.

Tessellation is the formation of the surface by arranging the sub-parts that build a surface without any gaps between them. The pieces come together like a jigsaw puzzle to form the whole. The logic of the mosaics coming together is one of the best examples of tessellation.

Folding enables sheet materials to be transformed into volumes. It is important not only in the creation of geometry, but also in the creation of the structure. With this method, the strength of the material can be increased.

Contouring is used in combination with subtractive fabrication. This method provides to obtain volumetric surfaces by processing a material with the milling method. In the study this method is experienced within the tessellation exercise.

Forming is a frequently used method for mass production. It refers to the production with moulding. The mould is produced by designing the negative of the surface / object and the final product is obtained by forming method. (Iwamoto2009) In the study forming is experienced within the moulding exercise.

The computational fabrication processes of the exercises were built on Kolarevic's (2003) classification. Kolarevic (2003) examined digital fabrication tools in four ways: two-dimensional, subtractive, additive, and formative. Two-dimensional fabrication refers to fabrication with CNC machine. Generally, sheet materials are fabricated by this method. Subtractive fabrication is the process of milling the design product from a block material by using electro-, chemical or mechanical methods. Subtractive computational fabrication can be performed with tools such as CNC cutting and robot arm. The difference from two-dimensional computational fabrication is that multi axis fabrication is used. Additive fabrication refers to fabricating the design product by adding the material on top of each other in a layered manner. For this reason, it can also be called "additive manufacturing". 3D printing is one of the most important tools of additive computational fabrication. Formative fabrication is reshaping a material with the help of a mechanical force such as heating. (Kolarevic, 2003)

Iwamoto's (2009) and Kolarevic's (2003) classifications define the main structures of exercises processes of this study. The exercises processes performed within this study focus on computational fabrication and they are summarized in **Figure 2**. The exercises are performed as a part of an elective course and completed with eight students.

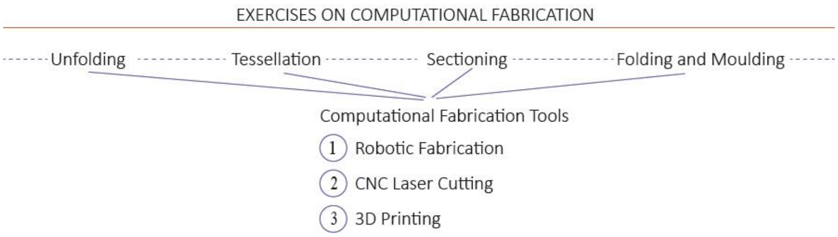

Figure 2: Exercises on computational fabrication

The exercises on computational fabrication consists of four exercises: unfolding, tessellation, sectioning, folding and moulding. The two main purposes of these exercise processes are to make the students to experience the computational design tools and to teach how file to factory process works. For each exercise various computational fabrication tools and methods are experienced. In the exercise process, a design problem is given to students. First of all, they try to find a solution, and think about how to define their design on a parametric model. In this phase they write the design phase step by step and then they try to perform the steps on the model. In this modelling phase Grasshopper plug-in is used because it allows the designer to see the whole design process. Thus, they find a chance to compare with the written steps and parametric model steps. Once the model is ready, the students prepare their files for computational fabrication. And in this phase, they see that each computational fabrication tool has its unique process. In this way, file to factory process is experienced.

The performed exercises are explained below. The aim of the exercise, the process, the learning outcomes, and selected outcomes are shared.

2.1 Exercise 1: Unfolding

The aim of the unfolding exercise is to make student to think about how a 3D complex shape can be created with a sheet material. In the exercise process, the student first tries to unfold the 3D shape with the conventional methods and then with the computational methods. This exercise gives a chance to experience the CNC laser cutting process. The exercise process is completed in two weeks:

1st week:
Some polyhedral forms in a digital modelling software environment are given to students **(Figure 3)**. Students can measure every detail of this form in this environment.

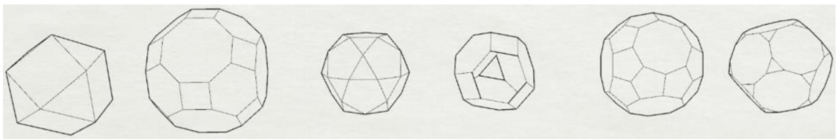

Figure 3: The first polyhedral forms

The first phase of the exercise is carried out with conventional methods. Students are asked to draw the unfolded form of their shapes first on paper and then in AutoCAD environment. In the first week the drawings are prepared for fabrication with the CNC laser cutting machine. As homework, slightly more complex polyhedral forms are given **(Figure 4)**. Students are asked to unfold those forms in digital environment.

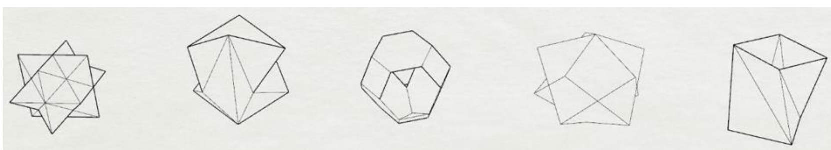

Figure 4: More complex polyhedral forms

2nd week:
Fabrication files for unfolded forms which was drawn both by conventional and computational methods are produced by CNC laser cutting machine. Joint details and production problems are discussed. Homework video for the next exercise is given.
The learning outcomes of this exercise are:

- To learn how to unfold a polyhedral geometry in both conventional and computational ways.
- To see the relation between sub-parts of a whole shape.
- To experience unfolding method one of the fabrication methods.
- To discuss about joint details.
- To experience both conventional and computational fabrication processes.

In the first phase of the exercise, only conventional methods were used, and in the second phase, the unfolding process was supported by computational tools **(Figure 5)**. Thus, both processes were experienced and the differences between them could be observed.

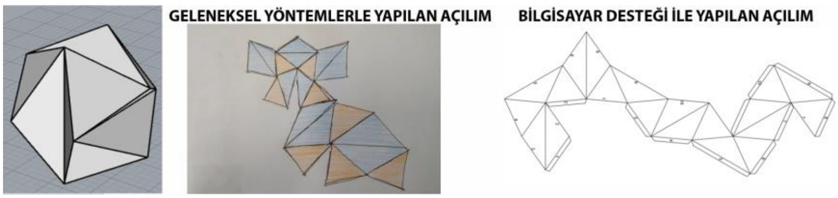

Figure 5: The difference between conventional and computational drawings

It was observed that the students were able to make the first simpler polyhedron unfolding by hand more easily, but they were able to do the proper unfolded forms with the help of computer for the second more complex polyhedrons. Thus, by unfolding with both processes, the students saw their deficiencies in three-dimensional thinking and had the opportunity to discuss the differences between the conventional and the computational process.

2.2 Exercise 2: Sectioning

Sectioning exercise focuses on producing a surface without compromising its integrity with its sections. The production process is carried out on a scale of 1:5. In the process, both the design and fabrication processes are carried out twice. In the first try, the students identify the problems they were confronted, and in the second try, these problems are resolved to obtain a more holistic surface. The aims of the exercise are to experience the design and non-standard mass production process for the sectioning method.

The exercise process is completed in two weeks:

1st week:

The design problem is defined as designing and producing a parametric bench. The parametric model is created by watching the homework video. In the video, surface creation with various sections, sectioning of the created surfaces in the XZ axis and panelization of the sections **(Figure 6)** are explained.

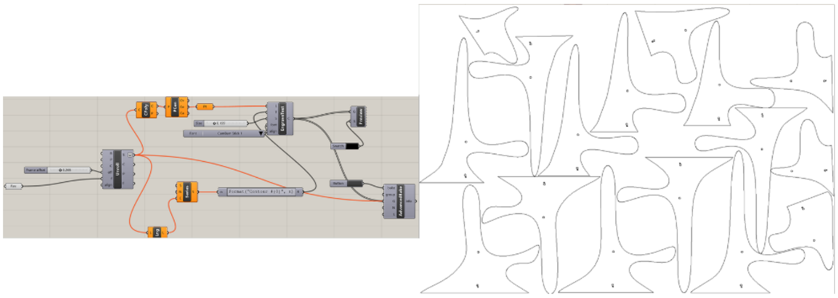

Figure 6: Panelization of parametric model

Student groups model their own designs and make them ready for fabrication. After the first designs **(Figure 7)** are produced problems related to design and details are discussed. As homework, it is requested to develop the same design and make it ready for fabrication.

Figure 7: The initial designs

2nd week:

The fabrication process on previous lesson is repeated **(Figure 8)**. A modelling video for the following week's design problem is given as homework.

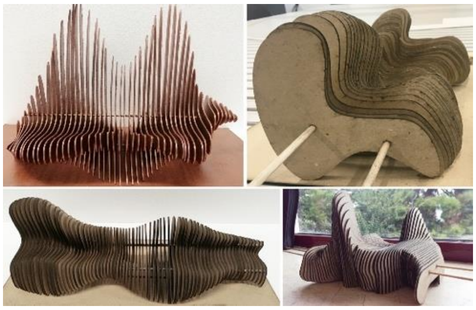

Figure 8: The reproduced designs

The learning outcomes of this exercise are:

- To experience the modelling and production preparation stages of the sectioning method.
- To be able to create sub-parts of a form by slicing without losing its visual integrity.
- To think on joints that make the structure durable.
- To experience non-standard fabrication process.

The exercise process was reconsidered in the second week of the exercise due to visual and technical deficiencies in the first designs. The students renewed and reproduced their designs by solving the joint details and aesthetic problems that they had determined from the first study. The results in the second study were quite different from the first, and the study process was successfully completed.

2.3 Exercise 3: Tessellation

The aims of tessellation exercise are to learn to model a dynamic design by differentiating the same sub-part and to experience robotic fabrication process. The tessellation method refers to the repetition of a subpart to form a surface. Within this exercise, the defined subpart was computationally differentiated and tessellated to design a wall. In the fabrication process robotic milling is used. In this exercise, since the students used the robot manipulator for the first time in the fabrication process, all the file-to-factory process was conducted by the lecturer and the process explained to students, step by step.

1st week:

The computational modelling steps are carried out by the lecturer. The surface modelled in the Grasshopper environment is produced in 1:5 scale **(Figure 9)**. In the production process, MasterCam software is used for the toolpath definition and Octopuz software was used for the robotic simulation. Students are informed about both software, and the preparation process for computational is explained step by step. Some concepts specific to robotic fabrication such as calibration of the robot manipulator, defining tool centre point, and the defining user frame are explained. The fabrication process is applied during the lesson.

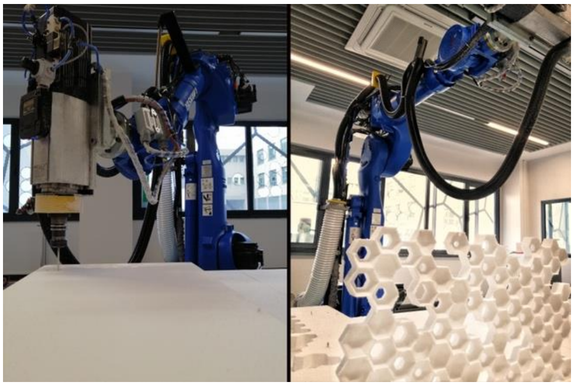

Figure 9: Robotic fabrication

The learning outcomes of this exercise are:

- To experience the modelling and fabrication processes of the tessellation method.
- To experience robotic milling process.
- To learn about mechanisms and working principles of robot manipulator.
- To learn about robotic calibration process.

During the exercise process, the design and fabrication processes of tessellation were discussed. This exercise is important for experiencing robotic fabrication. For this reason, the final product was designed by the lecturer and the fabrication process was organized by the lecturer. The students performed a similar modelling process.

2.4 Exercise 4: Folding and Moulding

The aim of this exercise is to bring computational fabrication and crafts together. This exercise is a two-step application. In the first step folding is performed with the use of CNC laser cutting method. With this step a mould is prepared. In the second step moulding process is performed and final product is produces.

1st week:

Students come to the lesson having done the pattern research that they can obtain by folding method. The folding templates found by the students are drawn in the CAD environment and prepared for fabrication with CNC laser cut. In preparation for the cutting process, the areas to be cut and the areas to be folded are determined. All cutting processes are completed until the end of the first lesson.

2nd week:

The three-dimensional shapes obtained by the folding method are prepared as moulds. The material to be poured into the mould is prepared. Within the scope of this exercise, white cement or plaster was used. The prepared material is poured into the moulds and left to dry **(Figure 10)**.

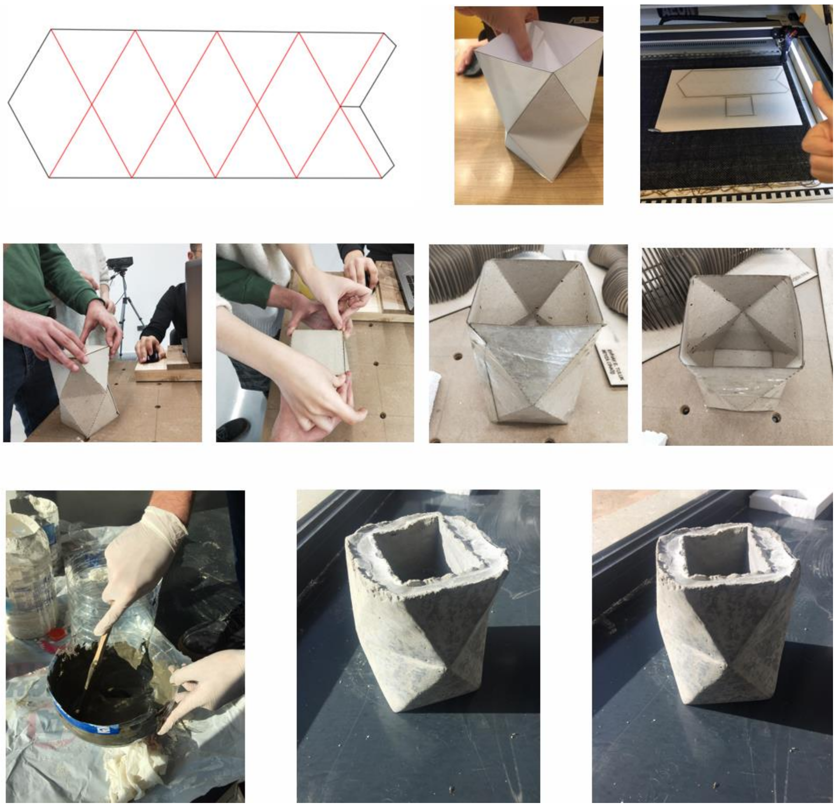

Figure 10: One of the selected works of folding and moulding

The learning outcomes of this exercise are:

- To use folding method for producing mould.
- To organize CNC laser cutting process for folding.
- To learn how to prepare moulding material and pouring process.

When the exercises on computational fabrication are evaluated as a whole, it can be said that the constructivist learning process, which allows students to experience is increased students’ learning motivations. It has been observed that students' encountering a problem in the process and trying to find a solution to that problem alone or as a team has a positive effect on the learning process. Students have experienced all the computational fabrication methods classified by Iwamoto (2009). Thus, they are expected to realize that the choice of digital fabrication method is also a part of the design process.

3. FINDINGS

The findings of the exercise processes involve to the students' comments on the aims and learning outcomes in the portfolios. These comments were compiled and presented in tables. Thus, it was tried to determine how the exercise was perceived by the student and which points were missing. Due to some exercise activities were carried out in pairs of students, only one of the comments is evaluated. The answers in the portfolio to the questions of “What is the aim of this study?” and “What did you learn from this study?” form the basis of the findings. In this context, the findings will be discussed within findings for aim and findings for learning outcomes.

The aim of the first exercise, the unfolding exercise, was developing the ability to think in three dimensions. When students' comments are examined **(Table 1)**, it is seen that they emphasize the transfer of three-dimensional forms to a paper in two dimensions. This study also provides the discussion of fabrication details such as thinking about the joint details, creating a form with the folding method. This exercise is important for build a base for further studies. It is seen that there are references to the two-dimensional and three-dimensional relations in the student comments, and in this sense, it can be said that the study has achieved its purpose.

Aim	Student Comments

To make student to think about how a 3D complex shape can be created with a sheet material.	S1: To establish a relationship between two dimensions and three dimensions and to think in three dimensions.
	S3: 3D shapes are tried to be thought of as 2D.
	S4: The aim of the study was to understand the sub-parts of 3D shapes and how they were combined.
	S7: To better understand the relationship between 3D and 2D, we converted the 3D object into 2D.

Table 1: The comparison of the aim of the unfolding exercise and student comments

In the context of learning outcomes, 6 out of 8 students who attended the course throughout the semester referred to at least one of the exercise's learning outcomes **(Table 2)**. Learning outcomes such as using computational methods to unfold a shape and thinking on details for the fabrication of this unfolded structure are important for the following larger scale and complex fabrication processes.

Learning Outcomes	Student Comments
To learn how to unfold a polyhedral geometry in both conventional and computational ways. To experience both conventional and computational fabrication processes.	S4: Thanks to this study, I learned that it is possible to have an idea about the unfolding of forms that seem very complex by first reducing them to the simplest unit.
	S5: The forms that were previously produced with conventional methods with a great loss of time and energy can be produced more easily and in a short time.
To see the relation between sub-parts of a whole shape.	S1: The relationship between three dimensions and two dimensions was understood more clearly.
To experience unfolding method one of the fabrication methods. To discuss about joint details.	S2: Thin materials are more suitable as thick materials will complicate the joining process.
	S6: The unfolding commands on Rhinoceros were learned.
	S8: We learned what kind of problems material differences can cause in fabrication.

Table 2: The comparison of the learning outcomes of the unfolding exercise and student comments

The aim of the sectioning method, which is the second exercise, is to create a model in a parametric way and to prepare this model for fabrication and to experience the non-standard mass production process. Students refer to the aim with keywords such as avoiding the usual and monotony **(Table 3)**. The students also emphasized the process of creating the computational model. In this context, it is seen that the aim of the study coincides with the students' opinions.

Table 3: The comparison of the aim of the sectioning exercise and student comments

Aim	Student Comments
To experience the design and non-standard mass production process for the sectioning method.	S1: The aim of the study is to design a bench that is more ergonomic, away from uniformity, and that people can enjoy.
	S2: To create a parametric bench by using Grasshopper.
	S4: To design a parametric product by using Grasshopper.
	S6: The aim is to create a different bench than the usual ones with an unusual design method.

When the students' comments are examined in the context of the learning outcomes of the sectioning exercise **(Table 4)**, it is seen that the students mention the problems they encounter during the fabrication process and the solutions they think on. Learning processes deepens when they experience the fabrication process personally. Students realize the importance of details and realize that it is a necessity to think about fabrication during the modelling process.

Table 4: The comparison of the learning outcomes of the sectioning exercise and student comments

Learning Outcomes	Student Comments
To experience the modelling and production preparation stages of the sectioning method.	S1: The computational process of the sectioning method was learned. In order to avoid errors in a curved section, all sections must have the same direction and the same number of points.
To be able to create sub-parts of a form by slicing without losing its visual integrity.	S2-S4: It was learned that the design phase was performed from the part to the whole, and the fabrication phase was made from the whole to the part.
To think on joints that make the structure durable.	S1: In the fabrication process, there were errors due to materials and construction methods. The pieces collapsed, and it was learned that at least one stick should have been used as joint element.
	S7: During the design phase, the structure of the parts was not considered, so the parts collapsed. Thus, a joint element was used.
To experience non-standard fabrication process.	*No comments about this learning outcome.*

Another important learning outcome of the sectioning exercise is to emphasize the concept of non-standard fabrication. However, it is seen that none of the students mentioned this concept. This situation can be considered as a negative side of the exercise process. Although non-standard fabrication is presented in the beginning of the semester, it is seen that students cannot establish the connection between these presentations and their studies during the semester. This concept should be explained more clearly in the future studies.

The aim of the third exercise, the tessellation exercise, is to experience the robotic fabrication process of a design product design with the tessellation method, and by using subtractive method. It is seen that most of the students refer to the aim of the study **(Table 5)**.

Aim	Student Comments
To learn to model a dynamic design by differentiating the same sub-part and to experience robotic fabrication process.	S1: To learn about the working principle of the robot arm and how to find solutions to the problems that may occur.
	S2: To comprehend the stages of 1:1 or scaled production of a parametric wall model using a robot arm.
	S4: The working principle of the robot manipulator and the softwares used for fabrication process were learned.
	S5: The production stages of robotic fabrication were learned.
	S6: The aim is to demonstrate the digital fabrication process of the product designed in Grasshopper and Rhinoceros.
	S7: To see how the parametrically created model is fabricated with robot.

Table 5: The comparison of the aim of the tessellation exercise and student comments

When the students' comments on the learning outcomes are examined **(Table 6)**, it is seen that no student refers to the tessellation method and the attention of the students is focused on the robotic production process. Since the students did not take an active role in the design process, they may not have referred to the tessellation method. In the robotic production process, it was observed that the attention of the students was not distracted during the lesson. It is seen that the students can properly understand the course process, which is a technical lecture. This emphasizes the necessity of integrating new experiences into the teaching process. In addition, it is seen that robotic fabrication methods can be learned at the undergraduate level.

Learning Outcomes	Student Comments
To experience the modelling and fabrication processes of the tessellation method.	*No comments about this learning outcome.*
To experience robotic milling process. To learn about mechanisms and working principles of robot manipulator. To learn about robotic calibration process.	S1: In this study, the working principle of the robot was learned. Before the fabrication process, the toolpath was created and then the process was simulated. The selection of materials, tools, etc. is important for the fabrication process.
	S2: We learned that the final product can be fabricated properly when the production stages are considered in a proper way.
	S3: MasterCAM and Octopuz software were experienced.First of all tollapath was defined on MasterCAM, and then simulation was performed on Octopuz. Finally robotic fabrication was carried out.
	S5: It was learned that how a parametric model be fabricated by robot. The toolpath definition and simulation processes were learned.
	S6: The meaning of G-code was learned. CAD to CAM process, MasterCAM software and simulation processes were experienced.
	S7: The working principle of a robot was learned. Simulation is important for minimizing the margin of error.
	S8: MasterCAM and Octopuz software were experienced.

Table 6: The learning outcomes of the tessellation exercise and student comments

The aim of the last exercise, the folding and moulding exercise, is to produce moulds with the folding method. In the students' comments, it is seen that the process of transforming a two-dimensional material into a three-dimensional shape is emphasized **(Table 7)**. The study is important in terms of bringing the two fabrication methods together and blending computational fabrication processes with conventional methods.

Aim	Student Comments
	S1: The aim was to produce a three-dimensional product from a two-dimensional

To bring computational fabrication and crafts together.	material. The unfolded form of an origami structure was produced.
	S2: Moulding process was performed with an origami structure.
	S4: The aim of the study was to make a 3D structure with the use of 2D material and with paper folding technique. This could be used to create wall modules, structures, etc.
	S5: It was aimed to create a form by using paper folding technique.
	S6: To produce a shape by folding method.

Table 7: The comparison of the aim of the folding and moulding exercise and student comments

It is seen that the students mostly refer to the mould making process with the folding method in their comments **(Table 8)**. This exercise is important for bringing computational fabrication methods and craft together. Conventional and computational making processes have their own kind of specific methods, and it is important to think these methods together.

Learning Outcomes	Student Comments
To use folding method for producing mould.	S1: It was learned that a three-dimensional form can be created from a two-dimensional material with the folding method.
	S2: Various forms can be created with origami method.
	S3: Various structures can be created with paper folding methods.
	S6: The designs can be produced with folding method by cutting with CNC laser. To produce with CNC laser the shape should unfold. Thus a mould could be produced.
	S7: It was learned that various forms can be created with the paper folding method and produced with a CNC laser machine.
To organize CNC laser cutting process for folding.	S1: Cutting method with CNC laser was learned.
	S2: It was learned that a form that can be unfolded can be produced by CNC laser cutting method.
To learn how to prepare moulding material and pouring process.	S1: It was learned that the mould should be made of a material that absorbs less water or that the mixture should be more viscous.

Table 8: The learning outcomes of the folding and moulding exercise and student comments

4. CONCLUSION

Education is the reflection of the future. Considering that computational design and fabrication processes will inevitably become a part of architecture. It should be accepted that computing and computational methods have become a part of architecture. This brings the necessity of changing the way of thinking.

This study offers a series of exercise process that integrates the computational design and fabrication methods with architectural education. In addition to this, the study searches flipped classroom model as a course method and portfolio as an evaluation method. The learning the software part of the exercises can be done as homework by YouTube videos. Thus, flipped classroom has a positive effect on the class that it can create a space for making. Portfolio evaluation method is useful for measuring the students' improvements. In the exercise processes every student organize their own learning process. This brings a difficulty for measuring the students. But in student portfolios how the student handles the problem, what the student learned or could not learn could be seen. Thus, it can be said that portfolio evaluation method matches with constructivist learning process.

One of the important outcomes of this study is integrating constructivist learning methods with education processes has a great contribution to learning process. In this way, students play an active role in learning process, and they have the chance to deepen their knowledge. Constructivist methods provide a steadier connection between the real world and the digital world. This also increases the student's motivation to participate in the lesson. The students begin to see the lesson as an activity, thus the problem of attendance in the lesson is prevented.

With reference to the findings, it can be said that the exercise processes are successful and fulfil the aim of teaching computational fabrication processes. Making computational design and fabrication laboratory a part of the education process, gives the students the opportunity to experience computational fabrication tools and methods. This has a positive effect on the learning process.

During the exercise processes, the students' knowledge on file-to-factory process is increased. They learned how to make ready a parametric model for computational fabrication. Based on student portfolios, it has been determined that students have begun to realize the potentials of computational fabrication tools. The students learned how to use computer aided manufacturing software, and even they could manage to define toolpaths on their own. This shows that, undergraduate architectural education level is not early to teach students computational fabrication tools and software. As a result, technology is developing rapidly. To catch up it, education system should be integrated with the novel technology.

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