COGNITIVE COMPARISON OF USING HAND SKETCHING AND PARAMETRIC TOOLS IN THE CONCEPTUAL DESIGN PHASE

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By

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COGNITIVE COMPARISON OF USING HAND SKETCHING AND PARAMETRIC TOOLS IN THE CONCEPTUAL DESIGN PHASE

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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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M.S. in Architecture

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With the advancements in the digital design tools, designers have been provided with new methods and tools, which lead them to new ways of thinking. The speed and impact of the use of digital tools in architectural design have increased at an astonishing rate in the last decade. However, the use of such tools in the initial stages of design, the concept generation phase for instance, still seems to be under the influence of hand sketching. The potentials, affects and the evaluations of the use of digital tools in the early phases of design remain to be investigated.

This thesis aims at examining the potentials of using parametric design tools in the conceptual design phase in comparison to hand sketching. It is intended to find out and evaluate the impacts of using parametric design tools on the cognitive behaviors of the designers, as well as assessing the satisfaction of the designers in using parametric tools in the early stages of design. Within this framework, an experimental study was conducted with three inexperienced and three experienced graduate architecture students using Grasshopper as the parametric design tool. A content-oriented coding scheme was used together with protocol analyses to collect the data. As a result of the research, significant differences were found between cognitive behaviors of the participants in using hand sketching and Grasshopper. Additionally, the findings show that all of the participants consider Grasshopper as a useful and important conceptual design tool. In line with these findings, this thesis suggests parametric modeling tools to be used more effectively in the architectural conceptual design phase.

Keywords: Parametric Modeling Tools, Hand Sketching, Conceptual Design Phase, Protocol Analysis, Cognitive Approach

ÖZET

KAVRAMSAL TASARIM AŞAMASINDA ESKİZ VE PARAMETRİK MODELLEME ARAÇLARININ BİLİŞSEL KARŞILAŞTIRILMASI

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Kasım 2018

Dijital tasarım araçlarındaki ilerlemelerle, tasarımcılara yeni yöntemler ve yeni araçlar sağlanmış ve bu gelişmeler tasarımcıları yeni düşünme biçimlerine yönlendirmiştir. Dijital araç kullanımının mimari tasarımdaki hızı ve etkisi son on yılda önemli bir oranda artmıştır. Bununla birlikte, bu tür araçların tasarım sürecinin ilk safhası olan kavramsal tasarım aşamasında kullanımı halen eskiz ve benzeri geleneksel yöntemlerin gerisinde kalmaktadır. Dijital araçların kavramsal tasarım aşamasındaki potansiyelleri ve etkileri de araştırılmaya devam edilmektedir.

Bu tezde de, parametrik tasarım araçlarının eskiz yöntemiyle kıyaslanarak kavramsal tasarım sürecindeki rolü irdelenmiş ve bu süreçte tasarımcıların bilişsel davranışlarının araştırılması amaçlanmıştır. Ayrıca parametrik tasarım araçlarının, kavramsal aşamada kullanımı hakkında tasarımcıların memnuniyet düzeylerinin ölçülmesi hedeflenmiştir. Bu çerçevede, parametrik tasarım aracı olarak Grasshopper'ı kullanmakta deneyimi olan üç deneyimli ve üç deneyimsiz lisansüstü mimarlık öğrencisi ile bir çalışma yürütülmüştür. Çalışmanın sonunda verilerin toplanması için protokol analizi yöntemiyle birlikte içerik esaslı bir kodlama şeması kullanılmıştır. Araştırmanın sonucunda tasarımcıların eskiz yöntemi ve Grasshopper kullanımlarındaki bilişsel davranışları arasında önemli farklar keşfedilmiştir. Aynı zamanda bulgular kullanıcıların Grasshopper'ı faydalı ve önemli bir kavramsal tasarım aracı olarak kabul ettiğini göstermektedir. Bu bağlamda, bu tez parametrik tasarım araçlarının, kavramsal tasarım aşamasında daha etkili kullanılmasını önermektedir.

Anahtar sözcükler: Parametrik Modelleme Araçları, Eskiz, Kavramsal Tasarım Aşaması, Protokol Analizi, Bilişsel Yaklaşım

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CHAPTER 1

INTRODUCTION

In the past few decades digital design tools have become as widely used as conventional methods in the field of architecture and other disciplines. These digital design tools enable different ways of designing and thinking. In recent years, parametric modeling tools also became widespread in architecture. Still, conventional media, like sketching, are significant and integral parts of the design process, especially in the initial conceptual design phases. Designers externalize their concepts and thoughts both through hand sketching, diagrams, and 3d computer modeling programs for developing their different moves and actions (Schön, 1983). Thus, both parametric design tools and hand sketching are very essential and effective for the conceptual design process in architecture. Within this framework, it is important to understand the roles of the conventional methods and parametric media in the conceptual design phase; to understand how these different design environments affect the cognitive behavior of the designers and introduce ways in which the parametric tools may be used more efficiently.

1.1 Problem Statement

For many years, in line with the developments in Computer Aided Design (CAD) technologies, a large number of different modeling tools were introduced to the architectural design environment. Their benefits have been adopted by designers and design communities. In the recent years, parametric modeling tools are added upon the existing CAD tools and they started to be used commonly by designers. Parametric modeling tools are based on rules and algorithms managed by variables that facilitates various design alternatives generation simultaneously (Yu and Gero, 2015).

On the other hand, conventional methods are still and widely used in architectural design. Goldschmidt (1991) expressed that the hand sketches are very important in the design activity for conveying designers’ thoughts and the sketches provides as a necessary and effective tool for dialectic thinking process of designers. Architects are able to express their ideas quickly and explore new alternatives by sketching.

Although hand sketching is a very effective way of designing in the early design process, a complementary tool is often needed to bring the design to a more detailed level. In that sense, while sketching is associated with conceptual design, parametric tools are seen as suitable for the detailed design process (Sanguinetti and Abdelmohsen, 2007). Actually, contrary to this conception, parametric tools may be used for generating different design concepts in the conceptual design phase of architecture. However, despite their capacity to be utilized in the conceptual design phases, the role of the parametric tools in the initial phases of the design process is unclear.

In order to explore the effects of parametric tools in the designers' conceptual design process, first the cognitive processes of the designers in hand sketching and in using parametric tools should be studied, compared and analyzed. The results are expected to be useful for using parametric tools more effectively and in the conceptual design phase.

1.2 Aim and Scope of the Thesis

This thesis aims to reveal and assess the influence of the parametric design tools on the designer's cognitive behavior and to evaluate the designer's satisfaction with the use of parametric modeling tools in the conceptual design phase. It is intended to understand the cognitive behaviors of designers while using hand sketching and parametric modeling in the conceptual design phase comparatively. As hand sketching is the commonly used method in the design generation phase, it is essential to understand the parametric modeling tools' role and potential in this phase in comparison to hand sketching.

Within this conception, in this study, an empirical experiment was conducted using hand sketching and Grasshopper as a parametric modeling tool in the conceptual design phase. This study was carried out by six participants, who are graduate students in Bilkent University Master of Science in Architecture program. Following a pilot study, a design session where the participants were asked to fulfill a conceptual design task was carried out, where the session was monitored. They were free to use in switching between Grasshopper and hand sketching. Protocol analysis method was applied and a content-oriented coding scheme based on the cognitive behaviors of designers was adapted. The results were analyzed through Spss program. It is expected that this thesis can respond to following research questions: Are there any differences between the cognitive behaviors of designers while using hand sketching and parametric design tools in the conceptual design phase? How do the effects of hand sketching and parametric tools compare while generating concepts in architectural education? Can parametric design tools support the conceptual design phase of the architectural process as much as hand sketching? Should students be encouraged to use parametric design tools more in the early design process?

1.3 Structure of the Thesis

This structure of the thesis comprises of five chapters. The chapters are structured respectively as follows:

The first chapter of the study introduces the problem statement, aim and scope and structure of the thesis.

The second chapter describes the history of hand sketching in architectural design. The effects of the hand sketches in the conceptual phase in design education are discussed. The change of the role of hand sketches in architectural education from the past to the present is examined. Moreover, the related previous studies are investigated and necessary literature review is done.

The third chapter focuses on the background of the parametric design. Information about parametric 3D modeling environments is given. In addition, the structure and operation of parametric tools are defined. The types of the parametric design tools are specified as textual scripting and visual scripting tools. Then, information about Grasshopper, which is one of the visual scripting tools is given. Finally, the role of the parametric design in the conceptual design phase in architectural education is discussed.

The fourth chapter of the thesis introduces the empirical research methodology to give detailed information about the experiment setup. The experiment conducted for comparing the effects of hand sketching and parametric design tool (Grasshopper) for analyzing students' cognitive behaviors in the conceptual phase of designing during architectural education. This section comprises four headings presented in the following order: the participants, experiment setup, data collection and data analysis and coding scheme. For analyzing the retrospective data from the experiment, on the graduate students' design cognition research has employed the protocol analysis technique is employed.

The fifth and the last chapter evaluates and discusses the results of the experiment analyses, proposing suggestions for further studies. This chapter is followed by a list of references.

CHAPTER 2

HAND SKETCHING IN ARCHITECTURAL DESIGN

In architectural design process, designers usually generate ideas by hand sketching, which is one of the most commonly preferred externalization tools. Hand sketches enable the transfer of designers' thoughts from their minds to paper. In this regard, the use of hand sketches is considered as an essential part of the design activity. Therefore, design process studies often examine and analyze hand sketching.

Design is a problem-solving process where personal decision makings are occurred. Through freehand sketches, drawings, diagrams and schemas, designers externalize their thoughts in early phases of design to enhance their different moves and actions through further reflection (Schön 1983). As the early design stage is the most intensive phase of creative ideas and concept production, how this stage is carried out is an important research field.

Various researches have been carried out in order to examine the architectural design process. Many studies on design process have focused on issues such as design knowledge, cognitive behavior of designers and influence of design tools on the design process, all for the sake of understanding the ambiguous nature of the design process.

2.1 Design Activity

In the past, many methodologies have been employed to explore the design process and the design activity (Schön, 1983; Akin, 1986; Goldschmidt, 1991; Simon, 1992). The main paradigms of approaching to the design process, the *rational problem solving process* (Simon, 1992) and *process of reflection-in-action* (Schön, 1983) were compared by Dorst and Dijkhuis (1995). Dorst and Dijkhuis (1995) express the difference as:

> Seeing design as a rational problem solving process means staying within the logic-positivistic framework of science, taking 'classical sciences' like physics as the model for a science of design. There is much stress on the rigour of the analysis of design processes, 'objective' observation and direct generalizability of the findings. Logical analysis and contemplation of design are the main ways of producing knowledge about the design process (262).
>
> Schön proposes an alternative epistemology of practice, based on a constructionist view of human perception and thought processes. He sees design as a 'reflective conversation with the situation'. Problems are actively set or 'framed' by designers, who take action (make 'moves') improving the (perceived) current situation (263).

When the whole design process is considered as a sequence that starts with the design problem and ends when the result product is reached, this process can be examined in a few phases. The first phase is the conceptual design phase and it is followed by the development, manufacturing and presentation phases. In fact, breaking up the design process as in scientific activities is a troublesome issue due to the inherent flexible structure of the process. For instance, the early attempts to explore the design process are based on analysis-synthesis-evaluation. However, the phases of the design process cannot be distinguished by definite boundaries, because the analysis and synthesis are intertwined in the whole process. In order to analyze design process, Akin (1986) divided the design process into interrelated sessions. He pointed out that synthesis is observed in the conceptual design phase, even though analysis is found throughout the entire design process. In this regard, Akin (1986) expressed the conceptual design phase with three activities; searching, representing and reasoning. Similarly, Wallas (1921) analyzed the creative design process with four activities in his 'the art of thought' book and proposed a model. Belardi (2014) discusses Wallas's creative process theory as:

> The first phase, 'preparation', consists of focusing on the problem, realizing that it can be solved, and collecting and organizing the required information. The second phase

> 'incubation', concerns the manipulation of the collected material not only via sequential reasoning but also through mental feedback circuits. The third phase, 'illumination' is concentrated on the epiphany of the solution, and ignores all hierarchies in activating all possible thinking modes: deduction, induction and abduction. The fourth and final phase, 'validation' focuses on the logical structure of what has been elaborated so as to make the idea comprehensible, communicable and feasible (14).

It is not unreasonable to express these four phases of 'preparation', 'incubation', 'illumination' and 'validation' as the sub-phases of the conceptual design phase, as this phase is the part of the design process which triggers creativity and the production and exploration of ideas are very intense at this stage.

In other approaches, while Newell and Simon (1972) accepted that conceptual design as a category of problem solving process, Coyne et al. (1990) observed this phase as a knowledge-based activity. In the conceptual phase of design process, design problems are described as "*ill-defined"* or *"wicked"* (Simon, 1973; Rittel and Webber, 1973) due to the facts that design processes are full of different variables, they do not have a precise solution as right or wrong, and also unexpected ideas or problems can occur, causing the designer to change his/her thoughts.

Moreover, design problems do not have a clearly defined goal situation and there is usually no explicit set of rules that can be used between the starting point and the goal point of the process (Holyoak 1990). It is not clear whether at the end of the process the designer can achieve his/her purpose. At the end of the process, the solution suggestion can satisfy the designer, but at the same time it can lead him/her into doubt as well. This is entirely due to the mysterious and creativity-based nature of the design activity. Parthenios (1995) expresses the unpredictability of the process as "that is why there is no such thing as 'the best solution'; there are only better ones. For each design problem, there are many right solutions. However, ‘wrong’ solutions are useful too, because they serve as guidelines.”

2.2 The Role of Hand Sketching in Conceptual Design Phase

The emergence of the drawing is based on very old times. In history, people had to express their feelings and thoughts in the absence of writing, so they were able to do this through drawings. Goldschmidt (2003) underlined the importance of the hand sketches by expressing a short story about the emergence of sketches in history and she told that in old times people used sketches as a means of a communication tool.

In the conceptual phase of architectural design, designers brainstorm and come up with different and creative ideas. In this phase, they try to make a decision to move to the next phase and find an appropriate solution to the design problem. Design sketches are considered to play pivotal roles in this part of the design process (Suwa and Tversky, 1997; Suwa et al., 1998; Suwa et al., 2000). Sketching is very important in this phase for defining, developing, revising and combining the varied ideas easily and quickly. The fact that they are done by hand, makes the process practical and easy. In other words, sketches considered to be conceptual design medium, generating and supporting creative ideas (Goldschmidt and Smolkov, 2006). Hand sketches continually offer iterative design process that allows designers to assess and reconsider different alternatives and results. Gallas and Delfosse (2015) stated that:

> The use of sketching creates an iterative process of design integrating “propose”, “evaluate” and “modify” activities. The iterative features of this process ensure the flexibility of the modification and appropriation activities characterizing early architectural design steps (Lawson, 1990). The flexible structure of sketching generates multiple interpretations of the externalized ideas and solutions through a continuous reflection process (Schön, 1983).

In the conceptual design phase, designers utilize unstructured and ambiguous expressions and pictorial presentations (Purcell and Gero, 1998). As the design evolves to further phases, more definite pictorial presentations, such as plans, sections and elevations are used to show the design idea and the details of it. The use of these pictorial presentations has become an important part of the design process and has been associated with creativity and innovation in design.

Do and Gross (2001) have frequently emphasized the importance of early drawings and raw sketches in the architectural design process. These preliminary sketches are not just communication tools in the early design stage, but they are also tools that enable the designer to see and interpret the form or the design alternatives that they are working on.

Furthermore, diagrams and various schemes are seen as essential parts of conceptual design process. Do et al. (2000) defined the diagram as: “a drawing that uses geometric elements to abstractly represent natural and artificial phenomena such as sound and light; building components such as walls and windows; and human behavior such as sight and circulation, as well as territorial boundaries of spaces” (483). In relation to that, diagrams provide clues indicating the relations among the tangible elements’ spatial features (Do et al., 2000). Some researchers agree that these diagrams and schematic drawings are included in the hand sketching activity, while some researchers separate them (Do and Gross, 2001).

Parthenios (1995) collected all of the drawing types under the title of sketches and divided them into two subtitles, as *geometrical* and *non-geometrical* (Figure 2.1). The non-geometrical hand sketches define diagrams and texts that consist of abstract symbols. On the other hand, the geometrical hand sketches are divided into three headings, as representative, abstract and symbolic. These contain tangible definitions and drawings describing specific geometries. While representative sketches define more realistic and detailed drawings, abstract and symbolic sketches are related to defining the spatial relationships on an abstract level.

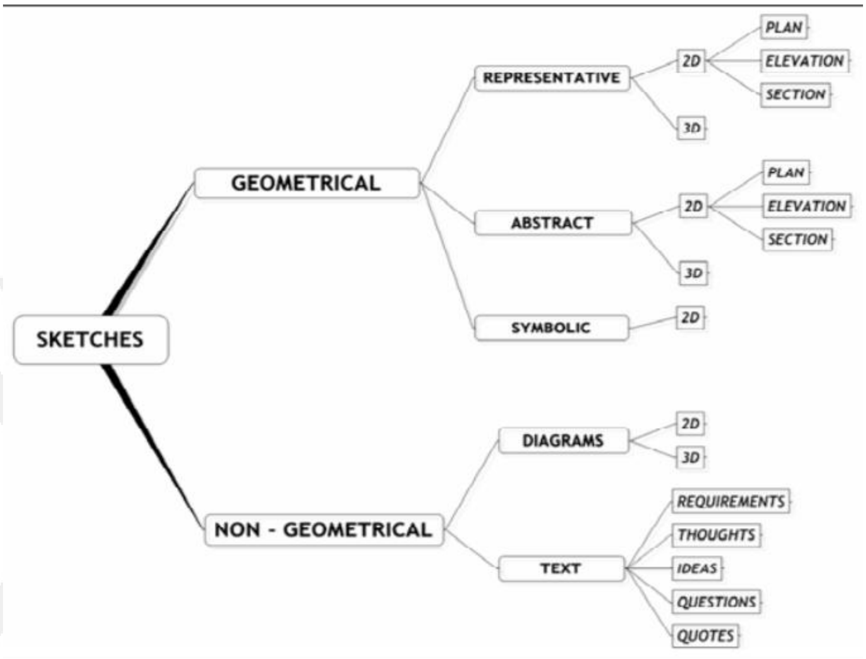


Figure 2.1: Categorization of sketches (Parthenios, 2005)

Most of the early design sketches are signs of searching and exploring process. They do not represent the permanence and also they are filled with open-ended thoughts. Over time, designers become open to exploration through hand sketching activity. Thus, the act of designing is part of the unexpected discovery (Verstijnen et al., 1998). Suwa et al. (2000) drew attention to that the unexpected discovery of designers is related to physical and perceptual characteristics of hand sketches. According to Goel (1995), freehand sketches are ambiguous and not well structured. Even though this ambiguity appears to be a negative aspect of sketching activity, it can support the design process and encourage designers to generate creative ideas and solutions.

Parthenios (2005) states the role of the hand sketches in the conceptual design phase as:

> Hand-drawn sketches have always been, and still are, the architect's primary tool in conceptual design. They play a crucial role in design thinking, design reasoning, and problem solving by providing a unique platform for exploration and experimentation. Sketches not only allow the architect to visualize his or her thoughts; they also provide valuable feedback and facilitate a constructive dialogue between the architect and his or her ideas. Architects need to "talk" with their designs, in order to explore, play, be surprised, get inspired, meet the unexpected, judge, compare, refine, reject and select. Many researchers have studied the role of sketches in conceptual design. Though they might not agree on a single model for the design process and might have different views on how architects actually perform design, they all concur that the hand-drawn sketch is the primary tool for conceptual design. Sketches have proved to be the architect's most useful tool during conceptual design. They are a transparent interface, with an inherited, almost natural fluidity, which excel in allowing the architect to design without having to think about the medium (133).

2.2.1 Sketching as a representation tool

Architects depend on different representations for decision making, solution finding and generating design ideas. These are important breaking points in the design process, which can directly affect design thinking. When design is considered as a cognitive process, how designers store and recall their ideas via different types of representations in design becomes an important research topic.

Akin (1986) proposed two modes, *verbal-conceptual* and *visual-graphic* to classify all the representation types. He pointed out that these two modes are generally interrelated and cannot be considered separately. He named the same cognitive processes working with both modes of representations as dual mode. The visual characteristics of the design process are examined in visual-graphic mode. These visual characteristics can be tangible signs of the production of sketches. On the other hand, the intellectual and abstract aspects of design are comprised in the verbal-conceptual mode. The verbal-conceptual mode is associated with creating the ideas in the mind before the designer makes them external. These two modes can be integrated with each other, but there are times when they are used one before the other. According to Akin (1995), if the visual mode is used initially, the verbal mode follows like a reflection of it. In some cases however, the designer may use the visualization as a tool after having found the solution to the design problem and the externalization becomes a reflection of thoughts.

Akin's (1986) visual-graphic mode description can be originated from Arnheim's (1969) 'visual perception' definition. He handled the thought process of designers together with perception. Parallel to this, he argued that both of them must be considered as a whole in the design process. Regarding this, Arnheim (1969) express that "Similarly, I see no way of withholding the name of 'thinking' from what goes on in perception. No thought processes seem to exist that cannot be found to operate, at least in principle, in perception. Visual perception is visual thinking".

The approaches of both Akin and Arnheim are consistent with that of Goldschmidt. Goldschmidt (1997) emphasizes that representations are images that can be grouped as *internal* and *external*. While drawings and sketches are considered significant external representations in architecture, internal representations are images that take place in the designers' mind. Sketching is an external representation tool as it is built on the interaction of the designer's mind, eyes and hands. Internal representations may be examined in terms of cognitive aspects. Various researches have been done for exploring the relation between the representation types and design tools (Akin, 1986; Akin and Lin, 1995). Gallas and Delfosse (2015) stated that "the precision level of the representations and the models increases and accompanies the evolution of the design activities." Goldschmidt (2017) expressed that both internal and external representations are used in the conceptual design phase by designers. She further classified external representations as one in which designers importing from somewhere and one where designers generate solutions during the ideation process. Thus, she associated external representations with sketching, while associating the inner thoughts as mental imagery.

2.2.2 Cognitive aspect of hand sketching

Cognitive science is a fundamental and interdisciplinary area that focuses on human information processing and the understanding of thinking processes. Arnheim (1969) described 'cognition' as: "all mental operations involved in the receiving, storing, and processing of information: sensory perception, memory, thinking and learning" (13). With the same framework, design can be considered as a cognitive process that examines designer's mind, how the designer collects, recalls and uses design information. Various researchers have done numerous studies for understanding how designers design and they have tried to investigate how designers' thought processes and behaviors work (Eastman, 1970; Akin, 1978, 1986; Goldschmidt, 1991, 1994; Suwa and Tversky, 1997).

Conceptual design phase involves some of the highest cognitive activities of designers including creativity, synthesis and problem solving (Cross et al. 1996). Hand sketches can contribute to all phases of design activity and affect the whole design process especially the conceptual design phase. In this regard, some researchers have investigated the cognitive aspects of hand sketching in conceptual design phase due to its unique and unpredictable nature (Suwa et al., 2000; Goel 1995).

Cross (2006) summarized the empirical studies' results about design cognition under three headings as *problem formulation, solution generation* and *process strategy*. Regarding this, Cross (2006) stated that:

> In analyzing design cognition, it has been normal until relatively recently to use language and concepts from cognitive science studies of problem solving behavior. However, it has become clear that designing is not normal 'problem solving'. We therefore need to establish appropriate concepts for the analysis and discussion of design cognition. For example, designing involves 'finding' appropriate problems, as well as 'solving' them, and includes substantial activity in problem structuring and formulating, rather than merely accepting the 'problem as given' (77).

Hand sketches can be associated with these three main headings cognitively, because they can be included in all stages of the design process. In other words, since hand sketches and drawings are fundamental tools to externalize ideas at every stage of design process, studies on the cognitive behaviors of the designers may naturally involve hand sketching.

Akin's study (1978) intended to establish a theoretical understanding for perceiving the design process's cognitive aspects. He analyzed the cognitive abilities of designers on the purpose of investigating the architectural design process stages. He tried to categorize the information processing mechanisms which belong to a priori knowledge of designers and generation of design solutions. Moreover, the conceptual design process was differentiated by Akin (1978) as '*pre-sketching'* and '*sketching'* according to Newell & Simon's (1972) problem-oriented approach.

In terms of the cognitive aspect of design, Schön (1983) examined the relationship between designers and their hand sketches. Designers quickly create various ideas and put these ideas on paper while sketching. They can examine and assess their own sketches while transferring ideas from their minds to paper, and discover unexpected ways of solving design problems. Therefore, hand sketching provides the designer to explore unintended outcomes and enables them to think back on what has been done in the design process. In this regard, Schön (1983) defined the design activity as a "reflective practice" within his "reflection-in-action approach". This approach has been often used in design field to investigate and evaluate the cognitive aspect of design process (Suwa and Tversky, 1997; Doorst and Dijkhuis, 1995). Furthermore, Goldschmidt (1991) expressed that there is a dialogue between designer's 'seeing that' and 'seeing as', where 'seeing that' is reflective criticism and 'seeing as' is the analogical reasoning and reinterpretation of the sketch.

One of the reasons why hand sketching is considered as a cognitive process is that sketches have continuously varying and unexpected contents, especially in the conceptual design phase. In this process, the mental images are transferred to paper and they become visual images. Thus, how the mental process works while sketching is one of the significant research areas of the cognitive design field.

2.2.3 Mental imagery and visual thinking

Imagery as a term has been used often in literature, by different researchers working in various fields. Arnheim (1969) referred to its importance and quoted Holt's (1964) definition about thought image "A faint subjective representation of sensation or perception without an adequate sensory input, present in waking consciousness as part of an act of thought. Includes memory images; may be visual, auditory, or of any other sensor modality, and also purely verbal ". Therefore, the mental imagery can be considered as an inseparable part of visual thinking in design (Arnheim, 1969, Mc Kim, 1972). Downing (1992) pointed out the role of place imagery in understanding architectural spaces (cited in Athavankar, 1997).

Mental imagery is accepted as having a significant role in sketching and visual design thinking. Hand sketching interacts with mental imagery. Goldschmidt (1991, 1994) described "interactive imagery" as a thinking method in the initial stage of creative design process. It is then reasonable to say that as designers have an iterative process in sketching, the mental and physical processes can interact with each other, leading to interactive imagery. In other words, designers both use mental images to sketch and they use sketching for generating new shapes in their minds simultaneously. Goldschmidt (1991) stated that: “Sketching, then, is not merely an act of representation of a preformulated image; in the context we deal with, it is, more often than not, a search for such an image” (131).

The hand sketches trigger the design process to be creative and they influence the process substantially. Verstijnen et al. (1998) stated that: “Creative processes extensively make use of visual thinking, or, in other words, there is strong contribution of visual imagery” in the creative design process. In the early design phase, when designers do sketching to generate various concepts and constantly think of different alternatives for finding appropriate solutions to the design problem, they create different ideas in their brains and they make use of visual images in their mind. Understanding designers’ mental process and sketching behaviors are very essential for creating more effective and creative design strategies and processes. Anderson and Helstrup (1993) purposed to compare hand sketching and mental imagery as a tool for design process. Their study was one of the first attempts to establish an information processing framework in order to discover the transfer of the idea to sketching. They hypothesized that the design decision was made when designer confronted a resource limitation. They utilized resource limitations to be the indicative factor and stimuli for idea generation but they did not find any difference between sketching and mental imagery. Verstijnen et al. (1998) focused on the mental processes in their experimental study to discover how sketching contributes to the creative design process.

Chandrasekaran (1999) examined the external visual representations as hand sketches, CAD drawings or diagrams with using internal representations as mental imagery in problem solving process. He tried to establish a framework that combines both internal and external representations in terms of perceptual representations. He suggested that multimodal internal representations are the design process's and cognition's vital parts in architecture. As a result, he pointed out that mental images are substantially good at the emergence of new perceptual associations although the external representations are more effective than mental imagery in order to perceive new objects. Chandrasekaran also studied how mental images are experienced and used by a human being and what internal mechanisms are involved in the use of mental images. Although he could not find definite answers to these questions, he found out that mental images have important contributions and roles in providing information and generating ideas when utilized with external representations as diagrams during the design process.

The general framework of the relationship among the mental imagery and hand sketching, and discussions on their interactions in the design process, especially in the conceptual phase, provide insight about visual thinking in design. In terms of the visual thinking understanding, it is necessary to obtain information about the role of different external representations in design and explore their effects on the thinking process. Evaluating and studying external representations in the whole design activity aim at identifying the effects of design medium in the conceptual design phase deeply. In order to be able to do that the design process should be analyzed and various types of external representation tools should be scrutinized through experimental and comparative studies as this thesis suggests.

2.3 Hand Sketching in the Digital Age

In the recent years, the use of conventional tools such as sketches and drawings has been greatly influenced by the development of computer technology in the field of design and the growing interest in these technologies. Efforts to integrate computers into design process have begun to spread rapidly in architectural education. While sketches are considered to be one of the most vital parts of design process, it makes sense to look for new ways to produce faster and easier solution proposals to the ill-defined design problems. Especially conceptual design phase is very crucial for generating new ideas, exploring different options and trying to develop solutions to the design problem. Although sketching is still indispensable in the conceptual design phase, new technologies such as building information modeling, computer-aided design and parametric modeling tools have provided various opportunities to the designers. Thus, the contributions of these new methods to this phase of design process cannot be ignored.

Thanks to new computational technologies, the change in the use of sketches and drawings has become inevitable. The interaction of these technologies with sketches and their role in design is still a very important discussion and research topic in design field. Sheer (2014) argues whether sketches will continue to be an integral part of the design process, or sketches and drawings be replaced by digital technologies. According to Goldschmidt (2017), digital tools have rapidly started to take over the sketches and drawings in the architectural design process. But she argues that hand sketches cannot easily be replaced and removed because of their cognitive benefits in the conceptual design phase especially in design education. Regarding this Goldschmidt (2017) stated that:

> It is now beginning to be possible to replace pencil, pen, charcoal, or brush with a stylus, and hand-draw on computer screens or tablets. The technology is not yet perfect, and the experience does not yet match drawing on paper, but we can safely assume that the gap will be narrowed in the near future. Despite imperfections, today many designers prefer “paperless” digital means. The trend has alarmed those who do recognize the value of manual sketching and drawing (86).

Computational tools enable to engage designers’ behaviors, mind and bodies differently than sketches. Transferring thoughts from mind to computer by these tools can profoundly affect and change the way of thinking, the position of a designer and the relationship between mind, eye and hand that drawing creates (Sheer, 2014). These tools allow designers to overcome their boundaries, to get rid of the limits of the sketching activity, to reach different design solutions and forms which cannot be achieved with hand sketches and drawings. With the support of these tools, the human brain can discover more and more alternatives than those which can be generated and imagined by hand sketches. In this regard, designers can also produce complicated, amorphous and curvilinear forms through computational tools (Goldschmidt, 2017).

With the use of new computational tools becoming widespread today, the role of hand sketches in design activity and interaction with these computational tools are significant research topics. Various studies are still ongoing to investigate and discuss the architectural design process with different perspectives. For instance, Parthenios (2005) completed four case studies for comparing different tools including computational and conventional ones and he found that hand sketches are still be beneficial as a beginning point for conceptual design phase. He states that ‘sketches are the most common transitional and ancillary medium; they are used to move information between different media and tools’.

Ibrahim and Rahimian (2010) tried to explore the novice designers' communication while working on a conceptual design problem. They have conducted a case study with the aim of investigating how different tools, digital and conventional, affect collaboration in conceptual design phase.They have created a table as a result of their literature review that show the differences between manual and Cad tools in the design process (Figure 2.2). With this research, it was observed that manual tools as hand sketching are useful in the beginning of the design process for novice users but they were inadequate for solving complex design problems and they restrict the users.

	Benefits	Challenges
Current manual sketching tools	•Flexibility in ideation due to tangible interface •Ease of use •Ease of learning •Ease of changing reforming the design alternative •Ability for using different scales of drawing and trading of between accuracy and clearness •Maintaining design idea during design process providing the ability to see all documents together and to compare	•Lower capability for shifting from micro to macro level and vice versa •More tacit information flow walkthrough •Lower details of visualisation •Fragile models and documents for editing or reviewing •Failing to add and control more details into design alternative due to weak level of visualisation •Difficulty in transition of the format when being used in the other design stages
Current CAD tools	•Easier documentation •Capability for zooming and panning for easier walkthrough •Capability for temporally omitting an object or group of objects •Capability for undoing undesired changes •More detailed, realistic, and elaborated perspectives due to high capability of visualisation	•Difficulty of obtaining ability to use •Arduousness of I/O devices which interrupt creativity of the designer •Losing consistency of spaces due to lack of ability to control ubiquitous design idea in an artistic way

Figure 2.2: Benefits and challenges of design tools (Ibrahim and Rahimian, 2010)

On the other hand, Belardi (2014) does not deny the digital technologies' innovative benefits and supports that they should be used and learned. However, he emphasizes that it is necessary to be aware of the boundaries and opportunities of all tools while designing and designers can be more creative when using the tools together with a pluralistic viewpoint.

CHAPTER 3

PARAMETRIC DESIGN

With the emergence of computers, the digital design age has started. In this age, a large number of different modeling tools have been introduced into the design environment, opening up a brand new page to the designers. Leach (2009) has described the computer as a powerful tool for designing and stated that design has changed depending on the digital technologies. The digital age has provided the designers with different ways of thinking.

Looking back in history, Ivan Sutherland used the computers for generating a project called SKETCHPAD in 1960, which is considered to be the first step towards Computer Aided Design (CAD) (Weisberg, 2008). Sketchpad worked on the principles of technical drawing based on 2D vectorial working space and it aimed to rise productivity of designers. Sutherland mentioned the significance of the CAD technologies and emphasized the difference between the conventional and computer-based methods (Sutherland, 1963). Soon after, the first personal computers were produced in 1980's and they became affordable. As such, computers became popular. Especially, Autodesk's Autocad software that includes a 3D visual interface became increasingly popular in those years (Davis, 2013). While Sketchpad could only be used in areas such as aerospace and automative industries due to its price, personal computers and Autocad could be widely used in the field of architecture and product design.

In time the computer has left its role as a representation tool in architecture. For Kolarevic (2005), digital media is not only a means of representation for visualization, but also a regenerative tool for diversification of form in architecture.

The increasing importance of advanced computer-aided design (CAD) and computer-aided manufacturing (CAM) technology on architectural design and fabrication, led to considerable changes in architectural design. Digital technologies have provided a wide field of opportunity for architects to discover innovative methodologies. The Architecture, Engineering and Construction (AEC) industry accepted the advantages of parametric and algorithmic tools and Building Information Modeling (BIM). Such modeling tools enable an interactive environment among different design disciplines that help designers achieve non-standard geometries and complex forms. In particular, parametric modeling tools are frequently used in the production of these amorphous forms and structures and they provide to solve more detailed and complex problems. In this regard, parametric design thinking and the use of the parametric modeling tools have succeeded in being integrated into the design and construction field.

3.1 History of Parametric Design

The digital design environment has developed very rapidly in the 90's and during this period, a new understanding, in which the parameters of objects could be controlled in 3D emerged. Parametric Technology Corporation deeply affected the CAD industry in 1987, when the company introduced a feature-based parametric modeling program called Pro/Engineer (Weisberg, 2008). Unlike previous software packages, this object-oriented program made it possible to vary the parameters and perform many manipulations between design instances. Also, it allowed the designers to navigate through non-graphical information and manage objects with different parameters of pre-defined algorithms. A large number of companies began to try Pro/Engineer software for testing the advantages of this new technological tool and comparing it to the existing systems that they were utilizing.

In the last decade, parametric modeling tools, also known as algorithmic editors, have been developed and presented to designers. These enable designers to encode their own rules in their designs. Also, these sort of modeling tools promote algorithmic and relational thinking. The algorithmic editors work with the parameters, definitions and rules that define the relations between the parameters. An algorithm is "a set of mathematical instructions or rules that, especially if given to a computer, will help to calculate an answer to a problem" (Cambridge Dictionaries, 2018). Furthermore, "parametric" is a derivation of "parameter", which is described as "a numerical or other measurable factor forming one of a set that defines a system" and "a limit or boundary which defines the scope of a particular process" (Oxford Dictionaries, 2018). That is to say, a parameter can describe either a constraint of a system or a relation between measurable factors such as rules.

The use of the term 'parametric' has a long history in the field of mathematics and the earliest examples of parametric terms used to describe three-dimensional models date back to 1800's. Although there are different arguments about the first appearance of 'parametric design' term, it is assumed that architect Luigi Moretti was the pioneer of the use this term in his writings in the 1940's (Bucci and Mulazzani, 2002). Bucci and Mullazzani (2002) states that Moretti emphasized the parametric design as describing the relations between the different parameters and also he gave some parametric architecture examples such as stadium project in his book. Moreover, he designed the Watergate Complex that is supposed to be the first major construction job that uses computers efficiently in the design process (Livingston, 2002).

3.2 Parametric Design in Architecture

In the last two decades, parametric design has been integrated rather swiftly into the field of architecture. Architects have begun to take inspiration from the parametric tools and benefit from their intensive potentials.

In architectural design history, Antonio Gaudi was the first to utilize the parametric equations in his works (Davis, 2013). Gaudi's associative thinking style and deep mathematical understanding were reflected in his designs. The Expiatory Temple of the Sagrada Familia was one of them that was designed between 1883 and 1926 in Barcelona and after his death the structure has not been completed. Mark Burry (2011), the chief architect of Sagrada Familia since 1979, indicates Gaudi's hanging chain model that was built with parametric design thinking. He is still working on the structure for completing by combining parametric modeling technologies and traditional methods. Moreover, Burry (Burry et al., 2008) organized an exhibition where the unconstructed parts of the Sagrada Familia were on displayed that were produced with parametric modeling tools and digital fabrication (Figure 3.1). The columns of Sagrada Familia were other instances that indicated the relational thinking of Gaudi (Barrios, 2006). Barrios (2006) succeeded to regenerate the original column designs by Gaudi with the aid of the parametric modeling tools.

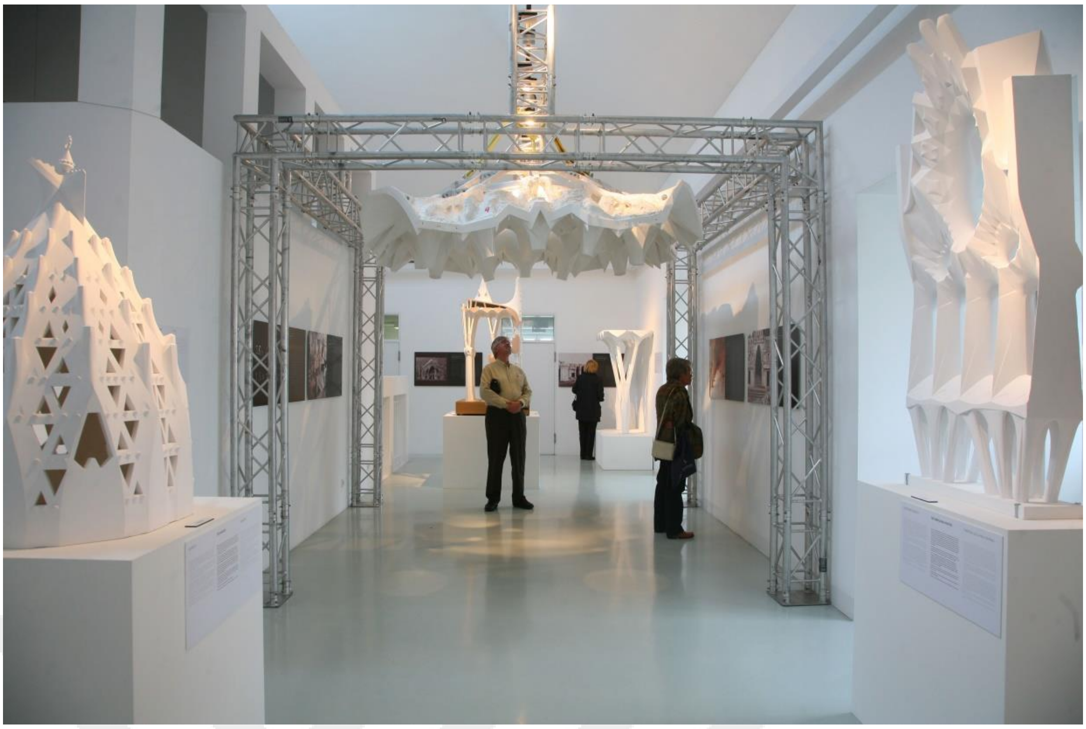


Figure 3.1: Gaudí Unseen: Completing the Sagrada Família Exhibition
(Burry et al., 2008)

In addition, Le Corbusier and Xenakis's Philips Pavilion in Brussels, Frank Gehry's fish-shaped roof structure in Barcelona and Nicholas Grimshaw's Waterloo International Station in London are among the pioneer examples in which parametric systems are used (Alvarado and Munoz, 2012). For instance, Waterloo Station's roof structure was designed with parametric design. In this building's curvilinear roof structure, a parametric model of a single truss is made for calculating the dimensions of the structural elements at different measurements. By making different variations of this model, the structural elements with different dimensions were generated in a short time.

In recent years, some well-known architects such as Zaha Hadid and Norman Foster have benefited greatly from the advantages of parametric design and have designed their buildings accordingly. With the contributions of the parametric design, Zaha Hadid designed Heydar Aliyev Cultural Center. Disney Concert Hall designed by

Frank Gehry, is a complex and remarkable building designed parametrically. Zaha Hadid's partner, Patrik Schumacher, has put forth a manifesto, describing Parametricism, as a new way of thinking. Hadid and Schumacher have signed a number of different projects from this point of view. Schumacher emphasized that parametric design has developed over the course of 20 years and has overtaken architectural movements, becoming a new pioneer movement (2009). In this new movement, a transition begins from an *architecture based on visual anxiety* to an *architecture based on performance*. Also, instead of the basic and foundational elements of architecture, the primitives like splines, NURBs and sub-divisors are used. These geometric structures, which form the basis of model design, are associated with the software (Schumacher 2009).

3.3 Parametric Modeling

The parametric modeling environments are fundamentally based on algorithms, which comprise of parameters and the relations between them, known as rules. The significant feature of parametric modeling is the ability to focus on dependencies between different designs components rather than the components themselves. The relational structure of the parametric modeling environments allows for variational design thinking that enables the exploration of complex forms in the design process (Monedero, 2000). In other words, parametric modeling generates the variations that manipulate the relationships between the components of a parametric model in such a way that some parameters can be automatically updated when others change. (Figure 3.2)

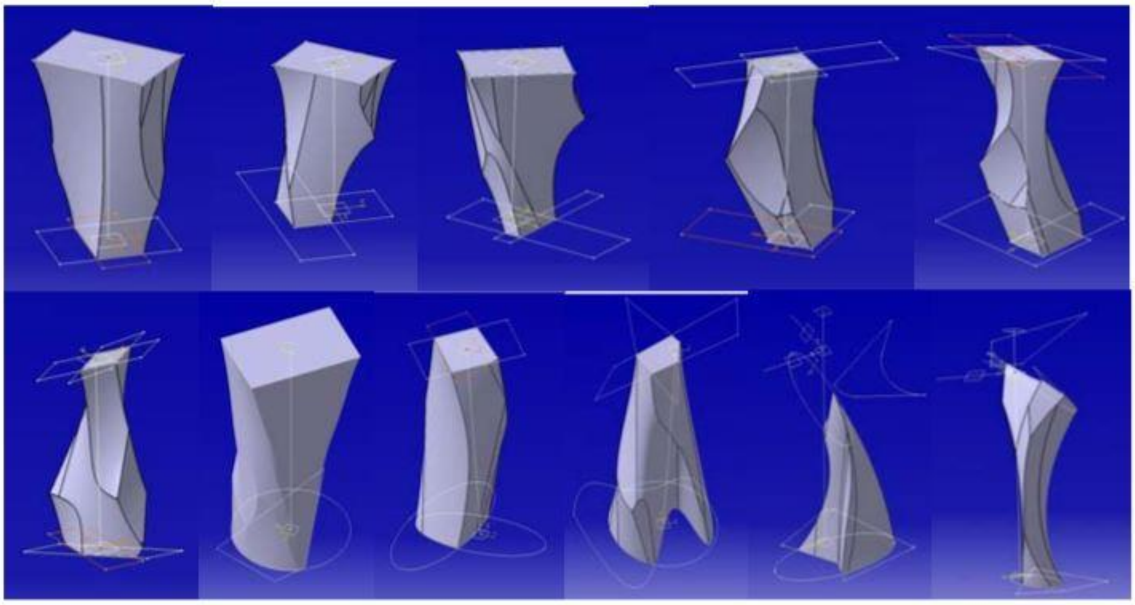


Figure 3.2: Parametric variations of a model
(Barrios, 2005)

While parametric design is the action of designing, a parametric model is the medium used into design process (Barrios, 2007). Parametric design requires a systematic and planned process, utilizing the parametric models. Due to the fact that a parametric model is part of a design process constructed with geometrical entities that have attributes that are fixed and others that can vary, the variable attributes are also called parameters and the fixed attributes are said to be constrained (Barrios, 2006). The fact that the parametric design system works with these parameters and constraints while giving the user the chance to create changes in itself with parametric variables affects the design process positively (Figure 3.3).

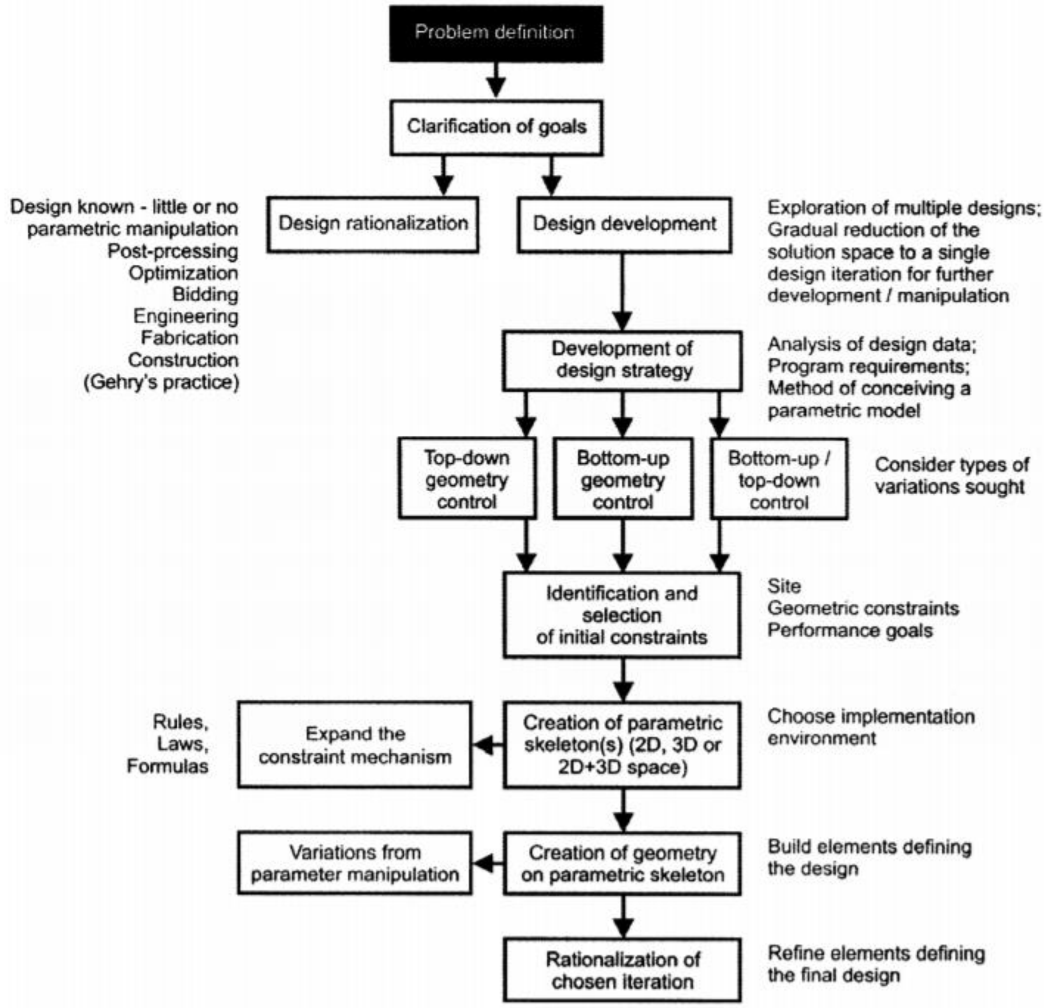


Figure 3.3: An example of parametric design system diagram (Gane, 2004)

Gane (2007) summarized parametric modeling's relational content under the categories of 'variables', 'constraints', 'dependencies', 'components' and 'rules'. Whereas variables are one of the essential factors of the variations, constraints are important factors that determine the limitation of the parametric model to be constructed and they also provide a restriction for the variation of forms to be created throughout the design process. Gane (2007) stated that: "Such constraints establish a *dependency* of the geometric elements on the variable(s) that defines them" (3). Determining the constraints and their relations are related to the conceptual design of the design process so, this can affect the design process from start to finish.

When the parametric design is examined in relation to this associative structure (Figure 3.4), parametric modeling can be summarized as the following steps basically: Defining the problem, describing the constraints, perceiving the dependencies, creating rules, producing variations and composing models.

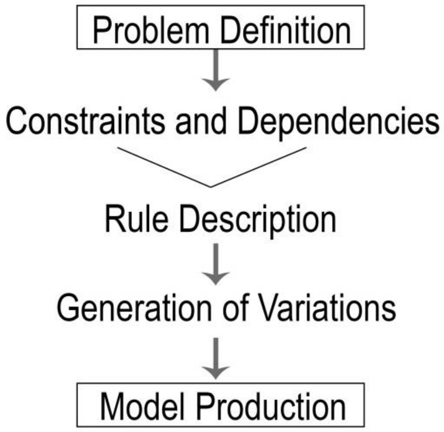


Figure 3.4: Parametric modeling process

Parametric design strategies have three main methods. These are *top-down* control, *bottom-up* control, or *both*. Each method influences how the model will behave and change. *Top-down* control is a highly structured method that maintains a hierarchical order between all components. Systems created with this method are directly dependent on other elements and deleting or changing an element based on the created relation causes the whole model to be collapsed or updated. Thus, the up-down method allows modifications to be made that allow both the modified and the entire model to be updated. Therefore, generation of the variations in parametric design is often associated with a top-down control methodology. (Harding et al., 2013) *Bottom-up* method uses a less rigid approach to the hierarchical order and content of the model. It is created to bring together elements of different and independently thought out elements into a complex. As long as certain relationships do not define the basis of a formation, changes and additions can be affected unhindered in the rest of the model.

3.3.1 Types of Parametric Modeling Tools

In recent years, the parametric modeling tools have begun to be used commonly among designers. With the improvement of the parametric CAD technologies, different types of parametric modeling tools emerged. Due to the fact that parametric design is a subcategory of algorithmic design, parametric modeling tools are the algorithm editors that are controlled by some variations and parameters.

The parametric modeling tools can be grouped under two principal headings as *associative-geometry based* and *BIM based* (Salim and Burry, 2010). Associative-geometry based tools are based on relational network between components. The designer recreates, defines, and constructs associations between the components with encoding and numerical descriptions. Rhino's Grasshopper plugin and Bentley's GenarativeComponents are the well-known tools that belong to this first group. On the other hand, BIM (Building Information Modeling) based parametric modeling tools are defined as an object-oriented software system by the national BIM Standard-United States. Also, CIC Research program described the BIM systems as 'processes focused on the development, use, and transfer of a digital information model of a building project to improve the design, construction and operations of a project' (cited in Kreider and Messner, 2013). These software programs are able to perceive the construction elements individually. Revit and Autocad software by Autodesk widely use BIM-based tools in architectural design environment similar to Graphisoft's Archicad and Gehry Technologies' Digital Project software.

This thesis focuses on the first group (associative-geometry based) of the parametric modeling tools. The common feature of the parametric modeling tools of this group is that they offer two different modeling areas for the users. Whilst one of these areas allows for the creation and editing of the algorithm, the other is used to display the algorithm's resulting geometry. Actually, these areas are associated with their representations which are analog and symbolic respectively. All of the existing parametric modeling tools use both of the representations to manipulate the geometries. A parametric system can be considered as tool for mediating between the content of analog and symbolic representations for gaining the procedural knowledge about form and performance in the description of algorithms and parameters (Dino, 2012).

The distinguishing feature of these parametric modeling tools, as stated in the previous paragraph is that, the contents of their algorithm editors are based on scripting. Burry (2011) emphasized that scripting can increase the productivity and provide the user with the ability to control freely without any limitations of black-box drafting software. "The schema of algorithm editors' scripting types can be divided into two main groups which are 'textual' and 'visual' (Dino, 2012)."

Textual algorithm editors are created with predefined commands through different software as Java or Microsoft's VBScript coding language. Generative Components from Bentley Systems Incorporated, Rhinoscript from Robert McNeel & Associates, and Autodesk's Mayascript and Pytonscript are widely used parametric modeling tools that offer text-based algorithm editors. (Figure 3.5)

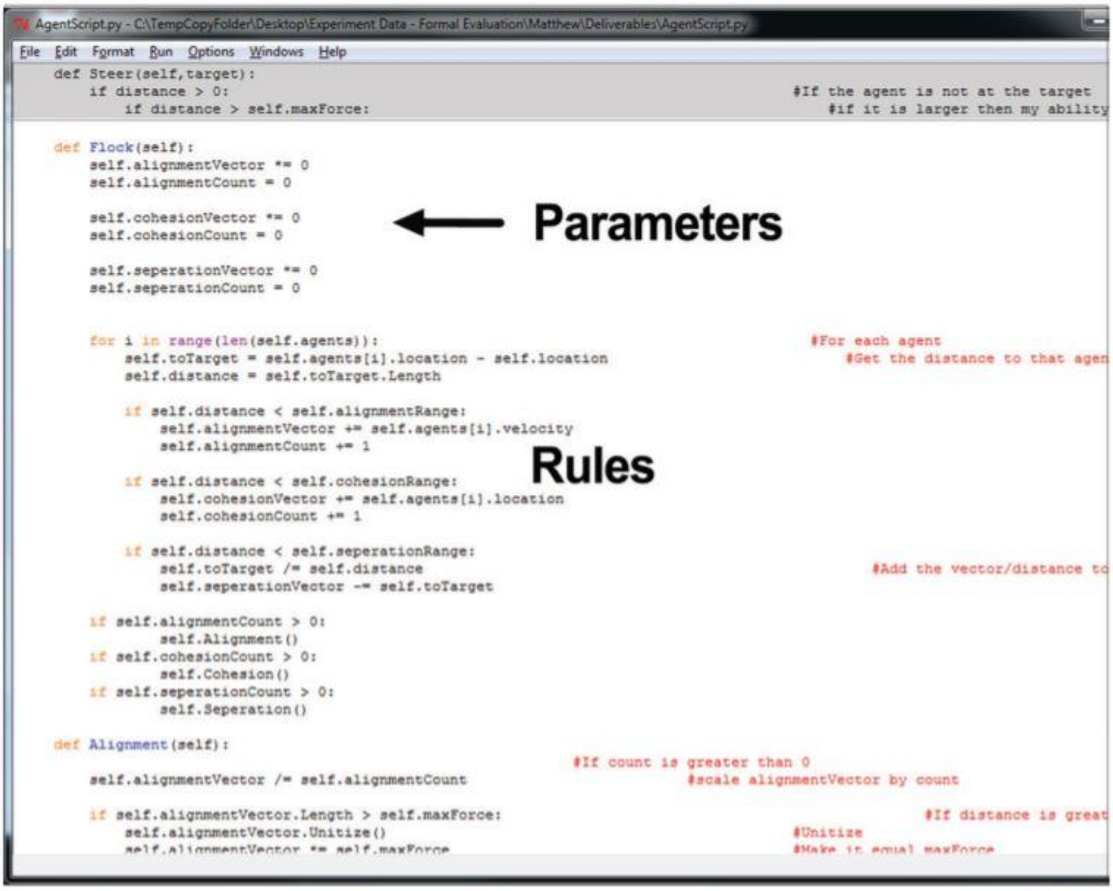


Figure 3.5: Python script example in Maya software

(Lee et al., 2014)

The increasing use of such design tools in the field of architecture is remarkable. However, the inability to integrate these tools into every stage of design and the need for users to have mathematical knowledge can limit the range of use of such tools. For some designers, textual scripting is a hard-won skill and they are challenging the required logical approach behind the tool (Burry, 2011). In addition to this, in these tools, to perform textual encoding, it may be necessary to change the parameters and re-enter the commands in the algorithm editor. Such processes and the textual infrastructure of the program can be challenging to discover the relationship between design components and to explore different design alternatives. Numerous discussions are being made to increase the use of these design tools in design and to integrate them in many areas, from the education to professional practice (Çinici, Akipek and Yazar, 2008; Burry, 2011).

On the other hand, visual algorithm editors have similar principals to textual ones but they demonstrate all the parameters and their associational structures visually instead of textually. Therefore, these visual parametric scripting tools are known as graphical algorithm editors. Thanks to the visualization of the components and the relations between them, modifications can easily be made and different design alternatives can be evaluated in less time. Thus, the visual infrastructure of the algorithm editor provides many advantages, especially for architects, unlike textual scripting tools. Many designers have found these tools more useful due to the low level of technical knowledge required on programming languages. (Dino, 2012) In addition to that, graphical algorithm editors provide designers with two-way control, enabling them to manage their designs both geometrically and parametrically. Since the connections between the parameters, inputs and outputs are also shown visually, it is very easy to find the mistake. In this regard, these tools can be easily incorporated into every part of the design process.

Revit's plug-in Dynamo from Autodesk and Rhino's plug-in Grasshopper from Robert McNeel & Associates are examples of graph-based algorithm editors. Additionally, such tools also contain sections that allow users to overcome some limitations and perform textual scripting to generate more efficient diagrams. For instance, Grasshopper allows for textual coding in a small size through VB.net and C#.net programming languages.

Grasshopper

In this thesis, Grasshopper is utilized for the case study. Grasshopper is a visual scripting environment generated by David Rutten at Robert McNeel & Associates and it is a plug-in of the Rhinoceros software (Tedeschi, 2010). It has a graphical algorithm editor which represents the parameters and the rules visually in its working space. Grasshopper has emerged with the goal of promoting the potential of relational modeling in Rhino. Moreover, Grasshopper is a software plug-in that creates a visual interface to the History command in Rhino, which is useful for relational modeling.

Grasshopper has become one of the most well-known parametric modeling tool in the last decade (AEC Magazine, 2009). Many architects prefer Grasshopper because it offers almost an intuitive way to discover design alternatives easily without textual scripting. The working space known as canvas is totally based on visual components that contain a large number of parameters. While operating with Grasshopper, the components are dragged to the canvas and connected to each other with wires. (Figure 3.6)

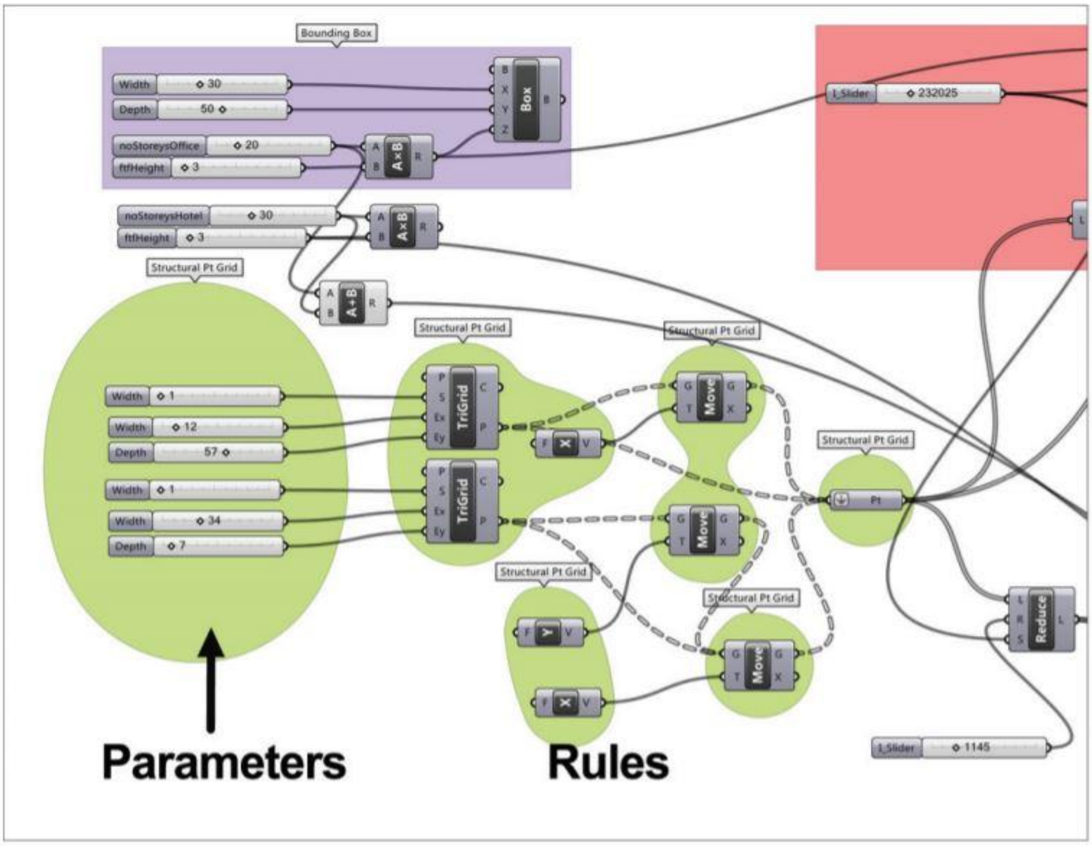


Figure 3.6: Grasshopper screen example

(Lee et al., 2014)

Grasshopper includes different types of components such as numerically based, graphical based or primitive components. For instance, primitive components represent nominal variables (rectangle, plane, circle etc.) that are common used parameters in Grasshopper. Otherwise, numerically based components, (panels, number sliders etc.) are related to the quantitative data that defines a range for alternating the design instances and directs the components’ boundaries. All of the components consist of inputs and outputs. Some components have single input and output and they can store the data. On the other hand, some components have multiple inputs and outputs and they can perform actions resulting in data. The basic idea behind Grasshopper is all about establishing a logical connection between inputs and outputs namely rules and then composing the definitions. All digital inputs required for geometry formation can be defined parametrically. Mathematical and logical operations can be performed on these parameters. This makes it possible to derive forms that have both geometric and logical relationships with each other, which are updated dynamically on the screen. In cases where the components of Grasshopper are insufficient, new components can be made by scripting. In this regard, Grasshopper supports two code languages that are VB and C# for scripting.

In addition to that, Grasshopper has various plug-in types such as Kangaroo or Honeybee for different intentions like performance evaluation, structural analysis and environmental analysis.

3.4 Parametric Design in Conceptual Design Phase

The conceptual phase is an important part of the design process, in which ideas are produced freely, different ideas are evaluated, creativity is at the forefront, and which influences the final state of design. Designers can navigate the various alternative solutions as desired in this phase without any constraints and reach the result that they want to achieve. Also, in the conceptual design phase, the production of ideas takes place very intensely, and this process is a mysterious area with full of unknowns (Cross, 2001).

At the early stage of architectural design, hand sketching has an important and dominant role for exploring different and creative design alternatives and communicating with designers (Goldschmidt, 1991; Lawson, 1994). However, with the developing technology, innovative digital design tools, especially parametric modeling tools, have started to be used within this conceptual design process. Nevertheless, hand sketching is still strongly associated with the conceptual design process, the impact of parametric design tools in this phase is still to be determined.

In the recent years, it has been observed that parametric modeling tools support the concept production process and its usage in this phase increases rapidly. Thus, the benefits of the parametric modeling tools for the concept generation process cannot be ignored. Schnabel (2007) focused on the structure of digital design studios and he stated that: “Parametric design techniques offer obvious advantages for engineering and manufacturing processes, now architects emerge to apply these methods in their creation of design suggesting solutions at an earlier stage of the process” (242). In this process, more alternatives can be produced by making variations through parametric modeling tools that support the idea generation. Previous researches were carried out on the integration of parametric modeling tools into the conceptual design phase and the evaluation of their cognitive impacts on users in architecture (Won,2000; Harding et al., 2013; Shih et al., 2015; Çinici et al., 2008; Gero et al., 2007; Lee et al., 2015; Stavric and Marina, 2011; Gallas and Delfosse, 2015).

Sanguinetti and Abdelmohsen (2007) explained an integration system in their article:

> We propose that sketching and parametric modeling can be integrated strategically as alternate externalization modes to support problem solving in conceptual design. With sketching, architects are able to externalize their ideas quickly and effortlessly, as the flexible structure of sketching provoke multiple interpretations through continuous reflection. With parametric modeling, architects must define a set of parameters and rule-based constraints. By modeling design objects as parametric, multiple design variations can be generated, modified, and evaluated (243).

Parametric modeling tools opened up an influential perspective for architects and led them towards a different thinking system. Although parametric design is perceived as just a technical issue that serves architecture by some, it is actually related to the fundamental change of architectural thinking, beyond the development of parametric design tools. Therefore, parametric design should be seen as a new thinking way as a change in the process. Parametric tools are not just about creating shapes or amorphous forms, they are actually related to thinking about an architectural problem parametrically, defining the design with input and output parameters. The whole process is about changing the thinking process rather than utilizing a specific parametric modeling software (Çinici et al., 2008). It is a significant issue that how much these tools will be able to contribute to the conceptual design phase when used alone or in combination with other tools. There is a cognitive process at the center of the idea generation stage, (Jin and Benami, 2010) and analyzing this cognitive process can provide a more effective way to incorporate these tools into the conceptual design phase.

CHAPTER 4

EMPIRICAL RESEARCH METHODOLOGY

This empirical study examines the effects of hand sketching and parametric design in relation to students' cognitive behaviors in the conceptual phase of designing during architectural education. The experiment defines the methods used to analyze and capture data about the students' cognitive behavior and evaluate their satisfaction in using Grasshopper as the parametric design tool. In this experiment, to achieve this goal two research methodologies were used. The first of these is protocol analysis method for investigating the cognitive behaviors then, the second one is questionnaire as a five-point Likert scale for assessing the satisfaction of the designers. The data are generated from the protocol analysis are quantitatively analyzed to identify the cognitive behaviors in a detail. By investigating the results of cognitive studies using protocol analysis with subjects' satisfaction levels utilizing Likert scales, it is possible to associate them.

This chapter of this thesis will give detailed information about the methodology that includes protocol analysis method, the participants, the experiment setup, data collection methods through retrospective interviews and questionnaires and also data analysis with the content-oriented coding scheme.

4.1 Protocol Analysis Method

Protocol analysis is an empirical research method which is widely used to understand how designers design and mainly aims at exploring the cognitive processes of designers (Cross, 2001; Cross et al., 1996; Van Someren et al., 1994; Ericsson and Simon, 1993). This method is often utilized to analyze design actions in design studios in education and also in the analysis of expert and novice designers' work. These works may be specific design tasks and be handled as group work. Protocol analysis is more formal than other methods used to investigate design thinking and it is a specific technique for capturing design activity in great detail (Cross et al., 1996). To investigate the cognitive behaviors of designers in protocol analysis, initially their verbal reports are collected from the recordings and then their verbal data are analyzed via an appropriate coding scheme. This method provides obtaining quantitative data from qualitative verbal reports in the context of design cognition in order to assess designer behaviors. These kinds of protocol studies, focusing on the participants, are concerned with how the information is processed and how it is turned into a reaction. Cross et al. (1996) categorized empirical research methods on design activity in three parts as *case studies*, *protocol studies* and *performance tests*. They emphasized the importance of protocol analysis as "Protocol analysis has become regarded as the most likely method (perhaps the only method) to bring out into the open the somewhat mysterious cognitive abilities of designers".

Protocol analysis was generated in psychological research field in the 19th century as the psychologists wanted to reveal the cognitive behaviors and mental processes by using introspective methods (Verstijnen et al., 1998). Van Someren et al. (1994) express that: "Introspection is based on the idea that one can observe events that take place in consciousness, more or less as one can observe events in the outside world." However, validity of introspection method has not been accepted as an experimental method due to the lack of repeatability of the experiment, misestimation and systematic deficiencies. Contrary to this, protocol analysis is considered as a reliable and valid methodology because it is based on codifiying the cognitive behaviors of designers through recordings and under observation (Akin, 1986).

Charles Eastman, who is among the first names who used this method at the end of the 1960s, conducted an experimental study on interior architecture students (EASTMAN, 1970). The method was later used by Newell and Simon (1972) to investigate the problem-solving process in design. In 1994, Nigel Cross, Henri Christiaans and Kees Dorst, brought together a group of international design researchers, who focus on analyzing cognitive behavior with protocol analysis method in Delft Protocols Workshop. 'Analyzing Design Activity' book, compiled from these studies, is one of the most referenced sources that includes various approaches about protocol analysis (Cross et al., 1996). Today, there are many research centers and communities that observe designers' cognitive activities through this methodology.

4.2 Stages of Protocol Analysis

The protocol analysis method consists of two consecutive procedures; *data collection* and *data analysis*. In data collection, verbal data are gathered from the participants. The subsequent data analysis part possesses several consecutive stages, namely, *transcription*, *segmentation*, *encoding the segments* and also *analyzing the coded protocols* quantitatively.

4.2.1 Data Collection

Design is a field of research where protocol analysis is often used. Dorst and Dijkhuis (1995) classify protocol analysis techniques used in design research as *process-oriented* and *content-oriented* approaches, which are related to Simon's (1992) "process of rational problem-solving" and Schön's (1983) "reflection-in-action process" theories respectively. The former approach focuses on defining the structure of the design process within the general taxonomy of problem solving (Eastman, 1970; Purcell et al., 1994). On the other hand, the content approach aims at dealing with the content of information, resources and information used in decision making (Schon and Wiggins, 1992; Suwa and Tversky, 1997; Suwa et al., 1998).

There are two approaches for collecting qualitative verbal data from the subjects in protocol analysis; 'concurrent' and 'retrospective' (Ericsson and Simon, 1993). Although each approach aims at revealing cognitive behaviors of designers, they differ in terms of the collection type and the content of verbal data. In order to obtain verbal data with concurrent protocol method, also named as the think-aloud method, the participants are asked to design and verbalize their thoughts simultaneously. In this method, participants are expected to express their thoughts while they are dealing with a design problem. The concurrent reporting on the information processes relates to participants' short term memory (STM). Participants have limited time to express their thoughts while designing in the experiment. Constraints caused by concurrency prevent the simultaneous interpretation of the design process (Ericsson and Simon, 1993). Therefore, concurrent protocol method is associated with the process-oriented approach of design process (Gero and Tang, 2001).

On the other hand, in retrospective protocol method, the verbal data is obtained from verbalization of a participant's recall of thinking after he/she completes the design task. When designers finish the design task, they are asked to report about the design process and reflect on what they did in the experiment. In most of the cases, after participants complete the experiment, they watch their recordings and videotapes of the design sessions to remember their design activities. These visual records are utilized as clues during retrospective verbalization to remind participants how they designed during the experiment. The retrospective protocol method relates to designers' long term memory (LTM). Retrospective protocol method is considered to be an appropriate method for the content-oriented approach of the design process (Tang and Gero, 2000).

Some researchers argue that the concurrent method interrupts the design process and some features of the design process cannot be explained (Lloyd et al., 1995). One of the reasons for this is the need to think aloud, which affects the designer's perception and concentration when designing (Lloyd et al., 1995). In the retrospective reporting technique, on the other hand, Ericsson and Simon (1993) pointed out that there may be deteriorations in recalling the design process from the memory. An effective way to prevent this is to keep the video recorder running during the process and watch the recordings afterwards in the verbalization period (Suwa and Tversky, 1997).

4.2.2 Data Analysis

In data analysis, the second part of the protocol analysis method, various procedures are applied to the verbal protocol sequentially. First of all, the video or audio recorded protocols of the participants are transcribed. Following that, segmentation and encoding procedures are carried out and the coded protocols are analyzed through graphics, frequencies, percentages and statistical tests, respectively. At the end of these analyses stages, researchers can quantify the qualitative protocols. As such, the designer's cognitive activity is represented using numerical information through the data analysis process. The consecutive stages of the data analysis are as follow:

Transcription

The first step in data analysis is the conversion of retrospective or concurrent verbal data into written text after the experiment. Transcription takes a long time as it requires to hear every word and transfer them to written form without any mistake. To shorten this transcription period and to facilitate the researcher in the process, there are some software programs that automatically translate data in English into written form (Lee et al., 2013; Lee et al., 2015).

Segmentation

The purpose of the segmentation is to divide the whole verbal data into smaller parts named as segments. Partitioning the protocol according to the coding scheme makes it possible to organize and analyze the protocol easily and clearly. There are two main ways for dividing the verbal data. Firstly, the segmentation can be done according to the designers' verbal expressions, pauses or tones of their voice and the syntactic markers (Van Someren et al., 1994; Ericsson and Simon, 1993). The other way is to perceive the change in the design intent and action of the designer. In this regard, each segment corresponds to a design intent in the design process. The change in the design intent indicates the beginning of the new segment (Suwa et al., 1998).

Goldschmidt (1991) divides the design process into 'design moves' and 'arguments'. She describes these terms as (Goldschmidt, 1991): "Moves are the basic coherent operations detectable in designing, and arguments are the smallest sensible statements which go into the making of moves." (125). In general, a design move consists of one or two arguments. Based on Goldschmidt's (1991) definitions, the segmentation methodology proposed by Gero and McNeill (1998) is similar to the definition of arguments, whereas Suwa et al.'s segments (1997) are associated with the description of design moves. Gero and McNeill (1998) utilized the concurrent protocol analysis based on process-oriented approach. Also, in other concurrent protocol analysis studies (Atman et al., 1999; Kim and Maher, 2011; Lee et al., 2013), each segment is linked to a specific timeline and each single action can become a segment because each action is related to a time interval that must be coded. In this regard, generally, it is expected that the size and intensity of segments in concurrent protocols are shorter than the segments in retrospective protocols. In addition to that in concurrent protocol analysis, each segment includes one code.

On the other hand, Suwa et al. (1998) used the retrospective protocol analysis method in their study, which is based on content-oriented approach. A segmentation method similar to that of Goldschmidt's 'design moves' was used in this study, evaluating the designer's goals by looking at the contents of thoughts. Another common point between these two studies is the analysis of the links between the segments in order to understand the reasoning of the design activity better. Suwa et al. (1998) analyzed the dependencies between the segments. Similarly, Goldschmidt (1990, 1991, 1994) examined the relationship among the design moves and she generated a method for analyzing them named as linkography. In retrospective protocols (Suwa and Tversky, 1997; Suwa et al., 1998), an individual segment can consist of one sentence or many. However, the segments in the retrospective protocols are closely comprised of meaningful parts and considered to be larger in size.

Encoding the Segments and Coding Scheme Types

A coding scheme enables researchers to obtain quantitative results from the qualitative verbal data. The creation of the content and structure of a coding scheme may vary depending on the researcher's purposes. Therefore, one of the most important and critical steps affecting the results is the appropriate construction of the coding scheme. In protocol analysis, a large variety of coding schemes have been utilized by researchers for analyzing the design process (Kan and Gero, 2009; Suwa et al., 1998). However, very few of these coding schemes have been reused by other researchers, either by taking the same or revising them. Many used to describe the design activity in two categories, process-oriented and content-oriented coding schemes, based on Dorst and Dijkuhuis's (1995) study.

In cognitive literature, process-oriented coding schemes have been used for indicating the categories related to the process of design (Atman et al., 1999; Gero and McNeill, 1998; Yu et al., 2013; Kan and Gero, 2009; Shih et al., 2015). Gero (1990) generated a process-oriented coding scheme for analyzing the verbal data. This coding scheme is comprised of three main ontological categories; *function*, *behavior* and *structure* (FBS) that represent abstraction levels of the problem domain (Figure 4.1). In this FBS structure, Function (F) refers to the intent of designers, behavior (B) is divided into two variables that are "derived behavior" (Bs) and "expected behavior" (Be) from the structure and also "structure" (S) indicates the components of an artifact and their relationships. Apart from these, the coding scheme has two different design issues; requirements (R) and descriptions (D) that represent necessities that are independent of the design and the documentation of the design. Kan and Gero (2009) state that "a design description never gets transformed directly from the function but undergoes a series of processes among the FBS variables". Additionally, this ontology defines the design process with eight transitions (*formulation, synthesis, analysis, evaluation, documentation and reformulation I, reformulation II, reformulation III*) among design issues. In this regard, FBS ontology has proven to be a universal coding scheme for many design environments (Kan and Gero, 2009).

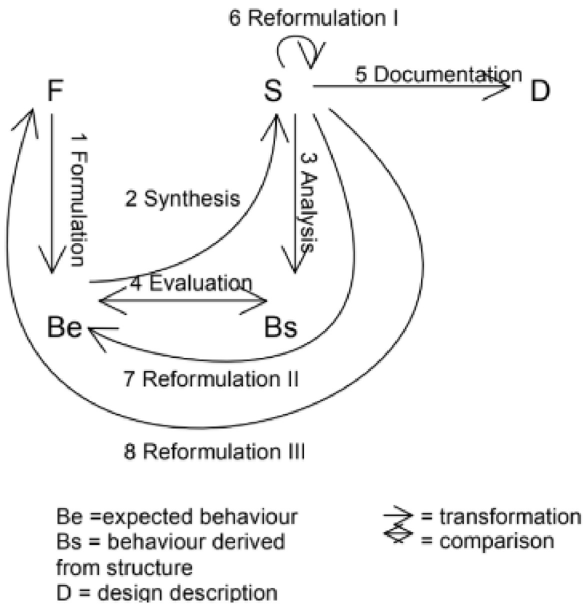


Figure 4.1: The structure of the FBS ontology (Kan and Gero, 2009)

On the other hand, the content oriented coding schemes are related to the content of the designer's cognitive behaviors and to the content of the design process. Suwa et al.'s (1998) coding scheme is one of the most well-known content-oriented coding schemes and is used by other researchers (Bilda, 2001; Bilda and Demirkan, 2003; Lee et al., 2013). This coding scheme is based on the information categories as *"emergent properties", "spatial relations", "functional relations" and "background knowledge"* (Suwa and Tversky, 1997). Suwa and Tversky (1997) state that: "We derived the four categories from theoretical discussions and historical evidence on how external representations convey meanings and concepts, from past literature on design processes that suggest what architects generally think of in design process, and from intensive study of the protocols." (388). These categories were revised in Suwa et al.'s (1998) study due to the insufficiency of dependencies and descriptions among the cognitive actions. In the new coding scheme, four cognitive action categories were devised as physical, perceptual, functional and conceptual, in order to show information processing in human cognition (Figure 4.2). Within these four categories of action, a specific coding scheme was developed as a result of experiments (Suwa et al., 1998). In the coding scheme, each action category is divided into subcategories and each subcategory is specified with a code for analyzing the verbal data.

In literature, while retrospective verbalization can be efficient for content-oriented coding schemes, concurrent verbalization can be appropriate for process-oriented coding schemes (Gero and Tang, 2001). In this regard, retrospective verbalization and content-oriented coding schemes are considered suitable for this thesis, considering the purpose and content of the study.

Category	*Names*	*Description*	*Examples*
Physical	D-action	Make depictions	Lines, circles, arrows, words
	L-action	Look at previous depictions	–
	M-action	Other physical actions	Move a pen, move elements, gesture
Perceptual	P-action	Attend to visual features of elements	Shapes, sizes, textures
		Attend to spatial relations among elements	Proximity, alignment, intersection
		Organise or compare elements	Grouping, similarity, contrast
Functional	F-action	Explore the issues of interactions between artefacts and people/nature	Functions, circulation of people, views, lighting conditions
		Consider psychological reactions of people	Fascination, motivation, cheerfulness
Conceptual	E-action	Make preferential and aesthetic evaluations	Like-dislike, good-bad, beautiful-ugly
	G-action	Set up goals	–
	K-action	Retrieve knowledge	–

Figure 4.2: Suwa et al.’s (1998) content oriented coding scheme

4.2.3 Previous Protocol Analyses in Conceptual Design Phase

L. Hay et al. (2017) carried out a comprehensive study for reporting the protocol analysis studies that focus especially on the cognitive approach of conceptual design process (Figure 4.3). They investigated 47 protocol analysis studies on architectural design, product design engineering and also engineering design. The total number of participants in these studies is 350 designers. In each study, the number of participants in the studies ranged from 1 to 36 and the participants' average number was 7. The following figure provides an overview of the number of participants, the type of tasks and verbalizations in the protocol analysis.

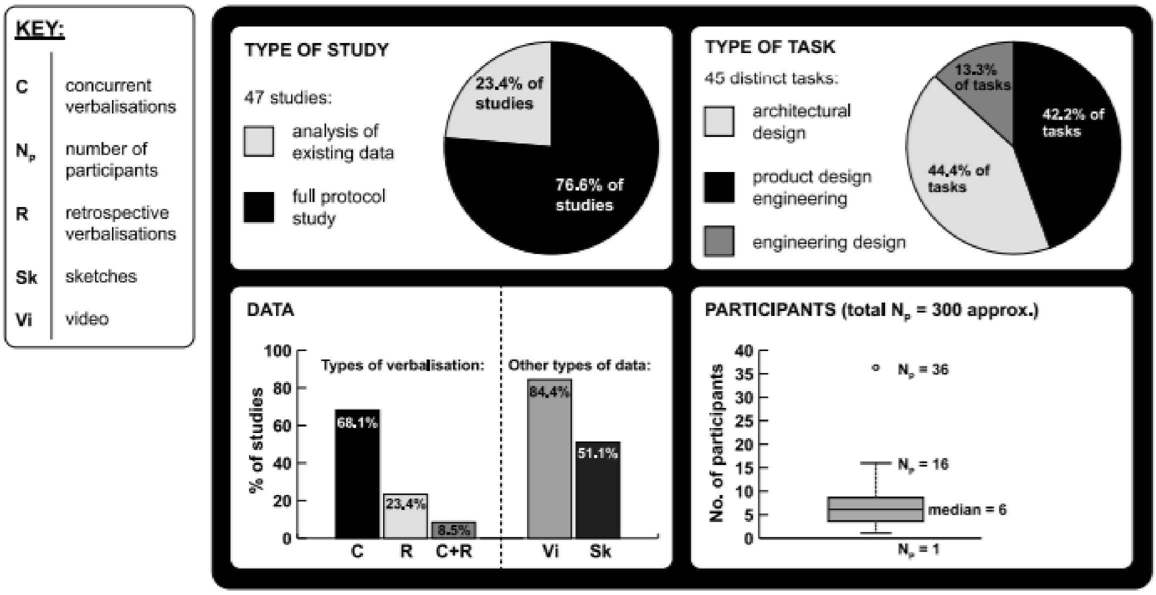


Figure 4.3: Protocol analysis studies review (Hay et al., 2017)

In this thesis hand sketching activity and parametric modeling tools were mentioned in Chapter 2 and 3, within the scope of conceptual design. Although there are various studies in which the efficiency of hand sketching and parametric modeling tools are studied separately, there are few studies that work on the efficiency of both, through protocol analysis methods. Table 4.1 shows some of those protocol studies following of which in explained in detail.

Suwa and Tversky (1997) conducted an experiment for exploring the thinking process of architects while sketching during the conceptual design phase. They aimed at revealing how architects interact with and perceive through their sketches and why their sketches are crucial for generating ideas. They conducted the experiment with 2 practicing architects and 7 students. They were asked to design an art museum conceptually in 45 minutes. After the sketching activities were videotaped, retrospective verbalization was done and the content-oriented coding scheme, as mentioned above, was applied. Suwa and Tversky (1997) found that practicing architects had more and longer dependency chunks than students due to the difference among their dominant cognitive behaviors and focus shifts.

Lee et al. (2015) analyzed the level of creativity and the relationship among the cognitive approaches in a parametric design environment via using consensual assessment technique and protocol analysis respectively. In their experiment, 2 expert and 2 novice architect participants utilized Grasshopper and Python script editor. They made three comparisons among the expert and novice users, geometric and algorithmic modeling environments and problem driven and solution driven design processes. The given design problem was the conceptual design of a high-rise building with five performance requirements, in one hour. As a result of their study, the researchers established a connection among cognitive activities of designers and their design outcomes. Lee et al. (2015) summarized the results in the following way:

> 1- The combined approach to parametric design provides better support for creativity than either the geometric or algorithmic approaches in isolation. 2- The text-based parametric design approach that produces more algorithmic activities, results in more unexpectedness during design, a quality which can also support creativity. 3- In parametric design, the solution-driven approach (rather than the problem-driven approach) is more effective for supporting creative outcomes as well as divergent thinking (20).

On the other hand, Won (2001) attempted to explore the visual thinking of designers cognitively while creating concepts utilizing digital and hand sketching. In the experiment, 6 graduate industrial design students participated and they were asked to design an alarm clock in an hour, using hand sketching and digital sketching tools separately. In this regard, Won (2001) made a comparison between these two media in terms of cognitive behaviors. He used three kinds of coding schemes as "S-I-D (seeing-imaging-drawing), SA-ST (seeing as-seeing that) and T-D (total-detail)". He explained that the digital environment has been found to lead the designer to use visual imagery more often than hand sketching.

Yu and Gero (2015) investigated the effects of the geometric and parametric modeling tools on designers' cognitive behavior in regard to the use of design patterns in the conceptual design process. They conducted an experiment for comparing these two modeling environments through using Rhino and Grasshopper separately. In the experiment, 8 participants, who are experienced in both modeling environments, were asked to design a community center and a shopping center conceptually in one hour. Yu and Gero (2015) have found out that use of the design patterns is more common and is better integrated into the structure in parametric design media (Grasshopper) than in geometric design media (Rhino).

Table 4.1: Examples of various protocol analysis studies

Year	Author	Field	Method	Medium	Experiment Time	Participants
*1997	Suwa and Tversky	Architecture	R.PA	Hand sketching	45 min	9
*2001	Won,P.	Industrial Design	R. PA	Hand-digital sketching tools	1 hour	2
2001	Bilda, Z.	Interior Architecture	R. PA	Hand-digital sketching tools	3 hours	6
2001	Kavaklı & Gero	Architecture	R.PA	Hand sketching	1 hour	2
2010	Tang et al.	Industrial Design	C.PA	Hand sketching-Geometric tools	1 hour	20
2013	Sun et al.	Engineering	R.PA	Digital sketching	open-ended	15
*2015	Lee et al.	Architecture	R.PA	Parametric tools	1 hour	4
*2015	Yu, R. & Gero, J.	Architecture	C.PA	Parametric-Geometric tools	1 hour	8
2017	Tahsiri et al.	Architecture	C.PA	Hand sketching-Geometric tools	40 min	3
2017	Shih et al.	Architecture	C.PA	Hand sketching-Geometric tools	75 min	6

R. PA = Retrospective Protocol Analysis

C.PA = Concurrent Protocol Analysis

* Explained in detail

Based on the previous protocol analyses studies, the framework of the study for this thesis is established. The average number of the participants was 7.5 in these studies. The participants in this thesis are relevant within the framework of the previous studies.

4.3 Participants

The experiment group consisted of 6 graduate students of the Department of Architecture at Bilkent University, Ankara, Turkey. They were randomly selected from the 10 students, who are enrolled in the graduate program of Department of Architecture. The selection of such a group of students is made to ensure that their levels of design skills are similar. The other 4 graduate students participated in the pilot study. Most of the protocol analysis studies on the cognitive behaviors of designers are usually handled with a relatively small group of participants (min 2- max 20 participants), but it provides an in-depth study of the samples and extremely rich data. (Akin and Moustapha, 2003; Yu et al., 2013) In line with the similar previous studies, it is considered that the sample size of this study is sufficient.

5 of these graduate students had prior knowledge about Grasshopper. They previously carried out some projects with this program during their undergraduate studies. The remaining group had basic knowledge about Grasshopper. They took courses on Grasshopper, but they did not use the software to design before. Thus, the participants can be grouped as 'experienced' and 'inexperienced' in this experiment respectively. Before the beginning of the pilot study and the main experiment, the subjects were asked to answer some questions about their knowledge in using Grasshopper (Appendix A). All of the participants (in pilot study and main study) were female and they volunteered for the empirical study (Table 4.2). They were all graduates of an architectural program in a university. The ages of the participants ranged from 22 to 26 with a mean of 23,3, and the standard deviation of their ages was 1,251 years. 6 of the students were from Ankara, the capital of Turkey, 1 from Tabriz in Iran, and the rest were from different cities in Turkey. The mean of their Cumulative Grade Point Average's (CGPA's) were found to be 3.26.

Table 4.2: General Profile of the Students

	Subjects	Gender	Age	Place of Birth	University Type	CGPA
Pilot Study	1	F	24	Konya/Turkey	Private	3.17
	2	F	23	Amasya/Turkey	Private	3.06
	3	F	23	Ankara/Turkey	Private	3.37
	4	F	23	Erzurum/Turkey	Private	3.14
Main Experiment	5	F	24	Ankara/Turkey	Private	2.98
	6	F	22	Ankara/Turkey	Private	3.31
	7	F	24	Ankara/Turkey	Private	3.44
	8	F	26	Tabriz/Iran	Private	3.71
	9	F	22	Ankara/Turkey	Private	3.04
	10	F	22	Ankara/Turkey	Private	3.42

4.4 Experiment Setup

The experiment setup comprises of the research setting, pilot study, main experiment, data collection methods, data analysis and content-oriented coding scheme that was adapted to verbal data respectively.

4.4.1 Research Setting

The computer lab FF216 of the Department of Architecture at Bilkent University was chosen as the experiment location, as it was appropriate for the experimental study in terms of its spatial and technological conditions. It was equipped with required software/hardware and provided a silent environment enabling the subjects to focus on their tasks in the experiment (Figure 4.4).

In this study, the subjects were free to use hand sketching and the parametric modeling tool Grasshopper. They were allowed to switch the method whenever they found necessary. Grasshopper was chosen for this study because it has a visual scripting structure that all of the subjects are familiar with. Additionally, Grasshopper is one of the well-known parametric modeling tools that has a shared environment with geometry-based modeling tool Rhino.

In the experiment, 3 different recording devices were utilized. First one is the Debut software program that records the changes in the designers' computer screens while using Grasshopper consistently. This program enables the subjects to watch the recordings later on and helps them to remember what they thought during the process. The screen records were useful for the participants' re-calling process in terms of their retrospective interviews.

Secondly, 3 video cameras were located above the tables, positioned between the two participants while sketching, in order to record every detail of the process. Finally, these videotapes were used in the retrospective interview sections with the participants for obtaining verbal data.

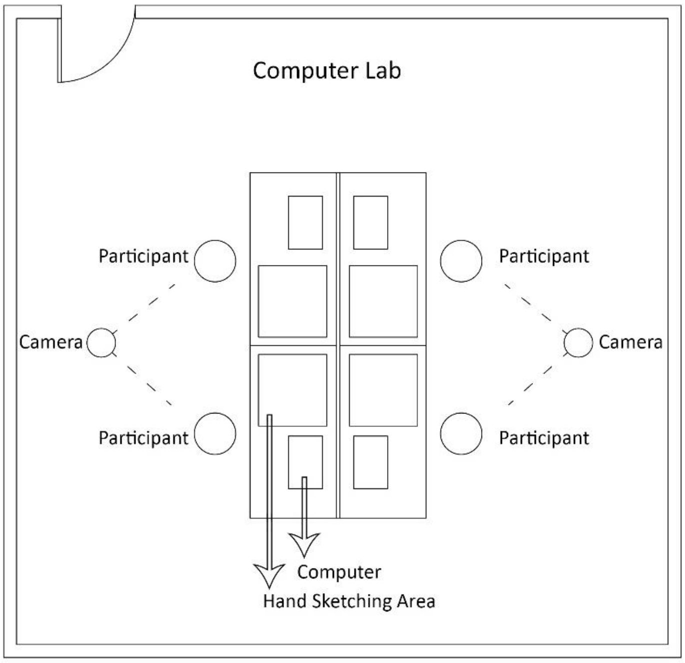


Figure 4.4: Working Environment Sample

4.4.2 Pilot Study

The pilot study is necessary for testing the actual experiment setting before and it allows checking all of the conditions and appropriateness. Before the main experiment, 4 graduate students of the Department of Architecture at Bilkent University attended to this pilot study voluntarily.

Two days before the pilot study, a training session was held with the participants on Grasshopper. The training session lasted 4 hours. The aim of this training session was to show some high-level examples and tutorials to the subjects. The training focused on the surface tools, the much-used parameters and components in Grasshopper and also demonstrated the relationship between them.

In the pilot study, the subjects were informed about the experiment process initially. After that, a design brief was given describing the design problem, content, definitions, and requirements. The design brief was structured with a simple design problem of designing a shelter and the subjects were only responsible for coming up with a conceptual design. This design problem has some constraints for directing the designer into a problem-solving process. To visualize the problem environment, the design brief was enriched with a relative site plan and a diagram. Then, subjects were left free to utilize hand sketching and Grasshopper alternatively in the design session. Generally, the intervals between 60 and 90 minutes are sufficient for the design task and provide data with the controllable intensity (Dorst, 1996). Therefore, they were given one hour to complete the design problem. At the end of the pilot study, 5 point Likert scale questions were given to the students for evaluating the experiment conditions in terms of time, place, tutorials and design task. In addition to this, another 5 point Likert scale questionnaires were given to them for assessing Grasshopper as a tool for conceptual design phase. While, the first Likert scale was only used in the pilot study to observe the conditions of the experiment, the second Likert scale will be used after the main experiment for analyzing the results. After that, the retrospective interviews were done and the coding scheme for this experiment was evaluated. Generally, the pilot study facilitated the evaluation of the following factors: The sufficiency of the time for subjects, appropriateness of research setting location, conditions and software programs, the adequacy of technical devices such as cameras and videotapes, level of design briefs and the convenience of the coding scheme and the Likert scale questions. As a result of this pilot study, the design brief, time and computer lab conditions were found to be appropriate for the subjects. According to the 5 point Likert scale, participants verified that the conditions were appropriate. While the coding scheme is considered to be also compatible with the study, the second 5 point Likert scale questionnaire was revised and some questions were added (Appendix A).

After the pilot study, the training session was cancelled due to its negative impact on the inexperienced participants. It had a direct influence on them and students tried to do similar designs to the ones they did in the training section, instead of exploring the potentials of the software. This situation was observed to be a restrictive factor for the participants. After that, in the main experiment, each subject determined to participate with their own level and knowledge without attending any training period.

In terms of the experiment setting, one problem was due to the high memory capacity required by Camtasia. The software captures high quality screenshots and this has caused computers crash due to insufficient hardware capacity. However, the problem was solved by changing the screen recorder software to Debut, which records in low quality resolution.

4.4.3 Main Experiment

At the beginning of the experiment, the process was explained to the participants in the computer lab (Appendix B – Figure B1). Before beginning the main experiment, each participant completed a survey about her educational background and experience in Grasshopper. After that, the design briefs were distributed to the participants and they were given 15 minutes to examine the brief before the beginning. When all participants were ready to design, they were requested to start Debut program for recording their computer screens and then, the experiment began. When a subject finished the experiment process, the supervisor closed Debut software and the video camera and also saved the recording. The experiment process comprised of one design session. The subjects had one hour to design, but they were allowed to finish earlier or later.

In the design session, a design brief including a problem definition, a site plan, and the requirements was given to the participants. In the pilot study, the design brief's relevance was tested. The design brief was arranged to allow participants to think freely in the conceptual phase of design and produce results. The following table (Table 4.3) shows the structure of the experiment in terms of the design brief, session, subjects and different design environments. The subjects were allowed to switch between hand sketching and Grasshopper without any limitation.

Table 4.3: Structure of the main experiment

Experiment Setup	
Participants	Six graduate students (architecture)
Place	Computer lab
Design Problem	Shelter
Duration	One hour
Design Session	One
Tools	Hand sketching / Grasshopper

In the design brief, the participants were requested to work on designing a shelter in the university campus. The given design problem was rather simple because it was expected that the participants would be encouraged to do different concept explorations. The shelter should be designed for maximum 15-20 people with a self-standing roof structure. Some other design specifications were also included in the design brief (Appendix B – Figure B2). In the design session, all of the participants were required to solve same design problem at the same time. In addition to that, the participants were expected to come up with conceptual designs, rather than detailed drawings.

4.5 Data Collection

The first phase of the protocol analysis method is collection of the verbal data from the subjects. The day after the main experiment, each participant was allocated at a different time interval and interviews were done. The participants were requested to watch their individual recordings during sketching and during computer modeling in order to remember their design activities. As Suwa and Tversky's study, they were asked to recall the experiment process and report what they were thinking and doing while watching their recordings in each session (1997).

In this retrospective protocol verbalization part, participants were not interrupted with questions, they just expressed the thoughts about the process in detail. In some instances, if the participant did not remember what she intended to do completely, she was allowed to watch the recording again and express her thoughts. The verbal data was collected from each subject for each different session in the experiment at the end of the reporting process.

On the other hand, at the end of the experiment, a five-point Likert scale (where 1 is the lowest and 5 is the highest) was used which evaluate some statements about the participants' satisfaction levels and opinions in terms of using Grasshopper.

4.6 Data Analysis and Coding Scheme

Linguistic data analyzing process is the second part of the protocol analysis. In this process there are three steps; transcription of the verbal data, segmenting the transcription and using an appropriate coding scheme for the segments respectively.

Data analysis process was done in order to elicit quantitative results from verbal data. In this data analysis, the segmentation process and the coding scheme was based on Suwa et al.'s (1998) study. Suwa et al.'s (1998) coding scheme consists of four action categories. Coding scheme associates with content-oriented approach of the design process that aims to reveal the contents of what designers see, attend to, think of and retrieve from memory while designing (Suwa et. al, 1998). In the empirical study handled for this thesis, Suwa et al.'s coding scheme was revised to be more suitable for a parametric design environment. In the revision process, the appropriate coding scheme was adapted by examining Zafer Bilda's (2001) and Lee et. al's (2013) coding schemes (Figure 4.5). The structure of hand-sketching and parametric modeling tools, and also the previous protocols obtained from the pilot study were evaluated for generating the coding procedure presented in this thesis.

Suwa et al. (1998)

Category	Names	Description	Examples
Physical	D-action	Make depictions	Lines, circles, arrows, words
	L-action	Look at previous depictions	–
	M-action	Other physical actions	Move a pen, move elements, gesture
Perceptual	P-action	Attend to visual features of elements	Shapes, sizes, textures
		Attend to spatial relations among elements	Proximity, alignment, intersection
		Organise or compare elements	Grouping, similarity, contrast
Functional	F-action	Explore the issues of interactions between artefacts and people/nature	Functions, circulation of people, views, lighting conditions
		Consider psychological reactions of people	Fascination, motivation, cheerfulness
Conceptual	E-action	Make preferential and aesthetic evaluations	Like-dislike, good-bad, beautiful-ugly
	G-action	Set up goals	–
	K-action	Retrieve knowledge	–

Lee et al. (2013)

Level	Category	Subclasses	Description
Physical	Geometry	G-Geometry G-Change	create geometries without an algorithm change existing geometries
	Algorithm	A-Parameter A-Change Parameter A-Rule A-Change Rule A-Reference	create initial parameters change existing parameters create initial rules change existing rules retrieve or get references
Perceptual	Geometry	P-Geometry	attend to existing geometries
	Algorithm	P-Algorithm	attend to existing algorithms
Conceptual	Problem-finding	F-Initial Goal F-Geometry Sub Goal F-Algorithm Sub Goal	introduce new ideas (or goals) based on a given design brief introduce new geometric ideas introduce new algorithmic ideas
	Solution-generating	G-Generation	make generation (or variation)
	Solution-evaluating	E-Geometry	evaluate primitives or existing geometries
		E-Parameter E-Rule E-Reference	evaluate existing parameters evaluate existing rules evaluate existing references

Bilda (2001)

Action	Subcategory	Action ID	Description
PHYSICAL	Draw	Dc	Making new depictions (drawing lines, walls, things which are object, furniture, accessories, space elements etc.)
		Dsy	Depicting a symbol that represents a relation (for hand-sketch only)
	Modify	Drf	Revising the shape, size, or texture of a depiction. These refer to stretching lines or areas, editing shape, color or texture in the CAD environment.
		Dd	Erasing a depiction/delete a wall or object.
		Md	Moving a depiction/object. Rotate an object.
	Copy	Dts	Tracing over a depiction on a new sheet of paper (for hand-sketch only)
PERCEPTUAL	Features	Pfn	Attending to the feature of a new depiction (shape, angle, size, texture)
		Pfnp	Attending to the feature of a view in 3D (imagery or graphical)
		Pv	Creating or attending to a spatial relation between two space components or area (symmetrical, adjacent, far, on the same axis...)
	Relations	Prn	Creating or attending to a relation between two objects/things
		Plo	Attending to the location of an object in a space component (alignment or geometrical definition)
		Prp	Discovering an organizational relation between things/objects (more than two things/objects)
	Implicit	Psg	Discovering a space as ground
FUNCTIONAL	Implement	Fn	Associating a new depiction, feature or relation with a specific function that was previously thought or newly discovered
		Fi	Implementing a previously explored or through function be creating a new depiction, feature or relation
	Reinterpretation	Fre-I	Re-interpretation of a function
	Thought functions	Fc	Thinking of a function to be seen implemented.
		Fnp	Thinking of a function independently of depictions
CONCEPTUAL	Goal setting	G	Setting up of goals. Introducing new functions, resolving problematic conflicts, and goals to apply introduced functions or arrangements [14]
	Knowledge retrieval		Retrieve knowledge.

Figure 4.5: Coding scheme sources

4.6.1 Transcription

The main experiment involved 6 graduate students and each student participated one design session that required of 6 protocols in total. In this part of protocol analysis, each record was listened and transcribed into a Microsoft Word document simultaneously. Each recording of the 6 designers were directly transcribed using NVivo 10 software. Although this software supported the automated transcription, the verbal reports were checked again by manually checking for mistakes. In addition to that, the collection of the verbal data was held in English in order to prevent any translation mistakes.

4.6.2 Segmentation

After the retrospective verbalization period, the verbal transcripts were obtained from the participants and the videotapes were watched for a number of times. Segmentation requires the separation of transcripts into smaller and meaningful fragments according to a rule (Suwa and Tversky, 1997) so that the transcripts can be analyzed more easily and valid. A new segment emerges when the designer changes his/her intention (Suwa et al., 1998). This change was considered as either as the transition between design decisions or an instant shift in a design strategy. One segment might consist of one or more sentences, and the same segment continues until the participant changes his/her intention or strategy. For example, if a participant extends the rectangle after creating it, this situation can define a new segment. Because at that moment the participant made a new decision and it refers to the subsequent design move. However, sometimes the subject does not like the design at all and he/she suddenly gives up and makes unexpected decisions. For instance, when a subject decided to change his/her idea about the form of the design, it was considered as a signal for a new segment.

The following table consisting of participant 4's segments might make the segmentation session more clear (Table 4.4). Participant 4 defined the points as space components and arranged their places to adjust their height in segment 12. After that, in segment 13, participant 4 defined the spatial relations and began to think about the structure's entrances and openings. It was an instant shift between two segments and then participant 4 continued with defining a new space component by drawing pipe lines in segment 14. Then, she redefined the pipe lines with using another component and so the next segment, 15 emerged.

Table 4.4: An Example of Segmented Protocols (Participant 4)

SEGMENT	PROTOCOLS
12	I wanted to understand the scale so I tried to create some points at 3 meters and according to that, I arranged other points' heights. Here… Place the points in the z axis. I am playing with them (points) in top view now. Because in a design we should be aware of the plan view, not only the sections or elevations. So I am thinking about all of the views and revising the height of the points again.
13	Here, I aimed to locate the entrances, I wanted the design to be, and I wanted everyone to enter this project from all views so I designed some openings in here. I am thinking about this (entrance) when I am rotating this shape. Yes... I am changing the direction in there for creating different shape.
14	After that, now, I am giving thicknesses to pipe lines. I changed the pipe lines radii and arranged them. I want to design thin lines, thin structure. Because I don't want it to be a heavy design. Do not want these steel parts to be too dominant in this design. The structure would otherwise be too heavy so I made them thin.
15	Then, I created delaunay meshes with the pipe lines. It (delaunay triangles) is for making surfaces. I brought these surfaces in line with each other. I was trying to create closed spaces. I like these triangle parts.
16	Now I am thinking about the general shape that becomes like a shell structure. Yes, it (structure) is closed. I can make openings wherever I want but in the end, it will be only like a shell structure even if I create furniture for standing or something like that with the triangulated shape. But I did not want to be like that. It is too planar and I do not like it. Because of that I added more volume.

In the verbal protocols, the designers usually explain their intentions like ‘now, I am thinking about...’ or ‘here I tried to figure out…’ and these statements might generate new segments in general. Although segmentation is easier with these statements, sometimes subjects may not be able to provide any clues about their intentions, but they give some hints before or after making a design decision. Subjects create new segments by giving clues about the transition to the next stage.

4.6.3 Coding Scheme Adaptation

Each segment consists of various cognitive actions that represent information processing levels in human mind. These cognitive actions can be classified into four main categories, namely as physical, perceptual, functional and conceptual respectively (Suwa et al., 1998). Each main action category can be divided into various subcategories which also have lower-level ramifications, called actions. Moreover, each lower-level action is abbreviated to an Action ID. Generally, the Action ID’s first capital letter implies the main action category name, the second capital letter refers to the subcategory name and the last letter shows the content of the action. The codes specific to the parametric design environment are shown in the coding scheme with a star icon '*'.

In cognitive literature, the information coming to the human mind is processed first sensorily, then perceptually and semantically (Suwa et al., 1997; 1998). Regarding this human cognitive process, physical actions correspond to sensory level, perceptual actions to perceptual level and lastly, functional and conceptual actions to semantic level (Suwa et al., 1998). Although the same action categories were utilized in this study, the coding scheme was revised considering Figure 4.5 and new codes were added in line with the purpose and the scope of thesis (Table 4.5).

Table 4.5: Coding Scheme of Cognitive Actions

ACTION CATEGORY	SUBCATEGORY	ACTION ID	DESCRIPTION
PHYSICAL	Create	Dcg Dcp Dcr	Creating new geometry/depiction Creating new parameter* Creating new rule*
	Modify	Dmg Dmp Dmr	Modifying the geometry/depiction Modifying the parameter* Modifying the rule*
	Erase	Deg Dep Der	Erasing a geometry/depiction Erasing a parameter* Erasing a rule*
PERCEPTUAL	Features	Pfg Pfa	Attending to visual features of a new geometry (shape, size, angle etc.) Attending to the graphical depiction of the algorithm*
	Relations	Prs Prl Prg	Attending to spatial relations among elements (proximity, alignment, intersection, etc.) Attending to the links between the parameters* Discovering a space as ground
	View	Pvf	Attending to the feature of a view in 3D (imagery or graphical)
FUNCTIONAL	Implement	Fn Fi Fi-re	Associating a new depiction, feature or relation with a specific function that was previously thought or newly discovered Implementing of a function independently of geometries Re-interpretation of a function
	Reactions	Fri	Exploring the issues of interactions between artefacts and people/nature (functions, tool-user relation, or psychological reactions)
CONCEPTUAL	Goal setting	Cg	The intentions designers want to achieve
	Retrieve knowledge	Ck	Retrieving knowledge from memory
	Evaluation	Ce	Making preferential and aesthetic evaluations (like-dislike, good-bad, beautiful-ugly, etc.)

* For parametric design environment only (Grasshopper)

Physical

The first main action category of the coding scheme is ‘physical’ actions which are divided into three subcategories as ‘create’ (C), ‘modify’ (M) and ‘erase’ (E). Physical actions have been referred to physical depictions and geometries in both hand-sketching and parametric design environment. They are classified as ‘D actions’ as in Suwa et al.’s (1998) study. In hand sketching, all physical cognitive actions are evaluated based on geometry and depictions. Although parametric design includes a geometric approach as well as hand sketching, it also involves an algorithmic approach. Therefore, in the present experiment, some codes are added to physical actions specifically pertaining to the algorithmic perspective of the parametric design environment.

The Dcg action is related to making a new depiction or generating an initial geometry in both media. This action corresponds to the creation of new lines, walls, columns, objects or arrow symbols that represents a relation between these elements. Similarly, modification of the existing geometry/depictions (Dmg) is one of the common cognitive actions. For instance, copying a geometry, revising the shape, and moving or rotating a geometry are included in this subcategory. If a designer uses an expression such as "I extend this curve", Dmg is coded as the associated action. Moreover, in hand sketching, tracing over a depiction on a new sheet of paper can be perceived as Dmg action. Lastly, the same rule applies to the deletion of the previously generated geometry/depictions (Deg) in Grasshopper and in hand sketching.

On the other hand, in Grasshopper, the content of D actions is slightly different than hand sketching. If the designer drops a component onto the algorithm space, that is, Grasshopper’s canvas screen, this action implies the generation of a new parameter

(Dcp). However, if he/she connects the parameters through wire-network, it refers to creation of a rule (Dcr). The same reasoning applies to modifying and erasing the parameters and rules in Grasshopper. While changing the value of a parameter that affects the geometry directly refers to the modification of a parameter (Dmp), changing the existing connections between the parameters without erasing implies modification of a rule (Dmr). Likewise, deleting a parameter is coded as (Dep) and disconnecting the link between the parameters is denoted as the action of erasing a rule (Der).

Perceptual

The second major category ‘perceptual’ represents the actions of visual and spatial approaches in the design process and they are named as ‘P actions’. This category has three subcategories which are ‘features’ (F), ‘relations’ (R), and ‘view’ (V) respectively. As defined in Suwa et al.’s (1998) coding scheme, the first subcategory is related to visual features of the geometries and depictions such as their shapes, sizes, angles or textures. The Pfg action is usually coded while attending a new visual or spatial characteristic to a geometry. For instance, if a designer mention that ‘the column is small and concrete’ or ‘that space has a triangular form’, it is considered as a new Pfg action. However, in Grasshopper, if a designer adds graphical features to a parameter, it is coded as a Pfa action. For instance, using number sliders or panels for variating the parameter refers to Pfa code.

The second subcategory of P actions refers to spatial relations between the geometries such as proximity, alignment, intersection. It also includes the organization or comparison of the elements such as grouping, similarity or contrast. The Prs action is related to the relationship among spaces and geometries such that ‘the seating area is adjacent to the stands’ or ‘the two sides of the roof covering overlap here’ or ‘these columns are on the same axis’. The Prl action is added in the coding scheme either because of the Grasshopper’s algorithmic framework. This action is related to attending the links among the parameters such as relocating and organizing the wire-networks visually on the Grasshopper's definition screen. Additionally, the Prg action is concerned with the discovery of a space as ground. This action is associated with the unexpected discoveries in the design process (Suwa et al., 1998). In other words, although the space has not been previously perceived as a place, it may suddenly appear as such depending on the changes in the design process.

The third and the last perceptual subcategory, named View is related to discovering the geometry in different ways. When using Grasshopper, sometimes the designer changes the view to either to two or three dimensional window for exploring the model. This action refers to viewing geometry (Pvf). Grasshopper enables designers to easily see the model in 3D and switch between other views, while designers have tried to draw plans, front views or sections in hand sketching to explain their ideas better and to imagine the other views of the model. Therefore, the Pvf action could be employed in hand sketching based on the visual imagery formed in designer's mind. For instance, the raw perspective drawings, quick sketches and diagrams refer to Pvf action.

Functional

Another main category in the coding scheme is 'Functional' which is related to actions of understanding non-visual information and taking into account the knowledge of physical and perceptual actions (Suwa et al., 1998). The F actions consist of two subclasses named as 'Implement' (I) and 'Reactions' (R). The first subclass denotes the functional criteria that the designer has created in his or her own mind, related to the design elements. The Fn action is encoded when a function is applied to a geometry or to a depiction. A designer can associate a newly discovered or previously thought function with any geometry, depiction or relation. Besides, if the designer refers to a function without commenting on any element in the design, it is perceived as Fi action. As an example, whereas 'I have designed the living space larger than the sales space' is associated with the Fn, the 'right side of the structure should see the music building' phrase is Fi code. The Fi-re code is one of the most important functional actions, which usually refers to the use of a function in the place of other functions depending on other design elements or on external factors. For example, in the given design problem, the designer working on an amorphous seating area that integrates with the roof covering, may find out that this is not suitable for the users. After that, when he/she decides that the seating area should be in a more rigid form and unconnected to the roof covering then, this action coded as Fi-re. As another example, this code includes the expression 'I have designed the whole area as semi-closed and semi-opened when I thought of the flow of people in it'.

The second subcategory, ‘Reactions’, refers to interactions among the artifacts and people or nature. It has only one encoded cognitive action, Fri, involving: the observation of the psychological effects of the people, the relationship between the design and the environment (main roads, pathways, other buildings, green areas, the potential users, the view and the sunlight and weather conditions), the consideration of the human scale, and the thoughts of the designer regarding the method used (user-tool reaction). For instance, ‘People can walk around in this way in the structure’ expresses the circulation of the users in the design and also coded as Fri. As another example, ‘this is a remarkable area’ or ‘users feel comfortable in this place’ demonstrate the psychological aspects of the users.

Conceptual

The last main category is ‘Conceptual’ that is related to actions at the semantic level of the information process of the designer’s mind. There are three subcategories of C actions which are ‘Goal Setting’ (G), ‘Retrieve Knowledge’ (K) and lastly ‘Evaluation’ (E). The first, setting up of the goals refers to the Cg cognitive action that denotes the intentions of the designers in the design process. In general, a goal can be generated by the initial aims or can be affected by them. On the other hand, a goal can be triggered by especially P and F actions. The second one, retrieving knowledge, coded as Ck, represents the recalling process from the past experiences of the designers. For instance, ‘The angles of the columns should be in this way for the structure to be durable’. The last action code of the Conceptual category is Ce. This is related to making preferential and aesthetic evaluations about the design solution such as like-dislike, beautiful-ugly or suitable-unsuitable. Criticism about the design solution in both media refers to this code.

In order to make the coding process of the data more understandable, it may be useful to show a partial example of the coding scheme. Table 4.6 indicates the encoded actions of the segments that are shown in Table 4.4. Although all of the conceptual and functional actions were encoded from the verbal reports of the participants, the vast majority of the physical and perceptual actions were obtained from the video recordings in the experiment. After examining the verbal reports and video recordings many times, the coding process was completed.

Table 4.6: A partial example of the encoded segments

Segment-12

Action Category	Action ID	Content
Physical	Dmg	
	Dmp	playing points
	Dmp	revising height
	Dmg	
Perceptual	Pfg	3 meters
	Pvg	
	Pvf	
	Prs	in z axis
Conceptual	Cg	tried to create
	Cg	wanted to understand
	Ck	in top view
	Ck	should be aware of the plan view
	Ck	thinking about all the views

Segment-13

Action Category	Action ID	Content
Physical	Dmg	rotating this shape
	Dmp	
	Dmp	
	Dmg	
	Dcr	
Perceptual	Prs	changing the direction
	Pvf	
Functional	Fn	entrances
	Fn	openings
	Fri	everyone to enter this project
Conceptual	Cg	aimed to locate
	Ce	different shape

Segment-14

Action Category	Action ID	Content
Physical	Dmg	arrange pipelines
	Dmg	change the pipeline radii
	Dcp	
	Dcr	
	Der	
Perceptual	Pfg	thin lines
	Pfg	thicknesses
	Pfg	steel
	Pfa	
	Prl	
Conceptual	Cg	I want to design
	Ce	too heavy
	Ce	too dominant
	Ck	these steel parts to be too dominant

Segment-15

Action Category	Action ID	Content
Physical	Dcp	delaunay mesh
	Dcp	pipeline
	Dmp	
	Dcr	
Perceptual	Prs	make surfaces
	Prs	brought these surfaces in line
	Prg	create spaces
	Pfg	triangle parts
Functional	Fn	closed space
Conceptual	Cg	I was trying to create
	Ce	I like these

Segment-16

Action Category	Action ID	Content
Physical	Dcp	
	Dcp	
	Dep	
	Dcr	
	Dcr	
	Dcr	
Perceptual	Pfg	triangulated shape
	Pfg	I added more volume
	Pfa	
	Prl	
Functional	Fn	it (structure) is closed
	Fn	openings
	Fi	create furniture for standing
Conceptual	Cg	I am thinking the general shape
	Ce	But I did not want to be like that
	Ck	it will be only like a shell structure
	Ce	too planar

CHAPTER 5

RESULTS

The results are shown in two main headings that introduce the findings related to the protocol analysis and post-task questionnaire. The main results of the study are evaluated through protocol analysis and the questionnaire results also provided additional and helpful assessment. While the results of the protocol analysis depicted the participants' cognitive behaviors in detail, the results of the questionnaire indicated the satisfaction with the use of the tools. An associative interpretation is held between the protocol analysis and the results of the questionnaire.

While examining the protocol analysis data, various quantitative definitions were used, such as frequencies, percentages and statistical analyses through Spss program. In this examination, the Mann-Whitney U test was conducted, which is considered a non-parametric alternative to the parametric independent t-test for statistical analysis of the data. Non-parametric tests are preferred when there are a small number of participants in the test groups. The Mann Whitney U test is utilized to compare differences between two independent groups. In addition to that, individuals in the same group should be randomly selected and are not assumed to be normally distributed. In this study, both the small sample size (in the experiment N=6) and other requirements (such as random selection, etc.) of the Mann-Whitney U test are fulfilled.

5.1 Post-task Questionnaire Results

In the beginning of the post-task questionnaire, a separate questionnaire was performed to collect participants' demographic data and data concerning their experience levels in using Grasshopper (Appendix A). According to this, all of the participants were graduate architecture students in the Bilkent University. The inexperienced participants, P1, P2 and P3, did not use Grasshopper and Rhino software much in their past. They learned the basics about these programs in some elective courses, but they practically used in several times. In addition to that they did not spend an extra time to improve their experiences except what they learned in the elective courses.

On the other hand, the experienced participants, P4, P5 and P6, took the same basic and advanced courses on using Rhino and Grasshopper since the beginning of the second year of undergraduate education. P4 and P5 also worked on complex parametric models in various international workshops. Moreover, P6 designed her studio projects through using Rhino and Grasshopper. They had good command of knowledge and practice on these modeling tools.

After the main experiment, participants were asked to answer the 5 point Likert scale questionnaire questions (Appendix A) to evaluate their satisfaction levels about Grasshopper in general. The questionnaire comprises of 10 questions, organized to gain an insight about how much the participants benefit from the advantages of Grasshopper as a parametric modeling tool and to what extend Grasshopper affects their design solutions at the end of the design session. Responses to question 1 (*In the design process, I preferred Grasshopper to hand sketching*) is concerned with the participants' preferences in the entire design session. 4 participants specified that they preferred Grasshopper to hand sketching. One participant who is inexperienced in Grasshopper preferred hand sketching strongly (Figure 5.1).

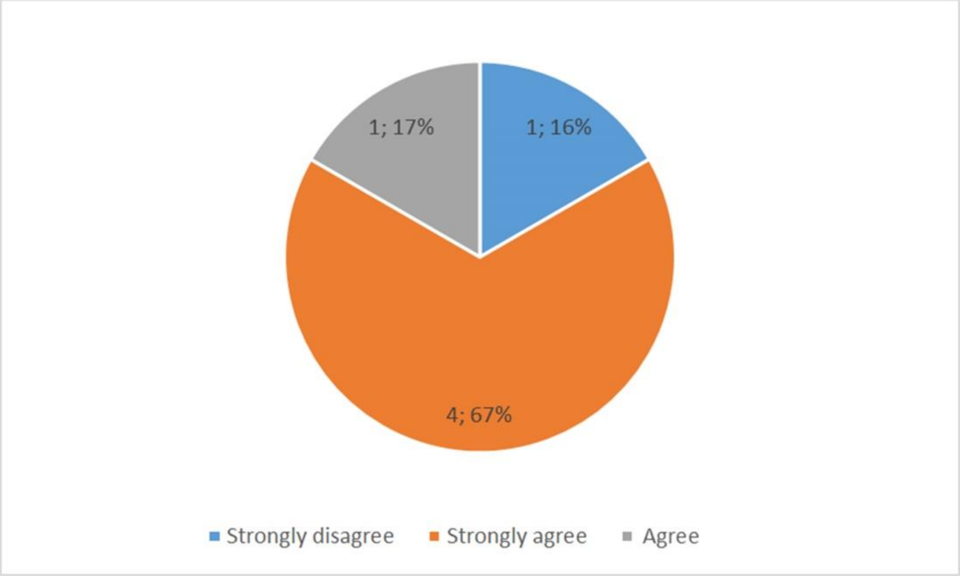


Figure 5.1: Responses for question 1 (In the design process, I preferred Grasshopper to hand sketching)

Questions 2, 3, 4 and 5 are related to the comparison of Grasshopper and hand sketching on specific issues. In question 2, 5 participants agreed or strongly agreed that Grasshopper provided them with different design alternatives than they would come up with if they had hand sketched (Figure 5.2). This idea was supported by answers to the questions 3 and 4, which mentioned that Grasshopper enabled participants to generate solutions more quickly and easier (Figure 5.3). High satisfaction from the speed and ease provided by Grasshopper has been confirmed by the majority responding positively to these three questions. There are no participants who disagreed with the statement suggested.

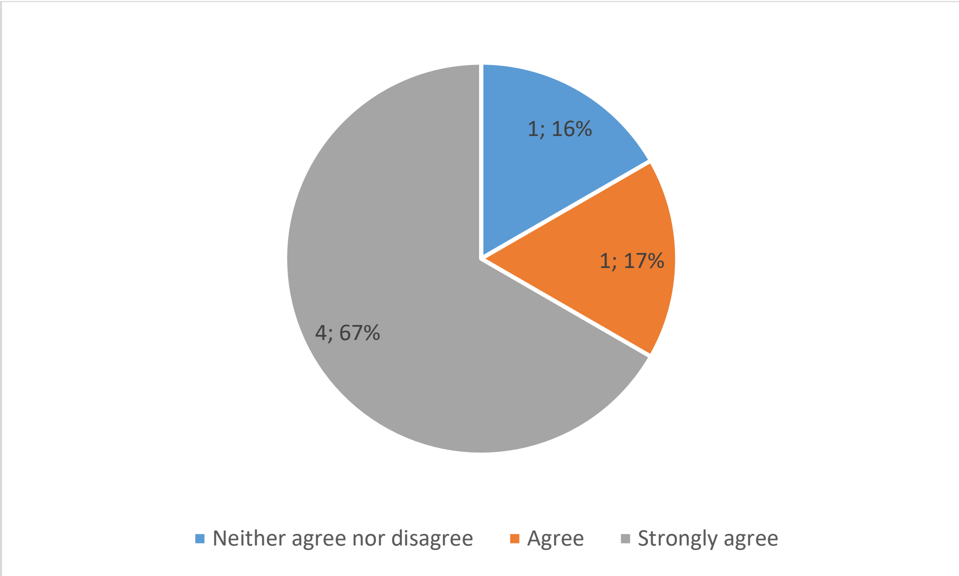


Figure 5.2: Responses for question 2 (Grasshopper provided me with different design alternatives than I would come up with hand sketching)

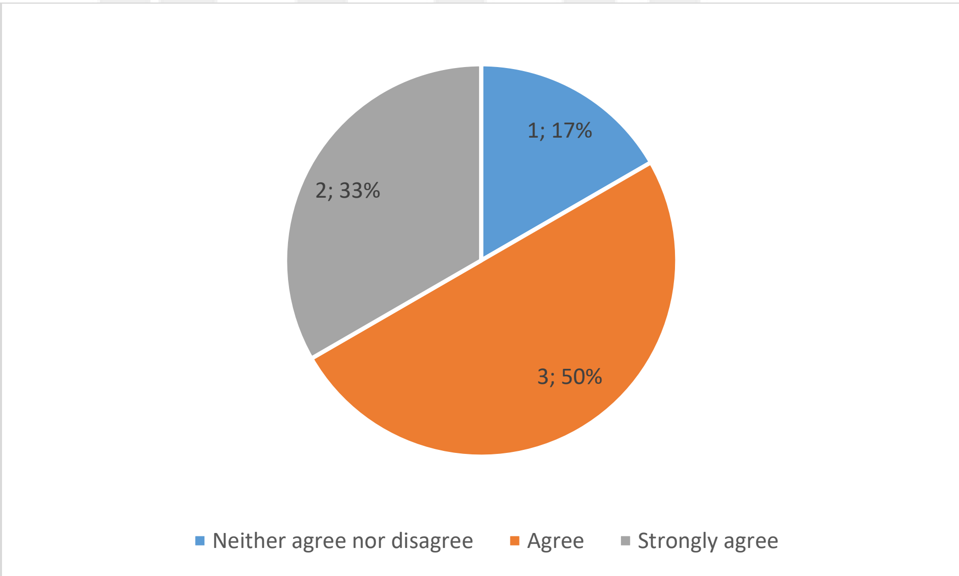


Figure 5.3: Responses for question 3 (Grasshopper enabled me to generate solutions more quickly) and responses for question 4 (Using Grasshopper made it easier to do my design task)

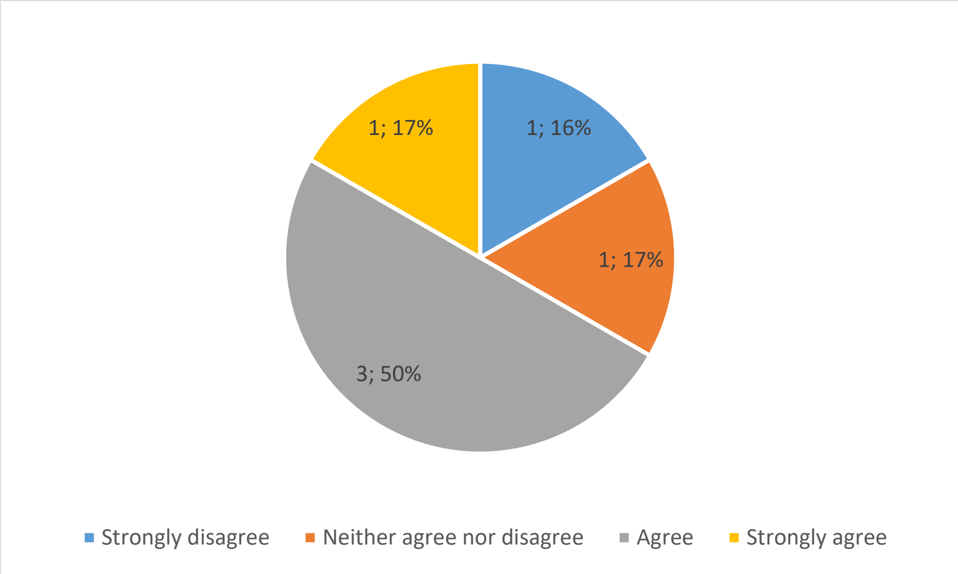


Figure 5.4: Responses for question 5 (The use of Grasshopper made it possible to come up with a more creative design, than I would generate through hand sketching)

On the other hand, responses for question 5 (*The use of Grasshopper made it possible to come up with a more creative design, than I would generate through hand sketching*) varied in the inexperienced participant group. All of the experienced participants agreed and one inexperienced participant strongly agreed that the use of Grasshopper made it possible to come up with more creative designs, than they would produce through hand sketching (Figure 5.4). Contrary to this, the other inexperienced participants neither agreed nor disagreed and strongly disagreed.

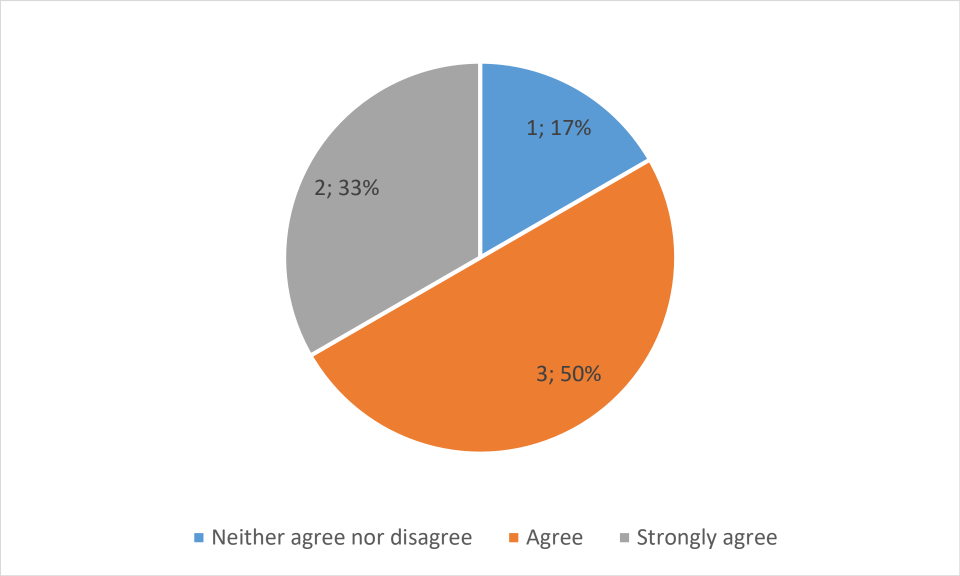


Figure 5.5: Responses for question 6 (In conceptual design phase, Grasshopper is useful) and responses for question 7 (In conceptual design phase, Grasshopper is effective)

Questions 6 and 7 refer to the contribution of Grasshopper in the conceptual design phase (Figure 5.5). Both the experienced and inexperienced participants found Grasshopper an useful and effective tool for generating concepts.

In the beginning of the post-task questionnaire, the experienced and inexperienced users were asked how much they used Grasshopper and other parametric modeling tools. According to the responses in the first part of the post-task questionnaire, three of the experienced users stated that they are using parametric modeling environment starting from the first grade and they utilized Grasshopper to carry out their projects. On the contrary, inexperienced users have mentioned that they attended some elective classes for learning Grasshopper, although not very effective. In question 8, despite the different levels of Grasshopper knowledge, all participants agreed or strongly agreed that if they had more knowledge in Grasshopper they would have preferred to use it more (Figure 5.6).

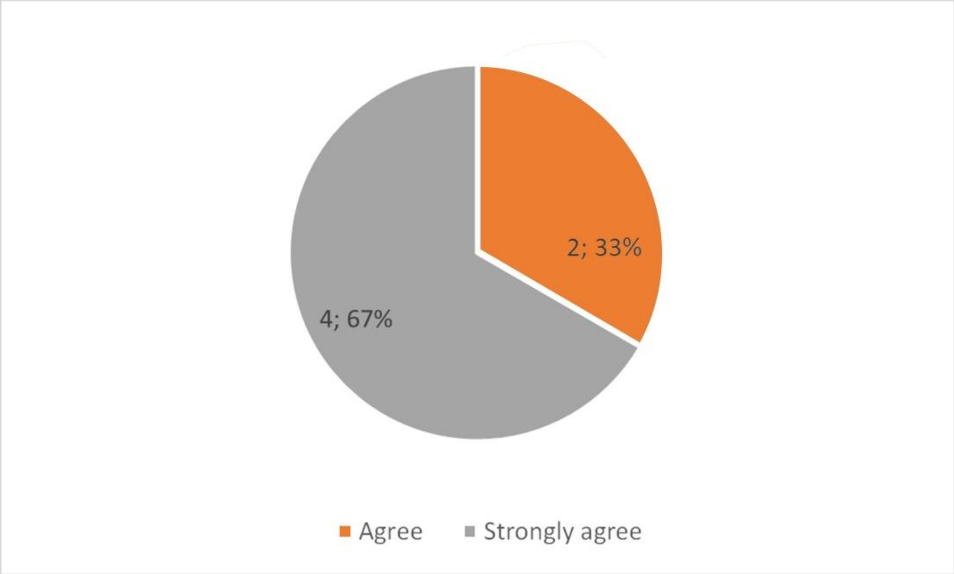


Figure 5.6: Responses for question 8 (If I had more knowledge in Grasshopper I would have preferred to use it more.)

The last two questions are related to the generated design solutions at the end of the conceptual design process (Figure 5.7 and 5.8). In terms of question 9, (*I would not reach the same design solution without using Grasshopper*.) 3 inexperienced and 1 experienced participants disagreed or strongly disagreed. However, other 2 experienced users mostly have stated that Grasshopper helps them to develop different design solutions and can lead them in the positive direction. In terms of concept development, they also added that they cannot reach the same design solutions, which are unpredictable and cannot be imagined without Grasshopper. Together with these considerations, experienced users are satisfied with their design solutions as seen in question 10 (*On the whole, I am satisfied with my design solution*). Contrary to this, two inexperienced users evaluated negatively their design solutions at the end of the design session.

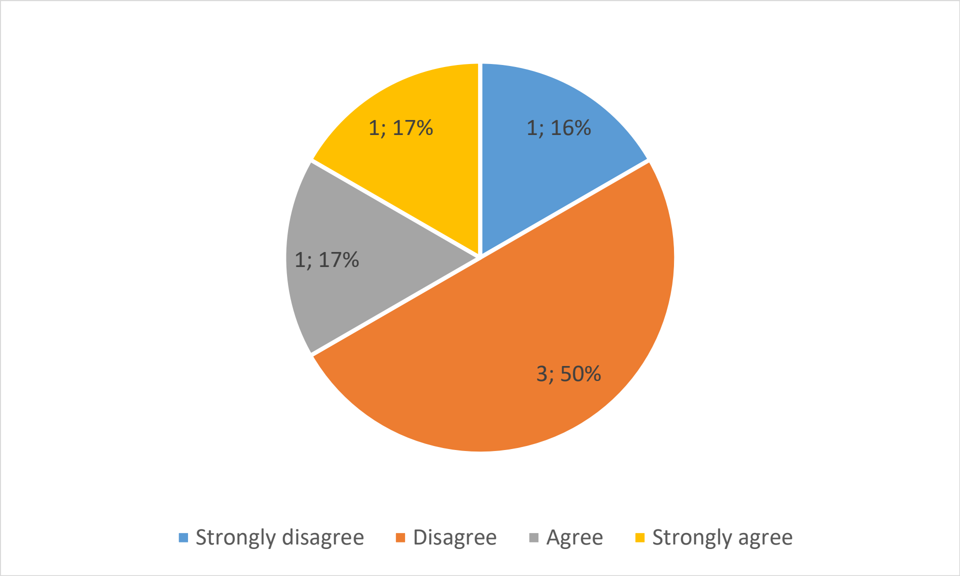


Figure 5.7: Responses for question 9 (I would not reach the same design solution without using Grasshopper)

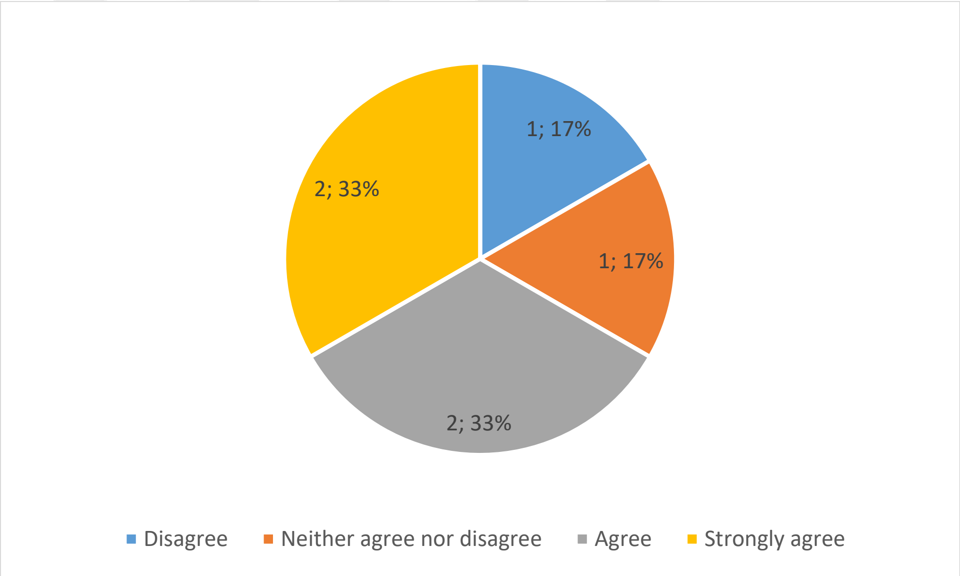


Figure 5.8: Responses for question 10 (On the whole, I am satisfied with my design solution)

5.2 Protocol Analysis Results

After the main experiment, the collected verbal data was first divided into segments, and then the coding procedure was carried out. The following analysis results are displayed in this order. Protocol analysis results are presented hierarchically in three headings, which constitute the analyses of data associated with segmentation, cognitive action categories and action sub-categories. In addition to that some dominant codes in the sub-categories were examined and analyzed individually.

Analyses have not only compared the parametric modeling tools and hand sketching, but also compared the experienced and inexperienced participants' cognitive behaviors. To make it simpler, the participants are shown with the letter P in the figures and tables (P1-P2-P3 are inexperienced and P4-P5-P6 are experienced users).

5.2.1 Analysis related to segmentation session

Segmentation provides separation of the design process in terms of designers' goals and intentions. In other words, segments indicate that designers have taken a new decision or their intentions have changed in the design process. Due to the emergence of a new segment through a new decision, designers' perspectives and problem-solving methods can be discovered. Thus, it is considered to be possible to redefine the design process, and to be able to examine this process in terms of designers' decision making processes. In this study, each participant had a different number of segments while using each media. This differentiation has revealed that designers' decision-making and problem-solving processes vary.

Results demonstrated that the total number of segments in Grasshopper (231) was higher than in hand sketching (140). The average number of segments is 38,5 in Grasshopper and 23,3 in hand sketching (Appendix C –Figure C1). The total number of segments of each individual participant while using different tools is indicated in the following figures.

In the experiment, there was just one design session, where the participants were free to utilize Grasshopper and hand sketching within the given time period. In Figure 5.9

and Figure 5.10, the session is divided into parts in itself in terms of the participants' switching points between the two media. According to these graphs, it is observed that all inexperienced users began their design processes with hand sketching whereas experienced users preferred to start with Grasshopper. Similarly, while the inexperienced participants ended the design process with hand sketching, the experienced designers finalized the process with Grasshopper.

The experienced group had more segments in total than the inexperienced group. Whereas experienced participants had more segments in Grasshopper than in hand sketching, inexperienced participants were exactly the opposite (for the detailed segmentation data please see Appendix C).

Segmentation method enables to decompose the design problem into episodes of goals and sub goals that the designers attended to obtain in the design session, which also reflected designer's intentions in solving the design problem. Experienced participants' segmenting of the design process had a common decreasing pattern (Figure 5.9). The high numbers of segments at the beginning of the design process show that the participant plays among different alternatives to achieve the best design solution. With the first shift between the two tools, it may be thought that the participant's decision makings will be more constant as she now knows what is expected. These results in a decrease in the number of segments because the intentions or goals would have less shifts compared to the beginning of the design process. On the other hand, inexperienced participants' problem solving behavior depicts a different pattern (Figure 5.10). There is an increase in the total segment numbers of two participants and decrease for one participant in the design session. This situation will be discussed in detail later, considering the participants' backgrounds and their approaches about using different tools.

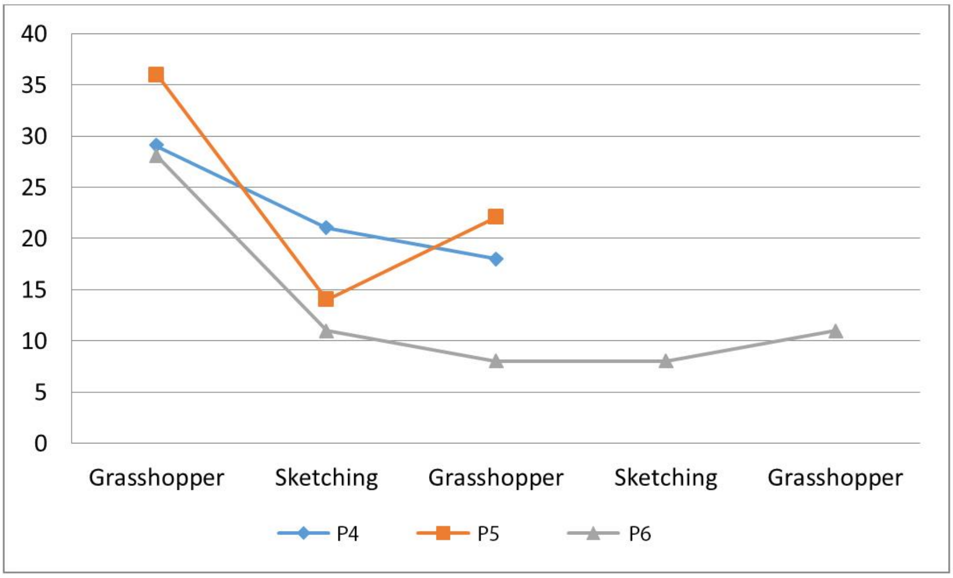


Figure 5.9: Total number of segments in hand Sketching-Grasshopper for experienced group

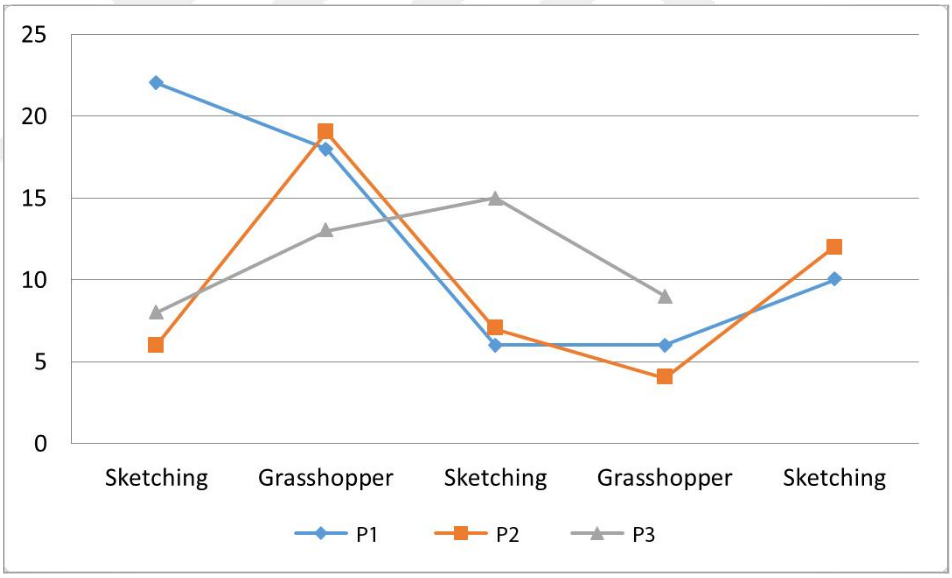


Figure 5.10: Total number of segments in hand Sketching-Grasshopper for inexperienced group

Additionally, all participants have different time periods when using Grasshopper and hand sketching. While the previous figures represent the switching points between the two tools, the following table shows the time spends of both of them in terms of experienced and inexperienced users (Table 5.1).

Table 5.1: Time Spent in using Grasshopper and hand sketching throughout the design session

P1		
Time	00:00 24:02:00	24 min. H.S.
	24:02:00 39:43:00	15 min. GR.
	39:43:00 45:50:00	6 min. H.S.
	45:50:00 50:11:00	5 min. GR.
	50:11:00 60:00:00	10 min. H.S.

P2	
00:00 05:32	5 min H.S.
05:32 35:06:00	30 min GR.
35:06:00 42:10:00	7 min H.S.
42:10:00 46:00:00	4 min GR.
46:00:00 60:00:00	14 min H.S.

P3	
00:00 08:45	8 min H.S.
08:45 22:28	14 min GR.
22:28 38:07:00	16 min H.S.
38:07:00 60:00:00	22 min GR.

P4		
Time	00:00 23:16	23 min GR.
	23:16 36:00:00	13 min H.S.
	36:00:00 60:00:00	24 min GR.

P5	
00:00 28:03:00	28 min GR.
28:03:00 45:05:00	17 min H.S.
45:05:00 60:00:00	15 min GR.

P6	
00:00 37:00:00	37 min GR.
37:00:00 43:18:00	6 min H.S.
43:18:00 52:48:00	9 min GR.
52:48:00 55:45:00	3 min H.S.
55:45:00 60:00:00	5 min GR.

GR: Grasshopper

H.S: Hand sketching

5.2.2 Analysis related to action categories

The cognitive actions belonging to each participant were encoded according to the coding scheme. In order to analyze the cognitive action categories, sub-categories and individual action codes with the two media, the data was normalized as percentiles of the total number of actions. In this section, firstly, the total number of main cognitive action categories (D: physical, P: perceptual, F: functional and C: conceptual) were displayed followed by the frequencies of the distribution of these cognitive actions represented separately (Appendix C-Table C1).

Figure 5.11 indicates general percentages of the total hand sketching and Grasshopper actions. 72% of the total actions according to the Figure 5.11 are related to Grasshopper and 28% are related to hand sketching activity.

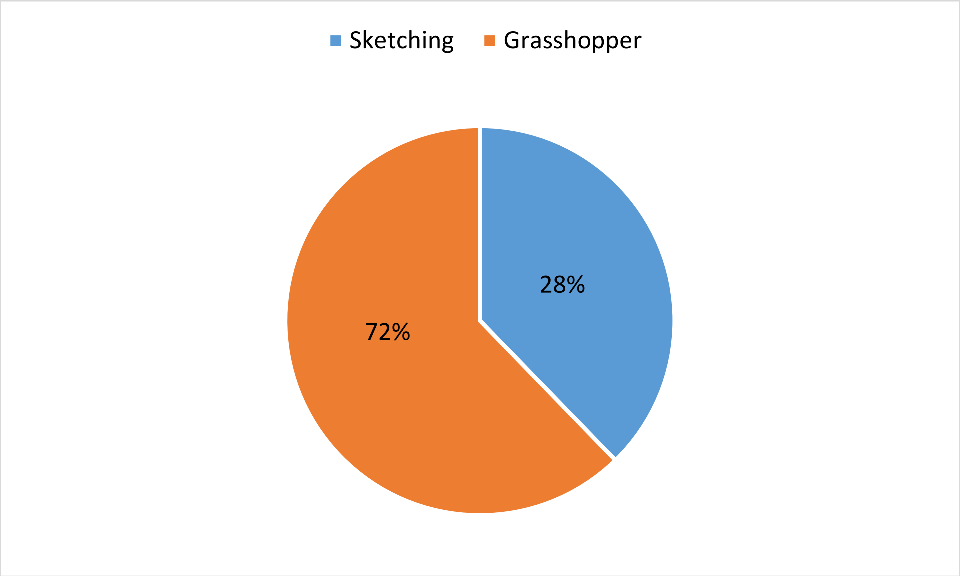


Figure 5.11: Distribution of the hand sketching and Grasshopper actions

The total numbers of cognitive actions in the design session for each individual participant are displayed in Figures 5.12 and 5.13. The experienced participants' cognitive actions have a common increasing pattern from hand sketching to Grasshopper (Figure 5.12) and the total number of cognitive actions was higher in Grasshopper than in hand sketching. Experienced participants have either frequently added new features to their existing designs to achieve the optimal solution, or have begun designing from scratch.

Similarly, inexperienced participants also had more actions in Grasshopper than in hand sketching, except for one (Figure 5.13). P1's score remained approximately the same, while the other two participants increased their cognitive action scores in Grasshopper compared to hand sketching. On the other hand, inexperienced users have a higher number of cognitive actions in Grasshopper even though their segment numbers in Grasshopper are lower than in hand sketching.

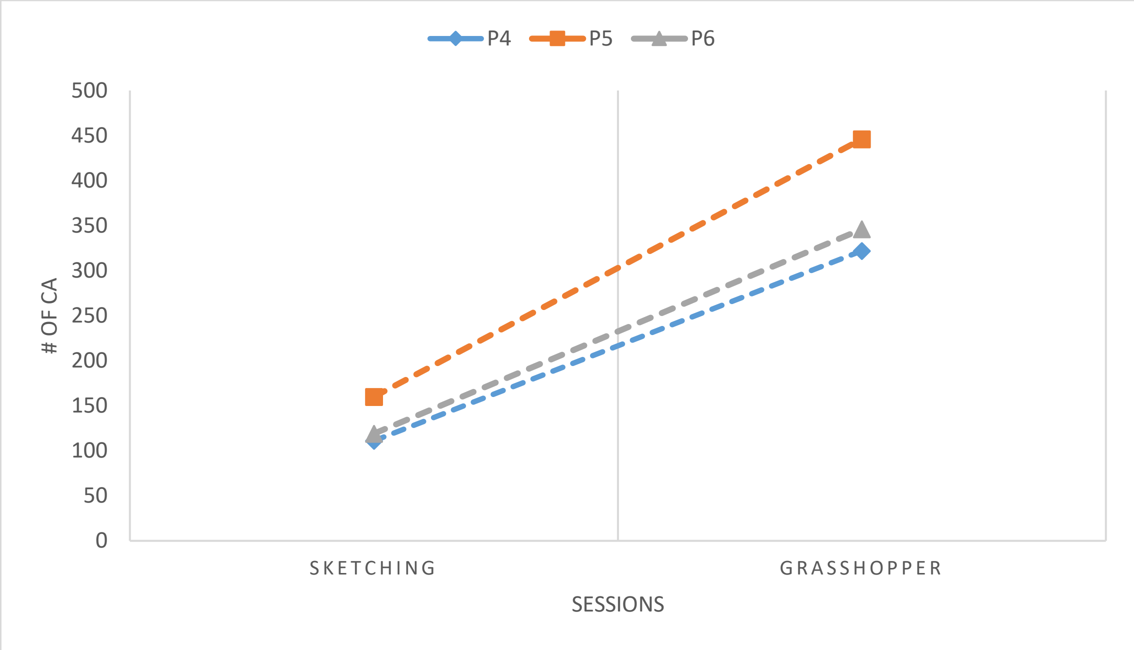


Figure 5.12: Total number of experienced participants' cognitive actions in the design session

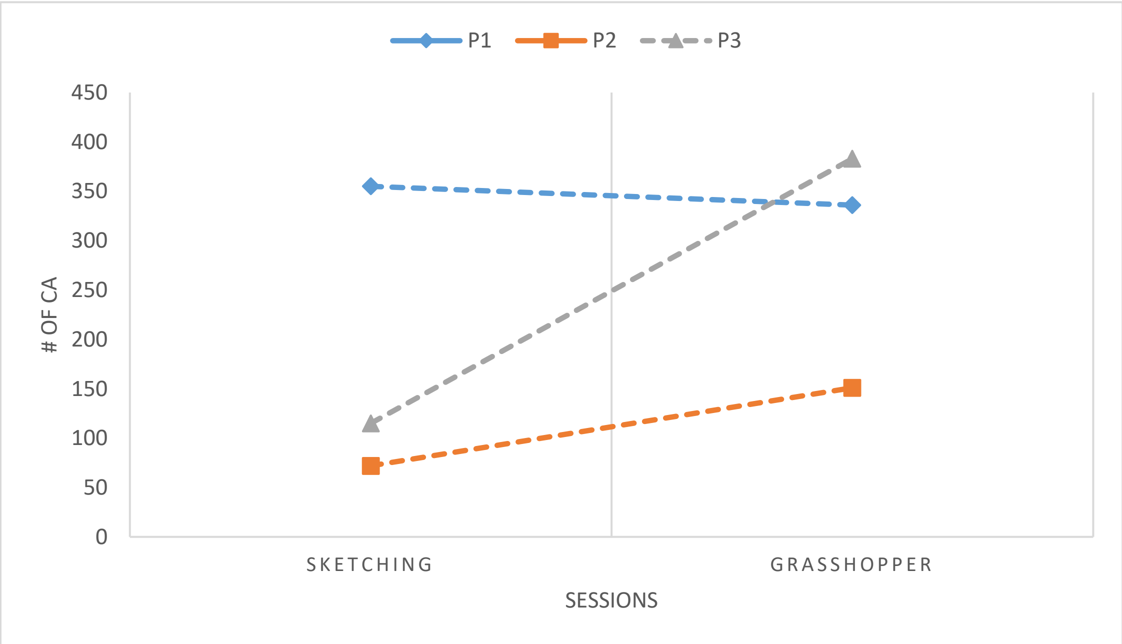


Figure 5.13: Total number of inexperienced participants' cognitive actions in the design session

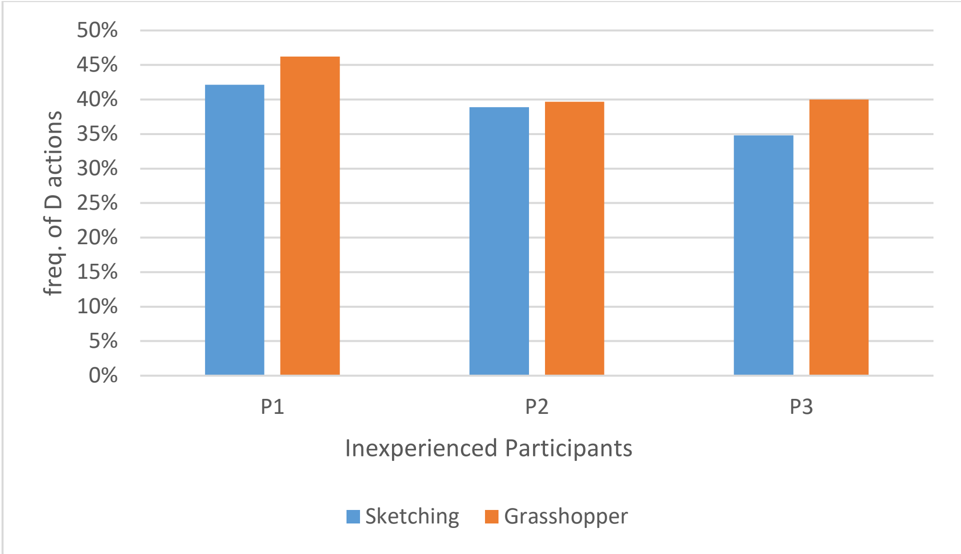
Table 5.2 indicates the distribution of action category scores and percentages throughout the design process. According to Table 1, all action categories have higher scores in Grasshopper than in hand sketching. Moreover, results indicate that participants engaged mostly in physical actions (D-actions=941) in Grasshopper and in the whole design session (D actions=1299). Following that, the second action category with the highest score is perceptual actions in total (P actions=1007) and also the third one is conceptual action category (C actions=653). Contrary to this, the functional actions (F-actions=316) occurred less in throughout the design process.

Table 5.2: Distribution of D, P, F and C actions in hand sketching and Grasshopper

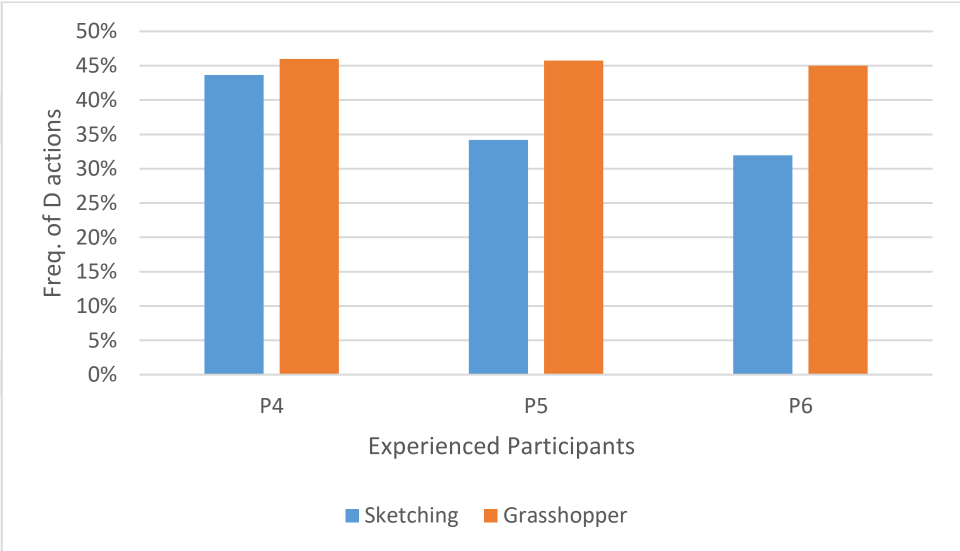
	Sketching		Grasshopper		Total	
	f	%	f	%	f	%
D-actions	348	24.25	1087	75.75	1435	100
P-actions	193	21.18	718	78.82	911	100
F-actions	160	46.78	182	53.22	342	100
C-actions	202	30.10	469	69.90	671	100

D-actions (Physical)

Figure 5.14 below, shows the percentages that are related to how the physical scores of the experienced and inexperienced participants change according to the two design tools. The physical action percentages of the inexperienced users in Grasshopper are higher than in hand sketching. The results are the same for the experienced participants. All the participants increased their physical action percentages when they switched from hand sketching to Grasshopper. The largest difference in the physical action percentage was observed in P5 and P6, who are experienced participants.



(A)

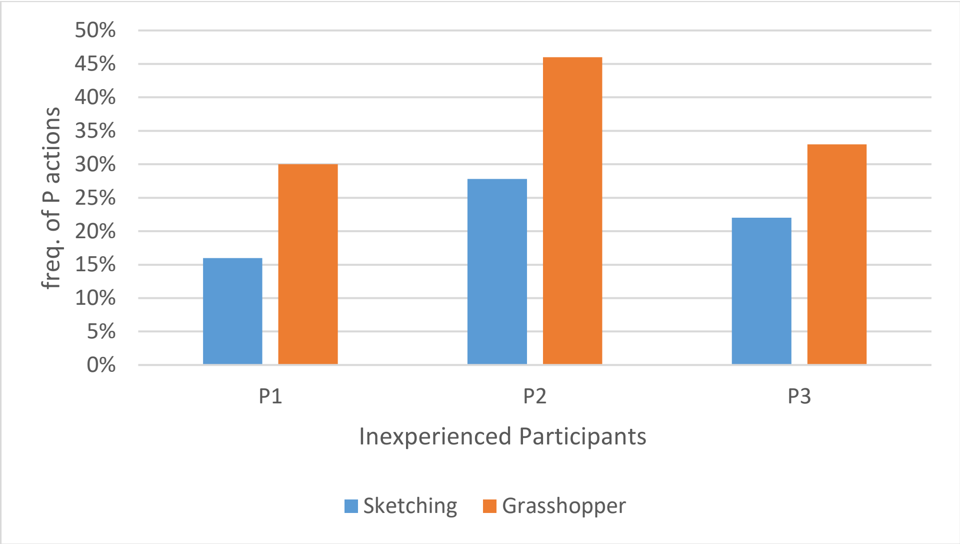


(B)

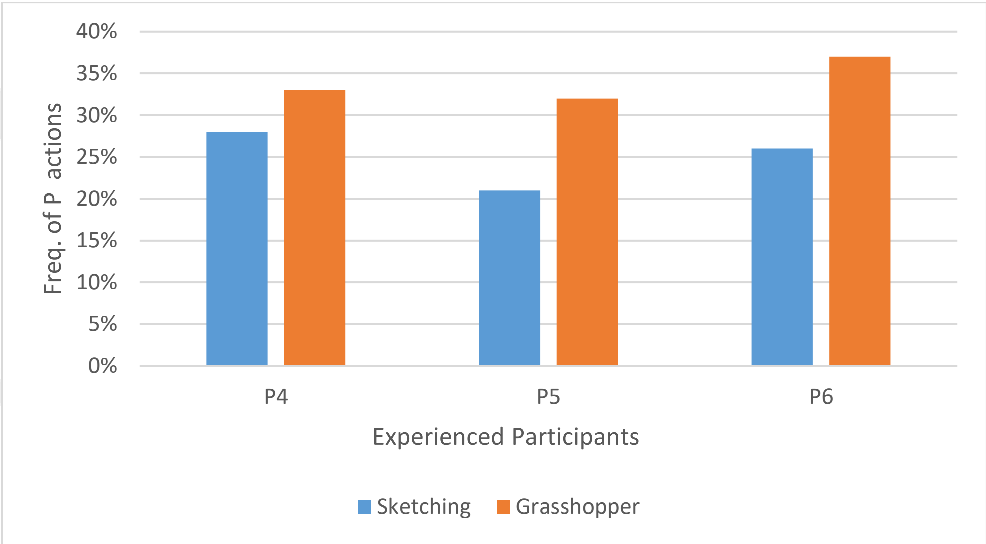
Figure 5.14: Frequency of D actions (A) inexperienced (B) experienced participants

P-actions (Perceptual)

The percentages of the perceptual actions of all inexperienced and experienced participants appear to be higher in Grasshopper as depicted in Figure 5.15. While looking at the differences between hand sketching and Grasshopper, it was observed that there is an increase in the frequencies of perceptual actions.



(A)



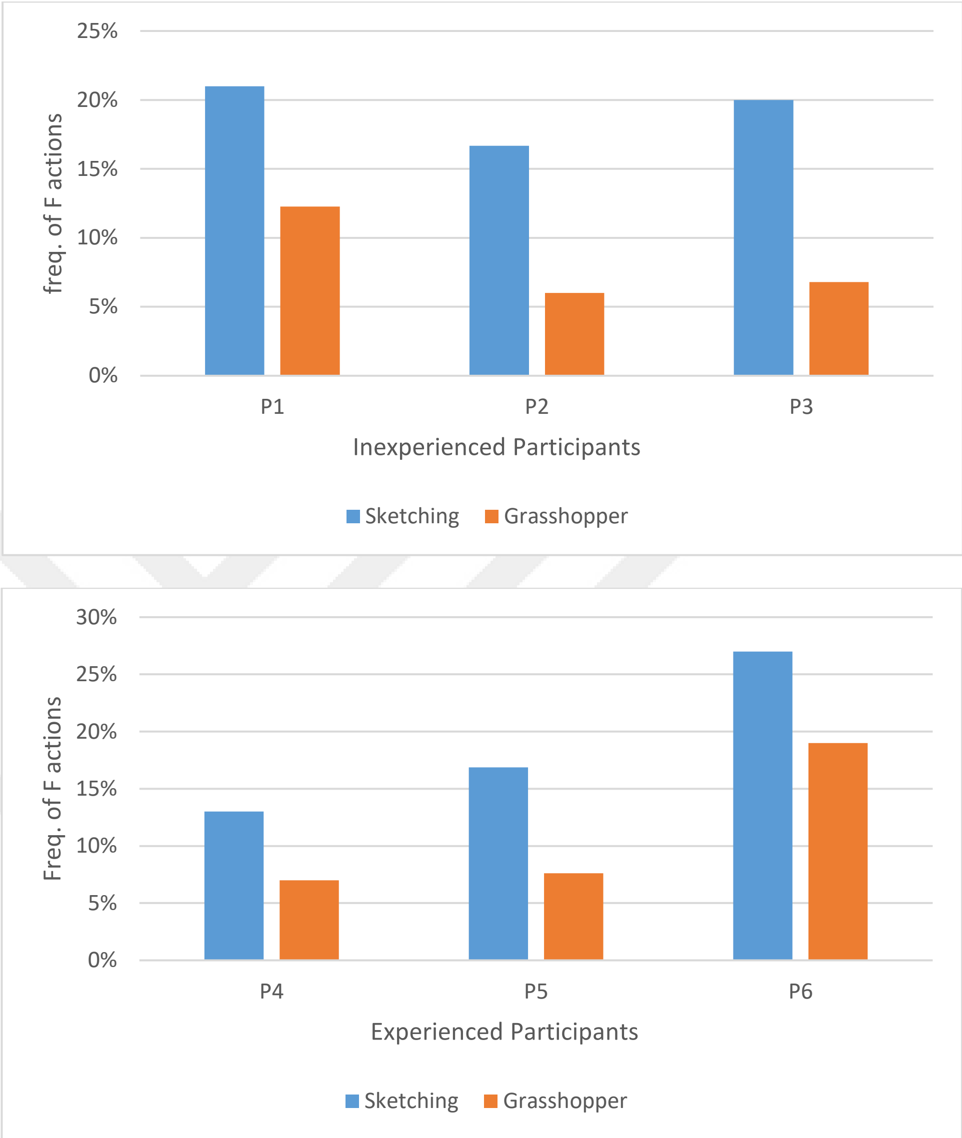
(B)

Figure 5.15: Frequency of P actions (A) inexperienced (B) experienced participants

F-actions (Functional)

The following two graphs show the difference between the two media related to inexperienced and experienced participants (Figure 5.16). According to this, all experienced and inexperienced participants had a higher degree of functional score in hand sketching. It seems that Grasshopper includes more functional actions than in hand sketching (please see Table 5.2), but the lower frequency of F actions means that the other action categories have higher frequencies in general. In the light of this, although Grasshopper contains more functional actions numerically in total, individual frequencies are lower in Grasshopper due to the high rate of the other action categories.

(A)



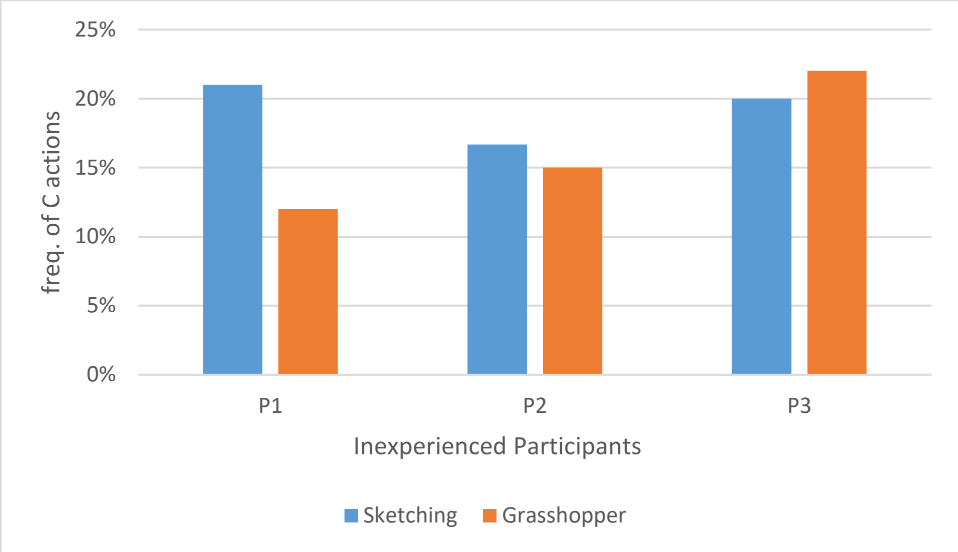
(B)

Figure 5.16: Frequency of F actions (A) inexperienced (B) experienced participants

C-actions (Conceptual)

Finally, the C actions diversified between individuals within the inexperienced and experienced groups (Figure 5.17). Two inexperienced and one experienced participants have higher conceptual action percentages in Grasshopper environment, while the percentage of one participant in both groups is lower than in hand sketching. Due to this diversification, no definite interpretation can be made on this action category. In addition to that, whereas in design session there is not a single pattern that would demonstrate the tendency of the occurrences of conceptual actions.

(A)



(B)

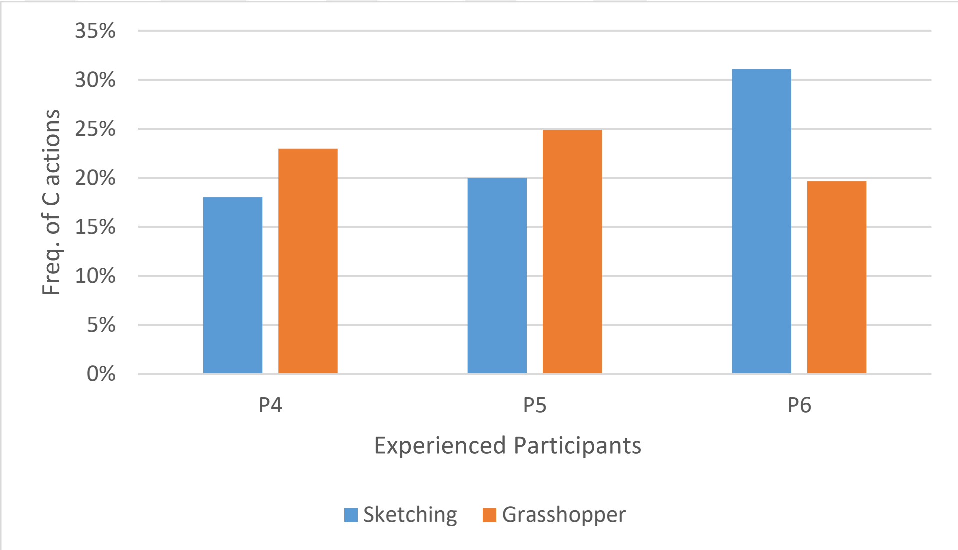


Figure 5.17: Frequency of C actions (A) inexperienced (B) experienced participants

Finally, the Mann-Whitney U test was used to determine whether these differences between Grasshopper and hand sketching were statistically significant. Table 5.3 and 5.4 show the Mann-Whitney U test results of how the physical, perceptual, functional and conceptual percentages of the participants were changed in terms of both tools. Accordingly, the mean physical score was statistically significant ($z = -2.082$; $p=0.037$

<0.05). Similarly, there was a meaningful difference among the percentages of perceptual actions (z= -2.882; p=0.004<0.05). While the mean number of physical actions and the perceptual actions was higher in the Grasshopper environment (M = 43.03, SD = 3.22; M=35.23, SD=5.39 respectively), functional mean score was higher in hand sketching environment (M = 17.93, SD = 3.92). Contrary to this, the mean conceptual actions were not statistically different according to the both of the tools (z=-1.922; p> 0.05).

Table 5.3: Mann-Whitney U Test- Percentage distribution of action categories in hand sketching and Grasshopper

	P1		P2		P3		P4		P5		P6	
	SKET	GRAS	SKET	GRAS	SKET	GRAS	SKET	GRAS	SKET	GRAS	SKET	GRAS
Physical	42.1%	46.2%	38.8%	38.7%	34.8%	39.9%	42.3%	46.6%	34.2%	43.8%	31.0%	43,0%
Perceptual	16.0%	30.5%	27.8%	45.5%	23.5%	33.9%	27.9%	32.4%	21.4%	32.7%	26.8%	36.4%
Functional	20.9%	11.0%	16.7%	2.6%	21.7%	4.8%	13.6%	5.1%	21.4%	5.3%	13.3%	5.4%
Conceptual	21.0%	12.3%	16.7%	14.2%	20.0%	21.4%	16.2%	15.9%	23.0%	19.2%	29.8%	15.2%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

S: Sketching, G: Grasshopper

Table 5.4: Mann-Whitney U Test- Comparison of action categories in hand sketching and Grasshopper

	Sessions						Significance	
	Sketching (M, SD, Media)			Grasshopper (M, SD, Media)			Z	p
Physical	37.21	4.60	36.83	43.03	3.22	43.40	-2.082	**.037**
Perceptual	23.89	4.65	25.13	35.23	5.39	33.30	-2.882	**.004**
Functional	17.93	3.92	18.78	5.81	3.06	5.20	-2.882	**.004**
Conceptual	21.11	4.98	20.50	16.25	3.52	15.55	-1.922	.056

5.2.3 Analysis related to action sub-categories

Sub-category distributions of four cognitive actions in the design process were represented in Figure 5.18 and Table 5.5. It was observed that while designers had a larger percentage of *feature*, *implement*, *reactions*, *retrieve knowledge* and *evaluation* actions in the hand sketching, the percentage of *create*, *modify*, *erase*, *relation*, *view*, and *goal setting* actions were higher in Grasshopper. The differences between the tools were small in *create*, *feature*, *reactions* and all of the conceptual actions. However, these differences were high for *modify*, *erase*, *relation*, *view* and *implement* actions in the two environments.

Figure 5.18 Distribution of action sub-categories throughout the process

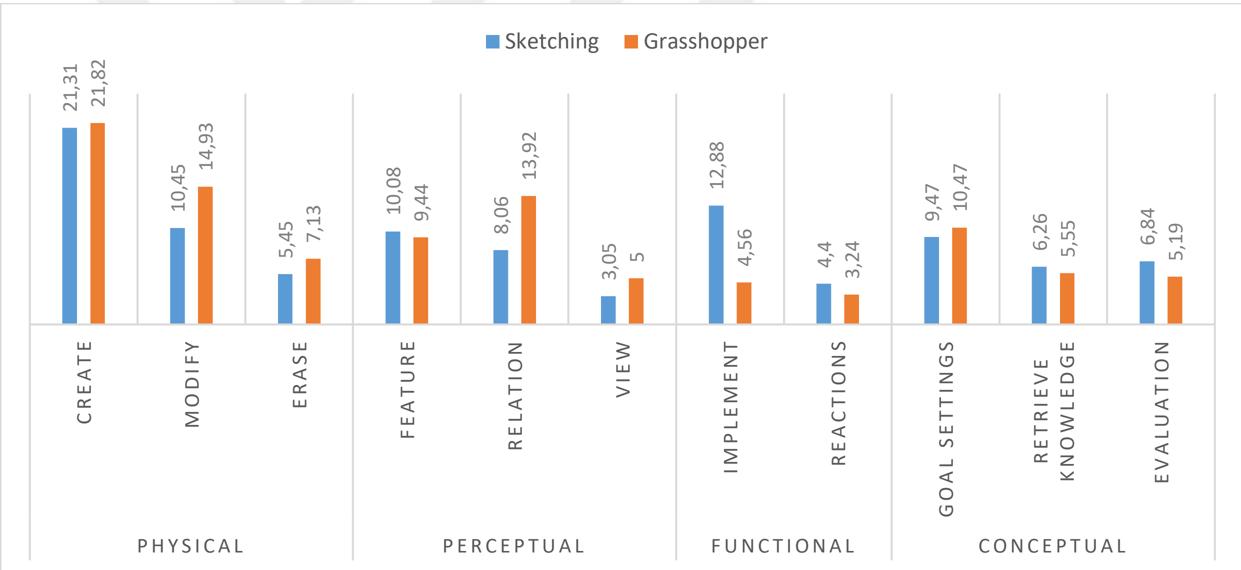


Table 5.5: Mann-Whitney U Test- Percentage distribution of action sub-categories in hand sketching and Grasshopper according to the participants

	P1		P2		P3		P4		P5		P6	
	SKET	GRAS	SKET	GRAS	SKET	GRAS	SKET	GRAS	SKET	GRAS	SKET	GRAS
Create	**24.1%**	**14.3%**	**20.8%**	**20.5%**	**19.1%**	**19.8%**	**23.2%**	**25.2%**	**21.5%**	**23.1%**	**19.2%**	**26.7%**
Modify	**11.8%**	**17.4%**	**12.1%**	**18.9%**	**13.0%**	**14.6%**	**9.7%**	**16.1%**	**8.5%**	**13.5%**	**7.6%**	**9.0%**
Erase	7.6%	9.8%	6.9%	7.3%	3.6%	3.5%	5.4%	5.3%	5.0%	8.2%	6.2%	8.7%
Feature	5.3%	12.1%	12.1%	6.6%	9.4%	8.6%	13.2%	8.7%	8.4%	9.6%	12.1%	11.0%
Relation	**8.5%**	**14.6%**	**3.5%**	**12.9%**	**8.6%**	**15.7%**	**8.9%**	**10.8%**	**10.6%**	**12.3%**	**11.5%**	**17.2%**
View	**2.5%**	**5.2%**	**4.1%**	**4.3%**	**4.5%**	**5.6%**	**2.6%**	**4.9%**	**2.1%**	**4.8%**	**2.5%**	**5.2%**
Implement	**11.3%**	**7.5%**	**13.8%**	**4.5%**	**17.6%**	**4.0%**	**13.3%**	**5.0%**	**12.3%**	**2.5%**	**9.0%**	**3.9%**
Reactions	4.7%	6.1%	4.8%	3.6%	4.3%	1.8%	3.7%	3.1%	6.6%	3.1%	4.3%	1.7%
Goal Settings	**8.2%**	**7.0%**	**10.3%**	**11.6%**	**10.4%**	**12.6%**	**9.8%**	**10.9%**	**9.4%**	**10.1%**	**6.7%**	**8.6%**
Retrieve Knowledge	10.0%	4.2%	5.2%	3.0%	5.2%	7.1%	4.5%	6.3%	7.1%	5.6%	8.6%	3.1%
Evaluation	6.1%	1.8%	6.4%	6.8%	4.3%	6.7%	5.7%	3.7%	8.5%	7.2%	12.3%	3.9%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

When the action sub-categories of hand sketching and Grasshopper are examined in terms of experienced and inexperienced users, the following results were found; first of all the dominant action sub-category was *create* with regards to three of them. It had almost equal values in both tools (Table 5.4). Then, secondly the other dominant actions were *modify* and *implement* which are the sub-categories of physical and functional respectively. While inexperienced users utilized *modify* highly in Grasshopper, represented *implement* more in hand sketching. Additionally, *relation* emerged considerably high in Grasshopper than in hand sketching. Similarly, the experienced users exhibited more *create* and *modify* action within two tools. Unlike the inexperienced users *create* action was higher in Grasshopper noticeably. Whereas experienced users showed relation, modify, view and goal setting largely in Grasshopper, *implement* and *reactions* were notably high in hand sketching.

Moreover, Mann-Whitney U test was carried out to determine whether these differences were statistically significant. The results of the test showed that *modify, relation, view* and *implement* rank score averages were statistically significant as seen in Table 5.6 ($p < 0.05$). *Modify* mean score (M = 14.93 SD = 3.47), the mean score of *relations* (M = 13.92 SD=2.36) and also the mean score of *view* (M=5.00 SD= 0.44) was higher in the Grasshopper environment while *implement* mean score higher in hand sketching environment (M = 12.88 SD = 2.87). The rest of the sub-categories did not indicate any significant difference statistically.

Table 5.6: Mann-Whitney U Test - Comparison of action sub-categories in hand sketching and Grasshopper

	Sessions						Significance	
	Sketching (M, SD, Media)			Grasshopper (M, SD, Media)			Z	p
Create	21.31	2.04	21.15	21.82	4.76	21.81	-.320	.749
Modify	10.45	2.16	10.75	14.93	3.47	15.36	-2.242	**.025**
Erase	5.45	1.54	5.20	7.13	2.34	7.75	-1.282	.200
Feature	10.08	2.96	10.75	9.44	1.94	9.17	-.484	.629
Relation	8.06	2.77	8.75	13.92	2.36	13.75	-2.722	**.006**
View	3.05	.99	2.55	5.00	.44	5.05	-2.732	**.006**
Implement	12.88	2.87	12.80	4.56	1.66	4.25	-2.882	**.004**
Reactions	4.40	1.35	4.50	3.24	1.59	3.12	-1.441	.150
Goal Settings	9.47	1.20	10.40	10.47	2.40	10.51	-.321	.748
Retrieve Knowledge	6.26	2.20	5.65	5.55	1.73	5.85	-.480	.631
Evaluation	6.84	3.09	5.90	5.19	2.12	5.80	-.641	.522

Analysis related to total individual algorithmic codes in Grasshopper

There were many individual codes in the coding scheme. However, the total scores of algorithmic and geometric actions while using Grasshopper are impressive. Both algorithmic and geometric actions can occur simultaneously in Grasshopper. That may be the reason for the low *create geometry* scores in Grasshopper, as algorithmic actions are used rather than geometric actions. Furthermore, the percentages of the algorithmic actions (dcp+dcr+dmp+dmr+dep+der) almost doubled and tripled the geometric actions (dcg+dmg+deg) in the case of all participants as seen in Figure 5.19.

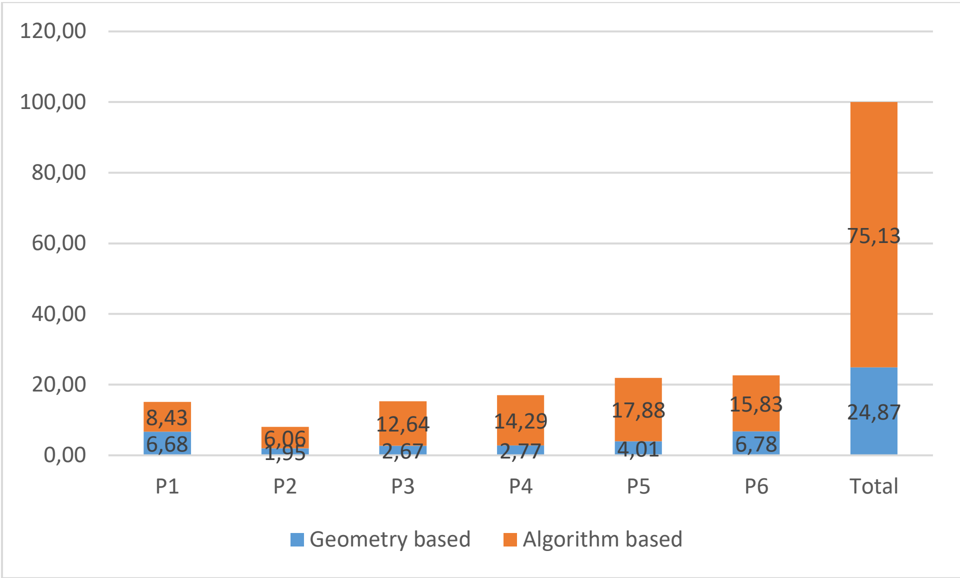


Figure 5.19: Distribution of geometry and algorithm based codes in Physical and Perceptual actions while using Grasshopper

CHAPTER 6

DISCUSSION AND CONCLUSION

This part of the thesis comprises discussions on the results, the limitations of the study, and recommendations for further studies. Basically, the protocol analysis results are discussed in relation with the post task questionnaire results. In addition, discussions about the findings are presented in relation to the examination of the profiles of the inexperienced and experienced participants and their verbal comments in the retrospective interviews.

6.1 Discussions about the Design Processes of the Participants

The segmentation results showed that the total segment numbers for all participants were higher in Grasshopper (231) than in hand sketching (140) in general. The main reason for that is experienced users' having a large number of segments in Grasshopper. This study found out that there is a difference in the average numbers of segments among the inexperienced and experienced participants. As stated previously, the experienced participants had more segments (206) in total and in Grasshopper (152) while, the inexperienced participants had more segments in hand sketching (86) than in Grasshopper (79).

These differences occurred according to the change of aims, intentions and decision making of the two groups. In the design session, the experienced participants produced many design alternatives related to the design task while searching for a form or solving a problem (Appendix D). For instance, P4 and P5 worked on four alternative solutions and P6 tried to create six independent options for the design problem. Contrary to this, the inexperienced participants generated fewer alternatives. As an example, P1 only worked on two alternative design solutions and her segment numbers had a decrease. So trying various alternatives provided an increase in the number of segments depending on the shift of intentions and decisions.

In the beginning of the design session, the segment numbers of the experienced participants decreased from the beginning to the end of the design session. They switched to hand sketching one or two times in the whole process. It is observed that the experienced participants have already transferred what they have done in Grasshopper to the paper. While Grasshopper is the main tool that they preferred in conceptual design phase, hand sketching is utilized as a supportive tool. The experienced users set the initial goals primarily and worked on variations. At the end of the process, the experienced participants were more stable in their decision making. In other words, experienced participants worked on their design solutions with a top-down perspective (Harding et al., 2013) with Grasshopper.

On the other hand, inexperienced users had an increase in total segment numbers (except P1). When the inexperienced users switch to Grasshopper, two of them increased their segment numbers and changed their intentions radically. These fluctuations in between the two groups of participants, experienced and inexperienced, in the total number of the segmentation graphs, show that they have different problem solving behaviors. This can be explained as follows; the inexperienced participants start the design process with hand sketches and they try to make different alternatives due to the guidance of the uncertain nature of the sketches (Goel, 1995) and change their goals or intentions less frequently. The fact that the relationship between the mind, hand and eye directs the designer to brainstorm while sketching (Fish and Scrivener, 1990) and triggers to think more on design solutions in beginning of the conceptual design process. However, all of the participants had higher segment numbers in Grasshopper in the initial stage of concept generation process. In light of these results, it can be said that Grasshopper can provide a convenient environment for concept production for both user groups in the conceptual design phase due to the support it offers for variational thinking. Stavric and Marina (2011) stated that visual editors such as Grasshopper "…do not require any previous knowledge of programming or scripting, and yet they make it possible for designers to generate a broad range of non-standard designs that can be changed interactively. This new parametrically based approach in architectural design enables architect to search for a completely new level in form generating processes" (9).

It is also worth mentioning that all inexperienced users began their design processes with hand sketching, whereas experienced users preferred to start with Grasshopper. This may be due to the difference in the participants' information levels and also to the inexperienced users' hesitance to use Grasshopper in the beginning of the design process. In accordance with the post task questionnaire results to question 8, if inexperienced users had more information about Grasshopper, they would have preferred to use it more. Additionally, in question 1, all of the participants (except P1) stated that they want to use Grasshopper more and made an effort to use this tool. Nevertheless, the results indicated that they could not utilize Grasshopper as much as they expected due to the lack of information background and experience. In line with this information, it can be thought that algorithmic design thinking and parametric design tools may be more integrated into architectural education. Applying the parametric modeling tools in architectural conceptual design phase and also architectural education have been discussed frequently in the last years (Özkar,2005 Stavric and Marina,2011; Aish and Hanna, 2017). For instance, Aish and Hanna (2017) evaluated different parametric modeling tools for integrating them to the beginning of architectural education. With the developments in parametric modeling tools, such an integration is almost inevitable (Stale and Cakula, 2010; Aish and Hanna, 2017).

6.2 Discussions about the Cognitive Behaviors of the Participants

The results show that the experienced participants' cognitive actions have a common increasing pattern from hand sketching to Grasshopper and the cognitive actions' total number was higher in Grasshopper than in hand sketching. This pattern matched up with the total number of segments in Grasshopper. The reason for this is mainly due to the fact that Grasshopper allows designers to produce a variety of alternatives and try different solutions in a short time. Experienced participants have either frequently added new features to their existing designs to achieve an optimal solution, or have begun designing from scratch. Other data supporting this situation is based on the answers given by the participants to question 2 of the questionnaire. The positive effects of Grasshopper resulting from the algorithmic framework can be observed in both the high number of cognitive actions and the high satisfaction levels of the experienced participants.

Similarly, inexperienced participants also had more cognitive actions in Grasshopper than in hand sketching. This may be a sign that inexperienced users may also benefit from advantages of Grasshopper in terms of supporting production of various design solutions (Barrios, 2006; Harding et al., 2013). Aish and Woodbury (2005) emphasized the positive side of the parametric design as: "parameterization can enhance search for designs better adapted to context, can facilitate discovery of new forms and kinds of form-making, can reduce the time and effort required for change and reuse, and can yield better understandings of the conceptual structure of the artifact being designed." (151).

The finding that the inexperienced users having a higher number of cognitive actions in Grasshopper in comparison to the segment numbers in Grasshopper can be due to the fact that the segment numbers and the length of the segments are independent from the total number of cognitive actions.

In terms of all action categories, all action categories have higher scores in Grasshopper than in hand sketching numerically. They mostly associated with the physical actions (D actions). The reason that Grasshopper's cognitive action percentages are higher in each category may indicate that Grasshopper is not just a 'form searching tool', but also a tool that supports and enhances all cognitive behaviors of the designer. This represents that Grasshopper can provide contributions to the design process and has positive effects in the conceptual design phase. When question 6 and question 7 are taken into consideration, the finding that all participants gave Grasshopper full score in terms of usability and efficiency is consistent with the high cognitive behaviors.

Action categories and Action Sub-Categories

The results indicate that the average percentage of the actions at physical level (D actions) is higher in Grasshopper (43.03%) than in hand sketching (37.21%). This significant difference is mostly dependent on the frequency of *modify* and *erase* actions. Although, the percentage for *create* action was higher in Grasshopper, the numerical values are close to hand sketching and no statistical difference is found. This is probably due to the fact that all participants have to modify the form and the structure in the conceptual design phase with the algorithmic parameters and rules. This finding is in parallel with the question 2, 3 and 4 in the post task questionnaire. The modification of the design can be made quickly and easily in Grasshopper.

Also with Grasshopper the participants could reveal different variations of their design solutions that are not considered and imaged before. In other words, the finding about *modify* action indicates that Grasshopper shows different variations of a design solution in a short time (Kolarevic, 2005) is an accelerating factor in the conceptual design phase. Abdullah and Kamara (2013) stated that: “Architects can also switch between operations such as extrusion, rotation, scaling, twisting, etc. to generate completely different instances within the same model, and explore more options – an essential requirement of the conceptual design phase.” (337). In parallel with this Dino (2012) emphasized the importance and benefits of the production of the design variations.

The average frequency of perceptual actions (P actions) of the participants is higher in Grasshopper (35.23%) than in hand sketching (23.89%). This is largely due to the high results in the *relation* and *view* sub-categories within the perceptual actions in Grasshopper. The results of these two sub-categories are also found to be statistically significant. The finding that the *relation* sub-category having a higher significant value can be supported by the idea that parametric modeling tools can promote generation of spatial relations between the design elements better and directs the designer to relational thinking. This finding is in parallel with the definition of parametric combination that Abdullah and Kamara (2013) mentioned as: “it provides another level of elaboration beyond the parameterization of the model elements via composing combinations between geometrical elements this will be done significantly by algorithmic rules and spatial relationships between them to generate a complex model.” (340).

Another finding is that the *view* action sub-category emphasizes the importance of 3D visualization in the form finding process while designing conceptually. All participants were able to make various evaluations and different modifications by using 3D view while generating different forms or design solutions. They desired to see all aspects and angles in the 3D view while externalizing the design idea unlike the hand sketching method. This finding is associated with the questionnaire results that show the high satisfaction level about Grasshopper in terms of preference, convenience and time saving. It is one of the benefits of the parametric modeling tools and also viewing in 3D can support the creating-viewing and modifying cycle. This is one of the factors which make parametric modeling tools beneficial during the conceptual design phase.

The results show that the average percentage of the functional actions (F actions) is higher in hand sketching (%17.93) than in Grasshopper (%5.81). This difference is statistically significant. This significant difference is mostly dependent on the frequency of *implement* action. According to functional actions it can be said that the hand sketches lead the designers to think more holistically in the design process. The functional actions lead the participants evaluate their design solutions in relation to external factors such as environment or psychological effects on the users. Grasshopper did not significantly affect the consideration of the function of the design solution.

The conceptual actions (C actions) represent the semantic level of the participants in the design process. The average percentages of the C actions diversified between individuals within the inexperienced and experienced groups. The reason for this is that C actions are related to the subjective evaluations of the users about the design solutions or their past knowledge, so no definite interpretation can be made for these differences. However, the difference of the C actions between hand sketching and Grasshopper is close to being statistically significant ($p=0.056$). This might support the claim that, since Grasshopper is a visual algorithmic tool, it requires as much conceptual actions as hand sketching. Moreover, the difference is largely due to the percentages of *goal setting* sub-category, which had the highest value in the C actions and is higher in Grasshopper than in hand sketching. This finding is in parallel with physical actions because creating, modifying and erasing the parameters or rules may cause a revision in the intentions.

Finally, the following tables (Table 6.1-6.2-6.3) are prepared to summarize the findings of this study. These tables are designed to show where the percentages of action categories and segments are more in Grasshopper or in hand sketching. Additionally, the red color represents the significant values statistically.

Table 6.1: General distribution of using Grasshopper and hand sketching according to the findings

	Segmentation	Cognitive Actions			
		Physical	Perceptual	Functional	Conceptual
Grasshopper	x	x	x		
Hand Sketching				x	x

Table 6.2: General distribution of using Grasshopper and hand sketching according to the findings in terms of experienced and inexperienced participants

		Segmentation	Cognitive Actions			
			Physical	Perceptual	Functional	Conceptual
Grasshopper	Inexperienced	x	x	x		
	Experienced	x	x	x		x
Hand Sketching	Inexperienced				x	x
	Experienced				x	

Table 6.3: General distribution of using Grasshopper and hand sketching according to the findings in terms of sub-category actions

	Cognitive Sub-category Actions										
	Physical			Perceptual			Functional		Conceptual		
	Create	Modify	Erase	Feature	Relation	View	Implement	Reactions	Goal Setting	Retrieve Knowledge	Evaluation
Grasshopper	x	x	x		x	x			x		
Hand Sketching				x			x	x		x	x

6.3 Conclusions

This thesis reviewed the potentials and contributions of parametric modeling tools in the conceptual design phase in comparison to hand sketching by indicating the cognitive activities of the designers and their satisfaction levels about Grasshopper. In the experiment procedure, first of all, a pilot study was conducted. Based on the feedback of the pilot study, the main study was carried out by the participation of 6 graduate architecture students from Bilkent University; 3 experienced and 3 inexperienced in using Grasshopper. The results related to the participants' cognitive behaviors were obtained from the protocol analysis with content-oriented approach. Additionally, by means of a post task questionnaire, participants' satisfaction levels were assessed individually.

The findings indicated that all participants are more effective in using Grasshopper in terms of perceiving and solving the design problem, utilizing and managing time, generating different alternatives and considering the relations of the design elements. The findings showed that in relation to the research question whether there are any differences among the cognitive behaviors of designers while using hand sketching and parametric design tools in the conceptual design phase, there is an increasing trend in the cognitive actions of the designers from hand sketching to Grasshopper, and the total number of cognitive actions is higher in Grasshopper than in hand sketching. This shows that Grasshopper is not merely a tool for form searching, but also a tool that supports and enhances all cognitive behaviors of the designer. This represents that Grasshopper can provide contributions to the design process and has positive effects in the conceptual design phase, in answer to the initial research question of whether parametric design tools support the conceptual design phase of the architectural process as much as hand sketching.

In comparing the effects of hand sketching and parametric tools while generating concepts in architectural education, the findings supported the idea that parametric modeling tools can promote generation and as such, students should be encouraged to use parametric design tools more in the early design process. The findings do not suggest a replacement of hand sketches in the conceptual design phase, but indicate that parametric design tools may support this phase strongly. The results showed that prior knowledge and experience in using the parametric design tool is an effective factor in the success of using the tools during conceptual design phase. Therefore, it may be suggested that the courses on parametric design tools become a part of the design curricula in the freshman years.

This thesis is one of the first and few efforts to compare hand sketching and Grasshopper by a content-oriented protocol analysis. The implemented research methodology provided insights into various aspects of designers' cognitive behaviors in terms of the use of these two tools. Further research on the raised issues would facilitate more implications for improving such tools, education, and architectural practice at large.

In order to provide contribution to further studies, the research limitations of the present empirical study and the recommendations should be taken into account. First of all, this study comprised of six female participants with different expertise levels in using Grasshopper. For further studies, an increased number of participants and a more balanced gender distribution are suggested to enrich the findings. In addition to that, in this study, the designers participated individually to the experiment and they did not carry out any collaborative work. The same study can be done with teamwork and this issue can be a further research topic in this field. Secondly, this study has focused on one parametric modeling tool, Grasshopper, a visual algorithm editor, in the conceptual design phase. However, there are various other parametric modeling tools, as mentioned in section 3.3.1, which may be utilized. The use of different tools, such as textual algorithm editors, and/or Building Information Modeling (BIM) tools would be beneficial to further explore the potential and advantages of adopting digital tools in the conceptual design phase. Thirdly, different methodologies from various perspectives can be implemented in order to analyze the design process. For instance, the linkography technique (Goldschmidt, 1990) or other process-oriented approaches (Gero and Mcneill, 1998) can give different results and thus, they can generalize and expand the findings. Finally, this thesis focuses on the cognitive processes of the participants in terms of their satisfaction levels about a parametric modeling tool. In further studies, using hand sketching and parametric modeling tools with regards to the use of mental imagery, creativity or design strategies can be investigated.

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APPENDICES

APPENDIX-A

Post-Task Questionnaire for the Pilot Study

1-) The given tutorials were beneficial.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

2-) The given time for the design task was sufficient.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

3-) Complexity of the design task was appropriate.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

4-) Organization of the design task was clear.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

5-) Experiment location had adequate conditions.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

6-) Software applications and computers worked fine.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

APPENDIX-A

Post-Task Questionnaire for the Main Study Part-1

Name:

Year:

Age:

The questions concern your Grasshopper usage background. Please read and answer the following questions carefully.

Did you use Grasshopper or other parametric tools before? How was your first experience?

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How is your education level about Grasshopper? Did you take any courses in your university about it?

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Have you spent time on your own to learn Grasshopper?

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Did Grasshopper help you on your projects? What was the benefits and drawbacks of Grasshopper?

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Did you use Grasshopper alone or with another tool (method) in your projects?

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………………………………………………………………………………………………
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Post-Task Questionnaire for the Main Study Part-2

Below is a list of statements dealing with your general feelings about yourself and your experiences. Please indicate how strongly you agree or disagree with each statement. (1-strongly agree, 2-agree, 3-neither agree nor disagree, 4-disagree, 5-strongly disagree)

1-) In the design process, I preferred Grasshopper to hand sketching.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

2-) Grasshopper provided me with different design alternatives, than I would come up with hand sketching.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

3-) Grasshopper enabled me to generate solutions more quickly.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

4-) Using Grasshopper made it easier to do my design task.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

5-) The use of Grasshopper made it possible to come up with a more creative design, than I would generate through hand sketching.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

6-) In conceptual design phase, Grasshopper is useful.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

7-) In conceptual design phase, Grasshopper is effective.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

8-) If I had more knowledge in Grasshopper I would have preferred to use it more.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

9-) I would not reach the same design solution without using Grasshopper.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

10-) On the whole, I am satisfied with my design solution.

Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
❍	❍	❍	❍	❍

APPENDIX-B

Figure B1: Working Environment (The Computer Lab)

Figure B2: The Design Brief

DESIGN BRIEF

- Designing “A shelter for the activity area of university students”
- Given time is “60 minutes”

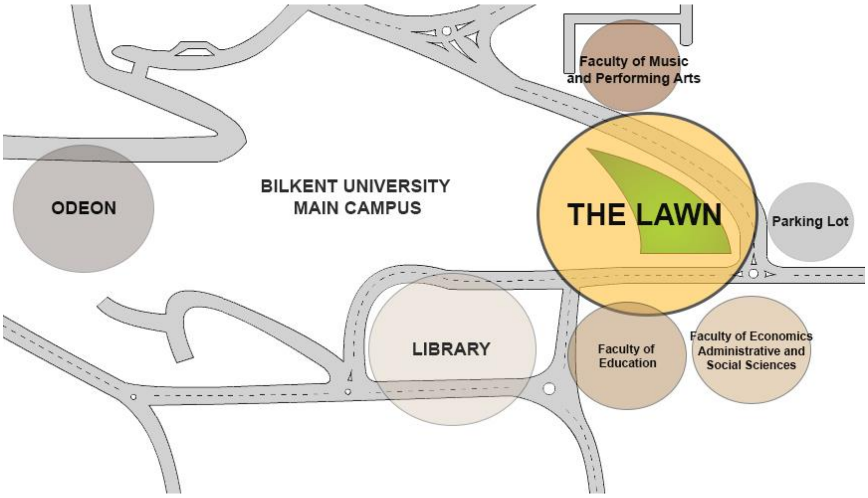
“The lawn” as it is known by the Bilkent students is a large green area next to the road connecting the Music Faculty with the Main Campus, which is occupied by Bilkent students for informal gatherings. You are expected to design a shelter in that area that is going to provide a semi-closure for the students. The shelter should be designed by considering the specifications below:

It is expected that the shelter will be a self-standing structure enabling partial shade from the sun and enclosure from rain and snow. The shelter should be designed for maximum 15-20 people, where users can have a pleasant time sitting and/or lying down on the grass. The site plan, boundaries of the area, related photographs and a diagram are given below at the bottom.

Coming up with a model that puts forth the concept of the design would be sufficient. The technical drawings and structural details are not required.

AREA INFORMATION:

-DIAGRAM



-SITE PLAN

-PHOTOS

APPENDIX C

Figure C1: Total Segment Numbers of the Participants

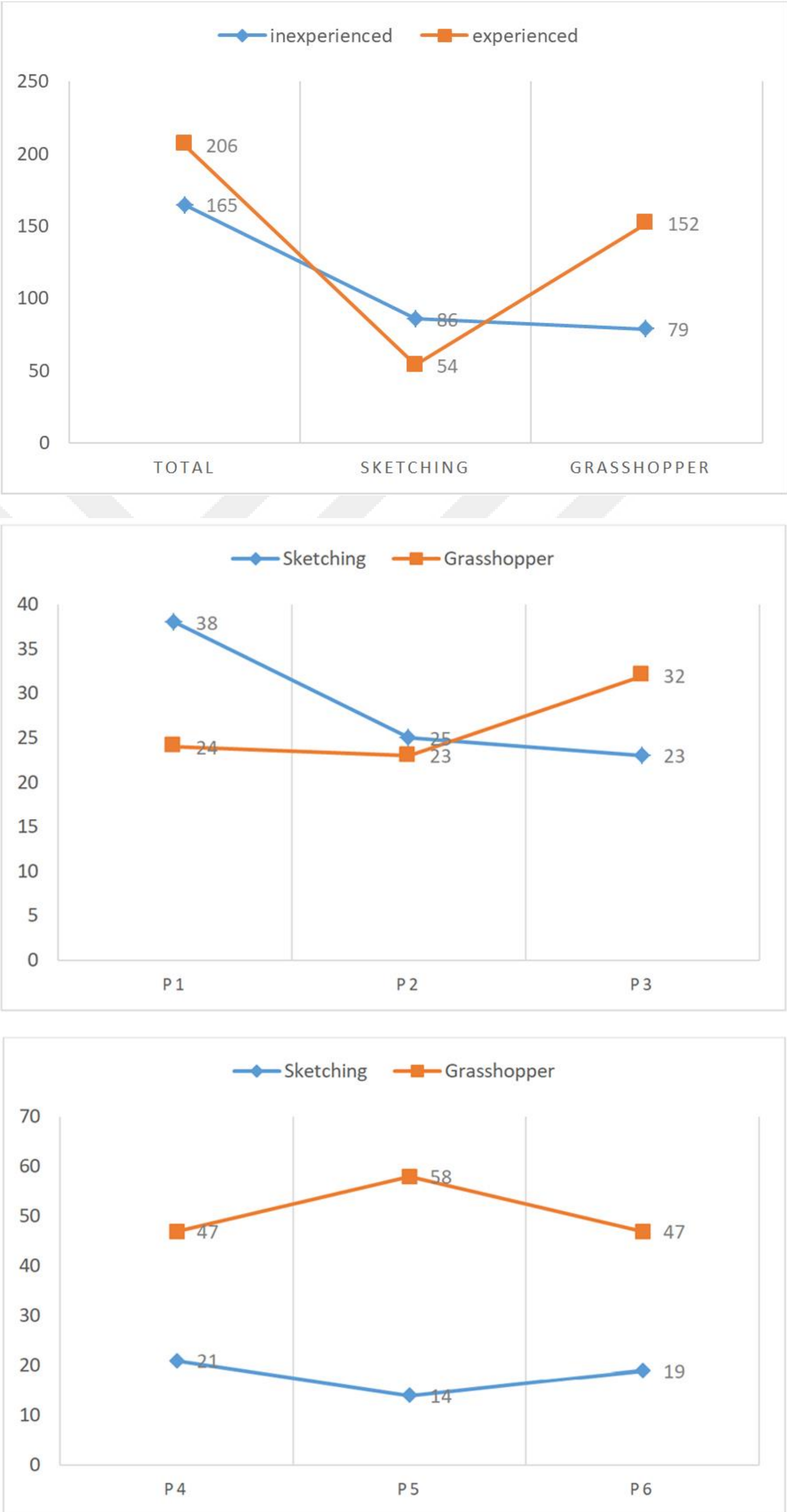


Table C1: Total numbers of individual codes of the participants

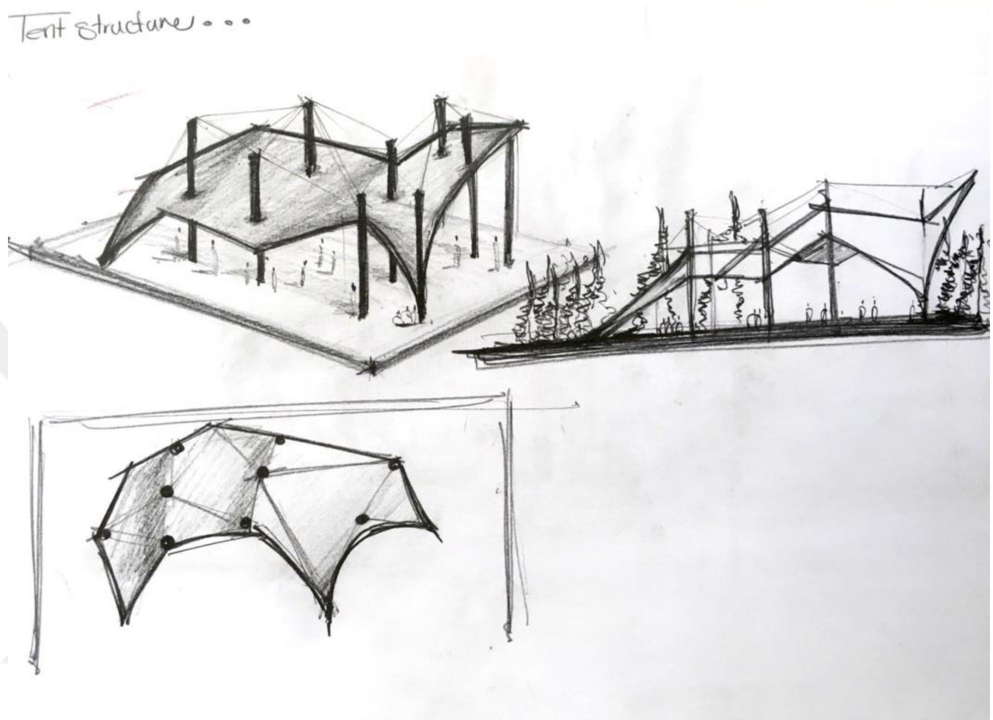
			P1	P2	P3	P4	P5	P6
Sketching	D	Dcg	82	15	22	26	31	23
		Dmg	40	8	15	11	12	9
		Deg	26	5	4	6	8	5
	P	Pfg	18	8	10	18	12	15
		Prs	14	5	8	7	12	11
		Prg	11	4	3	4	5	3
		Pvf	9	3	4	3	3	3
	F	Fn	17	6	14	12	11	6
		Fi	10	2	6	2	5	3
		Fİ-re	9	3	2	1	5	2
		Fri	18	2	5	4	11	4
	C	Cg	31	6	12	10	15	12
		Ck	32	3	6	5	5	9
		Ce	18	3	5	3	12	15
Grasshopper	D	Dcg	26	9	18	14	15	25
		Dcp	12	10	30	46	52	64
		Dcr	15	22	60	48	29	28
		Dmg	32	6	18	12	18	6
		Dmp	15	22	62	48	28	17
		Dmr	19	5	15	13	32	8
		Deg	15	4	5	6	16	13
		Dep	22	6	15	6	10	15
		Der	8	4	7	8	16	12
	P	Pfg	28	25	24	29	31	28
		Pfa	20	18	21	29	20	28
		Prs	16	15	52	32	26	30
		Prg	10	12	13	27	16	23
		Prl	15	13	16	19	20	21
		Pvf	14	3	6	6	8	4
	F	Fn	19	6	16	10	12	10
		Fi	5	2	6	4	4	3
		Fİ-re	4	1	5	2	4	2
		Fri	20	7	8	10	14	8
	C	Cg	30	16	66	32	45	35
		Ck	4	6	31	30	34	21
		Ce	6	11	41	12	32	17

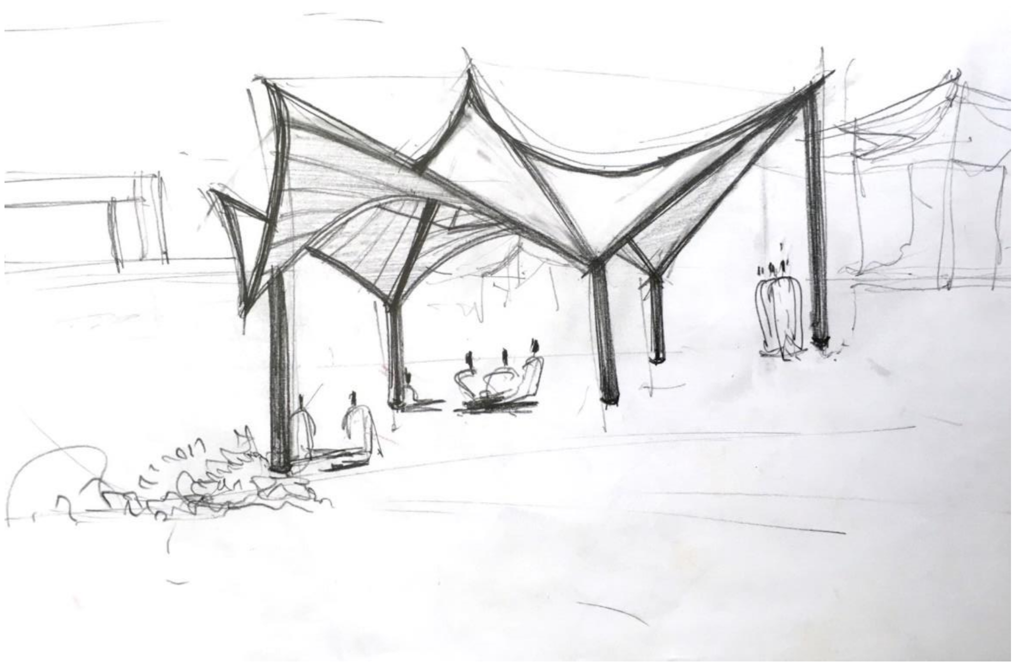
APPENDIX-D

Figure D1: The design alternatives of the participants

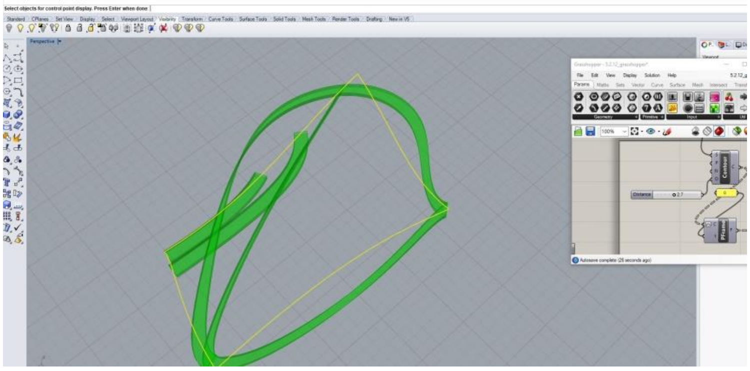
P1 (inexperienced user)

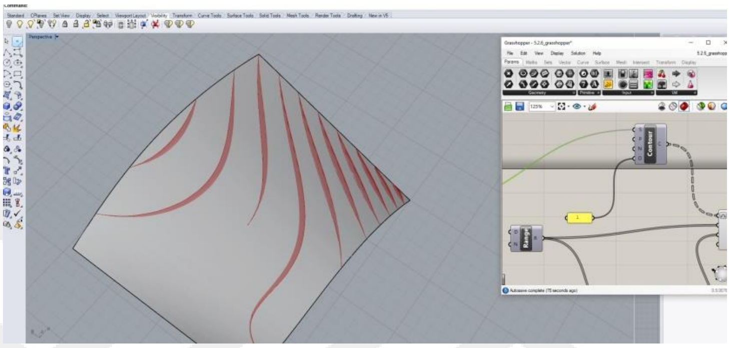
Sketches

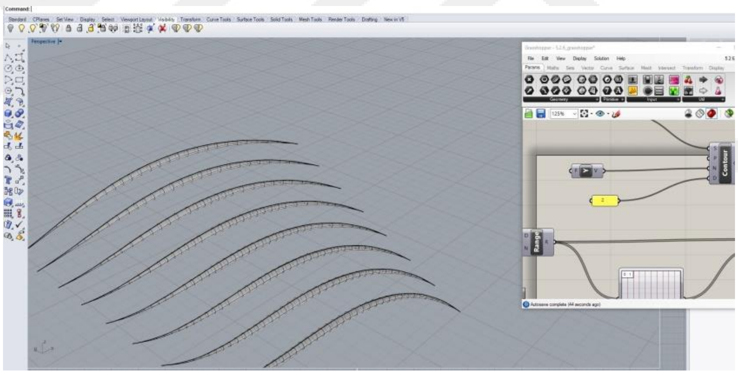




Grasshopper



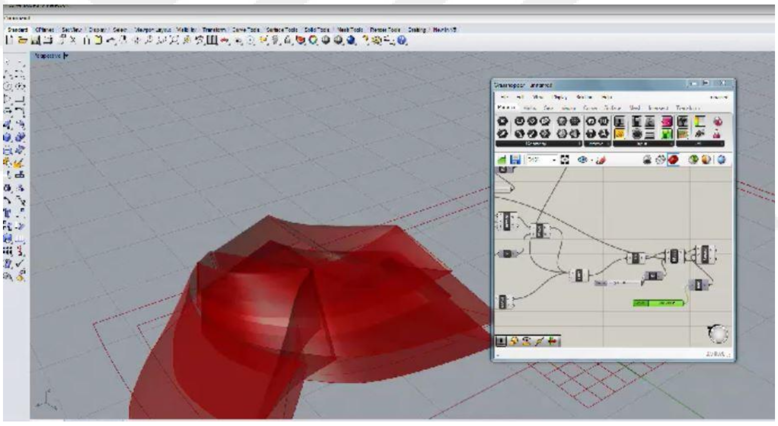


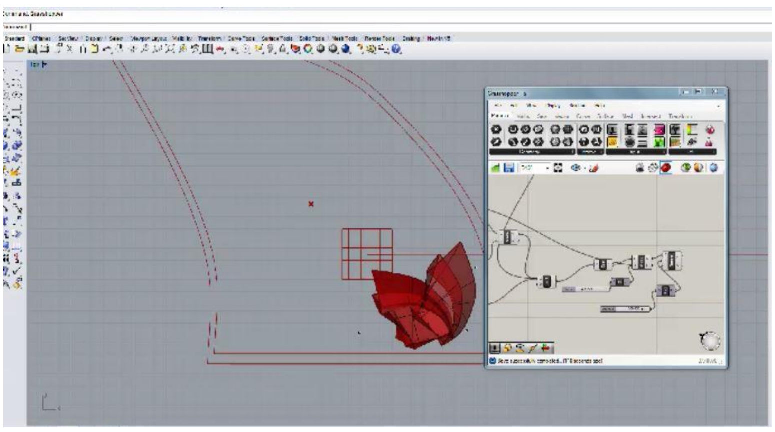


P2 (inexperienced user)

Sketches

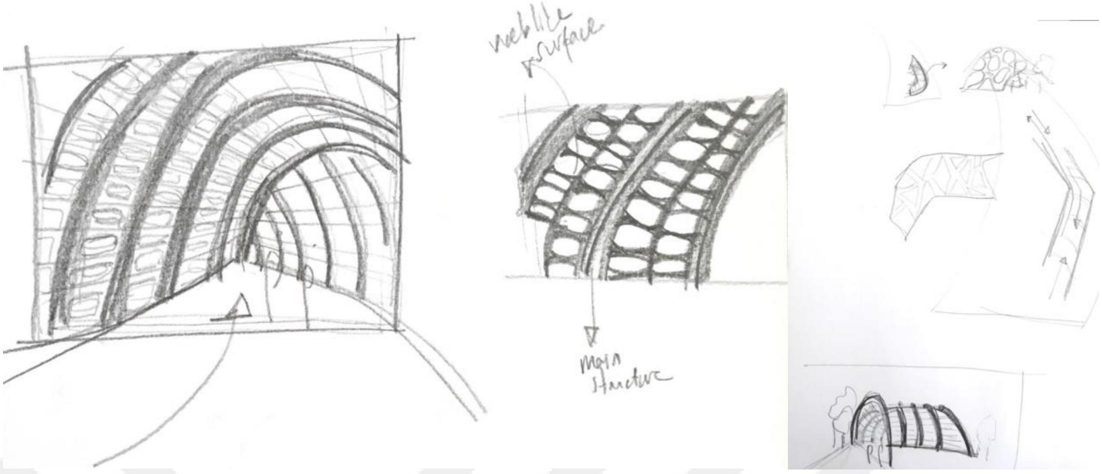
Grasshopper



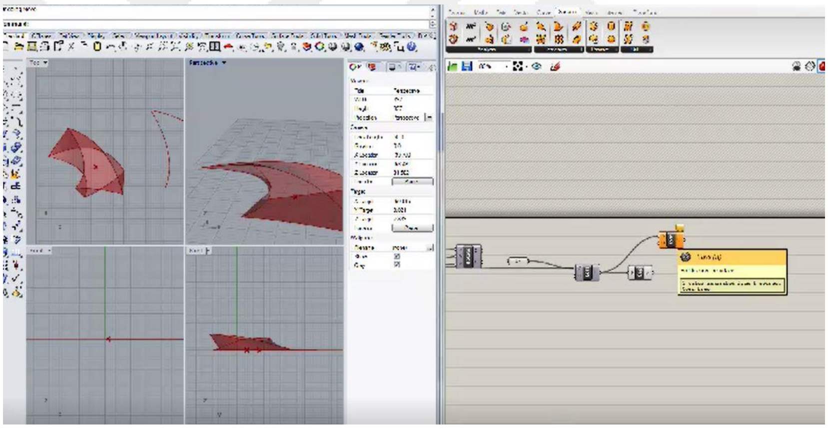


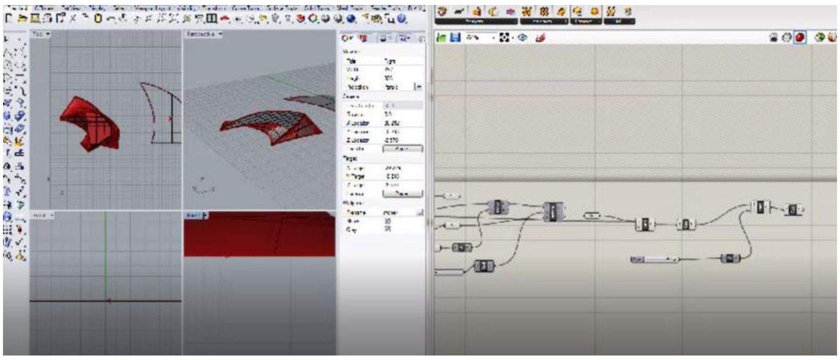
P3 (inexperienced user)

Sketches



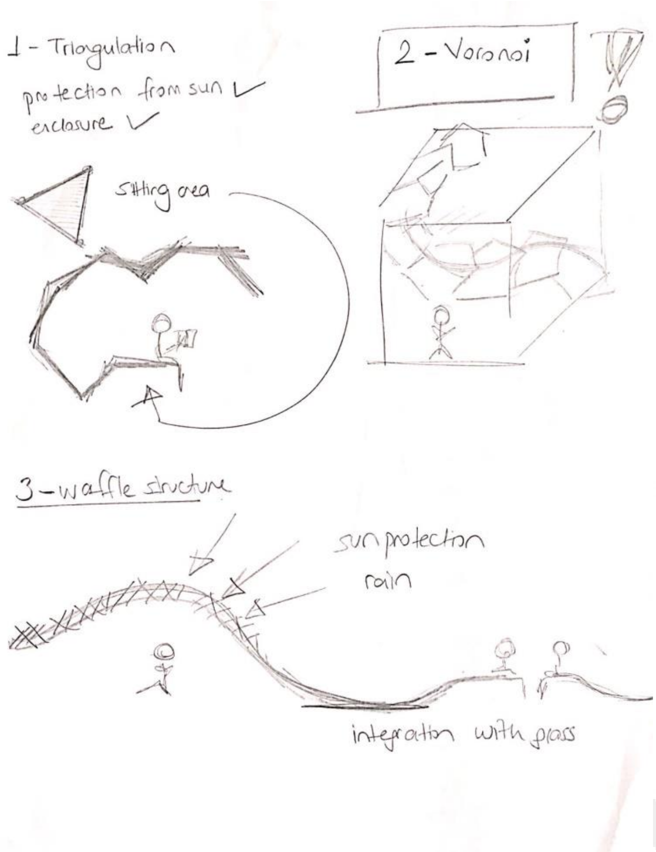
Grasshopper



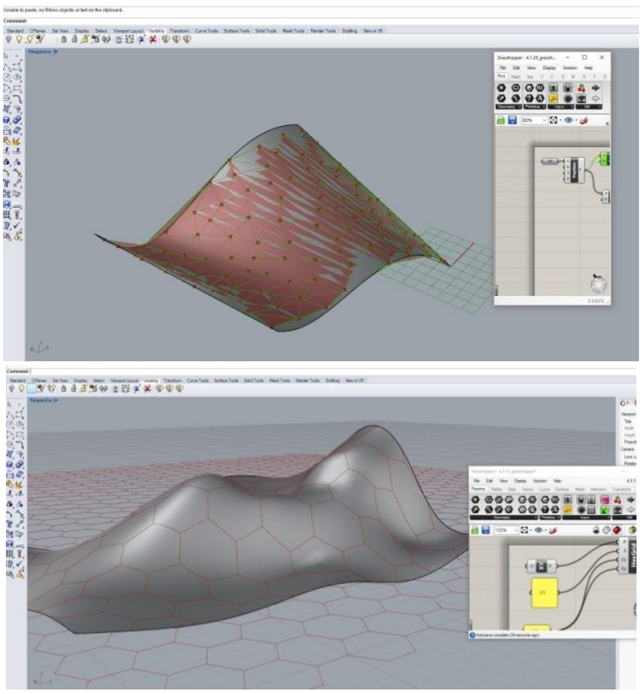


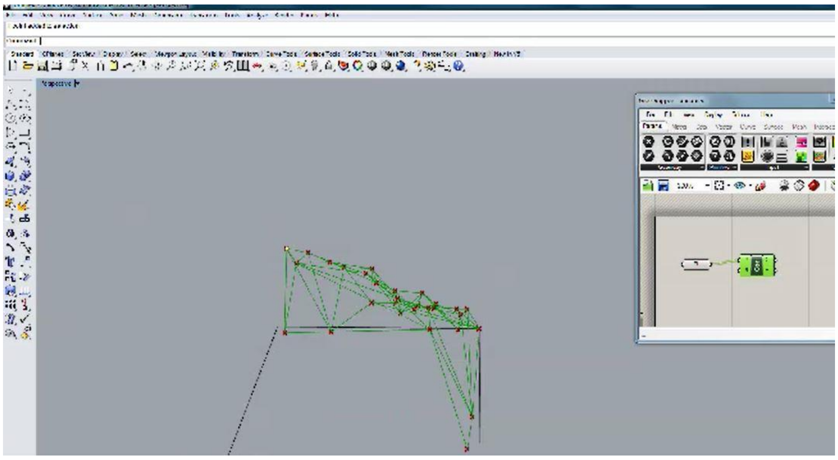
P4 (experienced user)

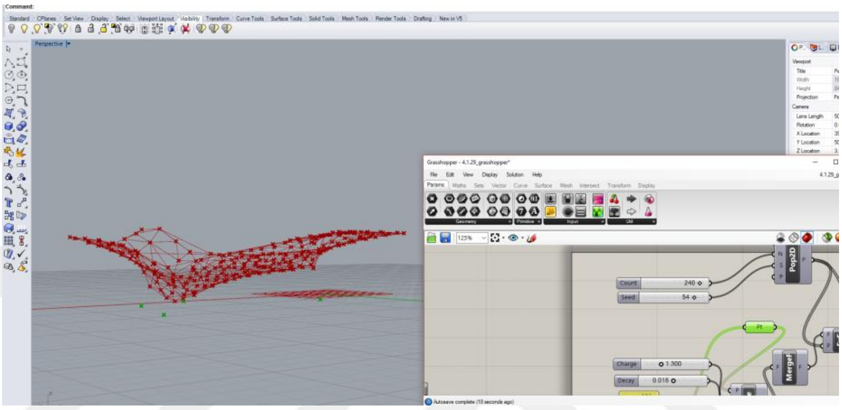
Sketches

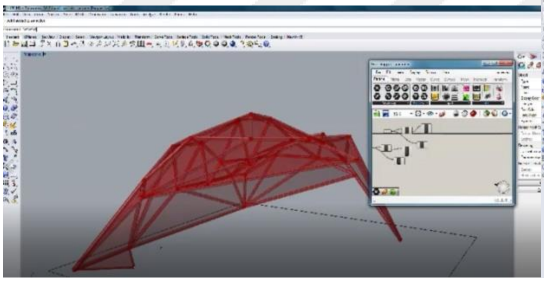


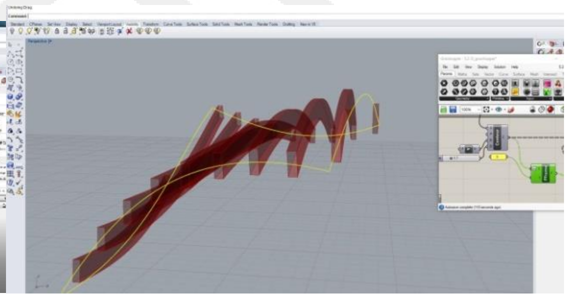
Grasshopper

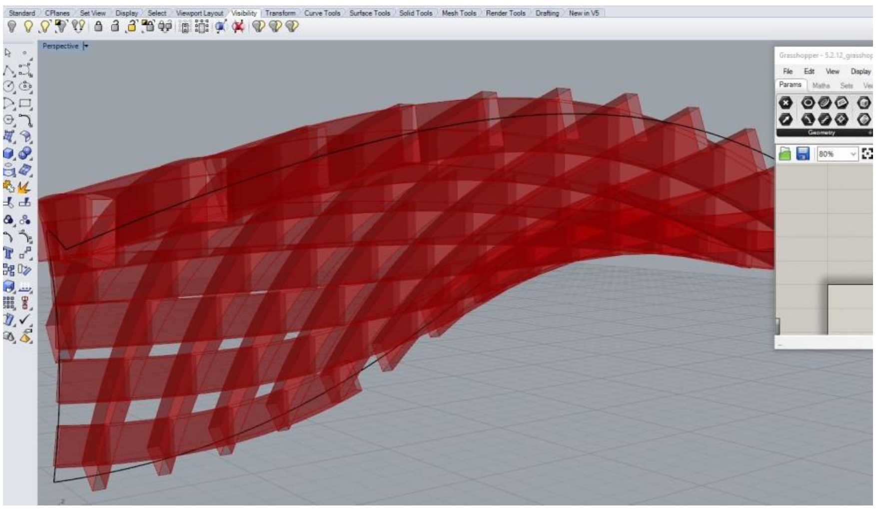






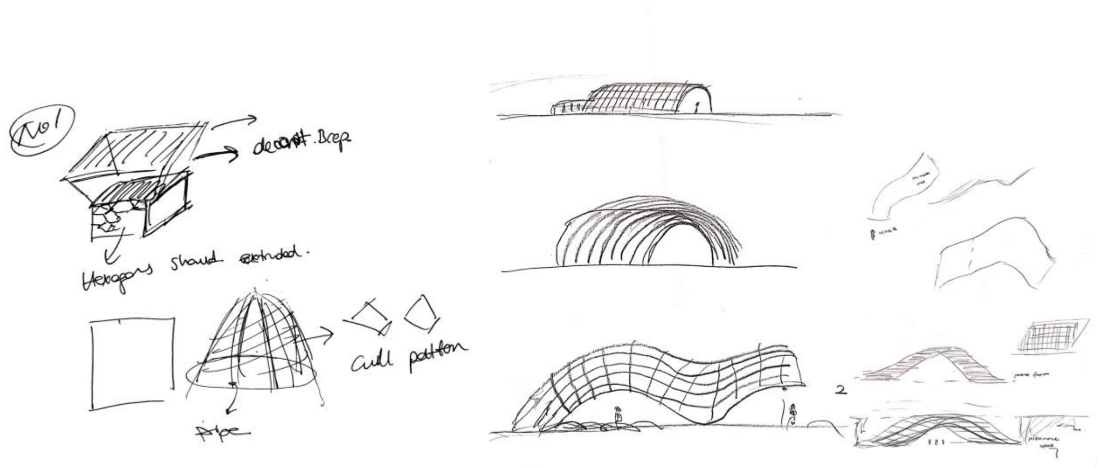




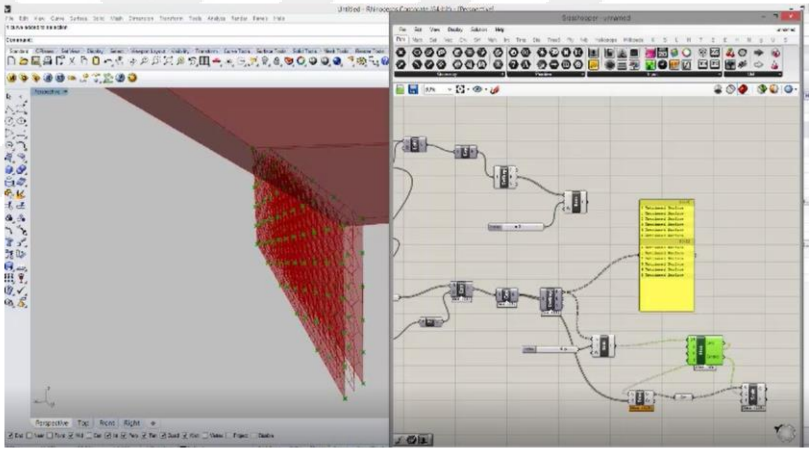


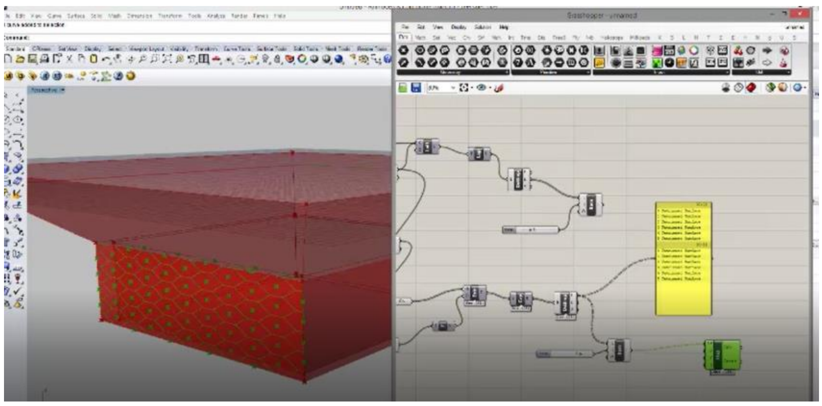
P5 (experienced user)

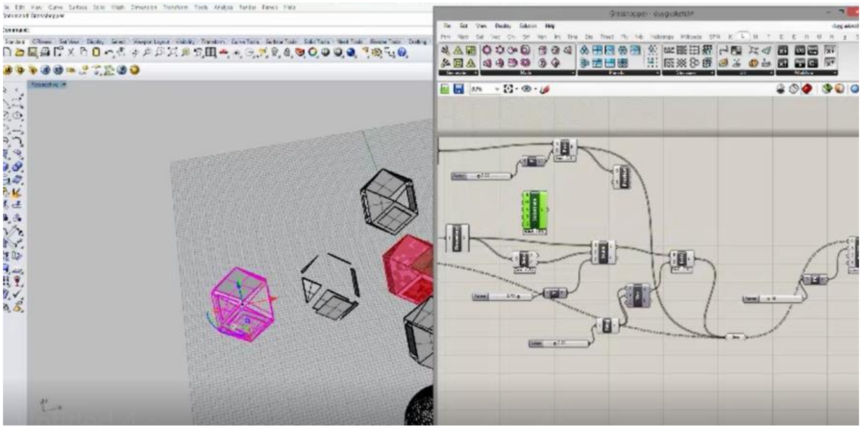
Sketches

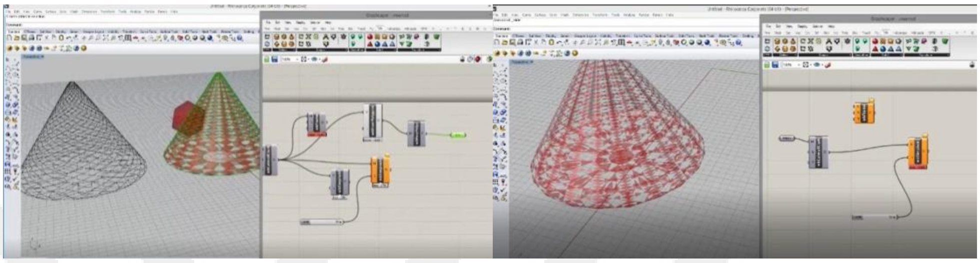


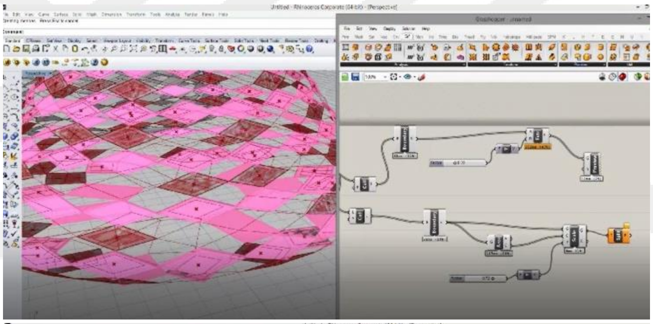
Grasshopper

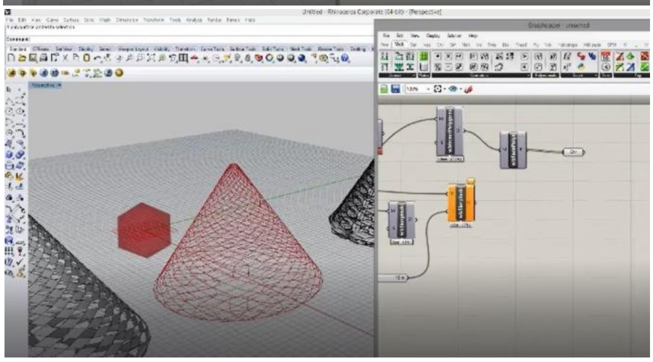


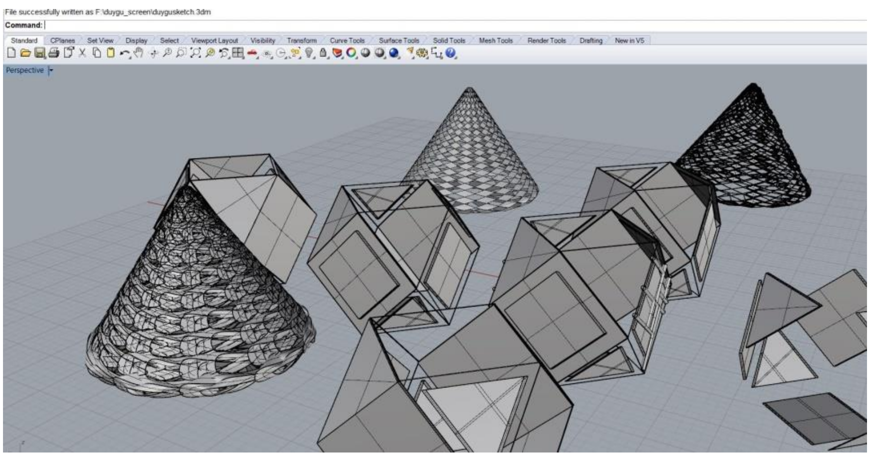








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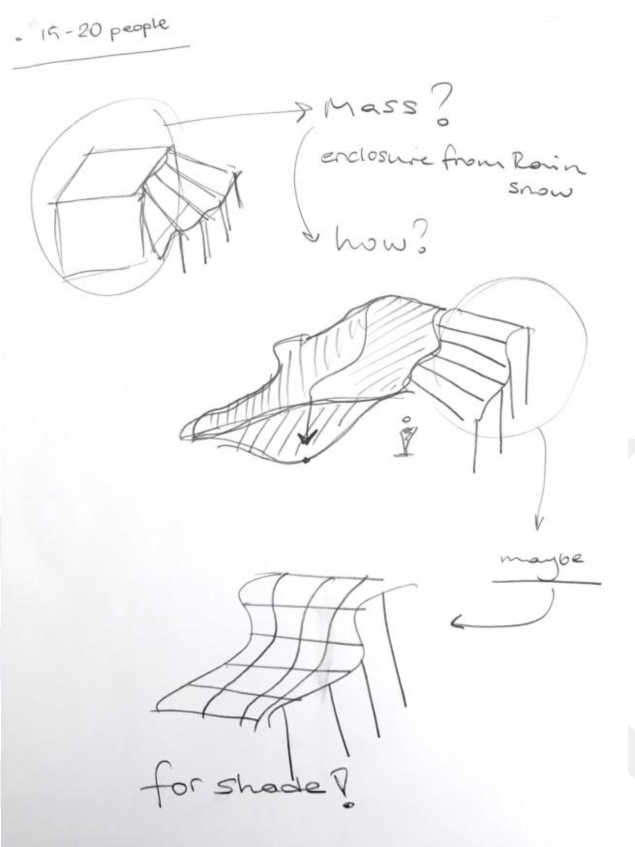
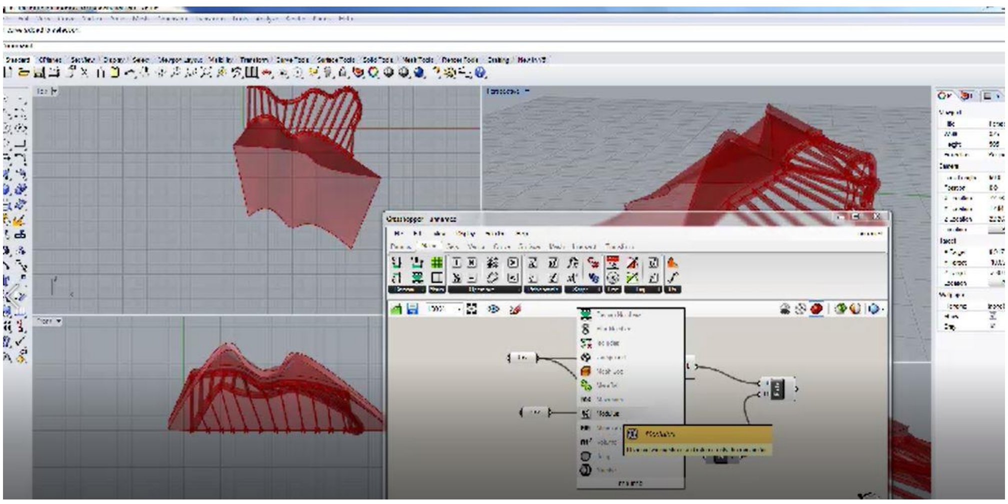
Command:
Standard CPlanes Set View Display Select Viewport Layout Visibility Transform Curve Tools Surface Tools Solid Tools Mesh Tools Render Tools Drafting New in V5
Perspective

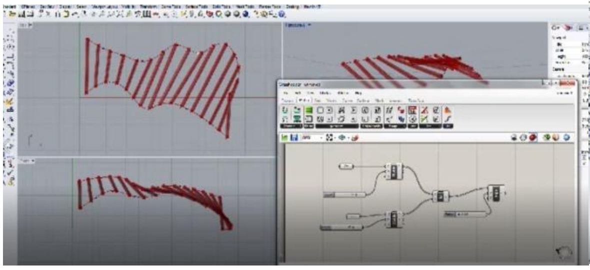
P4 (experienced user)

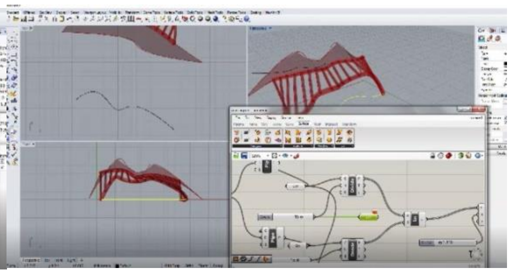
Sketches

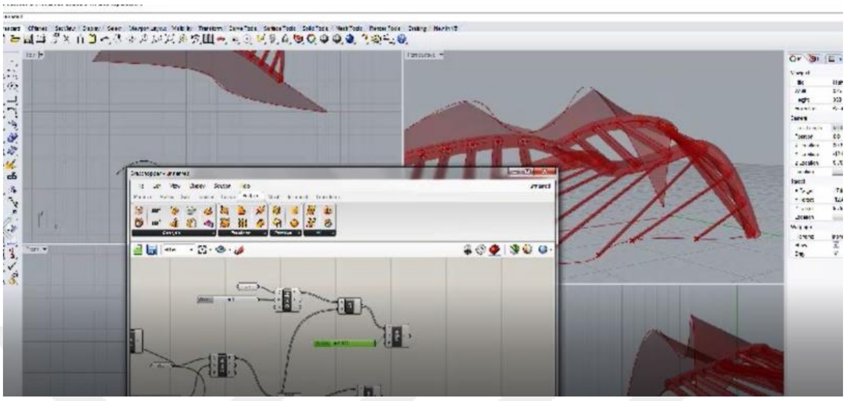


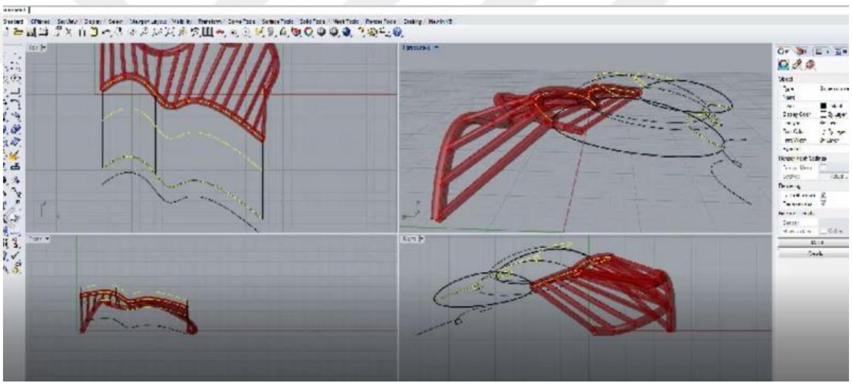
Grasshopper

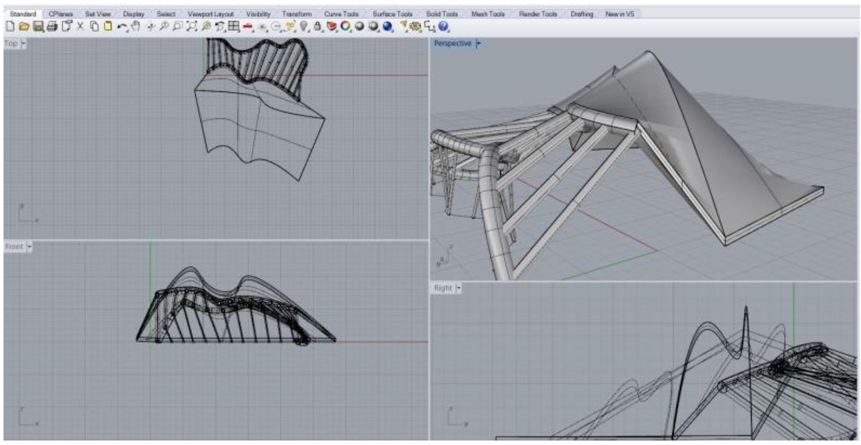











Standard
CPlanes
Set View
Display
Select
Viewport Layout
Visibility
Transform
Curve Tools
Surface Tools
Solid Tools
Mesh Tools
Render Tools
Drafting
New in V5
Top
Perspective
Front
Right