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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

QUESTIONING DESIGN TOOLS IN THE EARLY STAGE OF ARCHITECTURAL DESIGN PROCESS: PEN AND PAPER VS. DIGITAL SKETCHING

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Parvin HEIDARI

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
CAAD	Computer Aided Architectural Design
CACD	Computer Aided Conceptual Design
CAD	Computer Aided Design (Drafting)
CMs	Critical Moves
LI	Link Index
PC	Personal Computer
PDA	Personal Digital Assistant
SBIM	Sketch Based Interfaces for Modeling

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ABSTRACT

QUESTIONING DESIGN TOOLS IN THE EARLY STAGE OF ARCHITECTURAL DESIGN PROCESS: PEN AND PAPER VS. DIGITAL SKETCHING

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Architectural design has a special position in architecture education. It is the main and most effective study area to develop architecture student's design skill and knowledge. In the architectural design, designer focuses more on the conceptual stage of design. This stage is different from other phases of design process and provides fields that designer manipulates the design problem and generates and explores new ideas. Early stage of design generally begins with sketches and diagrams (referred to as traditional media) to explore ideas and solutions. The freehand sketch plays important role in design process by facilitating problem solving, generating ideas and externalizing them. The ambiguity and vagueness of conventional freehand sketching can be a source of creativity.

Nowadays, with the advances in digital technology, there are attempts to integrate digital tools with the early phases of design in order to make a digital design media in the architectural education. Recent developments in CAAD software shows a shift in focus toward conceptual design interface; but these tools have not developed and still fail to offer an appropriate design environment for sketching. Therefore, the application of digital tools has created debates among design instructors and researchers; the main point of these discussions is that computer software may impede the creative behaviors and this can lead to poor and non-creative design by students. So can be concluded that, architectural education in application of digital tools in the early design stages are facing problems and challenges especially regarding creativity.

This study focuses on conceptual design process and aims: firstly, to find out the relationship between conventional sketching and creativity, the current status of digital sketching and interface and whether it can replace traditional sketching in educational context. In experimental study, the digital based sketching is compared and evaluated with pen and paper sketching from creativity point of view via protocol analysis method and linkography, and whether it can enhance the creativity of students.

The findings emphasis on the strong relationship between creativity and conventional sketching method and show that there are attempts to create design interface to simulate pen and paper sketching features at digital medium for support creative design. As a conclusion, the findings of the empirical study also stressed out that designers in pen and paper sketching had richer design process and more opportunities for idea generation versus the digital sessions, and consequently they had more creative and productive design process. However, digital sketching depending on its nature can enable designers to make interconnectivity of ideas and create the number of different ideas, if they have sufficient experience and skills in digital sketching software.

Key words: Conceptual Design, Freehand Sketching, Digital Sketching, Creativity, Linkography, Protocol Analysis.

ÖZET

MİMARİ TASARIM SÜRECİNİN ERKEN EVRELERİNDE TASARIM ARAÇLARININ SORGULANMASI: SERBEST EL Vs. DİJİTAL ESKİZ

Parvin HEIDARI

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Eş Danışman: Assoc. Prof. Dr. Aslı SUNGUR ERGENOĞLU

Mimari tasarım, mimarlık eğitiminde özel bir konuma sahiptir. Mimarlık öğrencisinin tasarım becerisini ve bilgisini geliştirmek için temel ve en etkili çalışma alanıdır. Mimari Tasarım sürecinde tasarımcılar, tasarım sürecinin erken evreleri ve ya kavramsal tasarım üzerine odaklanırlar. Bu evre, tasarım sürecinin diğer evrelerinden farklıdır ve tasarımcının tasarım problemini manipüle ettiği, yeni fikirler ürettiği ve araştırdığı alanları kapsamaktadır. Fikirleri geliştirmek ve çözümler üretmek için bu evre genellikle eskiz ve şemalar (özellikle geleneksel ortam kaynaklı) ile başlamaktadır. El eskizleri, problem çözmeyi kolaylaştırmak üzere üretilen fikirleri ifade etme aracı olarak tasarım sürecinde önemli rol oynamaktadır. Bu anlamda geleneksel bir ifade biçimi olan serbest el eskizinin belirsizliği bir yaratıcılık kaynağı olabilmektedir.

Günümüzde dijital teknolojilerdeki gelişmeler ile, mimarlık eğitimde bir dijital tasarım ortamı oluşturmak ve dijital araçların kavramsal tasarım ile bütünleştirilmesi girişimleri ortaya çıkmıştır. CAAD yazılımındaki son gelişmeler, kavramsal tasarım arayüzüne odaklanma yönünde bir değişimi göstermektedir; ancak bu araçlar geliştirilmemiş ve eskiz için hala uygun bir tasarım ortamı sunamamaktadır. Bu nedenle dijital ortamın kullanımı tasarım eğitimcileri ve araştırmacılar arasında tartışmaların yaşanmasına da neden olmaktadır. Tasarımın ilk evrelerinde bilgisayar kullanımına karşı olanlara göre, bu tartışmaların ana konusu bilgisayar yazılımlarının yaratıcılığı engellediği üzerinedir.

Aynı zamanda bu durum öğrencileri zayıf ve yaratıcı olmayan tasarımlara da yönlendirebilir. Sonuç olarak, mimarlık eğitiminin tasarımın ilk evrelerinde dijital araçların kullanımı ile özellikle yaratıcılığa ilişkin sorunlar ve zorluklarla karşı karşıya kaldığı anlaşılmaktadır.

Bu çalışma, tasarım sürecinin ilk evrelerine odaklanarak, geleneksel eskiz ve yaratıcılık arasındaki ilişkiyi, dijital eskiz ve arayüzün mevcut durumunu ve eğitim alanında geleneksel eskizin yerini alıp alamayacağını ortaya koymak amacındadır. Tez çalışmasında dijital tabanlı eskizin, yaratıcılık bakış açısından geleneksel serbest el eskizi ile karşılaştırılması protokol analiz yöntemi ve linkografi yöntemi üzerinden değerlendirilmektedir.

Bulgular, yaratıcılık ile geleneksel eskiz yöntemi arasındaki güçlü ilişkiyi vurgulamaktadır. Yaratıcı tasarımı desteklemek için, dijital ortamda kalem ve kağıt eskiz özelliklerini simüle etmek, tasarım arayüzü oluşturma girişimleri olduğunu göstermektedir. Deneysel çalışmanın bulguları, tasarımcılarının kalem ve kağıt eskizinde, dijital eskizlere kıyasla daha zengin tasarım sürecine ve fikir üretme fırsatlarına sahip olduklarını ve sonuç olarak daha yaratıcı ve üretken tasarım sürecine sahip olduklarını vurgulamıştır. Ancak doğasına bağlı olarak dijital eskiz, tasarımcıların, dijital eskiz yazılımında yeterli deneyime ve becerilere sahip olması durumunda, fikirlerin birbirine bağlanmasını ve farklı fikirler üretmesini sağlayabileceği de görülmüştür.

Anahtar Kelimeler: Kavramsal Tasarım, Serbest el Eskizi, Dijital eskiz, Yaratıcılık, Linkography, Protokol analizi.

CHAPTER 1

INTRODUCTION

Architectural design as the most effective course in architecture education, has an unique role in developing architecture student's design skills and knowledges. In the architectural design, designer focuses on the early stage of the design process or conceptual design. In this stage designers have an effort to manipulate the design problem and generates and explores new ideas. This stage generally begins with sketches and model making to explore ideas and solutions; according to nature of conceptual design stage, sketches have an intellectual side related to thinking process and imagination that makes designer to sketch roughly. The freehand sketch plays important role in design process by facilitating problem solving, generating ideas and externalizing them. The ambiguity and vagueness of sketch can be a source of creativity because allows revising and reinterpretating old sketches that makes designer to get new insights, see new relations and meanings that lead to discovery of new ideas.

Nowadays, with the advances in digital technology, there are attempts to integrate digital tools with the early phases of design in order to make a digital design media in the architectural education. Recent developments in CAAD software shows a shift in focus toward conceptual design interface; but these tools have not developed and still fail to offer an appropriate design medium for sketching. So application of digital tools in the early design stage, has created problems and challenges that has been the source of many different researhes to evaluate digital tools campared to traditional freehand sketching.

1.1 Literature Review

Many researchers in this area have conducted experiments to compare and evaluate freehand and digital medium during sketching design process in a laboratory condition involving design students (e.g. Bilda & Demirkan [1], Won [2], Goel [3], Bilda [4] and Tang & Gero[5]). Several studies compare digital and traditional sketching media and highlight how they influence the designers' behavior [1].

Bilda & Demirkan [1] use protocol analysis technique to understand the differences of cognitive actions of traditional versus digital media during conceptual design phase. They find a significant difference that designer's goals and intentions more frequently changed in traditional media compared to CAD media. And traditional media had advantages over digital media, such as supporting the perception of visuo spatial features and functional relations of the design, production of alternative solutions, and better conceptions of the design problem. Their results showed more changes in decision-making, more redefinitions of spatial relation, and spent more time working with the problem in traditional media, and in contrast, had shorter problem definition stage and spent more time in modification and concept evaluation phases in digital sketching media.

A comparative research of Bilda [4] indicates the total number of cognitive actions was also relatively higher in traditional media. According to him this result cannot be interpreted, as designers tend to think, see, perceive less in digital media, but can be explained by designers' mode of thinking and reasoning in different media; Because designers have always used hand sketches as a cognitive tool throughout their education, not the digital media. Thus this might limit their cognitive interaction with the digital media. Also the results show that, the frequency of physical actions in digital media was higher, which points out the fact that frequency of other action categories was lower. This implies that designers tend to use the digital media for implementation of designs (or simulation purpose) but not as a medium which s/he interacts with to implement his/her alternative thoughts [4].

The won's [2] study aims understanding the differences between designers' cognitive visual thinking while they generate concepts using computer or conventional media. He concludes that, designer's cognitive behavior is simpler in conventional media and more

complex in computer media; also the attention of the designer shifts from the 'total' to the 'detail' of the sketch, but the shifting time is much more frequent and stands longer than in the traditional way. Furthermore, the visual thinking of cognition of the designer is different while he/she uses a computer to generate ideas in the stage of concept generation.

Another comparative study was conducted by Goel [3]. He compared protocols of design sessions where expert graphic designers solved a problem either via sketching or using a computer based drawing system. He [3] found no significant difference between the number of new solutions, duration and number of the design episodes was found. He claims that, compared to free-hand sketching, the computer based drawing system is non-dense and unambiguous and should consequently make lateral transformations difficult. His comparison reveals that significantly higher numbers of variations and reinterpretations are made within the free-hand sketching sessions versus digital sketching sessions. The differences between Goel's [3] conclusion and Won's [2] statement may be because of that Won's subjects were industrial designers while Goel chose graphic designers. The 3D nature of the object design might be supported better in computer environment by 3D visualization while graphic design, which proceeds in 2D, might not essentially need it.

Another research is Tang & Gero's [5] study that examines the design processes in a traditional and digital sketching environment that had been devised to emulate free-hand sketching. The results showed that the design processes of the digital and traditional environments were similar in terms of the speed of the design process, design issues concerned in the design processes, and the transitional activities. Therefore, this digital sketching environment is similar to free-hand sketching in all significant aspects of the design process. They examine the differences between designing in digital and traditional environments based on the FBS coding of the protocols collected. They claim that, in both environments there were no significant differences between the segment codes and transitions between segments in the two environments. These results indicate that this digital environment did not change the design process [5].

1.2 Objective of the Thesis

The ultimate goal of the early stages of architectural design is to find solutions for an existing problem and discover and explore new ideas. The freehand sketching is a common tool in conceptual phase for exploring ideas and externalizing them. But with advancing digital technology, there are attempts to integrate digital tools into the conceptual design. Application of digital tools for thinking and generating ideas in the educational context has been the debate subject among design educators and researchers who believe that, using of computer in the early stage of design can limit creativity of architecture students and prevent creative behaviors; and this creates many challenges and discussions.

Since these challenges in architectural design practice can be different, so this thesis focuses on early stage of architectural design at educational context and attempts to compare the pen and paper versus digital sketching as two design thinking tools in creativity point of view via an empirical study (as summarized in figure 1.1).

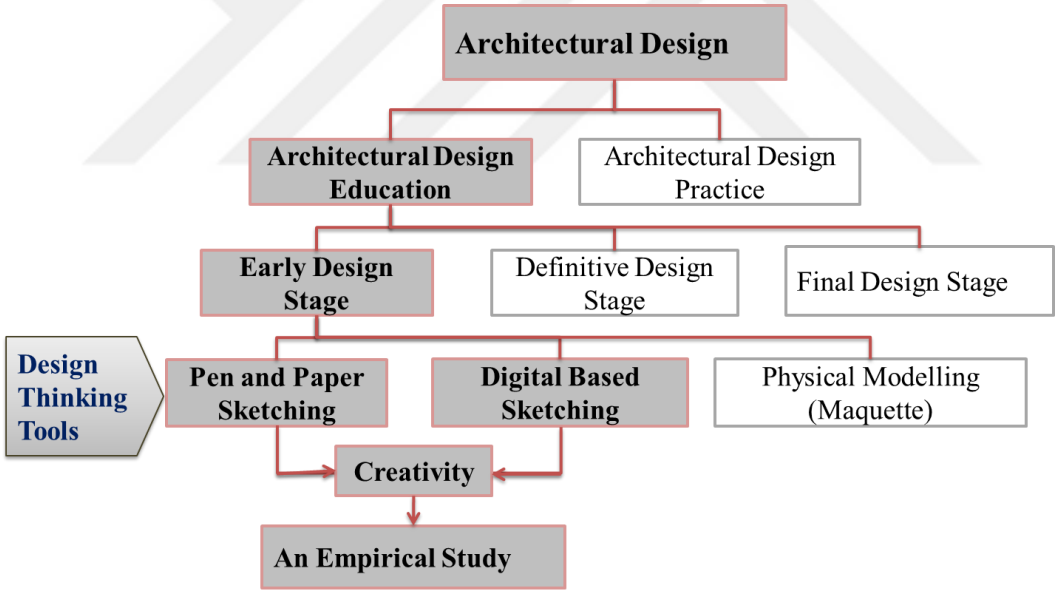


Figure 1.1 The scope of the study

So, the specific purposes of this thesis are:

First, study and investigate the freehand sketching features and properties regarding to creativity and discover the relation between them;

Second, study and evaluate the status of digital sketching tools in early design stages and their current challenges in educational fields especially relating to creativity, in order to find out recommendations for developing digital interface to support sketching and creative design process;

Third, compare and evaluate digital based sketching versus traditional pen and paper sketching in terms of creativity at an experimental work.

1.3 Hypothesis and Questions

According to research problem statement and purposes which have been considered for this thesis, the research questions are:

1) What are the current main tools in the early design phases of architectural design education?
2) What is the relationship between conventional sketching and creativity of design?
3) Why digital sketching is not yet used in the early phases of architectural design education?
4) In the early stages of design, can digital-based sketching replace traditional freehand sketching? Is it sufficient?
5) Can using digital-based sketching support creativity of students in the early stages of design?

So, it can be drawn a hypothesis as "*Digital-based Sketching Enhances the Creativity of Students in Architectural Design Education*" which has been examined at fourth chapter.

CHAPTER 2

ARCHITECTURAL DESIGN EDUCATION AND SKETCHING

2.1 Architectural Design Education

Architectural design as an intellectual field of study and experiment has an important position in educational area, and is known as the core of architecture curriculum. The history of design education shows "a progressive move from the workplace into the college and university studio", and in current design education system, "designer needs formal instruction and periods of academic study in an educational institution." [6]

Architectural design is a mental process; thus, "the design process yields different results for different architects due to the very nature of architecture" [7]. The essence of architectural design education is usually unsatisfied. Because, it is an activity to identify a problem and specify methods for dealing with this problem in order to achieve solutions [8]. Thus, the goal of architectural design education is to help students to explore design solutions. In order to achieve this goal, it seems that the design education should provide different design experiences and take an active role to facilitate knowledge acquisition, exchange and processes for students and designers with different mental and cognitive styles. This enables them to understand the design process and its applications in decision-making stage "through constructing and forming new thought(s), information(s) or design/product(s) over time with a certain accumulation of knowledge through this process" [9]. So, the architecture design is associated with concepts such as design and design problem solving to generate best solutions.

2.1.1 What is Design

There are many ambiguities in defining the design and different theorists have described it from various dimensions.

Webster's Dictionary defines design as 'the arrangement of elements that make up a work of art, a machine, or other man-made object'. The Dutch Van Dale Dictionary defines design as: 'devising and incorporating in a sketch, drawing a sketch of something', where 'sketch' is a synonym for 'plan' or 'design' (cited in [10]). Design as a mental activity also has been defined by different theorists. Asimow (1962) has defined it as "decision making in the face of uncertainty, with high penalties for error." (Cited in [8]) Gregory (1966) defines design as: "relating product with situation to give satisfaction." On the other hand, Christopher Jones (1970) has gone further and defined design, universally, as: initiating change in man made things (Cited in [8]). According to Gero [11], "design in one sense, can be conceived of as a purposeful, constrained, decision making, exploration and learning activity".

Design involves a sophisticated mental process that according to Lawson [6] enables of "manipulating many kinds of information, blending them all into a coherent set of ideas and finally generating some realization of those ideas". This procedure that commonly begins with a problem, is repeated activities that done between defining of problem and finding different solutions for it.

Zeisel [12] in his discussion related to the link between environment and behavior, presents five characteristics to understand the act of design; The first of these is "elementary activities" that Zeisel classified them as "imaging", "presenting" and "testing". The second characteristic is that design associates with two "types of information" which he defines as "a heuristic catalyst for imaging" and "a body of knowledge for testing". Third is "shifting visions of final product." Designers modify their expectations about the final result to respond to new information gained through the process of design. Fourth is "the domain of acceptable responses," where designers aim to achieve an acceptable solution within varied alternatives. The final characteristic is "producing the end product through linked cycles," where the conceptual shifts and product development in design occur as a result of repeating the elementary activities. So, the design problem solving is a vital and significant action in design process which

requires thinking, imagination and representation of solutions to reach an ultimate design alternative that does not arise in a vacuum.

2.1.1.1 Design Problem-solving

Unlike the problem of other sciences, the purpose of design problem is unclear and it changes in different environments [13], the ultimate goal of design is, finding an appropriate solution to in hand design problem. As Lawson [6], states “Full understanding of the design issue is not possible without any solution that explains it”; according to him design problem mostly defines a very wide area and designer can creates infinite possible solutions for problem in hand. Thus, the "ultimate design solution is vague and very difficult to achieve" [13].

Theoretical work demonstrates that there is an outstanding observation about the characteristics of design problem in architecture, that studding and analyzing of them help to develop solutions.

Goel [14] characterizes design problem solving as involving four development phases: problem structuring, preliminary design, refinement, and detail specification; and notes that each phase differs with respect to the type of information dealt with, the degree of commitment to generated ideas, the level of detail attended to, the number and types of transformations engaged in, and the symbol systems needed to support the different types of information and transformations. He classified design problem to “ill-structured” and “well-structured” problem solving. According to him “well-structured” mental states as being precise, distinct, determinate, and unambiguous; “Ill-structured” mental states, on the other hand are imprecise, ambiguous, fluid, amorphous, indeterminate, vague, etc. and he believes that, preliminary design is a classic case of creative, ill-structured problem solving. It is a phase where alternatives are generated and explored. This generation and exploration of alternatives is facilitated by the abstract nature of information being considered, a low degree of commitment to generated ideas [14].

Rittel and webber [15] have also categorized design problem into two sets: Well-defined and Ill-defined Problems. They explained the nature of ill-defined design problems which they termed “wicked” versus the relatively “tame” problems of

mathematics, chess, or puzzle solving. According to them the Well-defined problems or tame problems, are defined as those problems in which the ends and the goals are already prescribed and identified. And Ill-defined problems or wicked problems are defined as those problems in which the ends and the means of the solution are unknown. According to Goldschmidt [16], ill-defined and ill-structured problems are more complex than well-defined and well-structured ones.

Lawson [6] in order to explain design problem, offers a model for design problem includes: The first is "Design problems cannot be comprehensively stated*"* that means, it cannot be expected to emerge many components of design problems; the second is *"*Design problems require subjective interpretation*"* in this sense design problems, are interpreted as a mental perception. The third characteristic is *"*Design problems tend to be organized hierarchically," that is, there is not objective or rational way of specify the right level on which to tackle the design problems [6].

2.1.2 Architectural Design Studio

Architectural design in its current form has a unique and traditional education method, the 'studio'. The design "studio is a unique setting which, while preparing students to practice the profession of architecture, is also a locus of discourse on, and of, the field of architecture" [17] and is based on that "interaction among students in a group setting facilitates the free flow of ideas" [18].

In the architectural design in terms of learning and teaching, the traditional method of learning by doing, and tackling problems to solve them are embraced in contemporary studio. According to Lawson [6] "Students learn how to design by doing it, rather than by studying or analysing it"; it is concerned not only with learning but also with doing. Physically the studio is "a place where students gather and work under the supervision of their tutors" [6]. One weakness of the traditional studios according to Lawson is, "paying so much attention to the end product rather than the process" [ibid].

The desk crit (critique) is "the basic, most fundamental component of studio instruction in all schools of architecture" [17], where is based on assumption that teachers know how to design and how to respond to particular design problems [8]. According to Kurt [13] in the studio education, the professor initiates a design problem, the student

attempts to respond with a solution, and this are evaluated by the teacher during a desk critic or jury and are offered more suggestions to develop the design project. She has categorized the design studio practice into five groups according to the critic styles and/or given possibilities to the students to be creative and productive. This division is based on the number of students in each group, the number of teachers and how they interact with students, how students sit relative to each other and their position in the studio. According to her, in every crit types of the design studios, generally, "the design process is an educator-centered one" and "there is limited participation and collaboration between students" that these result "a communication problem". According to her educator centered, activities "inhibit students' creativity and prevent them from doing practice freely".

2.1.2.1 Creative Design Studio

A close examination of researches shows that, at the design studio, in terms of creativity, students are able to produce new architectural solutions but not creative ones [19]. In the traditional design studio, the instructor channel his/her knowledge and professional experience to the students; this can prevent the creativity of the students [9].

Kahvecioğlu [9] claims, that, "an architectural design studio should be more than a place of knowledge transfer and acquisition for students and for the studio tutor as a moderator, and should become a medium for improvisation". According to her, the design studio milieu as a creative climate is "an environment not only for defining and transferring the architectural knowledge", but it is also a productive environment, for creating new design knowledge and thoughts. She emphasizes on the role of instructor as key factor and states, "there is a need to help the students to identify where their interests and skills". She believes design education needs to be "in a structure that directs the student-designer towards a multi-dimensional and dynamic process of thinking". She recommends five contextual elements for developing a creative atmosphere in a design studio: *First*, freedom of expression; *Second*, providing an orientation toward learning and creating knowledge; *Third*, available sufficient resources for quality improvement; *Fourth*, engaging in challenging work systems that

can lead to innovative solution; and *finally*, creating a psychologically safe environment.

Sidawi [19] to enhance students' creativity recommends that, instructors should teach students how to look for innovative and potential architecture solutions; not impose their own ideas on students by following solution-based approach.

Finally, Kurt [13] introduces 'Constructivist Design Studio' and recommends that the traditional design studio could be transformed to the Constructivist Design Studio. According to her, constructivist teaching strategies carry with them labels such as "collaborative" learning, "learning communities", "problem-based", "discovery," and "hands-on" learning, that can reduce the existing problems of the design studios. She claims these studios focus on the design process not the end product, and new skills and tools can be developed for learning procedure according to the course contents.

2.1.3 Creativity in Design

Creativity – generating new ideas – is a critical skill in any fields and particularly in the field of design; and it is an important concept for the architecture profession especially at the educational field. Creativity as a cognitive and generative ability can be described and defined in many ways [20]; but, "despite considerable efforts in research on creativity the cognitive aspects of creative processes still appear to be fuzzy and hard to understand" [21].

According to Boden [22] "Creativity is a puzzle, a paradox, some say a mystery. Inventors, scientists, and artists rarely know how their original ideas arise." According to him, a dictionary definition of creation, "to bring into being or form out of nothing ," that, creativity seems to be "not only beyond any scientific understanding , but even impossible" [22]. Similar to him, Dorst & Cross [23] state, "studying creative design is seen as problematic because there can be no guarantee that a creative 'event' will occur during a design process, and because of the difficulty of identifying a solution idea as 'creative'".

Boden [22] distinguishes two creative families: Psychological creativity (*P creative*): a creative idea is apparent to the person in whose mind it arises and historical creativity (*H creativity*): the creative idea is P-creative and no one else has ever had it. Rhodes

[24] considers four attributes inherent to creativity and classified the creative studies from four perspectives: the creative *person* (the person who creates), the *process* (the process of creation), the *press* or *environment* (environment, context, or situation in which the creative act occurs), and the *product* (the product that is a result of the creative process) that known as 4P's.

According to Goel [14] *'Creativity'* is the new ways of looking at existing problems, or of seeing new opportunities. Taura and Nagai [25] maintain that creative design is the function of designers' ability to expand their thought space; Dorst & Cross [23] believe creativity in the design process "is often characterised by the occurrence of a significant event—the so-called 'creative leap'" [23]. According to Cross [26] "the 'creative leap' is not so much a leap across the chasm between analysis and synthesis, as the throwing of a bridge across the chasm between problem and solution".

According to Hokanson [20] must be distinguished between the concepts of "creativity", "innovation" and "intelligence", because, 'innovation', which is similar to creativity, "deals with the novel or new but is more concerned with the adoption and acceptance of new or different ideas". Whereas 'creativity' can be described as "the individual sparks that precede innovation". He claims that 'creativity' is also distinct from 'intelligence'. Intelligence is a raw cognitive ability to remember and know – "the ability to recall and use ideas from learning and experience"; thus creativity is an ability (and an aptitude) to generate the new [20].

2.1.3.1 Aspects and Characteristics of Creative Design

As previously suggested when teaching and studding design creativity, in addition to the final product, the creative process leading up to it should equally be considered, [27]. Indeed, creativity is a process to solve design problems. It seems that to distinguish this process from the non-creative one, there are certainly some characteristics and factors of creativity which can help to study and assessment this process. Salama [8] has pointed out three characteristics which distinguish the creative process: *first*, the creative process is not an ambiguous thing or subject not to be analyzed; rather, it is a subject to be empirically controlled. *Second*, the creative process is a term used to summarize a set of cognitive processes that occur in the human mind: perception, thinking, imaging,

analyzing and synthesizing and *finally*, the creative characteristics are generalized, and are not restricted to particular individuals.

Most definitions of creativity involve novelty and value; in other words, creativity generally include both elements of originality and usefulness [21]. Relation to this, Gero [11] argues that, creativity in design, "is not simply concerned with the introduction of something new into a design, although that appears to be a necessary condition for any process that claims to be labeled creative. Rather, the introduction of 'something new' should lead to a result that is unexpected (as well as being valuable)".

Kan and Gero, and their associates in different researches argue that there is relationship between the productivity of design activities and the creativity. According to them design productivity is positively related to creativity in least significant areas. Goldschmidt and Tatsa [18], also, claim that the most productive process is the most creative ones.

Creativity has two components: divergence and convergence[1]. Divergent thinking "expands, each connection leading outwards to many more". [28] Convergent thinking reduces, requiring connections across the divergent ones; this means an essential part of creativity is generation of new interpretations, that is divergent part. However, in creativity design process, one needs focused on end or outcome of design. That requires convergent thinking [28]. Creativity, also can be identified according to Hokanson [20] "as the ability to generate a wide number of ideas addressing a given problem or stimulus. It implies the ability to develop different types of ideas for any given instance, and also the ability to generate unexpected ideas". These are the three main aspects [20] which are categorized by researchers as fluency, flexibility and originality (Guildford, 1981; TTCT, cited in [8], [20], [29]); and the fourth factor is, *elaboration* (amount of detail in the responses) which were taken from the divergent-thinking factors found in Guilford's (1959) classification (cited in [29]). Then, the measure of flexibility (scored by the variety of categories of relevant responses) was eliminated because it correlated very highly with fluency. Instead of it, two norm-referenced measures of creative potential, "abstractness of titles and resistance to premature closure", were added to fluency, originality, and elaboration; (Hébert et al.,

[1]It will be discussed more extensively later

2002 cited in [29]). Torrance (1976) (cited in Kim [29]) defined *Abstractness of Titles* as "the degree beyond labeling; based on the idea that creativity requires an abstraction of thought", and *Resistance to Premature Closure* as "the degree of psychological openness; based on the belief that creative behavior requires a person to consider a variety of information when processing information".

Also, another feature of creativity, is "brainstorming" [21], that can be considered as an activity which can enhance creativity through the production of large number of ideas and with its social nature it helps creation and communication at the same time [8]. Knight et al [30], too, with introducing Creativity Support System believes that, in the idea generation stage, directed brainstorming "can produce a variety of possible solutions, and the generic creativity enhancement tools encoded in the Creativity Support System are employed to expand and enhance the list of alternatives".

In addition, the published literature relating to cognitive psychology, have recognized a number of creative behaviours; Musta'amala et al [31] have grouped them into seven categories which are "*novelty, appropriateness, motivation, fluency, flexibility, sensitivity, and insightfulness"* as shown in Figure 2.1.

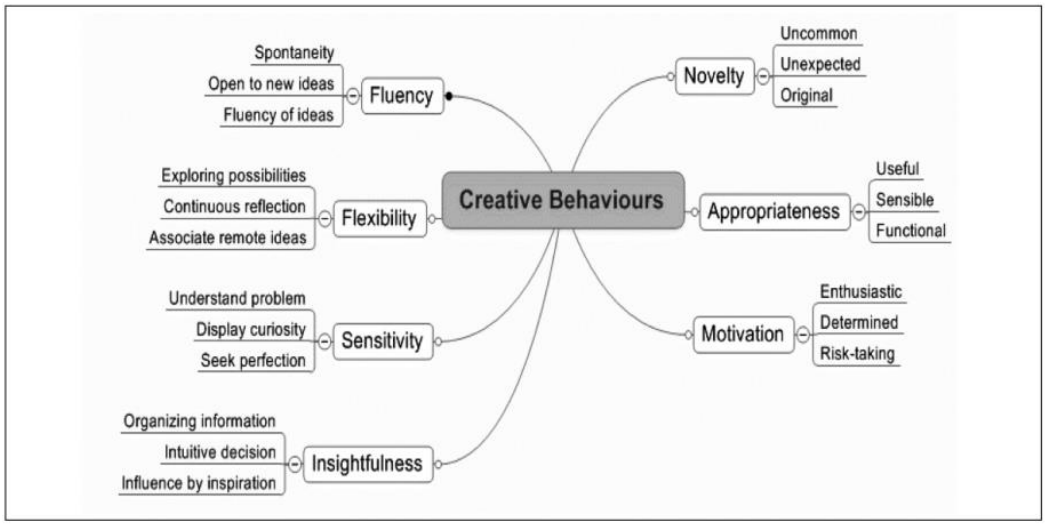


Figure 2.1 Creative behavior model [31]

2.2 Early Stage in Architectural Design Process (Conceptual Stage)

The conceptual stages of design are the most critical phases of design process because in these stages the design ideas are developed. The most original ideas emerge in these

phases, and these ideas, are developed or revised throughout the design process. Conceptual design or early stage of design is different from other stages of design. In this stage, designers can manipulate the design problems to understand the nature of them [33]. Then the alternatives are generated and explored from analyzing the problems. In this stages according to Pranovich [34] "the abstract nature of information .., a low degree of commitment to generated ideas, the roughness of details, and a large number of movements from one idea to a slightly different idea facilitate the generation and exploration of alternatives".

McFadzean [33] classifies architectural conceptual design phase to three stages: "the extraction of information from memory (fact-finding), reasoning and exploration (idea-finding) and the evaluation of attributes and resolution of specific problems (solution-finding and acceptance-finding)". Therefore, the most important action of designer in the early stages of design is, the generation of concepts and solutions to the existing design problem.

2.2.1 Design Thinking and Ideation

2.2.1.1 Idea Generation

Idea generation –that in some resources is called 'concept generation' (e.g. [25]) - is commonly understood as the generation and development of ideas. Idea generation, located in the schematic design phase, typically happens at the onset of the design problem when the designer starts exploring concepts and mentally visualizes potential solutions [35].

According to Taura & Nagai [25] "the very early stage of design, during which an initial idea or specification is generated, is called concept generation." Salama [8] defined idea generation as "a process of seeking creative solutions to problems." Similarly, Knight et al [30] stated that, "The stage of *idea generation* refers to the creation of candidate solutions to the problem at hand." Hamre [36] quoted Jonson (2005), who described an idea as the fundamental element of a thought that is visual, concrete or abstract. Thoughts put on paper and ideas generated, rough and unrefined, lie at the heart of every design solution. Indeed, ideas are thoughts that developed in designer' mind to reason with.

Taura & Nagai [25] classified the process of concept generation into two phases "the problem–driven phase" and "inner sense–driven phase". According to them, the problem–driven phase is the process of generating a new concept (solution) on the basis of the problem; the inner sense–driven phase seems to be related to the essence of the very early stages of design, even though the relation is indirect.

Creativity is closely associated with ideas [18]; and to design creative solutions, designer should generate new ideas. Also as initial ideas are often ambiguous in form and meaning, from their inception on, they are constantly modified and refined. Nevertheless, what are the sources of new ideas?

Taura & Nagai [25] believe that, a new concept is not generated from nothing; and the new concepts are generated by referring the some existing concepts, which lie in a designer's mind or real world. Of course they explain that, "we do not deny that a new concept might be generated suddenly in the designer's mind with no foretokening or basis." Haapasalo [37] believes that, the fundamental ideas generate from the subconscious during the incubation and thinking process of design.

In design process, generating a wide range of alternative solution concepts is another aspect of design behavior. How many alternatives are required to develop of design process?

Fricke [93, 96] (cited in [26]), via protocol study, finds out that both generation of few or large number of alternatives were equally weak strategies and could lead to poor design solutions. Where there is 'unreasonable restriction' of the search space (when only one or a very few alternative concepts are generated), designers become 'fixated' on concrete solutions too early. In the case of 'excessive expansion' of the search space (generating large numbers of alternative solution concepts), designers have to spend time on organizing and managing the set of variants, rather than on careful evaluation and modification of the alternatives. Fricke acknowledges that successful designers have a 'balanced search' for solution alternatives. He also finds out that the problem's precision degree that presented to the designers, influence the generation of alternative solutions. When the problem is precisely specified, designer generates more solution variants; and with an imprecise assignment (for the same design task), designer tends to generate few alternative solutions. In this respect, Lawson [6] states, "the

architect/engineer Santiago Calatrava feels that to explore too many alternatives is a sign of doubt".

Goel [3] analyzed and defined the act of sketching in a problem-solving phase. According to him, designer does not generate several independent alternatives and chooses between them, but generates a single idea and develops it through lateral and vertical transformations. Lawson [6] presents "Parallel lines of thought" concept and believes, "In a process, the designer generates many ideas each of which have at least some possible advantages, rather than focusing on one idea too soon. The process then becomes a matter of eliminating unworkable or unsatisfactory ideas and choosing between the remainder, possibly combining some features." According to him, "the refinement of each alternative is carried out in parallel with that of other ideas without attempting to resolve them too soon." So, according to Cross's [26] conclusion, generating a very wide range of alternatives may not be a good thing and "a relatively limited amount of generation of alternatives" may be the most appropriate strategy.

2.2.2 Design Thinking & Imagination

Design thinking as significant process in early design stage, is a unique process that is related to generate of ideas and design solutions; so design thinking as an issue that should be addressed. "Design thinking is coming from the research of cognitive psychology and cognitive science, trying to understand the behavior and inner thought of the designer" [38]. Lawson [6] as one of the main researchers in design fields finds design as a mental process and believes "…to explore what goes on in designer's mind becomes vital, and this leads into the realm of cognitive psychology, the study of problem solving and creativity, in short 'thought' itself".

2.2.2.1 Creative Thinking

Lawson [6] in his book *How Designers Think* argues that there is a type of thinking that is creative thinking. Creative thinking according to Cross [26], "has tended to be regarded as mysterious, but new explanatory descriptions of creativity in design are beginning to emerge from empirical studies". The foundations of architectural and design education is project-based, or problem-based, learning. It does not seek a single correct answer, but instead according to Williams et al [27] "encourages students to

make speculative and exploratory propositions". This teaching strategy is conducive to creative thinking [27]; that demands answers that lie outside conventional modes of thought. This is importance to support architecture students, throughout their training and learning process to discover solutions and develop their creative thinking [7].

Lawson [6] has identified five stages for creative thinking: First, he describes *the first insight*, which is exemplified by the formulation of the problem. Second, there is *preparation*, which means conscious attempt at solutions. Third, is *incubation*, which is exemplified by thinking without a conscious effort and following by *illumination*, a stage that represents the sudden emergence of the ideas toward the solution; finally, verification stage, which involves the conscious development of the ideas.

2.2.2.2 Convergent and Divergent Thinking

There is evidence that creative thinking involves both divergent and convergent thought that in previous section was mentioned as aspects of creativity. The notions of convergent and divergent thinking have a long history in creativity research. According to Lawson [6], "convergent ability has been associated with ability in science. The divergent task demands an open-ended approach … where there is no clearly correct answer." [6]

In this respect, Lawson [6] addresses, on the one hand, "rational and logical processes" and, on the other hand, "intuitive and imaginative processes".[1] According to him, “These two major categories have become known as convergent and divergent production” (Figure 2.2). With this point of view, the divergent thinking relates to tackle ill-defined problems and so requires producing several answers, in contrast, the convergent thinking relates solving well-defined problems leading to one correct answer [6], [8].

[1]According to Lawson [6], "This kind of simplistic taxonomy is perhaps as misleading as it is apparently helpful. If reasoning and imagining were truly independent categories of thought, one should not be able to speak sensibly of ‘creative problem-solving’ or a ‘logical artistic development’, which are both quite meaningful concepts".

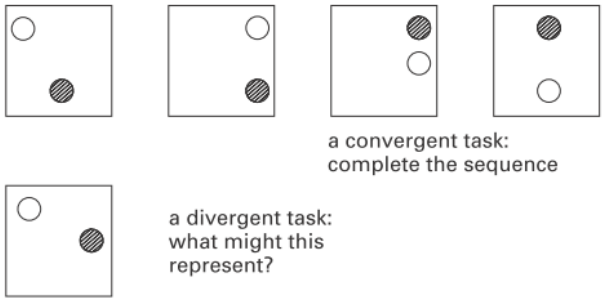


Figure 2.2 Convergent and divergent thinking [6]

According to Guilford (1956, 1959, 1960, and 1986) (Cited in [29]) the creative thinking involves with divergent thinking, which emphasizes on fluency, flexibility, originality, and elaboration. This point of view suggests that, divergent thinking measures the designer's ability to create several alternatives and new ideas for design problem and originality to select unusual ideas.

For a long time, the creativity literature has stressed the role of divergent thinking in creative endeavor. More recently, from the analyzing of design problems, it has been recognized that convergent thinking also has a role in creativity [39]. So, it is wrong to assume that divergence is the creative part of designing and that convergence is the boring and systematic part [6], [16]. There are many stages in any design process which according to Lawson [6] themselves pose convergent tasks some aspects of divergence, such as the "solution space", can be approached rationally and systematically. So the convergent and divergent thinking it seems that occur in cyclic phases within the design process [16], [39]. On the other hand, Cross [40] distinguishes the overall design as being convergent, but maintains that it also contains deliberate divergence to generate of a wide range of new alternatives and ideas (Figure 2.3).

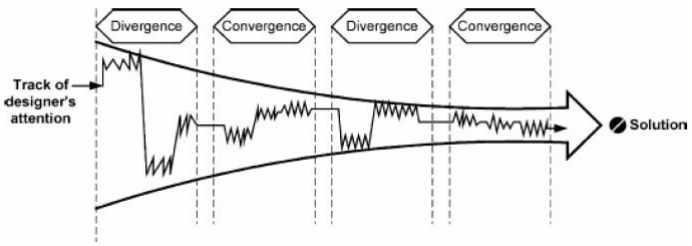


Figure 2.3 The overal design process is convergent, but it includes periods of both convergence and divergence [40]

Therefore, this discussion suggests that, creativity cannot only be seen as the ability for divergent thinking, but as a balance of convergent and divergent thought [6], [8], [16], [39]. Therefore, it involves both convergent and divergent thinking; this means that design process is often moving between convergent and divergent styles of thinking, encourages divergent thinking, as the designer first widens his research for possible solutions, and then uses convergent thinking to evaluate and develop one preferred alternative [8]. As a result, researchers suggest that in assessments of creativity "shifts between divergent and convergent thinking should be the yardstick instead of, or alongside measurements of divergent thinking" [39].

2.2.2.3 Visual Thinking and Imagination

As we know a good design does not begin with a drawing but with an idea, as an image which exists for a moment in the imagination [36]. Imagination is an important tool for design. Indeed, Images develop during the designing and are also reorganised and transformed many times in designers' mind [37]. Imagination is also the designers' ability to imagine the completed building whilst it is still at the design stage. Using imagery alone during conceptual design according to Bilda and Gero [41] can be a design tool "to improve idea development for generating thoughts on the fly without the need to settle them on a drawing sheet". They believe that, "It can support a brainstorming process where one is allowed to generate ideas without worrying about the constraints and the implementation of them".

The issue of imagining will be in reality is "the essence of visual design thinking" [42]. Visual thinking is a basic design tool that enables designers to use imaginary to represent concepts. Goldschmidt [43], states that "imagery is central to visual thinking in all of its manifestations to the study of designing and when first confronting a design task, in pursuit of coherent ideas, imagery is called on to assist in thinking". According to her [44] visual thinking is "the production of thought and ideas via imagery". She [43] also claimed that visual design thinking is "a rational mode of reasoning that gives rise to ideas and helps bring about the creation of form in design".

Indeed, visual thinking is a cyclical process that employed throughout the tasks of design process [42] that, according to Rauhala [45] "constitute our understanding and

enable our thinking. They bring thoughts to mind". They depend on personal experiences, design situation, that better-defined contexts create the clearer images. Actually, the pictures that complemented in designer's mind depend on understanding them [45].

2.2.3 Conceptual Design Tools

As understood from previous discussions that the conceptual design stage has a vital and important place in the architecture design process. During early stages of design, designers engage in various tasks, such as "concept formation, form making, testing functional capacity, and exploring structural and construction possibilities" [4]. The designers move among these tasks utilizing various media during the conceptual phase of design, such as unstructured forms of pictorial representations and models [4], [34], [46].

During the conceptual phase of design, "sketching" is entitled as the common term to cover the drawings, diagrams and pictorial representations [4]. Freehand sketching as an essential design tool has commonly been used in conceptual design stages to create ideas and solutions [1], [3], [47], [48], [49]. The traditional tools that used in freehand sketching are paper and pencil. The strength of the freehand sketching is partly to its economy of means (low cost), immediacy (single tool interface), and ease of its correction and revision. In addition, according to nature of conceptual design stage, sketching has an intellectual side relate to design thinking and imaginary that makes architect to create rough and abstract sketches [50], [51] to make the designer’s early ideas, and explain the design problem.

Design research literature has examined why freehand sketching has been a useful media for designing in the early stages (conceptual phase) of design process. One of the most influential views is that "sketching is a dialogue between the designer and what the drawings suggest" [43]. Some studies proposed that ambiguity is one of the key factors [3] because it allows seeing of new relations in the representations. Sketch also seems to be essential for revising and refining old ideas, generating new concepts and facilitating problem solving process [52].

2.3 Sketching

As previously pointed out, the idea generation process plays a critical role in the early design stages; and freehand sketching is known as a common tool in this stage because enables designers to externalize their thoughts easily. What is sketch and what are its roles within the design process especially in conceptual design thinking?

Sketching is one of the most explored activities in design cognition studies and significant researches have been done to evaluate its importance in the conceptual design process. Sketches have a relatively short history and Goldschmidt [53] detects its origins to "the late 15th century, an age of innovative developments in arts and sciences, supported by inventions and novel technologies". Artistic and design practices used sketching and called it pensieri in contemporary Italian, which meant ‘thoughts’ [4].

Goldschmidt [43] finds the role of sketches that play within the design process. She categorizes the sketching activity into ‘moves’ and ‘arguments’. She summarizes the ‘moves’ in three types as active sketching, reading off a sketch and reasoning without the involvement of sketching, also defines ‘Arguments’ within the moves in two types as ‘seeing as’ and ‘seeing that’. ‘Seeing as’ involves the designer in seeing the figural properties of a sketch, re-interpreting the depictions, and the relations among them, or discovering a new way of seeing them. She concludes that designer makes ‘seeing as’ arguments while sketching, ‘seeing that ‘arguments both while sketching and examining a sketch. According to her, in sketching activities ‘seeing as’ and ‘seeing that’ episodes are linked together in a dialectic process.

Suwa and Tversky [47] also argue that sketching enables designer to see unexpected relations and features that enables refining and revising ideas, they call this process as having a conversation with one’s self. Goldschmidt [53] similarly names sketches as self-generated displays and argues that sketching allows designer to review the whole history of design activities in a given session concurrently. Goel [3] defines freehand sketch to be very loose, not well structured and ambiguous.

Do et al [52] in their study, summarize the role of sketches in design as follows: Generating concept, externalizing and visualizing problem, facilitating problem solving and creative effort, and revising and refining ideas. Cross [48] asserts, the main aspects of sketching including: “Using drawings as a communication tool”, “Thinking and

reasoning aid", "Generating alternative solutions", "Capability to manage various levels of abstraction at the same time", "Storing and retrieving", "Recall of relevant knowledge", and "Problem arrangement".

Suwa et al [54] suggest that sketching serves at least three goals into design process: First, "as an external memory in which to leave ideas for later inspection. Second, as a provider of visual cues for association of functional issues; third, most importantly, a physical setting in which functional thoughts are constructed on the fly in a situated way". Also according to them freehand sketching plays, at least two key roles in design process: One is "*reinterpretation"* by associating depiction with abstract concept, functional issue, or meaning; another is "*unexpected discovery"* by externalizing ideas and inspecting afterwards, to lead a new discovery in unexpected ways. Both "reinterpretations and unexpected discoveries" can be a strong source for exploration of new design alternatives [54].

But, Lawson [55] quotes Herman Hertzberger, who look out from another perspective and believes that, when one sketches her/his ideas on paper, while sketching, her/his pencil and hands are finding something. This according to him is a dangerous way for an architect; he explained "You are influenced by what you are doing... and sometimes inspired by a drawing... but don't let the pencil determine your thoughts" [55].

These researches signify that freehand sketches have an interactive, cyclical and dialectic role in design process by facilitating problem solving, generating ideas and externalizing them. Sketch externalizes thought, forces abstraction, enables exploration of new ideas by revising and refining ideas to discover new relations and unexpected properties from existing sketches [3], [28], [34], [43], [44], [46], [47], [52], [56], [57].

Gharib [50], [58] quotes Ferguson (1994) who differs three kinds of sketches: "(1) the thinking sketch, (2) the perspective sketch, and (3) the talking sketch". Compared to drawing that designer make in the subsequent phase of the design process such as orthographic drawing, sketch remains fuzzy and imprecise, a feature that makes it essential in generating of ideas [59]. So, sketches take many forms, first more abstract then turning it into a feasible design idea. As the design process progresses, sketches become more structured giving more information about the project [56]. This thesis

concentrates on abstract sketch or according to Ferguson thinking sketch as it is fuzzy and imprecise that designer uses it in idea generation process.

2.3.1 Sketch as External Representation Tool

Experiments show that people cannot remember all design information and reason about design alternatives without using representations [49]. Design representations are external or internal [4]. In order to understand the role of representations in the conceptual stages, both external and internal are important to study.

External and internal representations are interpreted as sketching and mental imagery in the design field [4]. Internal representation according to Goldschmidt [60] is the mental image or 'the essence of cognition and imagery'. External representation could be physical representation including drawing which could be two dimensional or three dimensional depiction, diagram, graph, notation and can be 'visual and verbal' [60]. External representation also reflects the internal representation and they are not identical [53]. According to Goldschmidt [43], [61] there is cyclical loop between these two types of representations.

While the design ideas are emerging during conceptual design process, the abstraction and imprecision are important, [35], therefore external representation requires to be fluid, abstract, ambiguous and imprecise [3]. According to Suwa and Tversky [47] external representation, not only aids the design memory, but also facilitates inference, solving and understanding of problem. Goldschmidt [43], [44] and Goel [3] address sketching as external representation that allows reflective conversation to provide a rich source of new ideas for design ideation.

2.3.2 Sketch as Design Thinking Tool

It is intuitively reasonable that sketching is a valuable thinking tool that helps design thinking (internal representation). Without drawing (external representation), designers explore and resolve their thoughts with difficulty; according to Cross [48] drawing is more than an aid to memory; "it enables and promotes the kinds of thinking that are relevant to the particular cognitive tasks of design thinking" [48]. According to Pallasmaa [62] every act of sketching and drawing generates three different images:

"the drawing that appears on the paper, the visual image recorded in my cerebral memory, and a muscular memory of the act of drawing itself".

Won's [2] study on the relationship between drawings and visual thinking indicates that the production of a drawing is the quickest and most effective means to visualize the thought processes of designers. Designer uses drawing to transfer imagined visual information on paper [28], [43], [53], and as the ideas have a quick flow, the designers use sketching to record his/her thoughts quickly for more explorations [28].

Gharib's [50], [58] studies also show sketching process has two activities: "mental activities and technical activities. The mental activities contain cognitive and imagination activities, while technical activities are related to sketching behavior, tools, and graphical representation" (as shown in Figure 2.4). According to him, sketching as a mental activity, is related to some key terms such as "thinking, imagining, visual thinking, and visual imagination" [50], [58].

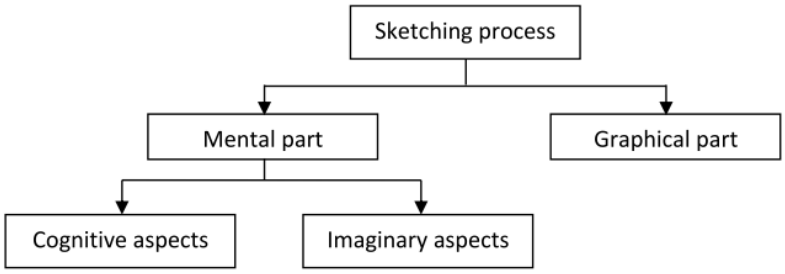


Figure 2.4 The sketching process parts [50]

The figure shows that, the mental side of sketching is related and integrated wit process between "thinking and imaginary". According to Gharib's [50], "This integration happened when the designer gets a feedback from the sketch, and begins to think about relations and constraints, and then starts to imagine solutions of transformations to develop the concept. This cycle of thinking-imagining-drawing is connected to the graphical side of sketching". In fact, the sketch feeds the debate between the "thinking" and "visualization of ideas", mainly through its characteristics of abstraction, vagueness and ambiguity. Therefore the recent researches have focus on both concepts of sketching and imagery hand in hand and consider free-hand sketch as a primary medium for design thinking and ideation, and a fundamental process of design and inseparable from the thinking process [4], [62].

2.4 The Relationship between Ambiguity in Sketching and Creativity

Designing an activity of solving ill-structured and highly complicated problems, is different from classical problem solving, thus, requires creativity. Sketching as a rough and quickly made drawing plays a vital role in early stage of designing and serves as a thinking tool for designers [63] and facilitates problem solving and creative effort [57]. So, there is certainly a strong relation between sketching as a tool and design creativity.

Outcomes of sketch studies showed that ambiguity is one of sketching aspects that gives it specific characteristics. Therefore, here we highlight ambiguity and its role in how new design ideas are generated via sketching. All of researchers who discovered and defined the act of sketching believe that the ambiguity of the sketch associates with reinterpretation that enables exploring of new design ideas. They believe that because sketches are ambiguous, they support many interpretations [3], [43], [44], [47], [53], [63]. The lines drawn by freehand sketches are uncertainty, so can be interpreted in differently and it inspires the designers with new solutions [50], and this can lead and enhance creativity [58]. Thus, designers use sketches by not just to express ideas but also to generate new ones. Designer from reexamining old sketches, may get new insights, see new relations, and make new inferences and new meanings that lead to the discovery of new ideas. These unintended discoveries advance the design [63] and prevent the early fixations of ideas [3], [53]; as Goel points out, ambiguity and uncertainty is important because designers do not like to crystallize thoughts and freeze developing of design too early. This supports the *Resistance to Premature Closure* factor, which is the degree of creativity measurement that previously pointed out. Goldschmidt [43] calls this reinterpretation process a "seeing-as" activity, while Goel [3] calls it "lateral transformation".

Lateral and Vertical Transformation: Goel [3] identified two types of operation that occur between consecutive sketching at the conceptual design stage, named: lateral and vertical transformation. (shown in Figure 2.5)

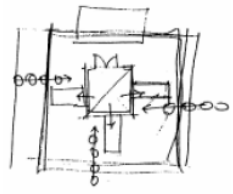
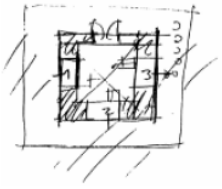
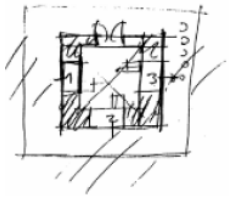
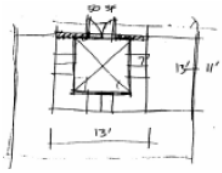
Lateral (divergent)	 **Figure A**	 **Figure B**
Vertical (convergent)	 **Figure B**	 **Figure C**

Figure 2.5 Examples of lateral and vertical transformations [3]

Goel [3] defined lateral transformations as transformation where "movement is from one idea to a slightly different idea rather than a more detailed version of the same idea", and vertical transformations as transformation where "movement is from one idea to a more detailed version of the same idea" [3]. Lateral transformations according to Goel are associated with unstructured, ambiguous drawings that happen in the initially design stages while vertical transformations are associated with more detailed and unambiguous sketching that generally occur during the detailed design stages.

Goel studies the ambiguity in terms of reinterpretation, which occurred during the design protocol, subjects interpret their earlier drawings, and it is the aspect of sketching which allows lateral transformation to occur. Goel claims that, because freehand sketching in the preliminary design process is "dense" and "ambiguous", it facilitates exploring of different ideas and creative shifts to new alternatives. Also, he [14] states, using of ill-structured (ambiguous) representation for ill-structured problem instead of well-defined ones in the early stages of design, develop significantly more “lateral transformations” to guide achieving more creative solutions. Therefore, with referencing to researches, ambiguity plays an interesting dual role in reinterpretation: the more ambiguous sketch, it is easier to reinterpret and the ability to enable different interpretations and meanings to one sketching is a proof of ambiguity.

Also, Purcell and Gero [56] suggest that ambiguous and unstructured sketching be considered pivotal element to affect design creativity. On the other hand, by considering

the ability of sketching to find as many as different alternatives to design problem, can state that, this is the characteristic of divergent thinking as the most important indication of creative thinking; this indicates too, the strong relationship between creativity and sketches. in addition, according to Guilford's concept of "divergent thinking" in order to evaluate creativity; namely fluency, flexibility, originality and elaboration can argue that, sketching is an effort to create different alternatives by interpreting the old ideas and become flexible about changing them to find an original idea instead of using conventional one and elaborate it.

Thus, sketches by their rough and ambiguity features that allow many interpretations, associate and support many characteristic of creativity. This is a proof of being a significant relationship between sketch and creativity.

CHAPTER 3

DIGITAL_BASED SKETCHING

3.1 Introduction

With the revolution of computer technology, more software are developed, which have been utilized in many ways including "drafting, design, simulation, analysis, and manufacturing" [31] to "visualize in three dimensions and to simulate aspects of performance and the coordination and control of production information" [64].

A brief look at history of computer in architecture indicates, by 1963, Ivan Sutherland's sketch pad system and then by the early 1970s, computer aided architectural design systems were beginning to transpire architectural design. But these were limited to support design process. Digital information processing capability was characterized after 1980s. Computational methods and tools associated with artificial intelligence. At about the same time, computer graphics provide designers visualization techniques as a rich tool kit from drafting to rendering, presenting systems. Powerful personal computers turned into wireless laptops in the late of twentieth century [7]. Nowadays, the digital technology began to affect the thought processes of the designer; therefore, digital media have enabled designer to move from drafting and visualisation to the optimisation and generation of ideas and opened up new horizon for the architectural designing [7]. With the advent of current digital sketching systems, there is a thought that it can be used in early design stage as well as detailed design stages [50], [58]; but, existing digital systems do not still support the early stages of conceptual design process thoroughly.

When computers are not commonly used in conceptual design phase, many architects use pen and paper and model making to express their designs and presentations; while in architecture schools, many, if not most, architectural students start their earliest design experiences quite naturally by using the computer [30]. However, today due to the low willingness of professors to use this technology, programs fully based on digital technology are not available in training.

Therefore the purposes of this chapter are study the status of digital sketching in the early design stages and their current challenges in the educational field especially regarding creativity and why digital sketching are not yet commonly used in the conceptual design of architectural education. Also by studying and investigating current digital sketching tools attempts to find out recommendations for developing digital interface to support sketch and creative design process. So, this chapter consists of three main sections. The first section outlines current discussions about the digital technology in the early stages of design and especially regarding creativity. The second section describes and reviews the digital sketching tools especially pen based systems and their possibilities, and in the third section, a pilot study is conducted to show the current situation of digital sketching in architectural schools in real world.

3.1.1 Literature Background

Thinking in sketching digitization started decades ago with SketchPad presented by Sutherland. From this date, a body of work was presented to enhance this direction of research [58]. According to background of the research issue, the literature can be consisted several study areas from different points of view.

Some researches (e.g Knight et al [30], Rauhala [45], Dokonal & Knight [65], Verstijnen et al [66]) review and explore the role that computers can play in the conceptual design stage and sketching process. Some studies (Musta'amala et al [31], Hamre [36], Lawson [55], & [64], Verstijnen et al [66], Haapasalo [67]) also attempt to provide empirical evidence on the potential links between CAAD and creativity in design process. They focus on searching and discovery of sketching behaviors and opportunities to support creative designing by using digital technology.

Other researches (such as Hamre [36], Gross & Do [68] & [69], Do [70], Lim [71] & [72], Vries & Achten [73]) describe current digital sketching programs -sketch-based and pen-based interface- to explore essential elements of sketching and focusing on their support for problem solving and creative designing. Some researchers study the sketching process from different approaches to collect information and knowledge that can help in designing process of the digital systems, (such as Pranovich [34], Gharib [50], Aliakseyeu [51], Gharib [58]), that aim to develop a sketching environment to feel as natural as sketching on paper to improve and enhance idea generation process. Also, some researches attempt to present a sketch-based modeling to convert of 2D freehand sketches to 3D models rather than enhance creativity in sketching process [34], [58].

3.2 Current Discussions on Digital Sketching in Architecture Education

According to available literature, the research is studied and classified as following sections that attempts to discuss on using digital sketching in the early stages of architectural design in education field and on using of digital sketching regarding creativity

3.2.1 Digital Sketching in the Conceptual Design

While digital media has begun to be engaged in design education, the using of both traditional and digital tools has been the subject of debate among design professors and researchers [1]; some of them, argue that the digital tools should replace traditional ones, while others believe that traditional tools such as freehand sketching should remain in architecture education. In recent years, the professors have been confronted with the polemics of traditional versus digital media or hand versus computer. This has always created challenges to students in choosing a specific tool for their designs, based on their proficiency in either medium. It seems that, the conservatism and anxiety of instructors toward using digital tools in teaching is natural because, the senior instructors have not ‘grown up’ with computers which makes them have unfavorable attitudes toward computers. Also, the staff and students may have different perceptions about computers.

Dorta [35] states, the problem here is that in the architectural schools, "ideation is still done as it has been since the Renaissance, by traditional analog manual tools, like sketches and physical models, without real support from current digital tools." Lawson [64] remarks that, there are evidences that influence of CAD in design education is resulting in good design skills being supplanted by good computer skills; he argues that, "it has always been possible to find excellent presentation combined with poor design. However, before the advent of CAD, it seldom happened in practice" [ibid]. Daru [74] posed four criteria for assessing computer based sketching as: "1) *is computer sketching didactically correct*? The ultimate goal is to learn designing rather than producing the nice or pleasing pictures…; 2) *is it useful*? The answer is positive if it gives additional possibilities for the idea production in designing or if it shortens the learning time of design sketching…; 3) *is it sufficient?* Can hand sketching he replaced by computer sketching entirely?.. 4) *is it harmful?* Are such exercises detrimental to traditional sketching experience?" Answer to each of them will open new contexts to discussion; each of them can be a research questions that leads to solve a part of digital sketching' problems in educational field.

Recent developments in CAAD software shows a shift in focus towards conceptual design interfaces**;** but, according to some researchers, these tools have not developed and still fail to offer an appropriate design oriented environment for design ideation [30], [32], thus, designers abstained from using digital systems to design thinking and still sketch using pencil on paper [50], [58]. As discussed by Bilda & Demirkan [1], the digital design software are not adequate for the ideation design stages, as they lack support for designers' process such as "doodling and sketching activities".

It seems that, the lack of using computers in the early stage of design process comes back to its inefficiency in enhancing creativity of students as an ultimate goal of design training.

3.2.2 Digital Sketching and Creativity

As outlined at the previous sections, the ultimate goal of the conceptual design stages is to investigate and explore different ideas for design problem. This task requires thinking and imagination, which lead to creative design; also noted, current digital media

systems apply well in the later stages of the design, while their applicability in the conceptual stages is poor. Additional to previous statements, most researchers believe that using of computers in the early design srage may impede the creative behaviors. According to them, if designers start to use CAAD from the beginning it can limit their creativity and 'can encourage poor design' [55]. Some researchers acknowledge that despite the using of digital media for the manipulating and editing of drawings in detailed stages and creating realistic images, traditional pen and paper sketching is still preferred for ideation and creative designing.

Lawson [64] states that, "the problem is that if the computer uses the wrong metaphor for describing design features, it can inhibit the creative integration that design requires in order to be what Hertzberger calls "real" as opposed to "fake" creativity." Verstijnen et al [66] examined 'combining' and 'restructuring' in freehand sketching as components of creative process, and evaluated these components on 3D digital programs. Neither of them supported well in current digital programs and they concluded that digital tools are not helpful for sketching in the idea generation and creative design process. Rauhala [45] believes "it seems impossible to use computers as a creative adviser or as a generator of totally new design solutions. Likewise using computers for generating new and creative associations seems to be in principle infeasible; because our creative imagination has something to do with discovering completely new metaphorical connections". Dokonal & Knight [65] claims 'that is not true anymore', and say that modern CAAD software is at least an additional possibility to start a design with clearly new benefits and still some disadvantages. According to Bilda [4] digital systems lack the cognitive aspects of architectural design, thus, trying to use computers creatively seems to be impossible [45]. Indeed, the mechanical nature of digital techniques and structured CAAD environment [68] have constrained their application during the early stages of design.

Computer-user interaction: According to researchers, the interaction between designers and computer is not sufficiently intuitive and natural, and it prevents the designers to focus and concentrate on the creative process. Gharib [50] and Dorta & Pérez [75] expressed that, the user interface based on commands, messages, menus, mouse, and keyboard is still hindering the creative flow in ideation and thinking process. Lawson [6] called these tools Computer Aided Drafting rather than design

tools, and he [64] explains that, the CAD software with a high resolution in representing distract the designers' attention from whole to detail and limit their ability to see and interpret things in new ways. On the other words, the use of digital systems does not match the development speed of thought and idea while in "traditional sketching, the pen is a natural extension of the hand, [so] … using the computer shift the attention away from the actual design process" [67]. In these statements, the lake of appropriate interaction between designer and computer as a design medium have been explained from different point of view, that seems nowadays with the emergence of pen based systems, part of these problems can be overcome. Although the skills and abilities of computer users in using programs, is the other reason that can provide a great interaction between designer and computer as a design media. In this respect, Lawson [55] states, "Computer might be useful prop for the average designer but hinder the better ones". This means a technology cannot be same for everybody; there are some people who find it difficult with digital system, but to some it is an enhancement to their skill to create something much more capable and creative.

Computer interface: Computers according to current sketching systems and accuracy are often non-dense and unambiguous and do not allow abstractions and uncertainty, that may hinder transformations, which play an important role in the early stages of design process [5], [21], [33], [75]. Daru [74] states that, "computers are not offering an adequate environment for design sketching". According to Dorta & Pérez [75], digital system encourages working with precision and details while allowing little room for vagueness, because computer interface (software and hardware) always demands specific abstract and accurate data; and discourages the designers to modify their ideas resulting in premature fixation due to its inflexibility that limits creativity.

Pranovich [34] believes that "in the early stages of design computers manifest their inability: they are inflexible, unimaginative, and tedious; and they support focuses on quantitative rather than qualitative support". According to Lawson [64], computers "are poor at recognition, interpretation and the reconciliation of conflicting demands". Indeed, the mechanical nature of digital techniques and structured CAAD environment have constrained their application during the early stages of design; and Haapasalo [67] claims, that, "it is very difficult to find mathematical algorithms, which can imitate or increase creativity".

These discussions show that a great part of the problem is relate to design appropriate computer interface systems to support the sketching activity and later the creativity. The interdisciplinary researches between architecture, mathematics and computer science can create proper solutions in this respect. For this reason, with advancing in new digital technology, there is evidence that CAAD start to be effective in conceptual design and sketching process related to creativity. Some researches have been conducted to explore it. Rauhala [45] believes, there is no evidence that the computer would thoroughly be useless in sketching process. According to him "they are not helpful in creativity itself, they can be indispensable in technically validating new ideas". The analysis and findings of Musta'amal et al's [31] studies, suggest "link between the emergence of creative behaviors and the use of CAD in designing"; and according to them it might potentially encourage creativity in designing.

In addition, the suggestions of different researchers indicate, digital media have elevated the mental ability of the designer to visualize and evaluate abstract ideas as a facilitator of design ideas but is not a creator of the content. Lawson [64] investigates three cases, one each from education, practice and research and tries to understand using of CAD in architecture where actually enhance creativity or not. Mohd et al [76] in their study indicate that digital technology in the design process can helps students to produce creative architectural design and help them in stimulating creative ideas during the sketching process, because it enables designers to rethink and revise previous ideas and to develope their designs.

The computer programs according to its nature and algorithm systems utilize and get help of different drawing orders; so can provide a context to manipulate and play with the old drawings, create new drawings and reach to different solutions. This reinterpretation of ideas can lead to creative thinking process. Haapasalo [67] believes that, the computer does not, by itself, influence creativity much; but "it has an impact on creative work.… with the computer, artists, designers may easily play with hundreds of solutions or variations. Thereby computers may have a supportive impact on creativity". According to him, the computer can be considered as a machine to achieve a greater ability to think.

3.2.3 Recommendations for Digital Interface for Supporting Sketch

Researches which attempt to find knowledge for designing sketch-based user interface, offer recommendations for supporting digital sketching tools in conceptual design. In order to better integrate the computer tools into the conceptual design process, Gross and Do [68] suggest that, “digital support for creative design in architecture should include retrieval of visual references with similar forms. This aims to support three aspects of creativity: combining ideas from different sources, using visual metaphor and analogy, and expanding the search space to include innovative solutions”. Lawson [55], [64] states two conditions; *First*, “the computer program must offer new possibilities, rather than simply aping existing ones”. *Second*, “the program must be in the hands of an artist who can be creative in the medium”. One possibility in developing digital user interface is movement in a flexible way and close to the natural and traditional sketching process [67] that provides benefits more than paper facilities, such as the ability to simulate the system to support creative design work.

To design an interface that feels natural to sketches, the system must be able to resolve ambiguities without interrupting the user [69]. In this way, the designers must be able to sketch, write, model or search for new ideas over the editing of existing drawings, in an easy, intuitive way in order to enable them to focus on the design problem solving and not on how to use the program [66]. So a digital sketching tool according to Do [77] “should recognize static drawing marks, such as simple geometric shapes, and their spatial relationships”; according to him**,** for building useful digital sketching tools for designing, one "must identify the dimensions of sketching. This includes identifying drawing components and design entities and the spatial relationships and transformations among them".

The familiarity of users with digital sketching programs and their ability to benefit of possibilities that digital media provides to design as Lawson [64] state, is a key aspect and reason that can determine the interest of users (instructors or students) to use digital sketching. This issue is explored in pilot study.

Therefore, in order to extensively enable users to generate more stimuli for their designs in the early design phases, computer-aided conceptual design (CACD) was gradually explored and developed [2], [5], [38], [71]. The disadvantages of the current situation of

CACD, which mimics free-hand sketching behaviors, show that "few digital tools exist to address the early phase of the conceptual design, where fuzzy customer requirements are mapped to function specification and ideas are developed" [5]. According to Tang & Gero [5], "a dense and ambiguous representation for CACD is still difficult". Some researchers such as Abdelhameed [42]**,** Norman [78] also believe architecture education courses require a transition from an analogue representation system to complete digital media, that Norman [78] calls it "paperless studio". According to them digital design tools should be primarily applied at the conceptual design stages and at early level of design education in order to enable the students to comprehend the use of computers as design medium instead of a tool solely for drafting.

3.3 Digital Sketching Tools

As previously outlined, sketching is generally associated with conceptual design and there are ongoing efforts to find out how computers may help in the conceptual design phases and sketching process [4]; therefore, researchers directed into developing "sketch-based interfaces for modeling (SBIM)" [50], [79].

The idea of sketch-based modeling is not new. It dates back to Sutherland's sketchpad system. In this system, the user produces 2D drawing by sketching directly on a computer display device using a light-pen. The sketchpad system can interpret the hand-drawing into straight lines and circle's arc [50], [58], [79]. In the last decade, there has been an emerging of both sketch-based interfaces and pen-based computing devices [79]. Each generation of sketch-based interfaces can be traced to different hardware devices that shaped their inception and evolution: the light pen, the digitizing tablet and stylus combination, later the mouse, more recently tablet PCs and PDAs and multi touch surfaces as well as pen based PC software [ibid]. According to Jorge & Samavati [79], "Areas within SBIM included sketch-based interfaces, where the goal was to easily create 3D models, and sketch-based interfaces, where the goal was to develop systems for recognizing, for example, hand-writing, command gestures, 2D diagrams, and mathematics"**.**

Generally, it seems that the digital sketching is different as a process with the freehand sketching, but they have a common aim, which is "to make representations that are for

conceiving and communicating in the conceptual design" [4] and many of them "take sketchy, rough drawings as input and convert them into straightened objects or clean curves" [77]. The development of early design tools has relied heavily on sketching input [80]; Do [70] divided the available interfaces for the sketching input in three categories: First, the regular drawing board, paper like interface that allows designers to sketch onto a digitizing tablet using a pen stylus. The second type of interaction allows bringing in a picture underlay (raster image) and multiple translucent layers on top and finally the transparent window maintains the drawing functionality of the previous two types of interface (paper, trace layer). Generally these tools mimic the traditional architectural environment, simplify interaction with the system and support various design aspects [34].

Generally, Sketching support tools[1] can be divided into two key classes: 2D sketching interfaces, for example tools like Cocktail Napkin [69] and Autodesk SketchBook Pro; and 3D sketching interfaces, such as tools like DDDoolz [73], and SketchUp. All of them according to Pranovich [34] aim "to improve the interaction with a design system such that this becomes more easy, intuitive, and natural for architects and approaches sketching". Actually 2D sketching interfaces imitate the pen and paper features. They have some disadvantages such as: these interfaces "use many menus and buttons in the same way as CAD systems use which make designers concentrate on the process rather than the idea", also, they enable designers to create impressive sketches for presentation but "not suitable for idea generation with all ambiguity embedded in the process" [50]. Therefore, Gharib [50], [58] believes that, it is essential to develop an appropriate 2D sketching interfaces that use freehand sketching in the same way of pencil and paper.

3.3.1 Pen Based Sketching Systems

As previously cited, the most of designers still rely on the traditional media– freehand sketching. Since the mouse-based computer software are unable in supporting the actions of sketching during preliminary design stage, many researchers (such as Hamre [36], Gross & Do [69], Lim, [71], [72]) attempted to research and develop of pen-based

[1]For more study about some of these tools see [34], [51]

systems. In 2D pen-based systems, instead of sketching and designing with a pencil on a paper, designer sketches with a pen on a touch screen. The difference between them is only the design environment.

These sketching systems attempt to make an experience similar to drawing with pen on paper and simulate the characteristics of it. These applications are implemented on a for example tablet PC with a pen input device, with pen-based interfaces that mimic pencil and paper sketching, by supporting of the computer to enhance and augment the process [69], [71], [72], [77], [81].

The pen-based systems have improved CAD interface to enable designers to “draw” and “diagram” directly onto the computer and complete the whole process of design in digital environment [72] by using a pen. The stroke of the stylus on the screen can create straight and curved lines in both two- and three-dimensions allowing full immersion in the creative thinking and projective process [36], [81].

Since, the emergence of stylus driven “touch-screen” PC tablet hardware, coupled with freehand sketch software; so, the purpose of this system according to Lim [71] is "to provide the CACD system with conveniences and functions like fast expressions of images in designers’ brains, ambiguity, resolution, gesture, and notions". Certainly, the additional of this new technological tool does not threaten traditional drawing; and can help designer to think while designing in the conceptual design stage.

The first tablet PC can be traced back to the 1960’s; GRIDPad in 1980’s and in 1990’s ThinkPad tablets are introduced. In 2001, Bill Gates introduced the world to the Windows XP Tablet Edition that included a touch screen and compatibility with the desktop computer. The unveiling of the Apple iPad in early 2010, provided the world with a device that bridged the laptop computer with the smartphone providing ultimate user mobility and flexibility. Today, the digital tablet has the stylus meant to substitute the pen and screen in lieu of a piece of paper [36].

Nevertheless, what are the advantages of using pen-based device to support designing when they merely emulate freehand sketching tool?

The major benefit of such tools in comparison with pen and paper is the facilitation of the transition from the early stage to more definitive stages of design [34]. Also, the use

of sketching using digital technology as it tends to reduce barriers to creative thinking because it does not rely on activating commands, like on a computer. The paperless environment a digital tablet creates increases flexibility for the user to generate ideas [36]; in addition, in her [36] experiment, all participants felt the digital tablet has immense potential for use in the design process to continue to enhance idea generation. So these electronic sketching devices, which, like traditional sketching, support indeterminate input can be more appropriate tools for creating of ideas [66]. However, according to Lim [71], "due to the cognitive behaviors displayed when using pen-based system and when using conventional pen and paper are different".

3.3.2 Three-Dimensional Digital Modeling

One of the features and facilities that digital tools have provided to design, especially in the early conceptual design stage, is three-dimensional modeling.

The findings of some researches show the significant of integration three-dimensional modeling to early stage of architectural design for producing unique design solutions. In this case, visual design thinking is performed through three-dimensional digital models that according to Abdelhameed [42] might be described as “sketching in space”. According to Haapasalo [67], "3D modeling, from the design point of view is aimed usually at the early phases of design in order to examine and visualize details or larger entities". Using easy to handle 3D modeling software helps to find appropriate design solutions.

3D modeling sometimes allows the students to understand their own design better and definitely increases their design abilities in a rather short time [81], and "has a good visual impact and gives freedom to the architect to think about objects, space and form on the same screen" [76]. But today there may be problems with three dimensions digital modeling, because, digital modeling introduces new possibilities that allow manipulation of forms, with fewer cognitive role. This is why 3D digital models are considered as a threat in design; and according to Lawson [64], in CAD environment, students enable to generate three-dimensional forms easily compared to manual and traditional media. Perhaps this encourages them that suppose and believe that what they have drawn is creative.

3.3.3 Samples of Sketch Based Systems and Modeling

Electronic Cocktail Napkin: is a pen-based, freehand drawing environment for design. Its goal is "to support the kind of informal drawings that designers do during conceptual design" [51] (Figure 3.1). A disadvantage of the Napkin according to Aliakseyeu [51] is that the display and drawing surface do not coincide, which can introduce eye-to-hand coordination problems. The major advantages of the tool are the principles of working with layers and the non-generic recognition system [51], [68], which allows "selecting and copying of diagram sketches between different layers" [70]. It supports "abstraction through end user programming of graphical rewrite rules" and "ambiguity by carrying alternative interpretations", and supports "imprecision with constraint based interactive behavior" [69].

Figure 3.1 Electronic Cocktail Napkin environment

DDDoolz: DDDoolz is a 3D drawing tool with modular masses. This tool enables designer to create directly objects in "a 3D environment without system interference" [51] in the early conceptual design process. By using DDDoolz the user "can create 3D objects composed of small boxes" [34] that serve as drawing unit for the geometric model (Figure 3.2). Currently, a standard PC interface (mouse, keyboard and monitor) is used for controlling DDDoolz [51]. The main advantage of DDDoolz is the possibility to create 3D models directly and quickly [34], [51].

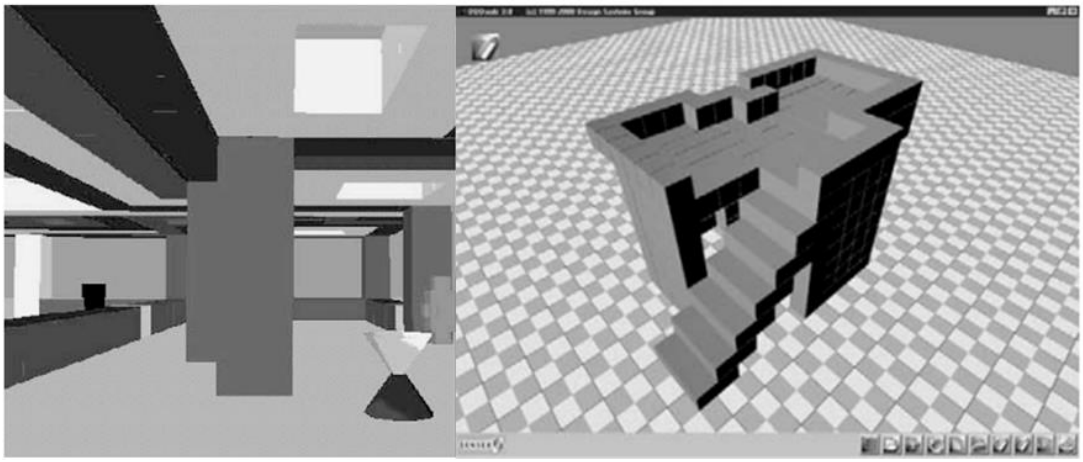


Figure 3.2 3D sketchs are created using DDDoolz [73]

SketchUp: This software is used during the conceptual phases of design and supports the mind to generate ideas freely, and it focus on rough models instead of solid modeling. It enables the designer to sketch directly in 3D on the computer, without the need for any reference drawings [36]. It has much more in common with model-making than working with sketches [65], [81]. According to Dokonal & Knight [65] the name of the software should be “Modelup” because it is much more about working with models than working with sketches.

Teddy: One of the more influential sketch-based systems is Teddy, which was presented as a simple method to create freeform [58], [79]. In this system the user can draw "several 2D freeform strokes interactively on the screen and the system automatically constructs plausible 3D polygonal surfaces" [34].

EsQUIsE: The EsQUIsE is a freehand design environment for freehand sketching to support conceptual design of architecture. It captures and interprets in real time digital drawings. The architect draws with an electronic pen on a digital layout (Figure 3.3) [82]. Suitable tools and functions for sketching (colors selection, digital eraser, sketch transformations, rooms labeling) are displayed in a menu at the left of the tracing surface. EsQUIsE can be used either on a virtual desk or on a Cintiq graphics tablet (see Figure 3.4) [ibid].

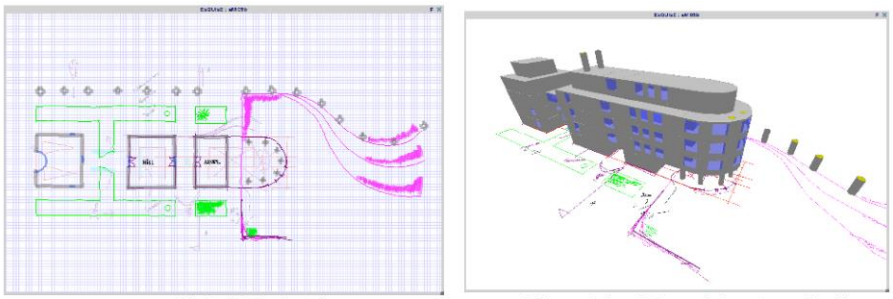


Figure 3.3 An overview is drawn on a digital layout with an electronic pen. The architect can then select those of the layout which are relevant to him and ask for an automatic generation of the 3D view (at the right) [82]

Figure 3.4 EsQUIsE is used on a graphic tablet [82]

SKETCHPAD+: Allows drawing on the surface of a large design table that is both a pen based digitizer and computer display. These freehand strokes, drawn directly onto the computer display, are projected into the application's virtual space to become the primary elements of a sketch model – a 3D drawing [51]. The pen-based digital table resembles the traditional design environment and it uses freehand sketching as a way to create 3D objects [70].

SKETCH: developed by Zeleznik et al [83]. SKETCH used a gestural interface and inferencing mechanisms to create 3D objects out of standard 3D geometric primitives such as cuboids, cylinders, and cones for conceptual 3D modeling [79], that inspired by combining some features of pencil-and-paper and some features of CAD systems [58], [58]; sketching three axial arrow lines will generate a box with corresponding dimensions [70].

3.4 Pilot Study (Current Role of Digital Tools in Early Design Stage; Evaluation of Architectural Schools)

A pilot study is usually conducted to investigate the initial situation of research problem in hand and executed as planned for the future studies but on a smaller scale; so, as a preliminary study, the results cannot be generalized to the whole. The previous discussions and reviewed literature in research area create an interest about the current situation of using digital sketching in architecture schools and educational field. This study in this section, aims to assess and understand how digital sketching tools are used in the early stages of design in architecture schools, as well as kinds of programs and software in real world. Therefore, according to purpose of this section a pilot study was done to obtain the architecture instructors' opinions about research problem.

3.4.1 Methodology of Survey

This survey conducted via online questionnaire that was sent to architecture instructors' emails. The research populations of this survey are the architecture instructors who had research in this field and samples were randomly selected from different university from worldwide. Their email addresses were obtained from their researches.

3.4.2 Findings of Survey

In totally from 180 questionnaires that were sent, only 63 people responded it. The 36 percent of respondents were from universities in Turkey and 64 percent from other countries such as Australia, Brazil, Canada, Belgium, Malaysia, Latvia, Cyprus, Bahrain, and Nigeria. The gender of instructors who responded to questioner were 71.40 percent Male and 28.60 percent Female; Their educational and research areas were generally stated in architectural design and education, design theory, digital and computational design, virtual design Studios, BIM, conceptual designing and ets. They mostly teach to junior, senior and graduate students and few of them have courses to freshman and sophomore students.

The questionnaire, in addition to the general questions, consisted of three sections: in the *first* section, instructors were told to answer about their and their students designing tool(s) by four questions.: first question asks about instructors' sketching media when

they start to design, second question queries about their students' sketching tools, third question explores instructors' preferred design tools for students and fourth question queries the successful sketching tools for students. Each question consist of four design method that respondents need to rate them.

In the *second* section of questionnaire, totally presented 15 questions as 15 statement that respondents need to rate the degree to which they agree or disagree with them. In this section, instructors were told to evaluate digital media in their design studios (Q.1 until Q.6) and its impact on the creativity and successfully of students (Q.7 until Q.10), in some of questions, digital sketching were assessed related to the creativity features (such as fluency, flexibility and originality) (Q.11 until Q.13) and also some questions explore the relationship between designer' sketching tools and their abilities and skills (Q.14 and Q.15). In the *third* section of survey, is asked of which digital design programs are used by instructors and their students in the design studios.

In the section one, the instructors' responses calculated and results as percentage shown in Figure 3.5. Findings show that the traditional freehand sketching in four questions gained the maximum positive values and has not any negative value. In addition, the working directly with CAAD programs has the minimum positive values.

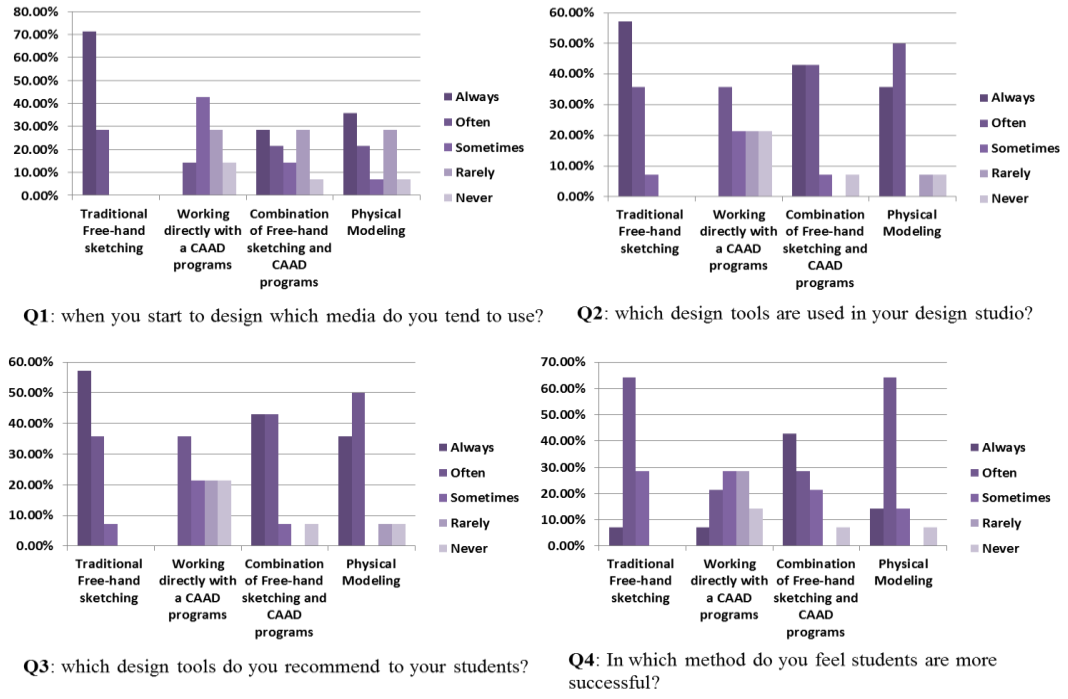


Figure 3.5 Questions of first section and percentage of answers

The responses of each participant were evaluated with the Likert analysis method. In this scale method, for 5 point ordinal scale (always to never) was given values from 5 to 1 sequentially. This values for each design and sketching method were calculated. Findings demonstrate that the "traditional free-hand sketching" tool with the highest percentage (100%) has been the common designing tool among the instructors and their students; and "working directly with a CAAD program" got the lowest percentage (50%) in positive tendency. The combining of freehand sketching with CAAD programs has an equal value with physical modeling method (86% positive tendency versus 14% negative tendency) as shown in Table 3.1 and Figure 3.6.

Table 3.1 Percentage of tendencies of teachers to design tools

Design Tool	Positive Tendency	Negative Tendency
Traditional Free-hand sketching	100%	0%
Working directly with a CAAD program	50%	50%
Combination of Free-hand sketching and CAAD program	86%	14%
Physical Modeling	86%	14%

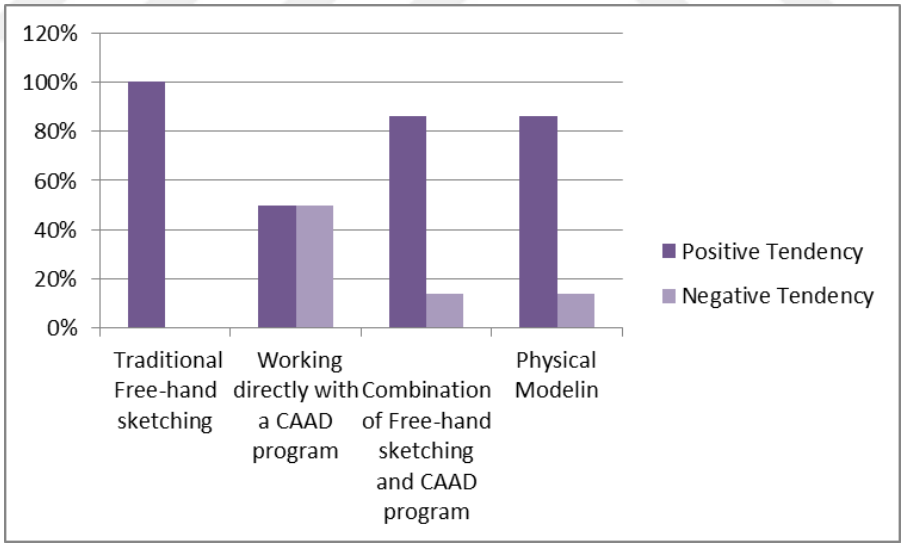
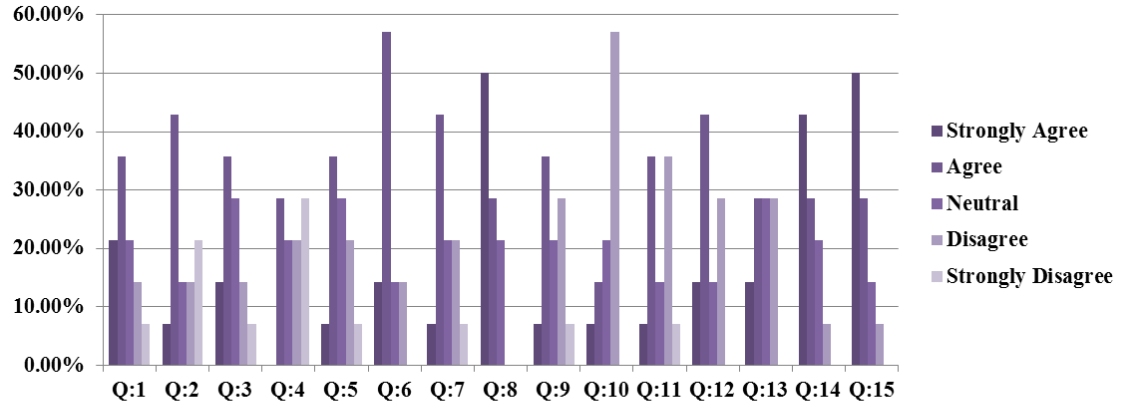


Figure 3.6 Percentage of tendency of teachers to design tools

In the second section of questionnaire, the opinions of respondents in agree or disagree with 15 statements as percentage are showed in figure 3.7. In this figure, the opinions of

respondents to each statement (strongly agree to strongly disagree) are shown separately as a percentage.



Q:1	**Students can think about design problem via digital media in my design studio**
Q:2	**We must start to teach our students from the outset to design with digital media**
Q:3	**Students feel more comfortable with digital based sketching.**
Q:4	**The student spends less time while designing with digital based sketching**
Q:5	**The Senior students are depended on computer at the early stage of design process**
Q:6	**Students can express their design thoughts better once they learn digital sketching**
Q:7	**If computer is used only as a tool it will limit design creativity.**
Q:8	**If computer is used to enhance design thinking it will help designer in creative design making**
Q:9	**Most successful students prefer digital based sketching**
Q:10	**In digital based sketching method I feel students more creative**
Q:11	**Digital based sketching enhances the students' ability to develop large number of ideas (Fluency)**
Q:12	**Digital based sketching increases the students' talent to generate various ideas (Flexibility)**
Q:13	**Digital based sketching increases the students' ability to produce new and unusual ideas (Originality)**
Q:14	**There is a relation between student's creativity and his ability in designing tools**
Q:15	**There is a relation between professor's ability in designing tools and his (her) recommended tools to students**

Figure 3.7 Questions to evaluate instructors' tendency to digital design tools

The results are evaluated with Likert analysis method; in this scale method, for five point ordinal scale (strongly agree to strongly disagree) was given values from 5 to 1 sequentially. The findings show that, the sum of instructors' positive opinions related to digital sketching in their design studios (Q.1 until Q.6) is 64 percent. Their opinions related the impact of digital sketching in creativity and successfully of students (Q.7 until Q.10) is 66 percent; their opinions about features of creativity in digital sketching (Q.11 until Q.13) are 65 percent and finally the sum of their opinions in Q.14 and Q.15 is 83 percent. (As shown in Table 3.2 and Figure 3.8) These show that more than 50 percent of respondents have a positive opinion related to the digital tools in the early stages of design.

In totally, the results are evaluated with Likert analysis method, after calculating the value of each answer for each respondents, findings show 64% of respondents have a positive tendency towards digital tools for supporting creativity, and 36% have a negative opinion.

Table 3.2 Total values in percent for question groups separately

	Q.1 until Q.6	Q.7 until Q.10	Q.11 until Q.13	Q.14 and Q.15
Total Value	64%	66%	65%	83%

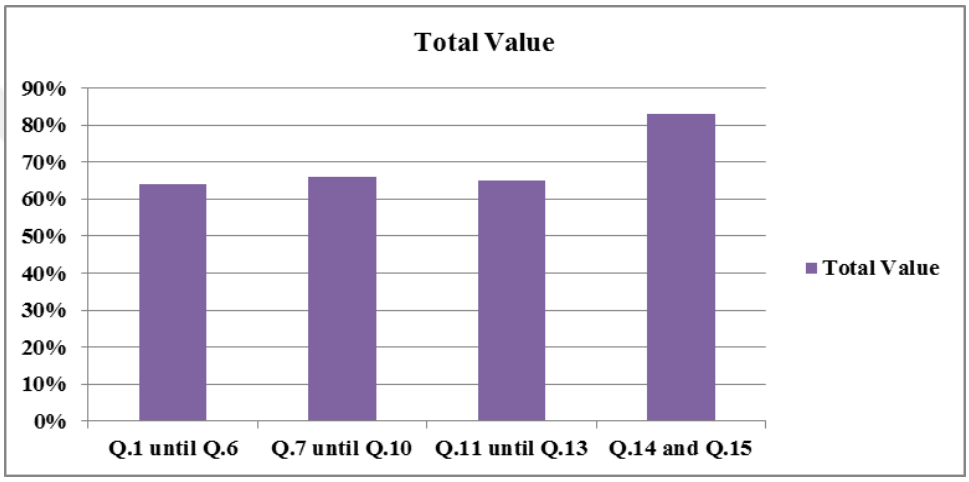


Figure 3.8 Total values in percent for question groups separately

In the third section, according to responses, digital programs such as Sketchup, Photoshop, Sketchbook and AutoCAD are the common digital tools that the instructors and their students use and prefer for designing. Other digital tools such as Hyve-3D, Archicad, Bailey Sketch (app), QsketchHDLite (app), Revit, Rhino, Balsamiq SketchiXML and Gambit Invision Axure programs, too, are mentioned.

3.4.3 Discussions

These results indicate that, freehand sketching is yet common design tools in early stages of design, but in many architectural schools, it is attempts to apply digital sketching tools especially among young students and educators. Findings of survey show some of instructors are strongly disagree with using of digital in the conceptual

design, in contrast some of them believe that with advancing in digital technology, these tools should apply to the early design stages and replace paper based sketching. For this reasons, it seems that pen based digital systems and tools due to their similarity to conventional freehand sketching have been attention.

The results of the first section of survey support the theoretical discussions that were posed in previous sections and this is a reflection of the professors' doubts over digital tools that instead of using them directly, they prefer the traditional freehand sketching or the combination of freehand sketching and CAAD program. The result of 50% positive to 50% negative desire to use of digital tools, also confirm that these tools are of interest and cannot be ignored. Although, instructors and students do not commonly use digital tools in the early design stages, but, the findings of second section indicate that, there is a tendency to use this technology among them, that with the advances in the user interface of digital programs and given the potential of these tools, it may be realized in the future times.

CHAPTER 4

EMPIRICAL STUDY

4.1 Introduction

The main goal of this study is to evaluate and examine digital sketching tools in the early phases of architectural design process and assess its impact on the creativity of the architecture students. In the second chapter, the existence of a strong relationship between traditional freehand sketching and creativity was proven. And sketch, essentially because of this important feature, is widely used by all professional designers and even novices. Also in chapter three was concluded that there are attempts and tendency to integrate digital media into early stages of architectural design and enhance sketch-based interface. Therefore, in this chapter the sketching process of two architecture students are compared in two digital environments with different sketching software versus the process of traditional pen and paper sketching via an experiment.

The data that derived from freehand sketching sessions are considered as the basis for evaluations, if the digital session's values are more than pen and paper sketching values, this can prove research hypothesis and implies their positive impact on student's creativity. So, it is necessary to select the criteria for evaluation of these processes from other researches. These criterions have been identified by researchers for evaluation of creativity and productivity of design. In this section, first the experiment and analysis methods are introduced, then criteria and parameters that have been applied in different researches are explored and introduced, and afterward, the experiment setting to compare the digital sessions versus pen and paper session is

stated. And finally, the findings and results of experiments are interpreted and discussed.

4.2 Experiment Methodology and Analysis Technique

4.2.1 Protocol Analysis method

Researchers commonly use protocol analysis method for "studying design thinking from the cognitive viewpoint" [16], this method relies on "verbal accounts given by subjects describing their own cognitive activities whilst participating in a task" [33]; and is successfully used to explore structuring of problem, generating of solution, and designer's behavior in the design process [26]. This method has recently been applied in evaluating sketching process during conceptual design [54] because it is a research methodology that is limited to short stretches of time — not more than a few hours [16].

Types of protocols analysis: Researchers address two types of protocols analysis method according to "the nature of the research problem", which has been classified by Dorst and Dijkhuis the "process-oriented" approach and the "content-oriented" approach. The former approach "focuses on describing design processes in terms of a general taxonomy of problem-solving, i.e. problem-states, operators, plans, goals, strategies, and so on" (cited in [54]); the content-oriented approach aims at revealing "the contents of information, resource and knowledge that are used for making inference" (cited in [46]).

Two types of protocols, also, are classified as *Concurrent* protocols (think-aloud) which are obtained from "verbalization of a subject's thinking while he/she is working on a given task"; *Retrospective* protocols are obtained from "verbalization of a subject's recall of thinking after he/she has finished works" (Dorst & Dijkhuis, 1995 cited in [5], [46]). Researchers have utilized both types of protocols according to "the nature of the research problem; process-oriented design studies tend to use concurrent protocols, while content oriented design studies tend to use retrospective protocols" [ibid].

The difference between concurrent and retrospective protocols according to Maher and Tang [84] are "in reporting timing: in the former, subjects report and design simultaneously; while in the latter designers design without interference and then report with the aid of videotapes recording their design sessions". Also according to them a typical protocol study has five phases: "1) conducting experiments; 2) transcribing protocols; 3) parsing segments; 4) encoding raw protocols by the coding scheme; 5) analyzing encoded protocols".

4.2.2 Linkography

Linkography is a technique that used in analyzing design protocols to investigate designers' cognitive behaviors. It according to Kan and Gero [85] has "different levels of subjectivity: determining the moves (segmentation), judging the links among moves (coding), and interpreting the meaning of the resulting linkograph (analysis)". It was first introduced to protocol analysis by Goldschmidt to assess design productivity of individual designer [85]. In linkography system, the design protocol is segmented into smaller units called a ‘move’ (or design idea or decision), that related moves are joined by a ‘link’ [16].

Kan and Gero [85] quotes Goldschmidt (1995 and 1992) who offers a general view of a design move as:“a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move” (Goldschmidt 1995), or “an act of reasoning that presents a coherent proposition pertaining to an entity that is being designed” (Goldschmidt 1992). In fact, the linkograph is considered to be a system in which every conceptual link between two segments is an event. It can be seen as a graphical representation of a design processes that traces the patterns of move associations [85], [86], [87]. It also may be seen as an enlarged depiction of a very small design space within which the designer is working at a specific moment [16]. Linkography – as a linked protocol – is a rich source of information that can be analyzed in many different ways. Linkography thus concerns itself with links among design moves, as it is believed that this is the best way to capture the essence of design cognition and behavior [ibid].

Moves: Goldschmidt identifies three types of moves: *orphan* moves, *unidirectional* moves, and *bidirectional* moves. A move which has no links, such move is referred to as an orphan move. Moves that link only backward or only forward are called unidirectional , whereas the others are bidirectional, as they have links both backward and forward [ibid].

In addition, she distinguishes a class of richly linked moves called 'Critical Moves'. Critical moves (CMs) are the most important moves, "those forming a particularly large number of links" [ibid]; on the other words, the high and more links will be necessary in order for a move to be seen as critical. Goldschmidt [16] states, "We could look at the overall number of links a move generates, or at the number of links in one of the two directions (backward or forward). Because it allows richer insights into the process, the second option was chosen so that criticality indicates links in one direction, either backward or forward." In the other words, according to her, it is sufficient that a move generate a designated number of links in one direction to be labeled critical, regardless of the number of links it generates in the opposite direction.

The threshold number for qualifying links as critical is flexible, and it is established in each study depends on the nature and the goals of the study [16], [39]. According to Goldschmidt linkographer has to indicate the threshold when he/she talks of critical moves by adding it in superscript: CM t, where t is the chosen threshold. Linkographer can indicate critical moves at three different thresholds, as shown in figure 4.1. It is good practice to choose a threshold that yields about 10 – 12 percent CMs of the total number of moves in a sequence [16]. CM percentage refers to the total number of CM in a design session in relation to total number of moves [].

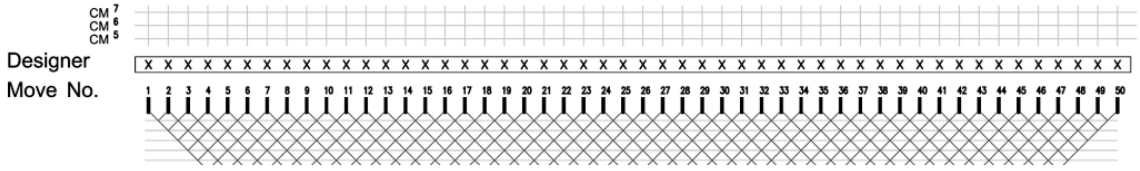


Figure 4.1 Three different thresholds for critical moves [16]

Links: in linkography technique that is concentrated on links, they are our variable and they are based on the contents of moves; therefore they have become nodes in a

graph that portrays the network of links among moves. The representation is therefore called a linkograph [16].

According to Goldschmidt [16], “deciding whether two moves are linked is done by using common sense under the condition of good acquaintance with the discipline and with the design episode in question”. First one numbers the moves sequentially. Then, starting with move 2, he/she tests whether it has a link to move 1. Next he/she goes to move 3 and tests whether it has a link to move 2 and whether it has a link to move 1. For move n , linkographer has to ask this question n – 1 times for possible links between move n and all preceding moves, namely 1, 2, 3, . . . , n – 1. For n moves, he/she must perform this test n (n – 1)/2 times in order to include every pair of moves in the sequence [16].

Two types of links are identified by Goldschmidt [16] "forelinks" and "backlinks". Backlinks are links of moves that connect to previous moves [88]. The symbol < denotes backlinking. Forelinks are links of moves that connect to subsequent moves [ibid]. Forelinking is denoted by the symbol >. Forelinks are therefore virtual and cannot be determined by judgment; they can be established only after the fact ([16], [18], [39]). Conceptually the two types of links have very different meanings, and therefore Goldschmidt distinguishes between them. Backlinks stand for “appraisal, evaluation, and confirmation”. In contrast, forelinks stand for “steps forward, the consideration of more options and possible solutions, further development” [39].

Another link type introduced by Kan and Gero [87], called horizonlink, which "carries the notion of cohesiveness between linked moves". According to them [88],

“Horizonlink carries the notion of distance/time between the linked segments. Segments that reside in working memory will usually have high interconnections; we refer to these linkages as the cohesiveness of segments. we refer to links that connect segments that are far apart, and those that are not in working memory as incubated linked segments”.

Pourmohamadi and Gero [89] explained that, "In backlink mode, each segment can be linked back to any of its previous segments. Therefore, the number of possible links at any moment equals the segment number minus one. In forelink mode, the number of remaining segments to the end of the protocol is considered as possible links for each

segment. Horizonlink is not a link itself but it is an indicator of the distance between two linked segments. There are n-1 rows in a linkograph with n segments and the number of possible states in each level equals the length of the protocol minus the level of the links."

4.2.2.1 Link Patterns

Three different linking patterns that identified in linkographs are: *chunk*, *web*, and *saw-tooth track* [16], [85]. These patterns in the linkography according to Kan and Gero [85] can be an indication of the structure of design process.

Chunk: a group of moves that are almost exclusively linked among themselves [85] and is graphically distinct as a discernible triangle called a chunk [16]. "A chunk is a block of links among successive moves that form links almost exclusively among themselves and are loosely or not at all interconnected with other moves" [ibid].

What is the significance of chunks in the design process? Goldschmidt [16] states, "The interlinked moves within a chunk stand for a cross-examination of relevant properties, related questions, and possible implications of a design issue. When this examination is exhausted, at least for the time being, or when it is interrupted, a new cycle of thought begins in which another issue comes under scrutiny."

She claims, chunks reflect the structure of the thinking process, which is easily captured in a linkograph thanks to its graphic properties. According to her, "In some linkographs it is difficult to define chunks. We can assume that the processes they represent are less structured than processes with clear chunking, as there is no sequential treatment of clearly outlined issues. Linkographs with no chunks represent poorly structured processes and are an indication of inefficient design thinking and reasoning." She concludes that "In particular, the presence of chunks tells us that the designer thinks systematically about successions of sub problems or issues. The lack of chunks is evidence of the opposite: that the designer is engaged in thinking about a single issue, or is "jumping" back and forth among several issues.

Web: A web is formed when "a large number of links are generated among a relatively small number of moves" [16]. The web is a portion of the network in which

the density of links is especially high. Webs are smaller than chunks and are not found in all linkographs [ibid].

What does a web signify? Goldschmidt states, “It records a brief and intensive passage of a few moves in which a certain issue is very thoroughly inspected and its aspects are woven together to make sure they are in agreement with one another.” According to her, webs are found when something needs particular clarification or when an idea is being built up by bringing up several of its aspects almost concurrently.

Saw-tooth track: A saw-tooth track is present when "a sequence of moves links each to the one preceding it" [16]. The link lines in such a case describe a zigzag pattern reminiscent of a saw-tooth. When this occurs, it is concluded that the thinking at that point is very linear — one thing leads to the next, and each move reacts to what was just said or done, without a more holistic view and with no attempt to widen or deepen the investigation [ibid].

4.3 Linkography and Assessing Creativity

This study has evaluated creativity into the design process rather than creativity in the design product or in the designer’s personality. The creative process is difficult to capture and difficult to study and protocol analysis is commonly used in such studies [16]. Researches show that there are not specify analysis method and criterions for assessing ‘creative design process’, for this reason, to evaluate creativity in this study, too, the protocol analysis and in order to analyze the results, the linkography method that are commonly used in such studies, have been applied. How to identify creativity of a design by ‘Linkography’?

In various design researches, some parameters have been defined as criteria for evaluation of creativity and productivity of design via linkography analyzing method. These criterions include *Link index, Critical Moves* (both developed by Goldschmidt) and *Entropy* (developed by Kan and Gero and associates) that have been used by researchers.

In this study, too, the link index, critical moves and entropy have been used as the main benchmark of productivity of design process that according to researchers can be seen as sign of creativity. Also the *lateral transformation* as the distinct feature that

freehand sketching makes during design process, has been counted for all sessions. In addition, the *Mean values of X and Y* of all sessions, as indicator of design structure were compared.

4.3.1 Link Index (L.I)

The link index value is calculated to evaluate the design sessions in protocol analysis to compare design productivity, which is considered as an indication of creativity [16]. Goldschmidt develops this value to evaluate productivity of the design process, according to her, a productive process has a higher link index value that shows a higher density of links in linkograph.

A link index is "the number of links divided by the number of ideas" [18] that generate them in linkographs or part thereof, expressed as a proportion. According to Goldschmidt, the Linkograph of the more productive process indicates higher link index value, more chunk and more web, and the highest link index are found "in webs, which are defined a priori as high-link-density groups of moves" [16].

A link index is a fast indication of the amount of linking activity in a design episode, which in turn hints at the designer ' s effort to achieve a synthesis. If the density of links is considered as an indication for the quality of ideas, Goldschmidt and Tatsa [18] claim that, "the most productive processes (which have the highest link index values and densest links) are the most creative ones'. But according to Goldschmidt [16] the link index is a value that must be used cautiously and only where appropriate, because according to her "we must be careful not to conclude that a high L.I is necessarily a hallmark of good or creative design. A high L.I. may be the result of many repetitions or many attempts to explore alternative ideas with little continuity among them." This suggests "more links in the design process does not necessary produce better designs" [87]. Although, this correlation between design productivity and creativity still needs further research to be accepted as true; indeed, link index numbers might be useful in discerning productivity of the design sessions (Goldschmidt,1992 cited in [16]) however are not sufficient to analyze the protocols [16].

4.3.2 Critical Moves (CMs)

As previously mentioned critical moves are one of the cases that can be extracted from linkography. Critical moves are of special interest because "they are prime contributors to a high level of interconnectivity of moves, which is how a design synthesis is achieved" [39]. Goldschmidt [39] distinguishes between CMs "due to a large number of backlinks (<CMs) and a large number of forelinks (CMs>) and in rare cases, a large number of links in both directions" (<CM>).

Goldschmidt [16] in her book raised a specific proposition for the first time that there is the correspondence between forward and backward linking and *divergent* and *convergent* thinking. She claims that linking moves forward and backward reflects shifts between divergent and convergent thinking.

Goldschmidt [61] proposes that "forelinks are roughly reflective of divergent thinking: new ideas come up in them, which further moves refer back to"; and that "backlinks stand for convergent thinking: they test, evaluate, confirm or question preceding moves in which a new proposal had been put forth". She [16] argues that inventive ideas, if they are to be successful, must be developed further and must be rigorously assessed against previous work, thus, according to her "we get both CMs> and <CMs that are well balanced between forelinking and backlinking that is, both divergent and convergent thinking take place, with frequent shifts between the two modes". She [16] states, "..., the flexibility to shift between divergent and convergent thinking is typical of creative thinking." According to her "the high percentage of CMs in this unit is also indicative of its highly productive nature; this means that creative episodes display a high proportion of critical moves". She [16] concludes that, the aim to show that connectivity, or good fit, or a particularly successful synthesis, is a product of rapid shifting between small divergent and convergent thinking acts. Thus, according to her:

"it is not enough to ask designers to generate more ideas, or even to generate innovative ideas. A designer has to acquire the mode of thinking whereby frequent propositions are immediately followed by evaluative steps that make sure that the design holds together at every moment. It is not enough to have ideas, even many

ideas; the ideas have to be good and they must be perfectly integrated and interlinked".

Also it was stated in previous sections that for a long time, the creativity literature concerns itself primarily with divergent thinking, and that psychometric tests are geared to measure divergent. But more recently, it has been recognized that "convergent thinking also has a role in creativity" [39], Indeed, "divergent and convergent thinking are seen as occurring in cyclic phases within the design process" [ibid] and creativity is the balance between two mode of thinking [16]. Therefore, Goldschmidt [39] proposed, "in assessments of creative potential, *shifts* between divergent and convergent thinking [or forelinks and backlinks CMs] should be the yardstick instead of, or alongside measurements of divergent thinking". Goldschmidt [16], [39] interprets this shifting as balance between < CMs and CMs >. According to her the equal proportion of the two types of CMs is suggesting balanced cycles of idea generation and assessment toward a solution and indicates that ideas that are brought up are pursued and inspected.

Also, she [16] states, "Special attention will be paid to forelinking critical moves. This is not to say that backlinking critical moves will be neglected or considered secondary"; according to her [39], "in the conceptual stage of design problem solving, there is more divergent thinking than convergent thinking, [because] the early idea-generation phase of designing, is considered to be the most creative part of the design process". So, it is concluded that "Linkographic studies have been able to establish a correlation between [independent] creativity assessments and the proportion of critical moves, especially CMs>, in a variety of settings" [61]. So in assessing creative and productive design thinking process by linkography, one should account forelink and backlink critical moves that the percentage of CMs of total moves is as an indication of productive design. Also the ratio of forelink CMs of total CMs and backlink CMs of total are significant to show the balance between two types of links. The balance between two types of links is also an indicator of creativity.

4.3.3 Entropy

The traditional study of linkographs uses link index and critical moves to benchmark the productivity of a design session [85]. Kan and Gero [85] believe that, "link index and critical moves approach might bias towards highly linked and saturated linkographs because a saturated linkograph will have a high value of link index and critical moves". According to them, "this would not create any problems as most of the linkographs with reasonable moves would have relatively sparse links".

Kan and Gero in their researches on protocol study have proposed the methodology to calculate the entropy level of creativity using Shannon's information theory and Goldschmidt's Linkography "on the basis that fully linked and empty linked linkographs represent substandard design processes" [87]. Kan and Gero, and their associates argued that, "there is a potential relation between the productivity of design activities and the entropy of linkographs" [86], that it is a hallmark of creativity [87].

In Shannon's information theory, "the amount of information carried by a message or symbol is based on the probability of its outcome. If there is only one possible outcome, then there is no additional information because the outcome is known" [85], [87].

Kan and Gero [85], [87] and Kan et al [88] argued that an empty linked linkograph can be considered as a non-converging process with no coherent ideas and a fully linked linkograph represents a fully integrated process with no diversification. According to Kan et al [88], "in both cases the opportunities for idea development are very low in terms of entropy; if we randomly pick a segment in an empty linked linkograph we can be sure that it has no links. This sounds obvious but if we consider this linkograph as a carrier with zero information content, because the outcome is known, it will have zero entropy. Similarly, a fully linked linkograph will also have zero entropy"; according to Kan and Gero the basic concept is that the high value of entropy present a richer idea generation process.

In order to measure the entropy of linkograph, Kan and Gero [87] present entropy measurement "based on the conceptual difference of forelink, backlink, and horizontal link (called "horizonlink"). Entropy is measured in rows of forelinks, backlinks, and horizonlinks separately" according to a probability algorithm devised

by Shannon as “linked” or “unlinked” (Figure 4.2). A mean value can then be calculated for each of the three types of rows [16].

Kan and Gero [85] suggested that “forelink entropy measures the idea generation opportunities in terms of new creations or initiations. Backlink entropy measures the opportunities according to enhancements or responses. Horizonlink entropy measures the opportunities relating to cohesiveness and incubation”. So according to them "a higher H value of forelinks signifies higher opportunity in initiating design moves, and a higher H value of backlinks denotes higher opportunity in building upon previous design moves". High values of horizonlink entropy usually "indicate a mixture of long and short links which suggests the cohesiveness and incubation of ideas" [85].

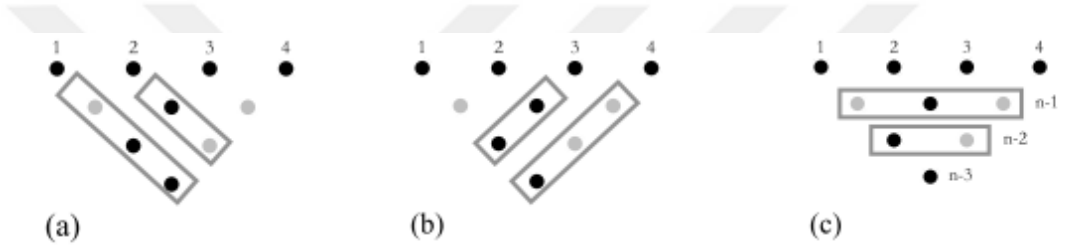


Figure 4.2 Abstracted linkograph for entropy measurement, black dots denote links. (a) Measuring entropy of forelinks, (b) measuring entropy of backlinks, and (c) measuring entropy of horizonlinks [87]

Horizonlink (Figure 4.2 c) carries the notion of distance/time between the linked moves [86].

Shannon’s theory looks at "the relationship between linked and unlinked nodes in a selected set of symbols to calculate the set’s entropy" [16]. Kan and Gero [86] explained that, "Using “linked” and “unlinked” as the symbols, the probability of “linked”, p(linked), will be the frequency (or number) of “linked” nodes divided by the total number of nodes in that row. Similarly, the probability of “unlinked”, p(unlinked), will be the number of “unlinked” nodes over the total number of nodes in that row". There are only two symbols, putting their probabilities in the following equation, the entropy (H) of each rows become [86]:

$$-p(\text{linked})\text{Log}(p(\text{linked})) - p(\text{unlinked})\text{Log}(p(\text{unlinked})) = H$$

Where $p(\text{linked}) + p(\text{unlinked}) = 1$

H will be zero if p(linked) equals 1 or p(unlinked) equals 1. H will have a highest value of 1 when p(linked) equals p(unlinked) equals 0.5 [16], [86]. When the linkograph is "either empty or fully saturated, the entropy is at its lowest level, H=0. Maximum entropy (H) is achieved when that relationship is unpredictable, because this situation is diversified and allows for surprise and further development." [16] High entropy is indicative of a productive process. The graph in Figure 4.3 is symmetrical, the slope of the graph decreases sharply as the probability moves away from 0 and 1. This graph shows that when the proportion of linked links is between [0.35, 0.65], H is over 0.93, that is, if the links in a row are between 35% and 65% it will produce a very positive value (rich design process) and the process is productive. Maximum entropy when p(Linked)=p(Unlinked)=0.5. If the links are less than 5% or over 95%, it will produce a very low H value (below 0.29). [85]

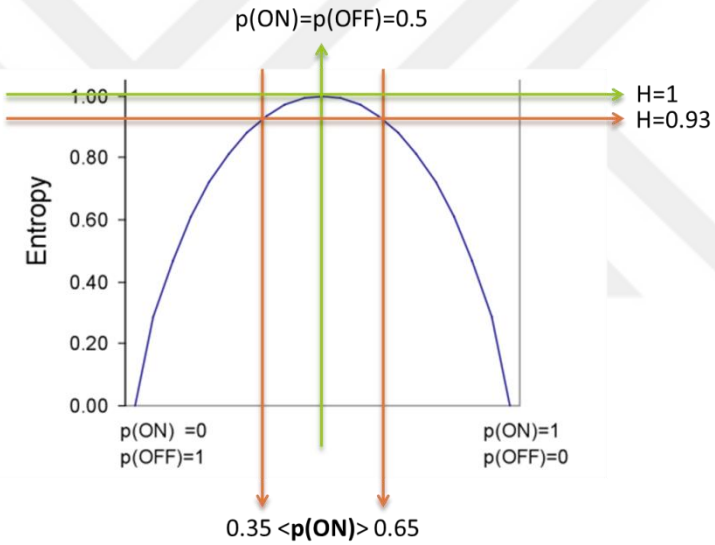
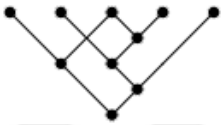


Figure 4.3 The graph of entropy and its maximum areas

Table 4.1 shows some possible linkographs together with interpretation of the design process they reflect [85] with their cumulative entropies. The cumulative entropies are "the summation of forelink, backlink and horizonlink entropies of all rows" [88].

Table 4.1 Some possible linkographs of five design moves and their interpretations [85]

	Linkographs	Interpretations	Entropy
Case 1		Five moves are totally unrelated; indicating that no converging ideas, hence very low opportunity for idea development.	0
Case 2		All moves are interconnected; this shows that is a total integrated process with no diversification, hinting that a pre-mature crystallization or fixation of one idea may have occurred, and therefore also very low opportunity for novel idea.	0
Case 3		Moves are related only to the last one. This indicates the process is progressing but not developing indicating some opportunity for ideas development.	5.46
Case 4		Moves are inter-related but also not totally connected indicating that there are lots of opportunities for good ideas with development.	8.57

In case of forelink, if the idea in a move is weak, the idea can be found to be almost without any influence in the conversation and it will not have a lot of forelinks (p(unlinked) is close to 1) and this makes a low entropy. However, if an idea have too many forelinks (p(linked) is close to 1) [87], this might indicate the flow of the conversation is fixated on that one idea and show that the switch to new ideas in the conversation is not taking place; which is also indicated by a low entropy [87], [88]. Similarly, in case of backlink entropy, if an idea is very novel, it will not have backlinks (p(unlinked) equals 1), this represented by zero entropy. If an idea is backlinked to all previous ideas (p(linked) equals 1), it lacks novelty and the resulting entropy by zero [87].

According to Kan and Gero [87], "Moves that are close will usually have better interconnectivity; we refer this as the cohesiveness of moves. Links that connect moves that are far apart, we consider those as incubated linked moves. The measurement of horizonlink entropy will encourage the occurrence of incubated

segments and discourage too strong cohesiveness." Therefore, low values of horizonlink entropy can indicate full cohesiveness that shows the ideas are wholly focused on one move [87], [88].

4.3.4 Mean value of X and Y

Kan and Gero [85] statistically describe a linkography according to "the total number of nodes, the mean values of X and Y – that is the centroid or the average position of all the nodes, and their deviations in the X and Y axes". They calculate the mean value of X by "adding all the X coordinates of the nodes and dividing by the total number of nodes", which is the average location of the links in the x-axis [85]. According to them, the mean value of X shows whether more links appear through the beginning or ending of the design sessions. "A higher mean value of X implies that more nodes appear at the end of a session and a lower value suggests that more nodes are present in the beginning of the session" [85]. In the same way, to calculate the mean value of Y, they add "the Y coordinates of the nodes and dividing by the total number of nodes" which is the average location of the nodes in the y-axis [85]. The mean value of Y shows the depth of the ideas, therefore it finds out the lengths of the nodes. According to them, there are a same relationship between the mean values of Y and lengths of links. In addition, they measure the standard deviations to show "the dispersion of the distribution" which "suggest how concentrated the nodes are clustered around the means" [85].

In this respects, Kan and Gero [87] use the concept of good and bad moves, that according to them, "good ideas produce more integration towards the end of a session and bad ideas less integration towards the end". Also, Kan et al [88] state "the higher entropy towards the end of the session suggests better inter-connectivity of ideas".

Kan and Gero [87] explain that, "If entropy measures idea generation opportunities, then entropy should drop towards the end of a session because as the designer approaches "a finished design" there should be fewer opportunities for ideas. The increase in entropy at the end of a session means a better integration of moves which might indicates that the moves contribute to good ideas". This can be concluded that if the study aims to evaluate the outcome of design sessions, the entropy should be

increase towards the end of a session, while if the study aims to measure the idea generation process, the entropy should be higher in the beginning of session.

4.3.5 Lateral and Vertical Transformation

Gürsoy [59] derived from the linkographs lateral and vertical transformations, a distinction based on work by Goel [14].

Goel's [14] study shows that the ambiguity and uncertainty of freehand sketching work well for exploring new thoughts and creative shifts to new alternatives that allows lateral transformations. So, the lateral transformations are a main feature of freehand sketching that can be used to interpret linkography in assessing creative process. It was previously pointed out the ambiguity of freehand sketching enables it to stimulates creativity. So, it can be assumed that there are a correlation between the level of ambiguity of the design representation mode and the number of lateral transformations.

The criterion for a distinction between the modes of transformation are based on the distribution of links in Gürsoy's work: "dense clusters of links correspond to vertical transformations while scattered links denote lateral transformations" [18]. Therefore, according to Gürsoy's [59] "vertical transformations generally would form chunks and webs, while lateral transformations remain as non-interlinked moves or form saw-tooth tracks". She due to this idea, develops a method to explore lateral and vertical transformations by interpreting Linkography.

Gürsoy [59] to determine the lateral transformations in linkography, first colors dense clusters of links (chunks and webs) in the linkographs as triangles, each of which is considered to represent one lateral transformation, Later, are colored the triangular area between two sequential moves that linked together. Then, unlinked moves (orphan moves) are added to this count, as they too are considered to be lateral transformations, since they are "sudden changes in the design process"[59]. The total sum of colored triangles and unlinked moves is the number of lateral transformations that occurred during the design process (figure 4.4).

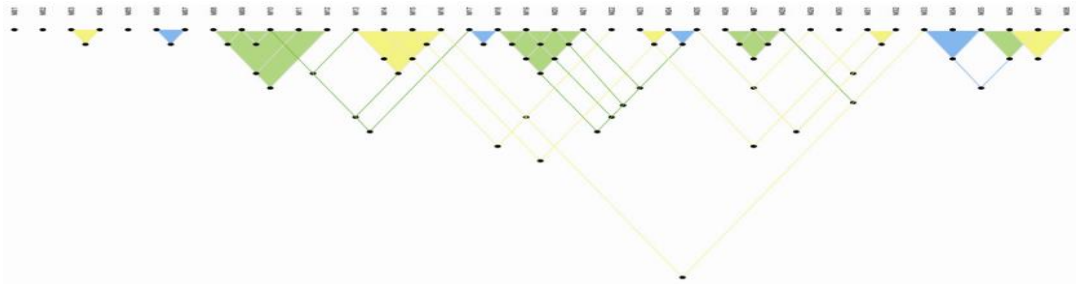


Figure 4.4 Example of lateral transformation determination on linkographs [59]

According to her vertical transformations are harder to determine than the lateral ones. She adopts the idea of a vertical transformation value (that is, the depth of the process defined as the mean distance of links from the y axis) from Kan and Gero [85]. Gürsoy's [59] uses their method to interpret the mean value of Y of the Linkography as vertical transformations.

4.4 Experimental Setting; Pen and Paper vs. Digital Sketching and 4p of Creativity

The main purpose of this research was to evaluate and examine digital sketching tools in the conceptual design phases of architecture and assess its impact on the creativity of the architecture students. In order to evaluate creativity in this study was used the key work of Rhodes [24] that classified creativity into four fields identified as the four Ps of creativity: person, process, product and press (environment). In this way that, the sketch process of each *person*, in both pen and paper and pen based digital medium were compared with each other, so the *person* was assumed as constant variable and has not any impact in evaluation of protocol. Also, because of this study focuses on early conceptual design stage, so the final *products* were not important. Thus it was going to understand, how changing the *media (press)*, as the main variable, can influence the designers' creativity. In the other words, the aim of this experiment is that if we switch the design medium from paper based sketching to digital based sketching environments, what changing can be made in students' creative thinking process (figure 4.5). For this purpose, the process oriented design study that tend to use concurrent protocol, were selected.

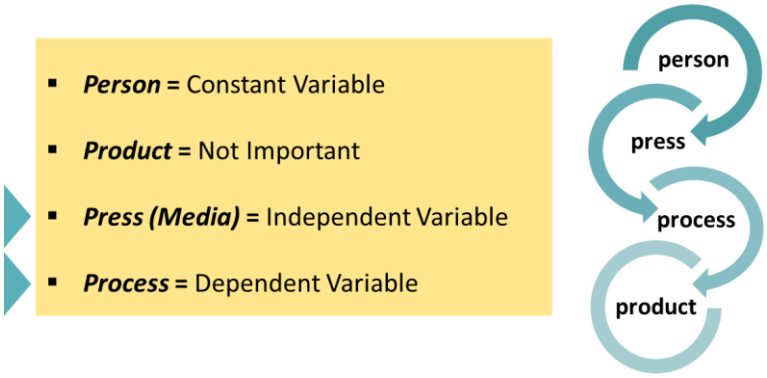


Figure 4.5 Four Ps of creativity and research variables

In the second chapter, since the existence of strong relationship between traditional freehand sketching and creativity was proven. In fact, the sketch, essentially because of this important feature, is widely used by all professional designers and even novices. Therefore, in this experiment, the sketching process of two architecture students was compared in two digital environments with the process of traditional pen and paper sketching via protocol analysis method. Sketching in the digital environment was carried out on a pen-based system. Each participant was asked to sketch at three sessions with three different design problems. For each participant, the sketching process in three environments were compared and evaluated together. For evaluation of the data, the linkography analysis method was utilized.

In this research, the parameters, which have been identified by researchers as criteria for the evaluation of creativity and productivity of design, via linkography analysis method, have been used. These parameters include: Link Index, Critical Moves and Entropy. The Lateral Transformation and Mean values of X and Y were calculated to verify and explain the main criterions (figure 4.6). In various researches, the link index, critical moves and entropy have been used as benchmark of productivity of design process that according to researchers can be seen as sign of creativity.

These five criterions were separately identified in at least five different researches that somehow aimed to evaluate and assess the productivity and creativity of design. The Link Index and Critical Moves have been developed by Goldschmidt and used by her and other researchers frequently in different and separate researches. The Entropy value has been developed by Kan and Gero and used by them and other researchers in different ways. The Mean values of X and Y have been introduced by Kan and Gero to

explain design integrations. The lateral transformations are a main feature of freehand sketching that can be used to interpret linkography in assessing creative process. Gürsoy developed a method to explore lateral transformations by interpreting Linkography and this method was used in this research too. In this experiment, these five criteria have been combined and utilized together to study creativity of design sessions. These criterions have not been used previously all together. They have been used for the first time together in this study. If the outputs of these criterions are match together this can lead to valid results of experiment.

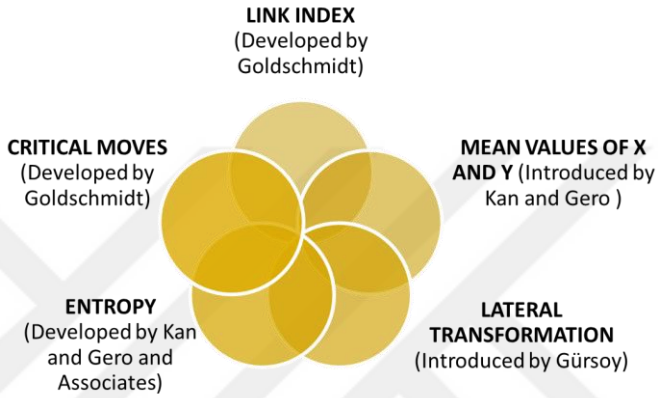


Figure 4.6 Five criteria for evaluation of design creativity

The derived data from freehand sketching tests were considered as the basis for evaluations. If the digital session's values were more than pen and paper sketching values, this could prove research hypothesis and implies positive impact of digital media on student creativity.

4.4.1 The Procedure of Protocol

4.4.1.1 The Design Sessions, Tasks and Subjects

Design Tasks: Since these tests were conducted in three sessions, and taken advantage of three different medias to test; also performance of each subject in three design sessions have been compared and evaluated with herself/himself and comparing the experiment values between subjects was not the target of this study, therefore design tasks for each session should be different. In addition, this study aims to test the thinking process, so it has been tried to select design problems based on mental

background of participants, which they have not encountered before. Also, the design tasks were selected according to possibilities of design media and subjects' skill and experience to enhance their design performances.

The design tasks given to participants for these three experiments were conceptual design first, for *paper* based sketch session, were requested to design a gallery of art in the school of architecture with green architecture approach, second, for digital pen based session with '*SketchBook pro'* software, to design a memorial for Iranian poets and third, for digital pen based session with '*uMake'* software, to design an entrance gate for amusement park (figure 4.7). The design task for pen and paper session is more complex than digital sessions and the design task for uMake session is less complex than other sessions. Also, this study have focused on exploring designers' behaviors at the conceptual design stage, so, participants were requested to consider concept generation and problem solving process to achieve design solutions; no detailed plan layout was required.

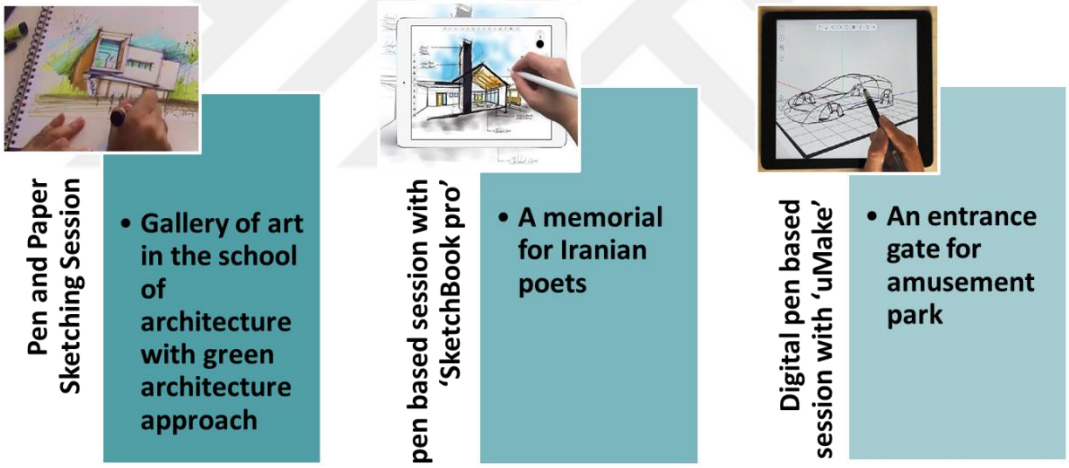


Figure 4.7 Three design tasks for two subjects

Subjects: Since the study has been conducted in three sessions, therefore the people, who were selected to test, should necessarily have sufficient skills or experience in both media (paper and digital based). Indeed, they were invited based on these factors: their CAAD and freehand backgrounds and intending to use CAAD in their projects. Their educational grades were not important here. For these reasons two successful students - who have good grades in architectural design studio courses - from

architecture faculty, one a graduate student (SUB1) from Ruzbeh University of Zanjan, and other, a sophomore student (SUB2) from Azad University of Zanjan, participated in these experiments.

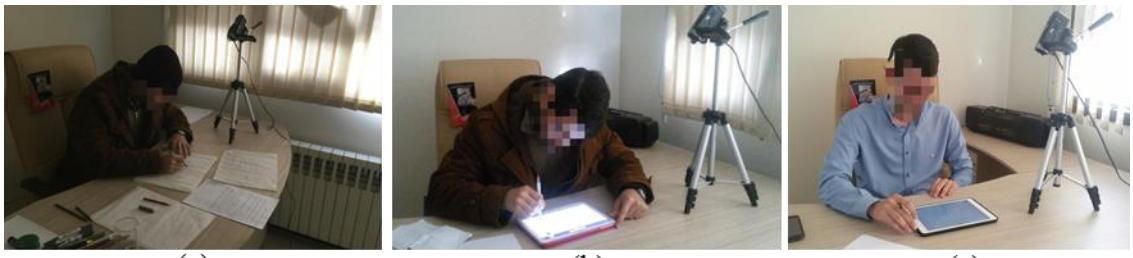
Design Sessions: The design sessions for each subject contain Pen and paper, Sketchbook and uMake sessions; and three sessions for two subjects were held in the same place, under the same conditions and at intervals of one or two weeks. Before digital sessions, since two software are new for subjects and they had not encountered them before, so for each software was held several hours for training. The uMake which is very new software, have some problems over devices and systems that creates some limitations in training and learning process.

Before starting each session, a brief about design task was written, given to participants and verbally described them. In three design sessions, subjects stayed alone in the same and quiet room and attempted to sketching and thinking about design problem. The experimenter could sometimes enter to control cameras without any interference in subjects' design processes.

During the three sessions, participants' sketching activities and their verbalizations were videotaped and recorded by two video cameras at two different points; first camera placed near of subjects to record their sketching and designing behavior, and second to capture a general picture as shown in figures 4.8 and 4.9.

(a) (b) (c)

Figure 4.8 Design sessions in (a) pen and paper, (b) sketchbook and (c) uMake of **SUB1**



(a) (b) (c)

Figure 4.9 Design sessions in (a) pen and paper, (b) sketchbook and (c) uMake of **SUB2**

According to the nature of experiment and importance of design thinking process, in each design session, the subjects had 60 minutes for examining, but if she/he finished the session earlier or later than one hour, these did not cause any problems.

In pen and paper session, subjects were requested to work on the design task while sketching only on sheets of tracing paper in A4 size in order to equalize screen to tablet size of digital sessions. In second and third design sessions, subjects were asked to sketch and design ideas only on a tablet PC with the help of two software. In second session subjects attempted to solve a design problem with a 2D interface software, "Sketchbook Pro" which mimics paper based medium; and in third session, subjects were requested that design and draw with 3D interface software named "uMake". During the two digital experiment designers were not allowed to sketch manually.

4.4.2 The procedure of the analysis

In order to analyze the protocols, first the verbalizations of participants from the think-aloud sessions and their physical actions as transcripts of the protocols were noted. Later, the transcripts of protocol were segmented into the design moves. The Goldschmidt's definition of move that describes it as a step, an act, which transforms the design situation, was taken as reference while segmenting the transcripts of protocol to design move. The segmentation was carried out in a way that a change in subjects' intentions and in the contents of his/her thought or action flags the start of a new segment.

In addition, to specify linking between the moves, Goldschmidt's instruction that was described earlier was utilized. In the other words for determine the links and relations between moves, first in an excel file the moves were wrote respectively with a unique

number. Then for each move were tested whether it has a link to each previous move respectively. The relation between move and its previous moves were determined according to subjects' physical actions, semantic and syntactic actions and their design intention. If a design action or intention occurs as a segment for the first time so, it cannot have any link with its previous moves. If a move occurs at a previous segments and is now being continued or revisited (but not contiguous), then it has relation with these segments. The small sections of six design sessions are shown in tables 4.2 to 4.7. Then for each designer, three Linkographs were produced and totally six Linkographs from six design sessions were obtained (figures 4.10 to 4.15).

Table 4.2 Example of segmentation of SUB1 in pen and paper session

NUMBER	UTTERANCE	LINK	LINK	LINK	LINK	LINK	LINK	LINK
78	Drawing a curved line for separating the spaces in the section	77	58	57				
79	That this area …. is the main space (writing 'main')	78	71	64	59			
80	And this is the service area (writing 'service')	78	73	67	66	63	62	61
81	Here we use grass (drawing grass in the slope of the second section)	52	49	42				
82	And maybe there's an entrance …. here (drawing a bridge as a horizontal line between the ground and the building)	81	74	35	34	24	23	16

Table 4.3 Example of segmentation of SUB1 in sketchbook session

NUMBER	UTTERANCE	LINK	LINK	LINK	LINK	LINK	LINK	LINK	LINK	LINK
84	Now here are four parts ... that it can be seen as signs of poems in each part	83	82	79	78	76				
85	Metal walls showing steel structure	84	83	79	78	74	72	71	70	25
86	Here we can have water as a fluid of life (drawing two squares)	84	83	78	68					
87	Changing the color and thickness of the pen to blue	59								
88	Coloring between the two squares in blue	87	86							

Table 4.4 Example of segmentation of SUB1 in uMake session

NUMBER	UTTERANCE	LINK	LINK	LINK	LINK	LINK	LINK
100	let's consider a gate for the entrance to create a sense of a game home (selecting the top line of the rectangle and extruding it in two directions)	99	93				
101	shifting the back line of rectangle	100	99	93			
102	From here ... we draw a line that connects to it (drawing two horizontal and vertical lines in the side view)	101	100	99	93		
103	Change the size and position of the vertical line	102	101	100	99	93	
104	I want to draw a straight line here… (change and correct the horizontal line)	103	102	101	100	99	93

Table 4.5 Example of segmentation of SUB2 in pen and paper session

NUMBER	UTTERANCE	LINK	LINK	LINK	LINK	LINK	LINK
24	As have said, I should have a central courtyard	18	13	1			
25	The total volume is outside .. about two meters from the edge of the central courtyard	12	23				
26	Drawing vertical and horizontal lines in perspective	25	23	21	20	14	
27	Now ... we need to specify the entrance (drawing the entrance on the smaller side of voume)	15	16	17	21	26	
28	Drawing a curve form over volume	10	11	19	21	14	26

Table 4.6 Example of segmentation of SUB2 in sketchbook session

NUMBER	**UTTERANCE**	**LINK**	**LINK**	**LINK**	**LINK**	**LINK**	**LINK**	**LINK**	**LINK**
111	Painting forehead of arc in blue	110	109	108	107	106	105		
112	Here the poetry of' Saadi 'is written (pointing to the blue forehead)	111	108	106					
113	Change the type and thickness of the pen	110							
114	Given that here the marble stone is used ... all of this (referring to the back frames and the middle square)	97	95	98	64	63	57	55	40
115	Apart from this, a polished blue building, written in poetry of poems referring to the suspended rectangle)	101	99	54	49	41	35	23	20

Table 4.7 Example of segmentation of SUB2 in uMake session

NUMBER	UTTERANCE	LINKS	LINKS
68	Now, for the same reason, let's take a lot of diagonal lines	66	3
69	There are also ideas of things in amusement park	1	
70	Like a carousel (drawing a circle)	69	1
71	Like a skating rink (drawing a curve line)	69	1
72	Select the curved line and move it slightly	71	69

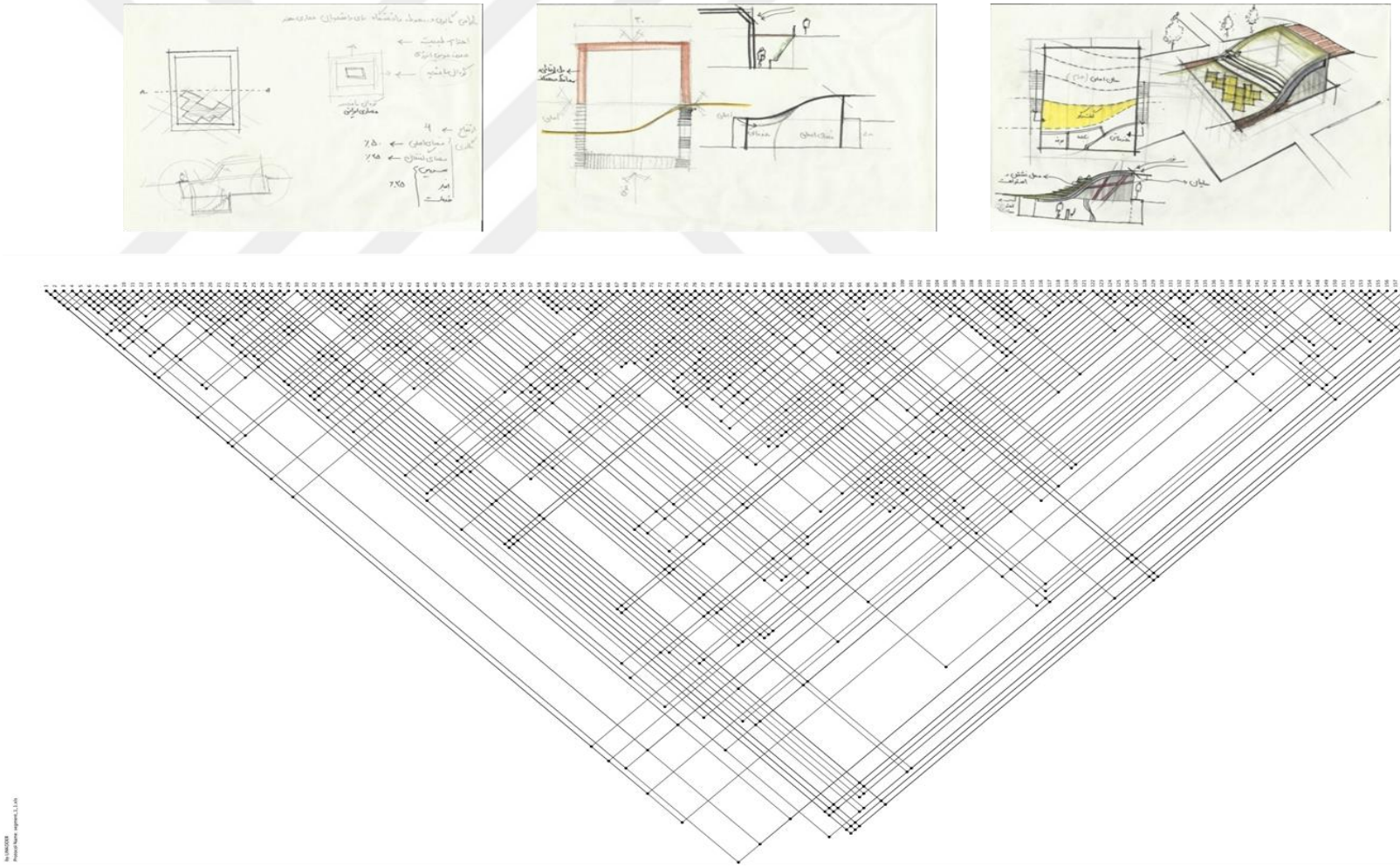


Figure 4.10 Designs and linkograph of SUB1 in pen and paper session

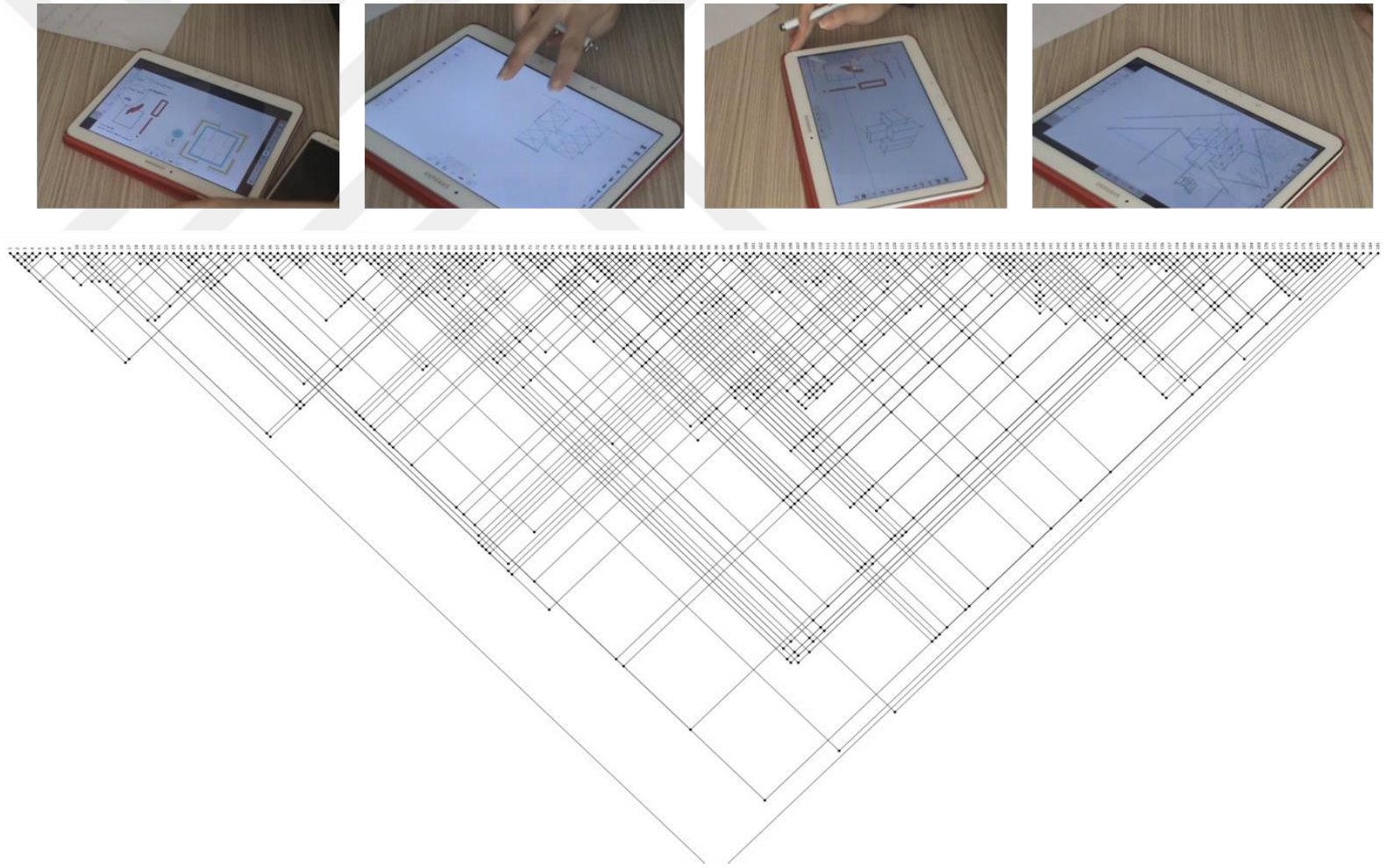


Figure 4.11 Designs and linkograph of SUB1 in sketchbook session

Figure 4.12 Designs and linkograph of SUB1 in uMake session

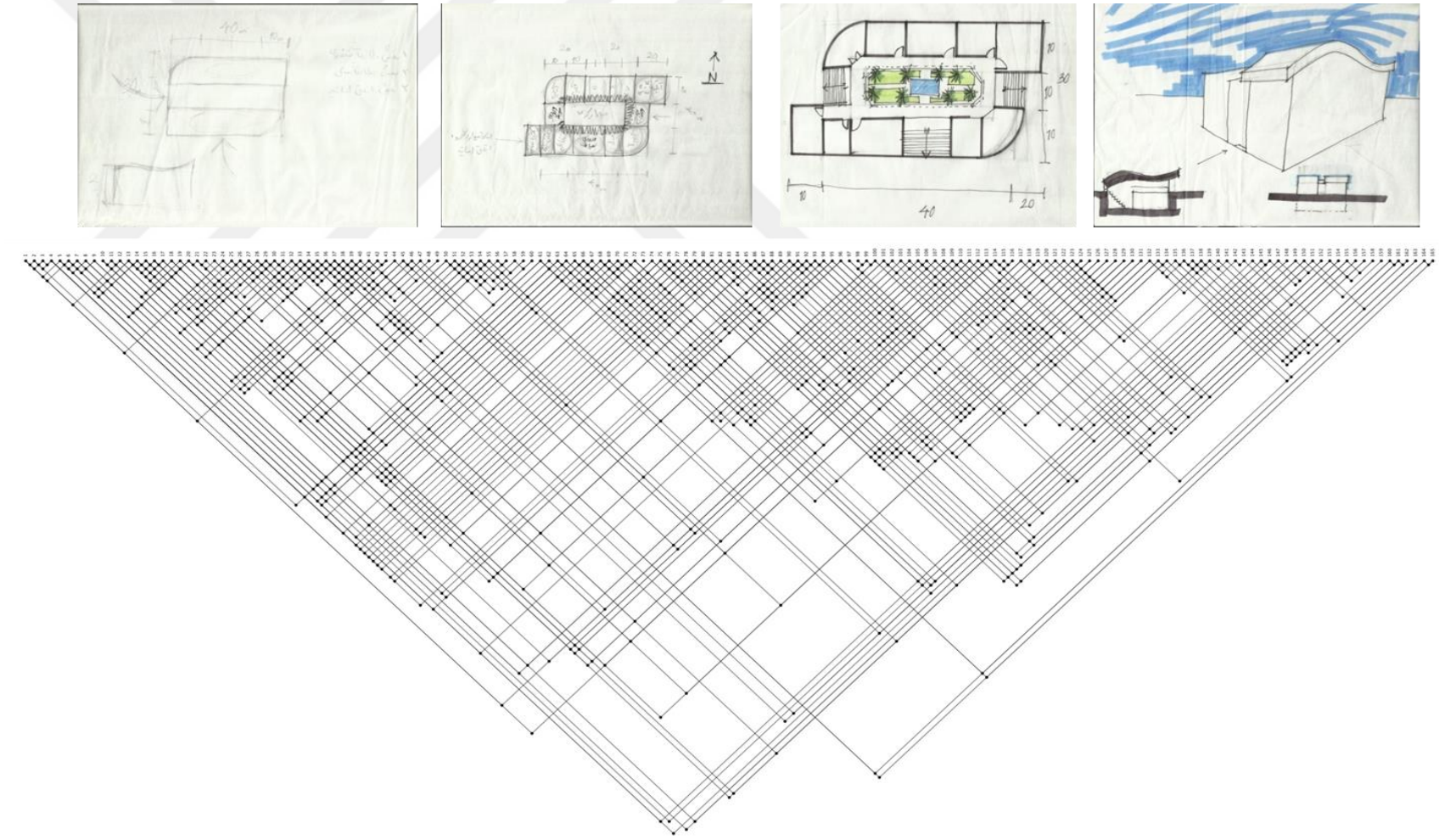


Figure 4.13 Designs and linkograph of SUB2 in pen and paper session

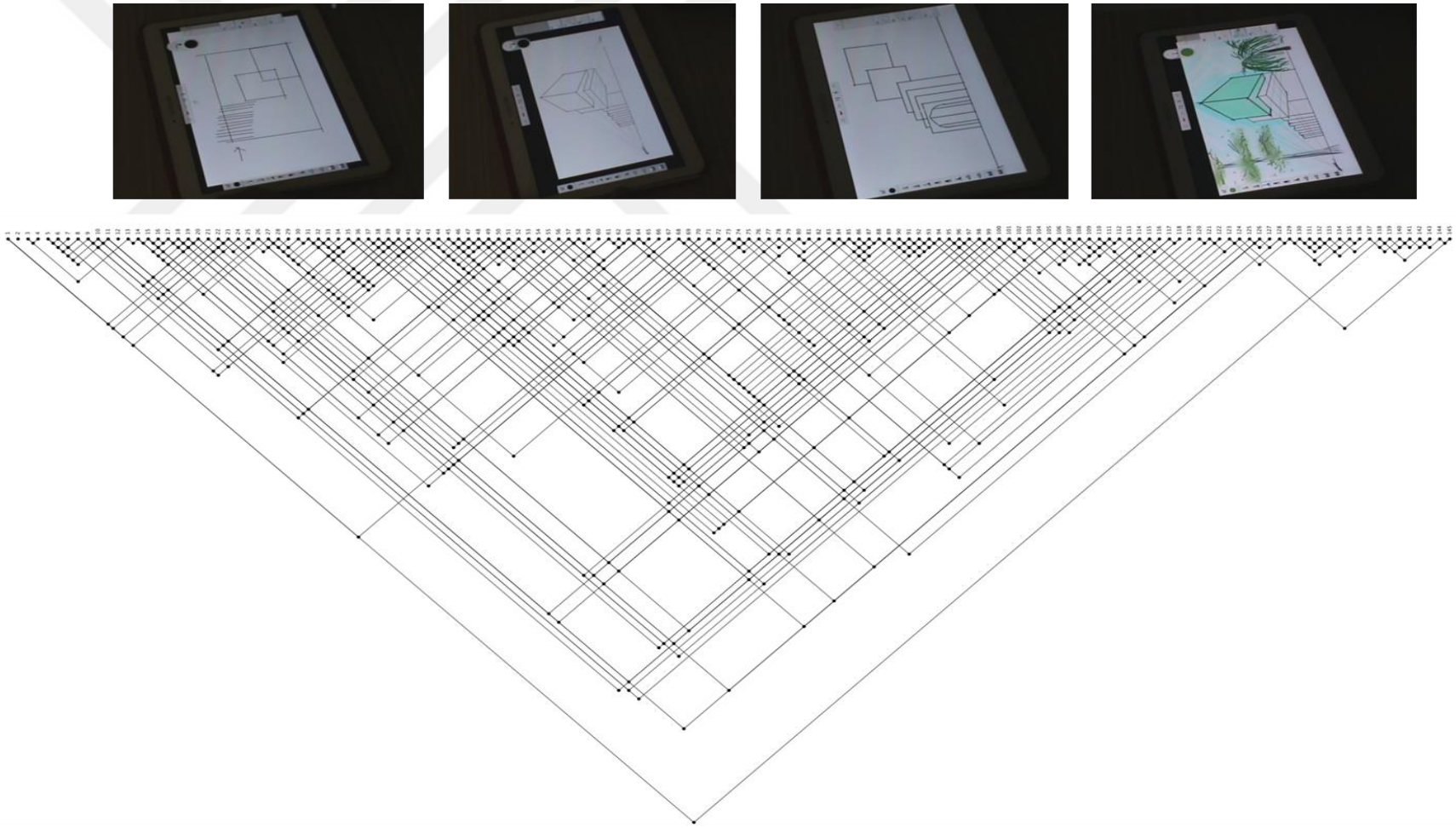


Figure 4.14 Designs and linkograph of SUB2 in sketchbook session

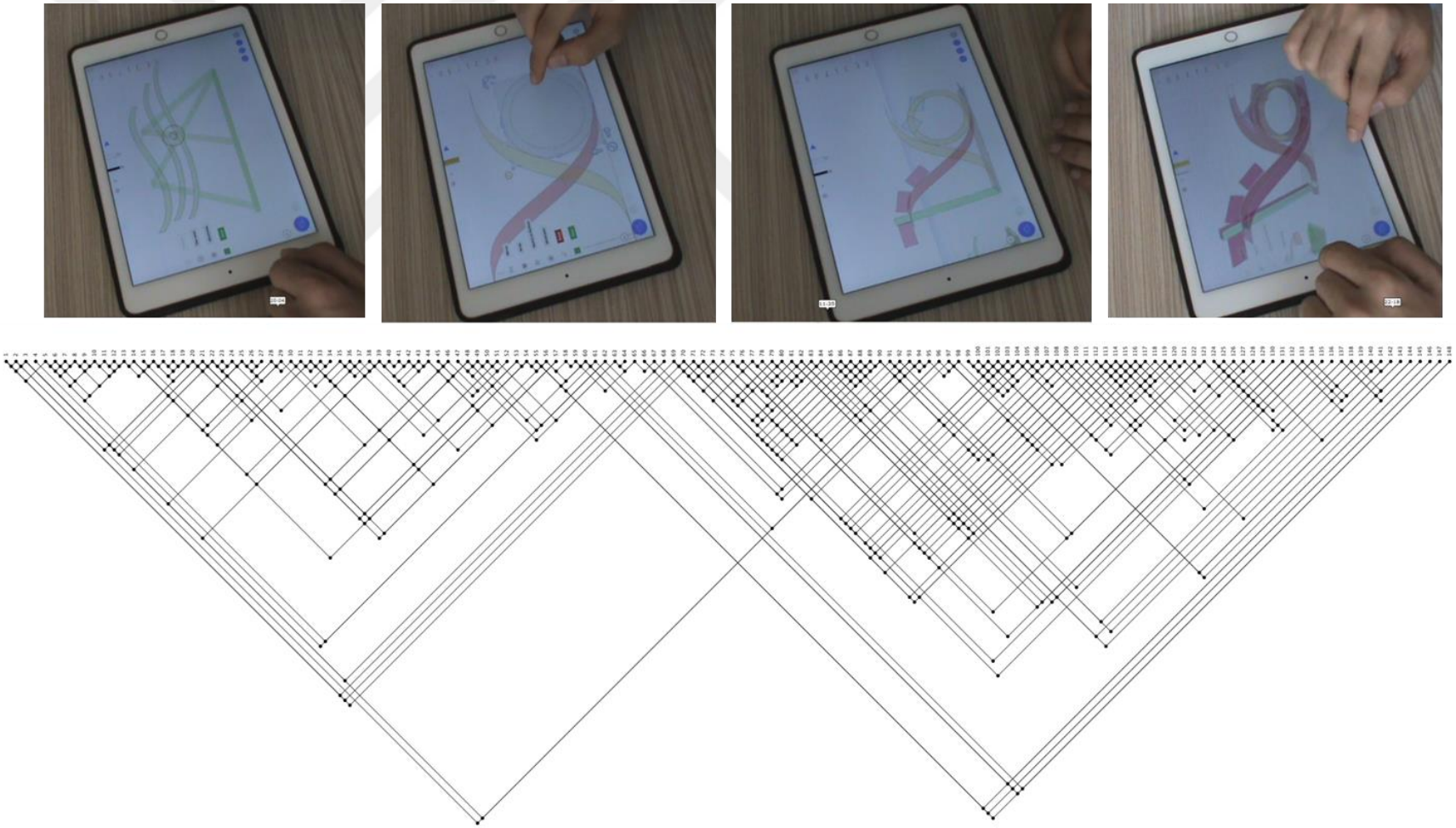


Figure 4.15 Designs and linkograph of SUB2 in uMake session

4.5 Results and Discussions

The design sessions of two subjects were recorded and the utterance from each design sessions was segmented and labeled as a design move, then were explored the links between moves to analyze of design protocol related to creativity.

Once, the Linkographs were obtained, for each linkograph, first the 'Link Index' and 'Critical Moves' percentage values, as traditional benchmarks for productive design session, were calculated. These values provide a context to discuss concerning the productivity of the design comparatively, which according to related researches is considered as an indication of creativity. Then the 'Entropy' values as recent hallmark for productivity are evaluated. Also, the mean values of x and y of sessions were compared, Further, lateral and vertical transformations as ambiguity of sketching process were counted for each session.

The analyses were carried out with the help of LINKODER (LINKOgrapher) software [89]. The excel file of each linkograph that each segment is annotated with a segment number were dragged and dropped to LINKODER software. Then the software read the input data and calculated general statistics for the imported protocol. In the general statistics window can be observed values such as total segments, total links, link ratio per segment, Mean values of X and Y and their Standard Deviations and also Forelinks, Backlinks and Horizonlinks Entropy. These values for six sessions (with Pen and paper, Sketchbook Pro and uMake software) of two subjects (SUB1 and SUB2) are shown in figures 4.16 to 4.21.

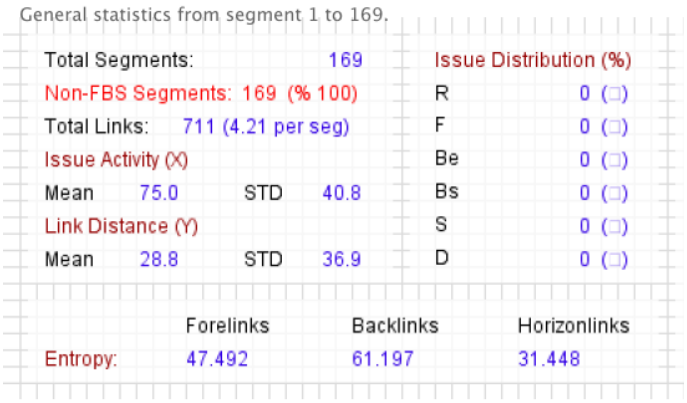


Figure 4.16 General statistics from Pen and paper session of **SUB1**

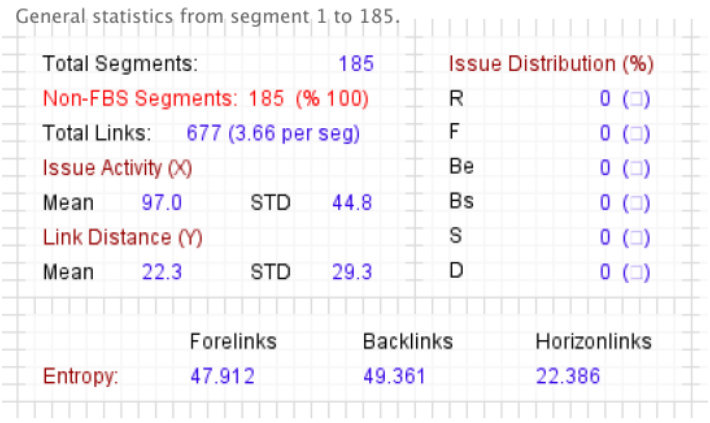


Figure 4.17 General statistics from Sketchbook session of **SUB1**

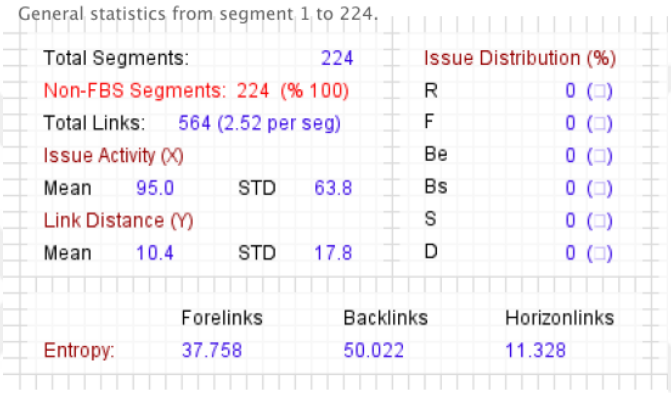


Figure 4.18 General statistics from uMake session of **SUB1**

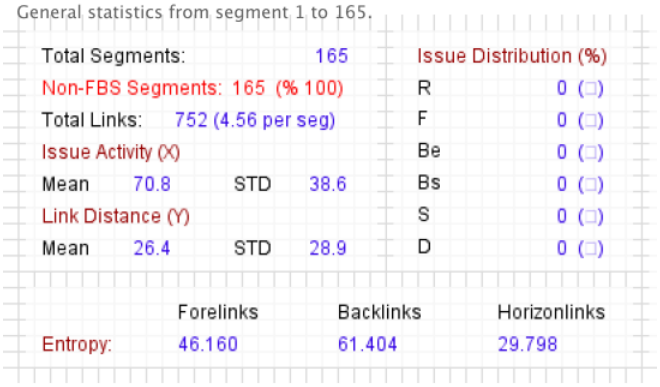


Figure 4.19 General statistics from Pen and paper session of **SUB2**

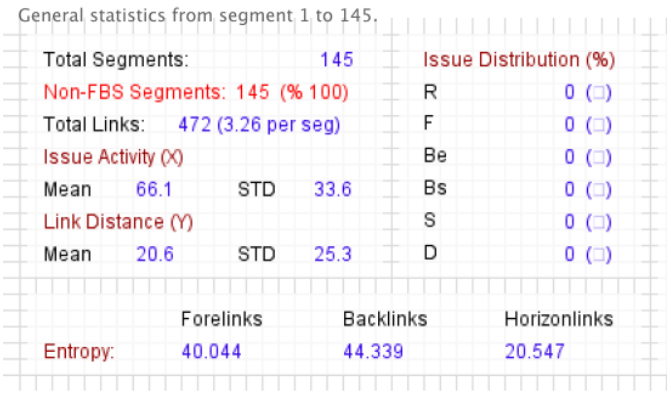


Figure 4.20 General statistics from Sketchbook session of **SUB2**

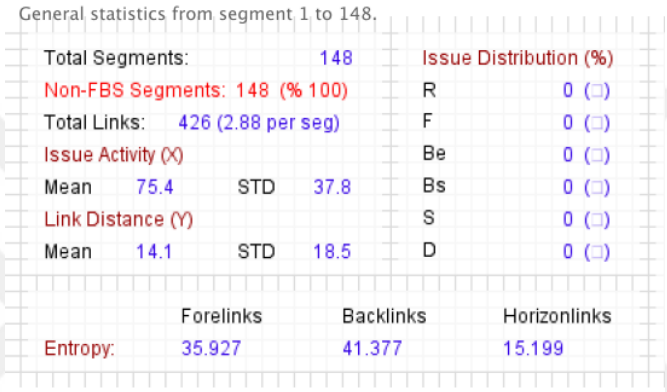


Figure 4.21 General statistics from uMake session of **SUB2**

4.5.1 Link Index (L.I.) of Subjects' Sketching Sessions

The Link ratio in the general statistics of software is equal to link index value that Goldschmidt introduced it. Also, it can be calculated by dividing total links on total segments. This value for six sessions has been summarized and shown in Tables 4.8 and 4.9.

Table 4.8 Link Indexes of **SUB1** in three sessions

	Pen and paper S.	**Sketchbook S.**	**uMake S.**
Total Segments	169	185	224
Total Links	711	677	564
Link Index	4.21	3.66	2.52

Table 4.9 Link Indexes of **SUB2** in three sessions

	Pen and paper S.	**Sketchbook S.**	**uMake S.**
Total Segments	165	145	148
Total Links	752	472	426
Link Index	4.56	3.26	2.88

In this experiment each subject are compared with herself/himself in three sessions, so for SUB1, the value of link index from the pen and paper session (4.21) is higher than two other sessions, and the Sketchbook session's value (3.66) which mimics the freehand environment, is close to pen and paper, but higher versus uMake session (2.52). Similarly, for SUB2, the value of link index from pen and paper session (4.56) is higher than two other sessions, and the Sketchbook software session value (3.26) is higher compare to uMake software session value (2.88) with little difference (Figure 4.22).

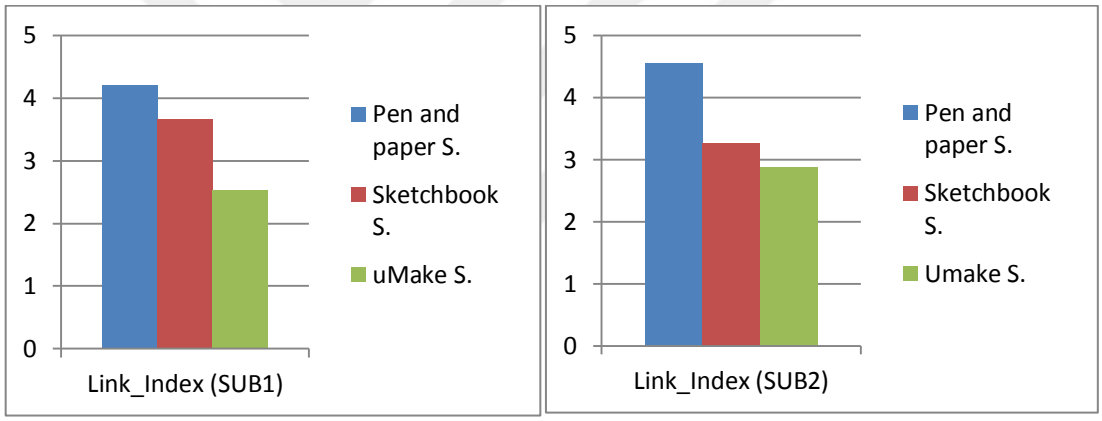


Figure 4.22 Comparison of link index of three sessions for **SUB1** (left) and **SUB2** (right)

These results indicate that two subjects in pen and paper sessions create more links over moves and according to link index values are more productive (as an indication of creativity) compare to their digital based sessions. Although, the link index is important value to determine productivity of design, but isn't merely sufficient and according to Goldschmidt the link index should be used carefully, because it may be the result of repetitions of main ideas and attempts to explore alternatives with little continuity among them. The other values (such as critical moves, entropy and lateral transformation) may confirm these results or not.

4.5.2 Critical Moves (CMs) of Subjects' Sketching Sessions

Tables 4.10 and 4.11 present the total critical moves over the total number of moves and their percentages, forelink and backlink critical moves and their percentages over the total critical moves of the SUB1 sessions and the SUB2 sessions respectively. In these tables three thresholds with 7, 8 and 9 moves have been considered for determine that a move is recorded as forelink or backlink critical moves.

Table 4.10 Critical moves as percentage with more than 7, 8, and 9 links for **SUB1**

	Forelink CMs>			**Backlink <CMs**			**Total* CMs (%)**	**No. CMs[7]**
	CM^7 (%)	CM^8 (%)	CM^9 (%)	CM^7 (%)	CM^8 (%)	CM^9 (%)		
Pen and paper S.	37 (21.9)	28 (16.6)	21 (12.4)	30 (17.8)	14 (8.3)	7 (4.1)	40%	67
Sketchbook S.	35 (18.9)	27 (14.6)	17 (9.2)	31 (16.8)	25 (13.5)	18 (9.7)	35.7%	66
uMake S.	17 (7.6)	14 (6.3)	11 (4.9)	15 (6.7)	10 (4.5)	7 (3.1)	14.3%	32

*<CMs> are counted twice.

Table 4.11 Critical moves as percentage with more than 7, 8, and 9 links for **SUB2**

	Forelink CMs>			**Backlink <CMs**			**Total* CMs (%)**	**No. CMs[7]**
	CM^7(%)	CM^8(%)	CM^9 (%)	CM^7 (%)	CM^8 (%)	CM^9(%)		
Pen and paper S.	39 (23.6)	31(18.8)	28 (17)	32 (19.4)	25 (15.1)	13 (7.9)	43%	71
Sketchbook S.	24(16.6)	16 (11)	12 (8.3)	18 (12.4)	15 (10.3)	10 (6.9)	29%	42
uMake S.	16(10.8)	12 (8.1)	6 (4.1)	5 (3.4)	1 (0.7)	1 (0.7)	14.2%	21

*<CMs> are counted twice.

Table 4.10 shows that, SUB1 in the pen and paper session has in total 40 percent critical moves which is higher compare to the two other sessions (Sketchbook with 35.7 and uMake with 14.3 percent). From these figures the pen and paper session of SUB1 seem to be more productive than her digital based sessions. The sketchbook session, has higher critical moves than uMake session. This figure, too, demonstrates

that sketchbook session is more productive versus uMake session. Also, the CMs percentage of pen and paper session and sketchbook session are close together.

Similarly for SUB2, the table 4.11 shows that, the pen and paper session has totally 43 percent of critical moves which is higher than the two other sessions (Sketchbook with 29 and uMake with 14.2 percent). From these figures the pen and paper session of SUB2 seem to be more productive than his digital based sessions. Also, the sketchbook session has higher critical moves compared to uMake session. This figure, too, demonstrates that sketchbook session is more productive than uMake session (figure 4.23). These results agree with results of link index values for SUB1 and SUB2 that show the pen and paper sessions for two subjects are more productive, consequently more creative, because they have higher link index and critical moves percentage versus the digital sessions. Also the sketchbook sessions of two subjects have higher value of link index and critical move percentages compared to their uMake sessions.

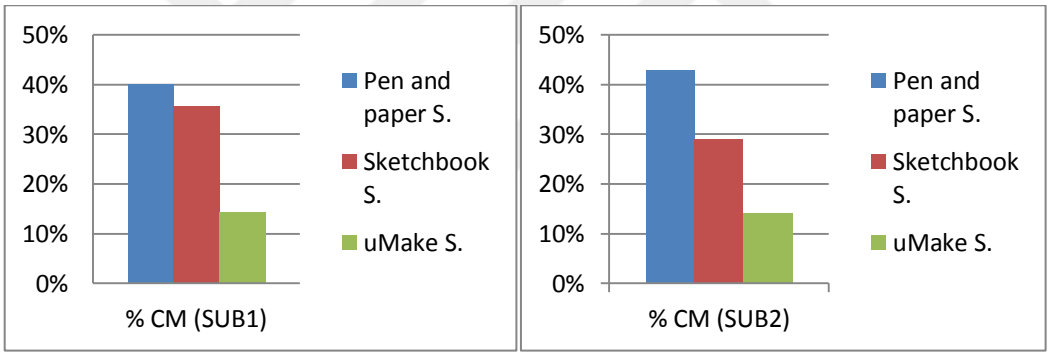


Figure 4.23 Percentage of CMs in three sessions for **SUB1** (left) and **SUB2** (right)

Tables 4.12 and 4.13 show the percentages of forelink CMs and backlink CMs of total CMs at the level of CM^7, for each session, to measure the shift between divergent and convergent thinking or find out the balance between the forelink and backlink CMs were counted. These values are important according to reviewed researches about a cyclical shift between convergent and divergent thinking as an indication of creative thought.

Table 4.12 Percentage of critical forelinks and backlinks of total critical moves for **SUB1**

	No. CMs	**% CMs**	**%CM^{7}> of CM**	**%<CM^{7} of CM**
Pen and paper S.	67	40%	55.2	44.8
Sketchbook S.	66	35.7%	53	47
uMake S.	32	14.3%	53.1	46.9

Table 4.13 Percentage of critical forelinks and backlinks of total critical moves for **SUB2**

	No. CMs	**% CMs**	**%CM> of CM**	**%<CM of CM**
Pen and paper S.	71	43%	54.9	45.1
Sketchbook S.	42	29%	57.1	42.9
uMake S.	21	14.2%	**76.2**	**23.8**

Fore SUB1, table 4.12 shows that the percentage of forelink CMs of all three sessions are higher than backlink CMs, but with little differences that indicate in three sessions the proportion of the CMs> to <CMs are almost equal (almost close to 55:45). This also means that in three sessions, there are balance between forelink and backlink CMs with more CMs> than <CMs in all sessions.

And for SUB2, table 4.13 shows that the percentages of forelink CMs of all three sessions are higher than backlink CMs, but with high differences in uMake session. This indicates that in pen and paper and sketchbook sessions, the proportion of the CMs> to <CMs are almost equal (close to 55:45) and tend to be rather balanced, with more forelinks CMs compared to backlinks CMs. This proportion in uMake session is close to 76:24.

According to earlier values of link index and CMs percentages, as a result, it seems that the balance between two types of CMs are more important parameter in assessing creativity than the percentage of forelink CMs. A frequent shifts between convergent (backlinks CMs) and divergent (forelinks CMs) thinking and balance of them according to researchers is a proof of creative thinking process. Goldschmidt evaluates the balance between divergent and convergent thinking by measuring the percentages of the forelinks and backlinks CMs within the total critical moves.

4.5.3 Entropy of Subjects' Sketching Sessions

The values of forelinks, backlinks and horizonlinks entropy are shown in general statistics window of LINKODER software (figures 4.16 to 4.21). These values for two subjects (SUB1 and SUB2) in three sessions (Pen and paper, Sketchbook and uMake) have been summarized and displayed in tables 4.14 and 4.15. Also in figures 4.24 and 4.25 these values are compared together.

Table 4.14 Three type entropy and their cumulative total entropy for **SUB1**

	Pen and Paper S.	**Sketchbook S.**	**uMake S.**
Forelink Entropy:	47.49	47.91	37.76
Backlink Entropy:	61.2	49.36	50.02
Horizonlink Entropy:	31.45	22.39	11.33
Cumulative Total	140.14	119.66	99.11

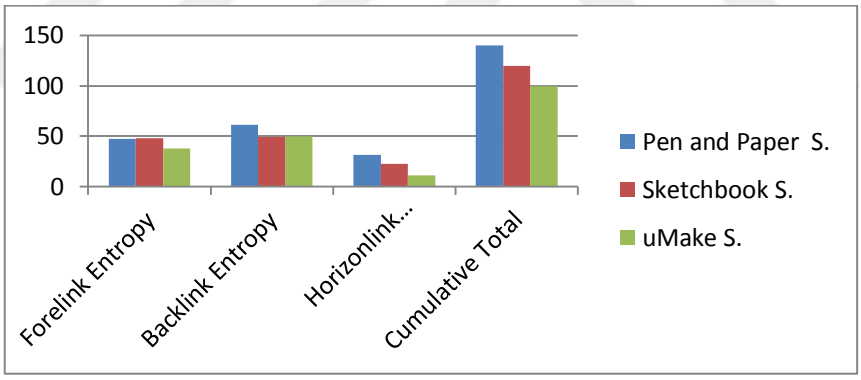


Figure 4.24 Comparison between three types of entropy in three sessions for **SUB1**

Table 4.15 Three type entropy and their cumulative total entropy for **SUB2**

	Pen and Paper S.	**Sketchbook S.**	**uMake S.**
Forelink Entropy:	46.16	40.04	35.93
Backlink Entropy:	61.4	44.34	41.38
Horizonlink Entropy:	29.8	20.55	15.2
Cumulative Total	137.36	104.93	92.51

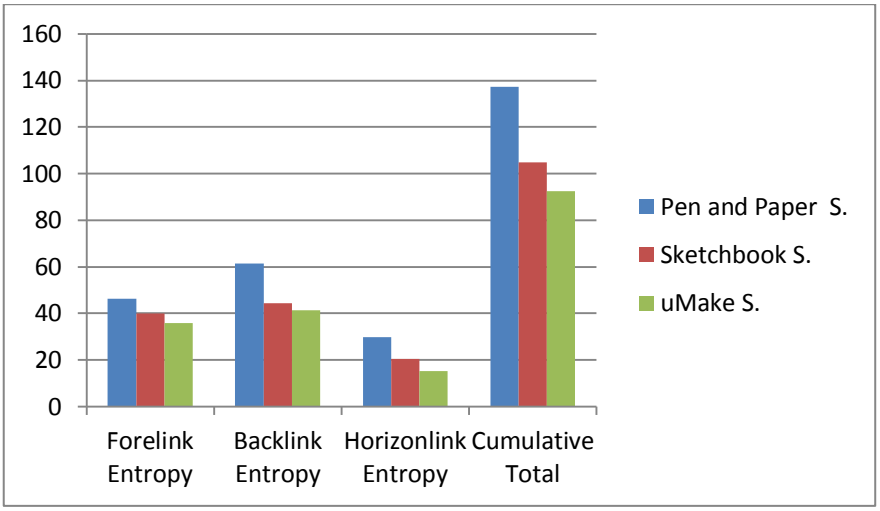


Figure 4.25 Comparison between three types of entropy in three sessions for **SUB2**

According to table 4.14 and figure 4.24, for SUB1, forelinks entropy values in two sessions (Pen and paper and Sketchbook) are almost equal (47.49 against 47.91) and are higher versus forelinks entropy of uMake session (37.76). In the same way, the backlinks entropy values in pen and paper session (61.2) is higher than two other sessions, and uMake session (50.02) and sketchbook session (49.36) have almost equal backlinks entropy. In horizonlinks entropy, the pen and paper session has a higher value (31.45) compared to two other sessions; also, entropy of sketchbook session (22.39) is higher than uMake session (11.33). In all three sessions, the values of backlinks entropy are higher than forelinks and horizonlinks entropy. In total, the value of cumulative entropy shows that the pen and paper session have higher entropy value (137.36) compared to two other sessions and the entropy of sketchbook session (104.93) is higher than uMake session (92.51).

These results demonstrate that in the case of forelink entropy, the pen and paper and sketchbook sessions have nearly same forelinks entropy that denote these sessions have higher opportunity in initiating design moves compared to uMake session. This shows in pen and paper and sketchbook sessions of SUB1, ideas are relatively high in connection that have many influences in conversation. This agrees with structure of linkography and the results of link index values. In uMake session designer generates some new ideas without any connection between them that cause a low forelinks entropy.

In the case of backlink entropy, the pen and paper session has a higher value than digital sessions, that indicates ideas in pen and paper session are build more upon previous ideas and are revisited of them compared to digital sessions. Digital sessions have almost equal backlinks entropy, but with two different reasons; in sketchbook session ideas are backlinked to many previous ideas while in uMake session ideas are very novel, that in both situations, the bachlink entropy tend to be low.

And finally in horizonlink entropy case, the pen and paper session has higher horizonlinks than digital sessions that shows it is a mixture of short and long links that indicates it has both cohesive and incubated ideas. In uMake session, interconnected moves are close together without any away links that encourages strong cohesiveness; in contrast, in the pen and paper session linked moves are far apart that encourages the occurring of incubation. In all three sessions the high values of backlinks entropy compared to forelinks and horizonlinks entropy could shows higher opportunity of building ideas on initiating moves.

According to table 4.15 and figure 4.25, for SUB2, forelinks entropy value in pen and paper session (46.16) is higher than sketchbook (40.04) and in sketchbook session forelinks entropy value is higher compared to uMake session (35.93). In the same way, the backlinks entropy values in pen and paper session (61.4) is higher than two other sessions, and uMake session (44.34) and sketchbook session (41.38) have almost equal backlinks entropy. In horizonlinks entropy, the pen and paper session has a higher value (29.8) than two other sessions; also the horizonlinks entropy of sketchbook session (20.55) is higher versus uMake session (15.2). In all three sessions the values of backlinks entropy are higher than forelinks and horizonlinks entropy. In total, the cumulative entropy values show that the pen and paper session have higher entropy value (137.36) than two other sessions and the entropy of sketchbook session (104.93) is higher compared to uMake session (92.51).

For SUB2, results denote that in the case of forelink entropy, the pen and paper session has higher values than digital sessions. And the uMake session has lower forelink entropy than other sessions. This suggests that the designer in uMake session creates low opportunities in new initiations that shows ideas have almost a little impact in conversations compared to other sessions. In the case of backlink and

horizonlink entropy of SUB2, the results and discussions related them are similar to results of SUB1 and follow up the same logics. This similarity is visible in qualitative outcomes of experiments; and the structure of linkographs also, illustrates and reflects this similarity. For SUB2, also, in all three sessions, the high values of backlinks entropy compared to forelinks and horizonlinks entropy could shows higher opportunity of building on initiating moves.

In totally, the cumulative entropy signifies that both SUB1 and SUB2 in their pen and paper sessions have a richer idea generation processes and more opportunities for developing ideas compare to their digital sessions; so, the pen and paper sessions of SUB1 and SUB2 seems to be more productive and creative than their digital sessions. And among digital sessions, sketchbook sessions seems to be more productive compared to uMake sessions.

The results of entropy outcomes also match the results of link index and critical moves as earlier benchmark, and once again emphasize on productivity and creativity of the pen and paper sessions (in figures 4.26 and 4.27, these three results are shown and compared for three sessions of SUB1 and SUB2).

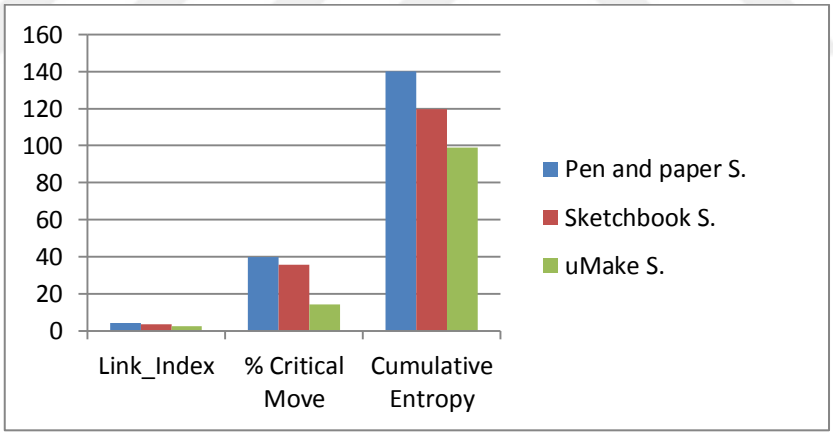


Figure 4.26 Results of link index, critical moves and entropy in three sessions for **SUB1**

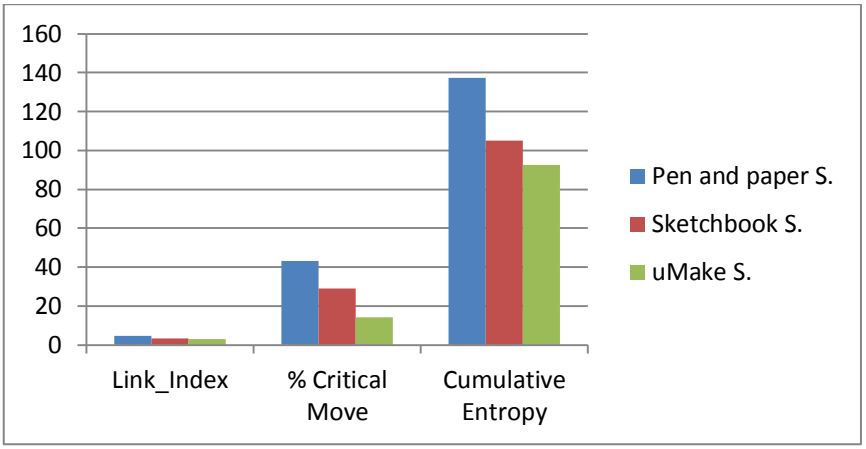


Figure 4.27 Results of link index, critical moves and entropy in three sessions for **SUB2**

It was found for six design sessions, the entropy have certain relationships with the link index and critical moves of linkographs. The sequence from high to low values, in three sessions for three parameters, is same and identical. This figure illustrates for both participants, the pen and paper sketching have higher values of link index, percentage of critical moves and entropy compared to digital sketching; also among digital sessions, these values in digital sketching process with Sketchbook are higher than uMake sketching process.

4.5.4 Mean Value of X and Y of Subjects' Sketching Sessions

The mean values of X and Y and their standard deviation (STD) for two subjects in three sessions, extracted from LINKODER software, have been shown in tables 4.16 and 4.17.

Table 4.16 The mean values of X and Y and their standard deviation in three sessions for **SUB1**

	Pen and paper S.	**Sketchbook S.**	**uMake S.**
Issue Activity (X):			
Mean	75	97	95
STD	40.8	44.8	63.8
Link Distance (Y):			
Mean	28.8	22.3	10.4
STD	36.9	29.3	17.8

Table 4.17 Mean values of X and Y and their standard deviation in three sessions for **SUB2**

	Pen and paper S.	**Sketchbook S.**	**uMake S.**
Issue Activity (X):			
Mean	70.8	66.1	75.4
STD	38.6	33.6	37.8
Link Distance (Y):			
Mean	26.4	20.6	14.1
STD	28.9	25.3	18.5

For SUB1, table 4.16 indicates that the mean values of x in sketchbook and uMake sessions are almost equal (97 and 95 respectively) and are higher than pen and paper session (75). Also, STD of uMake session (63.8) is higher than other sessions. These results suggest that the links in sketchbook and uMake sessions are distributed more toward the end of the session compared to pen and paper session; also show that in digital sessions designer creates more ideas versus the pen and paper session. But the differences between these two sessions (sketchbook against uMake) imply that the links of two sessions have concentrated around the means differently. The high value of STD in uMake session indicates that the nodes are more dispersed than the other sessions.

For SUB2, table 4.17 shows that the mean value of X in uMake session (75.4) is higher than other sessions and this value in pen and paper session (70.8) is higher than sketchbook session (66.1); and differences are almost equal. Also, STD value in pen

and paper and uMake sessions are almost equal (38.6 and 37.8 respectively) and are higher than sketchbook session (33.6). These indicate in the uMake session, the nodes are distributed more towards the end of the session and more dispersed compared to other sessions.

Comparing the mean values of x with previous link index, critical moves and entropy values suggests that, the digital sessions have higher mean values of x than pen and paper sessions; while, the pen and paper sessions have higher values of entropy compared to the digital sessions. This indicates more nodes among moves, were created in the beginning of pen and paper sessions. Reviewing the linkographs, the uMake sessions have a spares links that caused dropping in entropy. So, the higher entropy in pen and paper sessions, does not correlate here with the distribution of links toward to the end of the sessions which is the indication of better inter connectivity of ideas; and this can suggest that, designers in pen and paper design sessions, created bad design moves that produced less integration towards the end of sessions. But since this study aims to evaluate idea generation process, so the dropping of entropies toward to end of sessions, according to researchers, does not produce any problems. Because more ideas are created in the beginning of a session, and it seems there are poor opportunity for ideation at the end of a session.

The mean values of Y and STD for both SUB1 and SUB2, in pen and paper sessions are higher than other sessions and these values in sketchbook sessions are higher than uMake sessions; these indicate that the link distance in pen and paper sessions for two subjects, are longer than other sessions. Also, a higher standard deviation in pen and paper sessions, suggest more mixture of long and short links.

4.5.5 Lateral and Vertical Transformations of Subjects' Sketching Sessions

Lateral transformation numbers for two subjects in three sessions, are counted based on Gürsoy's [59] study that was described earlier. These values are the sum of colored triangles and orphan moves for each linkograph (as shown in table 4.18 for two subjects during three sessions). Also the mean values of Y (shown in figures 4.14 to 4.21) of linkographs of three sessions for two subjects are applied to compare the

vertical transformation of each design session. These values have been shown in tables 4.19 and 4.20.

Table 4.18 Lateral transformation determination on linkograph for **SUB1** and **SUB2** in three sessions

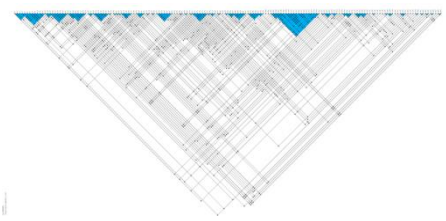
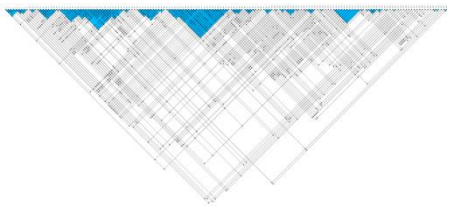
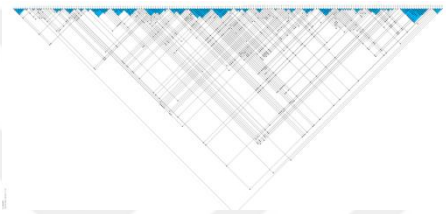
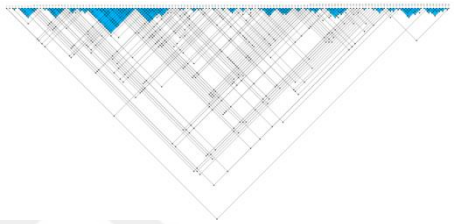
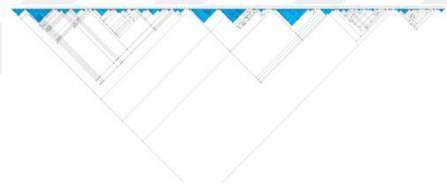
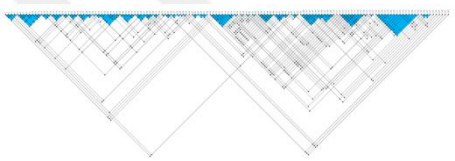
	SUB1	**SUB2**
Pen and paper S.		
Sketchbook S.		
uMake S.		

Table 4.19 Lateral and vertical transformation values for **SUB1**

	Lateral Transformations	**Vertical Transformations**
Pen and paper S.	47	28.8
Sketchbook S.	51	22.3
uMake S.	68	10.4

Table 4.20 Lateral and vertical transformation values for **SUB2**

	Lateral Transformations	**Vertical Transformations**
Pen and paper S.	38	26.4
Sketchbook S.	45	20.6
uMake S.	42	14.1

Tables 4.19 show SUB1 in digital session with uMake software produced higher lateral transformations (68) compared to other sessions; and in digital session with sketchbook software made higher lateral transformations (51) than pen and paper design session (47). These results, too, are inconsistent with the previous results of link index, critical moves and entropy. Also SUB2, similarly made higher number of lateral transformations in digital session with sketchbook software (45) compared to other sessions but close to uMake session (42); he created the least number of lateral transformations in pen and paper session (38).

Also, tables 4.19 and 4.20 show two subjects, in three design sessions, produced vertical transformations values with certain relationships and have the same sequences from high to low values; the pen and paper sessions of two subjects are higher vertical transformations values compared to other sessions and for each subjects the sketchbook sessions have higher vertical transformations than uMake sessions.

Due to the nature of digital media, it is possible to cancel or undo old orders and start again to draw a new and different order or idea; therefore, given this fact, a part of the large number of lateral transformations in digital sessions can be interpreted. For example, the SUB1 at the uMake design session created more ideas, without further detailed working on them; she was frequently drawing and then undoing the drawn order and ideas or started the next new idea. Lateral transformation as previously is defined as a transformation where “movement is from one idea to a slightly different idea” [3] and vertical transformation is a transformation where "movement is from one idea to a more detailed version of the same idea" [3]. Thereby, it can be one of the reasons for increasing the number of lateral transformations in digital sessions. In fact, this was predictable according to the counting method of the number of lateral transformations. Also, in both pen and paper design sessions, designers moved forward with further detailed and repeated work on main idea, which shows a high number of vertical transformations, as well as a drop in number of lateral transformations. This is especially evident in the SUB2 design process; as can be seen, in pen and paper design, he has the least lateral transformations, even compared to the SUB1.

4.5.6 Overall Results

The overall outcomes of this study from five experiment values are summarized in below as shown in tables 4.21 and 4.22.

Table 4.21 Comparison of the overall outcomes of experiment for **SUB1**

	Link Index	**% CMs**	**Entropy**	**Mean Values of X**	**Lateral Transformation**
Pen and paper S.	4.21	40%	140.14	75	47
Sketchbook S.	3.66	35.7%	119.66	97	51
uMake S.	2.52	14.3%	99.11	95	68

Table 4.22 Comparison of the overall outcomes of experiment for **SUB2**

	Link Index	**% CMs**	**Entropy**	**Mean Values of X**	**Lateral Transformation**
Pen and paper S.	4.56	43%	137.36	70.8	38
Sketchbook S.	3.26	29%	104.93	66.1	45
uMake S.	2.88	14.2%	92.51	75.4	42

The tables 4.21 and 4.22 show that, the link index, critical moves and entropy values, as indications of productivity and creativity of design sessions, have similar relationship in three sessions for two subjects. On the other words, each subject has high values of link index, critical moves and entropy in pen and paper compared to his/her digital sessions; also two subjects in the sketchbook sessions make higher values of link index, critical moves and entropy versus his/her uMake sessions. However, the mean values of X and lateral transformations number, as confirmations of main values, are different relationship in three sessions of subjects as discussed in previous sections.

CHAPTER 5

CONCLUSION

In the first chapter of this study, the objective of thesis and research questions and hypothesis were introduced. Based on research questions and hypothesis, also according to purposes of study, the chapter two has been established in order to study the conventional freehand sketching as commonly design tool in architectural education and discover the relationship between sketching and creativity. This chapter depend on different research related to freehand sketching, responds to questions 1 and 2 and suggest that paper based sketching is yet the main and avant-garde design tool, because it, regarding to own specific features, can encourages creativity of designers. Chapter three established based on questions 3 and 4 and aimed to find out and explore the current situation of digital sketching in early design stages and its challenges and obstacles for integrating to conceptual design especially in creativity point of view, and why it is not commonly used in educational context. In this chapter, a pilot study was conducted to evaluate design educators' opinions about digital sketching and their tendency to use them, also, whether it can replace traditional sketching. And finally, chapter four was founded based on question 5 that aimed evaluating and comparing the digital design sketching versus paper based sketching, and investigating the impact of digital media on creativity of students via protocol analysis method and linkography analysis technique. The findings of three chapters were discussed in related sections and in following the conclusions of results and discussions are suggested.

5.1 Relationship between Traditional Pen and Paper Sketching and Creativity

In chapter two, architectural design as the core of architecture education, and also design problem solving and creativity as a key element in design idea generation process have been described. Also this thesis focuses on early conceptual stage, so in this chapter traditional freehand sketching as the main designing, thinking and presenting tool, especially related to creativity has been explored and evaluated.

The findings indicate that, the architectural design as a complex, ill-defined and ill-structured problem solving, unlike the science and mathematics, don't has single correct answer. It is realized in studios that follow the learning by doing method; the procedure commonly begins with a problem and an effort to solve it. In current mode studios are based on educator-centered method that can inhibit students' creativity. So the design studio should be a productive environment to create new design thoughts rather than imposing the instructors' own ideas on students.

The early design stages of design as the most important stages in design process relates to design thinking, problem solving and idea generation activities, and is the foundation for design development. Idea generation is the creation of new solution to the existing problem that is developed in designer's mind; so it is related to creative design thinking and imagination process. Divergent and convergent thinking are two modes of creative thought. Findings suggest that design involves both convergent and divergent thinking that creativity can be seen as a balance between these two modes of thought rather than the ability for divergent one.

Findings show that during the preliminary design stage, paper based sketching is used as the main designing tool for thinking, solving problem and exploring the best solution. Sketches externalize thought and provide a playground for discovering unexpected properties through revising and refining old ideas that can enhance creativity. Sketch by its ambiguous features associates with creativity and supports reinterpretation that impedes designers to crystallize and fixate ideas too early. Also sketching is an effort to generate different alternatives and changing them to find an original ideas, it is an activity that is sequentially moving between convergent and divergent thinking. All of them are evidence to prove the strong relationship between sketches and creativity. So according to first and second questions of research, the pen

and paper sketching is yet common and main design tools in the early stages of design and also it has a strong relationship with creativity.

5.2 The Situation of Current Digital Sketching in the Conceptual Phases of Architectural Design

In chapter three, the current status of digital sketching in early design stage and their challenges in the educational filed, especially related to creativity are explored. Findings indicate that computer by new interfaces began to affect the thought process of designer in the early stage of design that has created a wave of discussions and challenges in architectural research and education. Recent developments in digital tools show a shift toward conceptual design interfaces; but due to third research question, they are still not commonly used in the early design stages. It seems that this returns, on the one hand, to the user interface of digital systems that encourage working with precision and detailed and do not allow vagueness and uncertainty which plays a significant role in conceptual design, and on the other hand, using of digital systems does not match the speed of thinking process of designer unlike the conventional freehand sketching. In addition, in this case the ability of users to use this medium should not be ignored.

Studies show despite to all of these, digital tools can support and enhance creativity. They can encourage creative behaviors and allow stimulating and exploring wide range of design alternatives by rethinking previous ideas and improve them. Therefore, many researchers attempt to propose recommendations to enhance digital interface or new working ways in order to support creativity and sketching. According to researches in order to designing computer interfaces that feel natural and close to traditional sketching and support creativity, the digital systems must be able to solve ambiguity and enable the designers to concentrate on the design problems and not on how to use the programs; so a digital sketching tool should recognize marks, shapes and their spatial relationships by identifying the dimensions of sketching. The emergence of some pen-based sketching systems, has created a strong desire - especially for the younger designers - to use them in the conceptual design phases, while the inadequacy of these software in encouraging ambiguity and creativity, has

caused that, many of experienced designers and academics to doubt in using these tools, or even, entirely oppose to use them in the design thinking process.

The results of pilot study in educational field also support the current discussions in research field and theoretical findings that suggest the professors doubt over digital tools that instead of using them directly, they prefer the combination of freehand sketching and CAAD programs. So according to theoretical and survey findings the digital based sketching is not sufficient and cannot replace traditional sketching (question four of research). However, findings indicate that there is a tendency to use these tools among educators and their students. It is expected with the advances in user interface of digital programs, in future times, they will be used as designing and thinking tools in the early stages of architectural design at educational context. The interdisciplinary researches between architecture, mathematics and computer science can create proper solutions for these problems.

5.3 Comparing and Evaluating Digital Sketching Tools vs. Pen and Paper Sketching in Terms of Creativity

The main purpose of this research was to evaluate and examine digital sketching tools in the conceptual design phases of architecture and assess its impact on the creativity of the architecture students.

In this research, the parameters, which have been identified by researchers as criteria for the evaluation of creativity and productivity of design, via linkography analysis method, have been used. These parameters were combined and used together for first time in this thesis and include: Link Index, Critical Moves and Entropy. The Lateral Transformation and Mean values of X and Y were calculated to verify and explain the main criterions. The results of experiment show the values of link index, percentages of critical moves and entropy match together. On the other words, there are certain relationships between results of link index, critical moves and entropy; and there are same sequences from high to low values in three sessions for three parameters. This figure illustrates both participants in the pen and paper sketching have higher values of link index, higher percentages of critical moves and entropy compared to digital sketching. This indicates subjects in pen and paper sessions created the more dense

linkographs that shows interconnectivity of moves in conventional sketching sessions were more than digital sessions. Also they had a richer idea generation process and more opportunities for developing ideas in their pen and paper compared to digital sketching processes.

Also among digital sessions, these values in digital with 2D Sketchbook sketching software are higher versus 3D uMake sketching process. This may be because of that the Sketchbook software on pen-based systems provides an environment that imitates the pen and paper sketching medium that allows designer to sketch on a tablet with a digital pen or touch a finger.

The convergent and divergent thinking, as apparent in <CMs and CMs>, tend to be rather balanced, but with superiority to divergent thinking. This according to Goldschmidt [39] shows that "in creative design, one finds more divergence than convergence but the proportions, which appear to remain rather stable, also boast a fair amount of convergence".

The higher mean values of x in the digital processes suggest that, designers in pen and paper design sessions, produced more integration in beginning of sessions. Since this study aims to evaluate idea generation process, so the dropping of entropies toward to end of sessions, does not produce any problems in creativity point of view. Because more ideas are created in the beginning of a session, and there are few opportunity to create ideas toward the end of sessions. Also, findings show the digital media support designer to make more lateral transformations over its working nature. This contributes designers to create more different ideas and prevent early crystallization. Therefore, the subjects in their pen and paper sketching processes were more productive and consequently more creative compared to digital 2D and 3D sketching processes.

Consequently, findings imply that, these results cannot be interpreted, as designers have lower tendency to think, explore and develop ideas in digital medium, but may be explained that designers accustomed to think and reason in manual media; because they have always used conventional sketching for designing throughout their education, not the digital media. The students who participated in this experiment, had sufficient skills in pen and paper sketching, but less experience in Sketchbook and

uMake software, they only had few hours practice before the main exams. They had skills and experiences in working and designing with 3D modeling software such as Sketchup and 3D max, but these software were not suitable for the purposes of this study. Maybe if designer had the equal experience in digital programs, they could mad different results and produced rich design process and more links over moves during linkographs similar to sketching on paper. This situation according to digital background of students in current architecture schools is normally expectable. For this reason, students, with Sketchbook software because of its similarity to pen and paper sketching, can create more creative and good design process versus the uMake software. Working with uMake application was a completely new experience for them; and this certainly affects the sketching process of the participants. These applications can be used in other experiments with designers who have enough skill and experience in working with them. Finally it seems, the using and application of digital sketching in early design stages is irrefutable and in future times, parallel to progress of technology, designers can develop the suitable software for sketching and idea generation purpose with potential possibilities. This study and similar studies can be starting point for more research in this area to solve related problems and introduce optimum solutions to integrate digital sketching into the conceptual design process of architecture especially in educational field.

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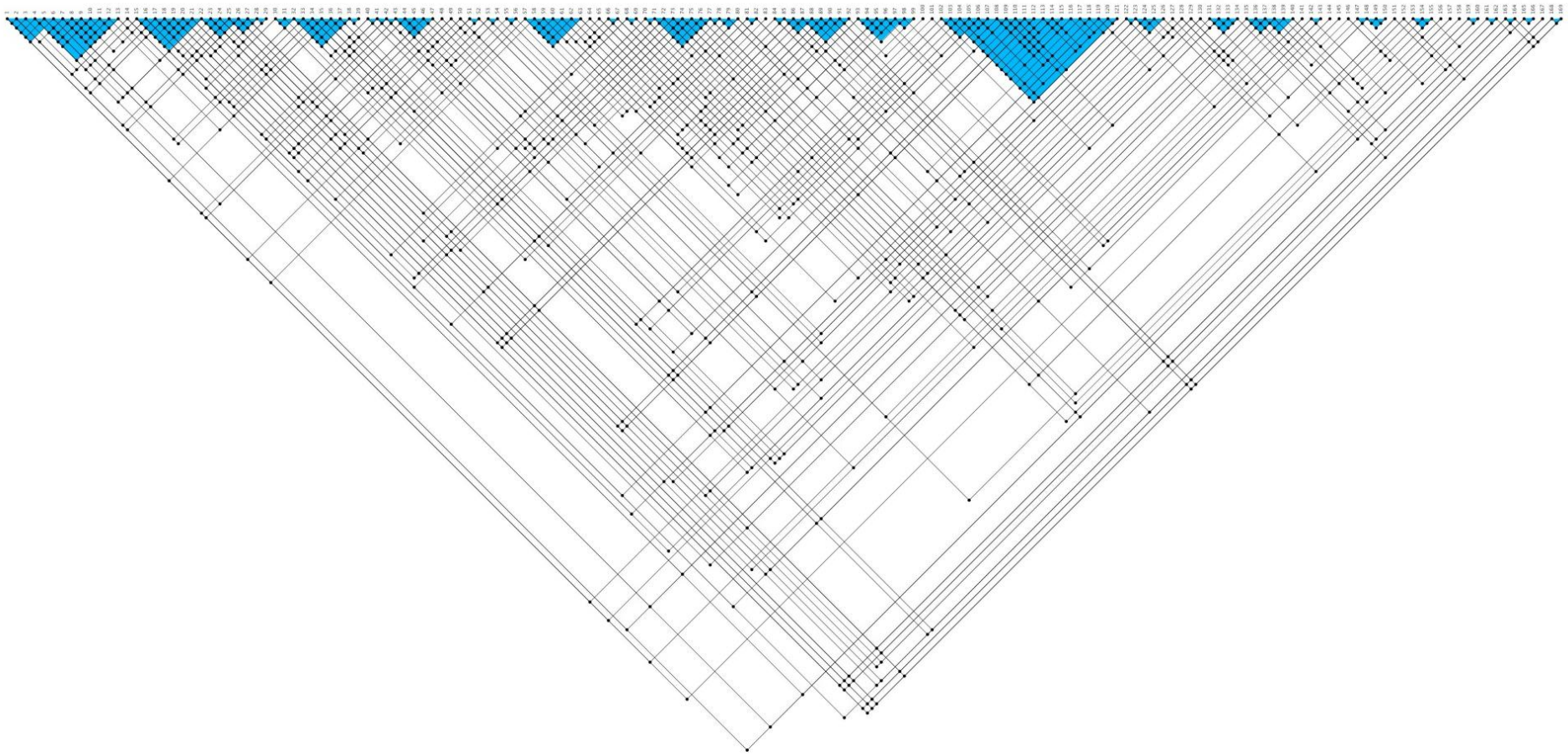
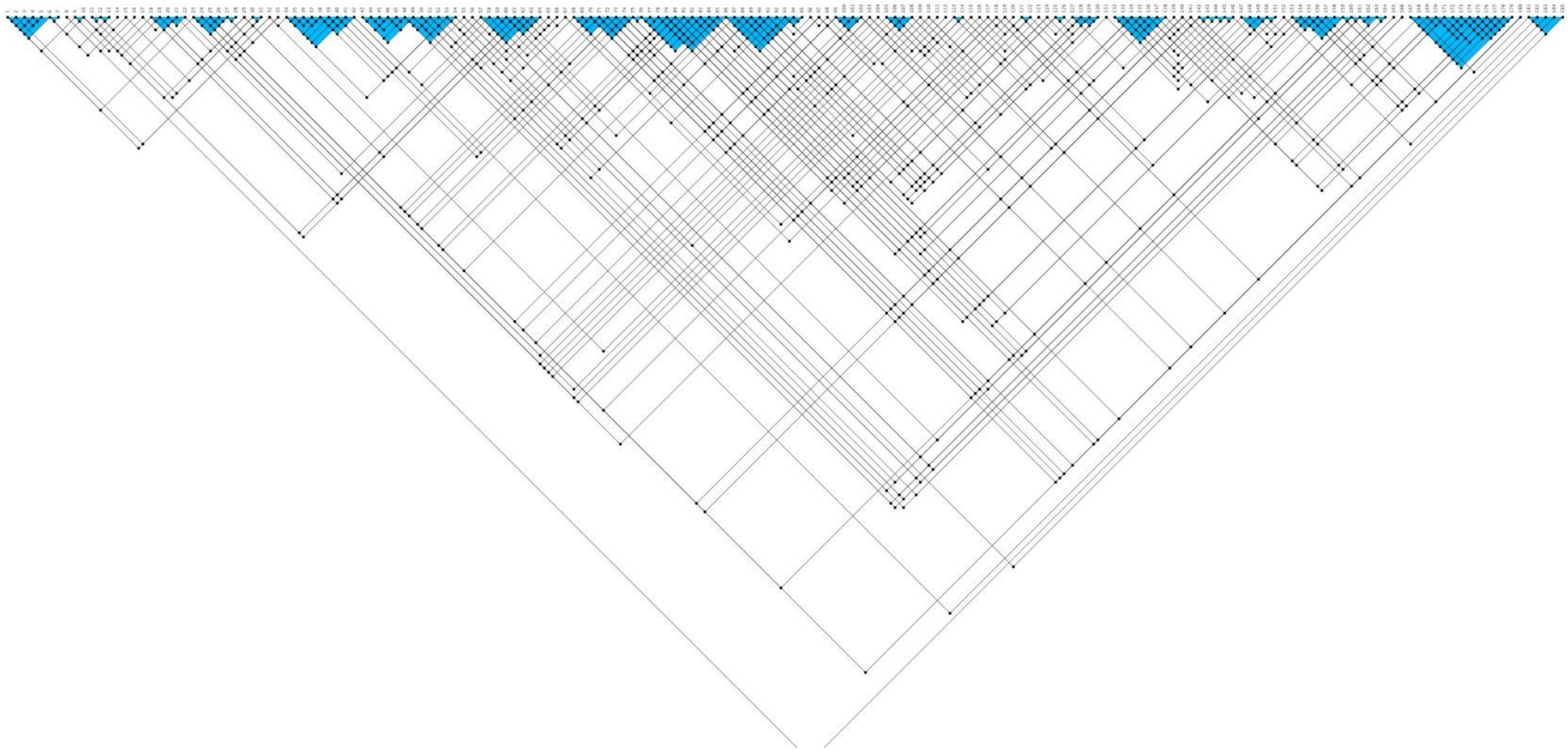
APPENDIX-A

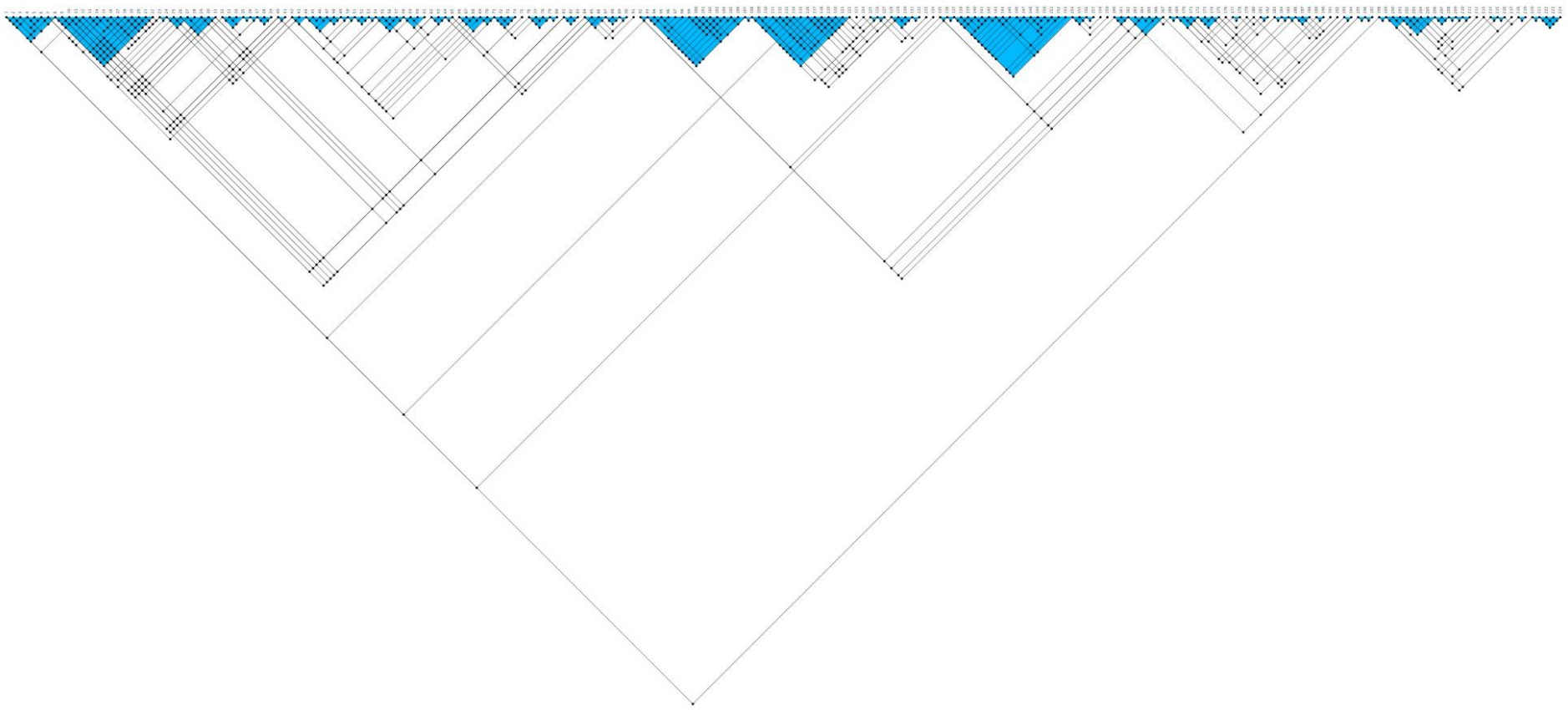
LATERAL TRANSFORMATIONS OF SUB1 & SUB2



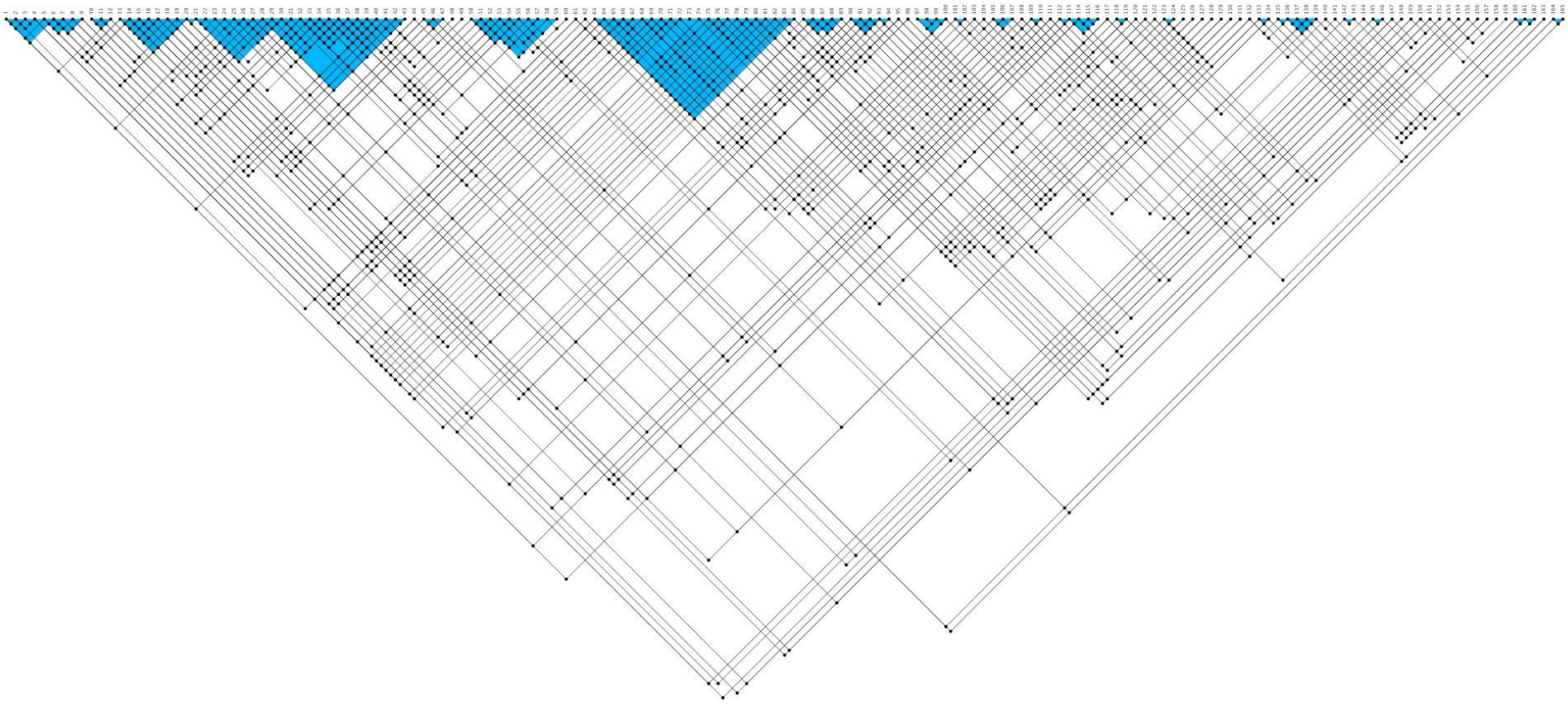
Lateral Transformation of SUB1 in Pen and Paper session



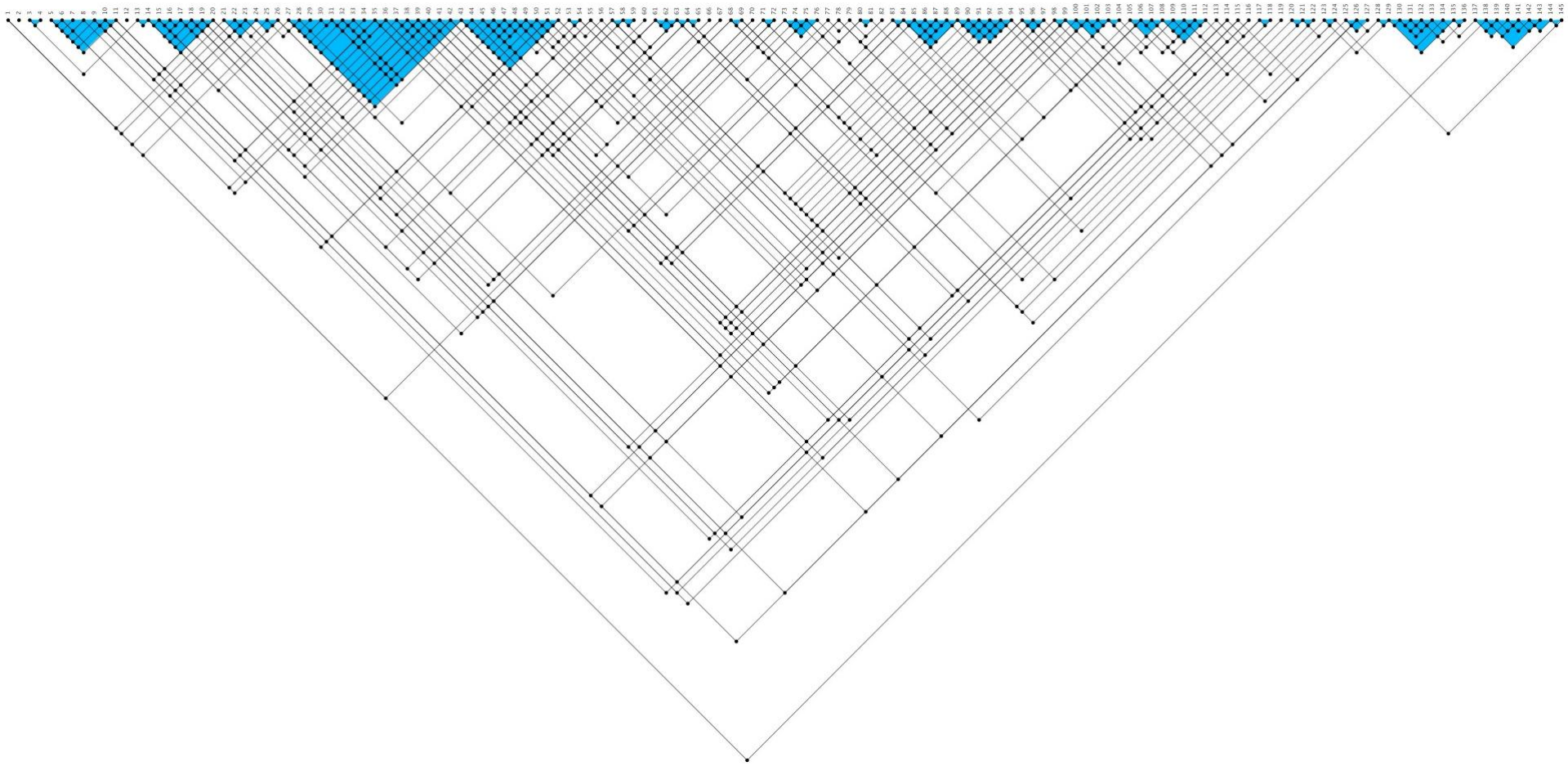
Lateral Transformation of SUB1 in Sketchbook session



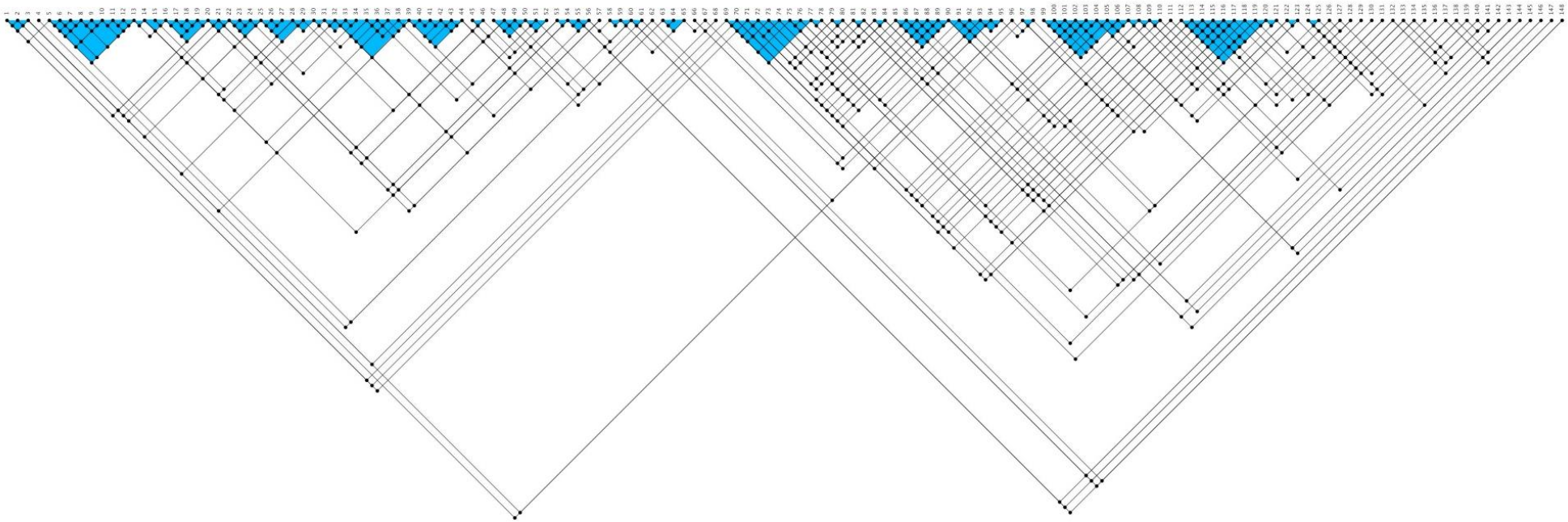
Lateral Transformation of SUB1 in uMake session



Lateral Transformation of SUB2 in Pen and Paper session



Lateral Transformation of SUB2 in Sketchbook session



Lateral Transformation of SUB2 in uMake session

APPENDIX-B

DIGITAL BASED SKETCHING SOFTWARE (2D & 3D)

1. 2D Sketchbook Pro Program

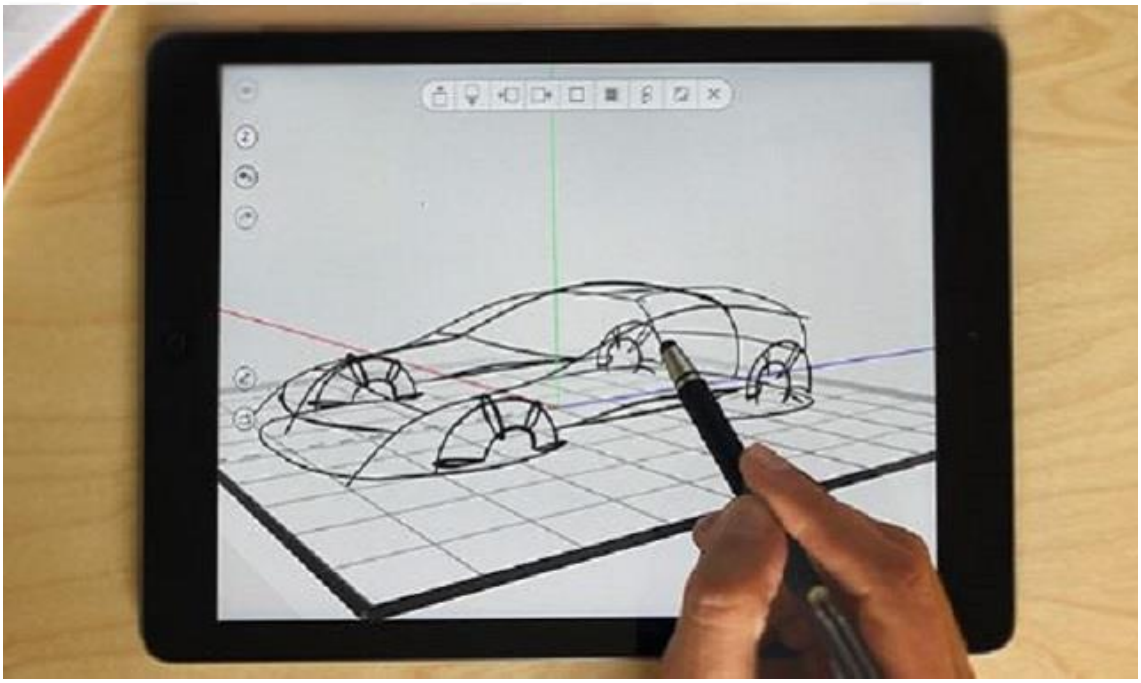
Sketchbook is one of the most used pixel graphics software and Autodesk's most popular two-dimensional software that offers an easy-to-use, intuitive interface that allows new users to be productive within minutes (http://images.autodesk.com). Sketchbook Pro uses the radial / pie interface for design, which it's superbly tools facilitates conceptual design. Drawing tools such as brushes, shadows, color palettes, rulers, lines, shapes, stamps and so on.., are among the SketchBook sketch tools.

SketchBook Pro will not only emulate traditional pencil and paper but give a new level of speed and accuracy like never before (http://images.autodesk.com) with ultra-

responsive digital pens, pencils, airbrushes and markers. Autodesk SketchBook Pro drawing and painting software has been designed for use on desktop and tablet PCs or digitized pen tablets. It's a flexible, universal sketching tool for iterating ideas.

2. 3D uMake Program

uMake is a new mobile app for the iPad device that allows users to sketch out their ideas in 3D space using natural sketching gestures. uMake combines a freehand sketching experiences with powerful 3D work space. Powerful tools allow users to create complex shapes with ease to be able to more effectively sketch and communicate an idea. uMake launched in November 2015 on the iOS App Store and is now currently available for the iPad.



Currently uMake does not use measurements or dimensions, or have a way of setting scale. The reason for this is that the concept behind uMake is to be more around sketching in 3D space. Sketching in uMake is just like sketching on paper-- just draw a line on the screen with a finger or stylus to start a sketch. The power of uMake's sketching experience is in both its intuitive nature - that being just like sketching on paper, combined with the ability to sketch a line in 3D space, and its power to create beautiful boolean curves that are then editable (https://www.umake.xyz/).

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2010	Zanjan Sama College	Executive Secretary of Conference of Electronic
2001-2005	Armanshahr Consulting Engineers, Tehran	Manager of Local Engineering Office at Zanjan
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PUBLISHMENTS

Papers

1. Heidari, p. & Polatoğlu, Ç. (2018) Current Discussions on Digital Sketching in the Early Stages of Architectural Design in Education, International Journal of Architecture & Urban Planning, Iran University of Science & Technology (ACCEPTED)

Conference Papers

1. Heydari, P., Hojjati, A., (2013) Transformation Process of Intermediate Cities with a Review Literature and Global Experiences, National Assembly of Sustainable Architecture and Development Conference, 13 march 2013, Bukan, Iran.

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