THE EFFECTS OF PERFORMANCE-BASED DESIGN TOOLS ON DESIGN THINKING PROCESS

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ABSTRACT

THE EFFECTS OF PERFORMANCE-BASED DESIGN TOOLS ON DESIGN THINKING PROCESS

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Design thinking is identified as a paradigm for dealing with problems in many professions, particularly in the field of Architecture. The design thinking process is fundamentally problem-solving to find the best solution. The complexity of design problems increases because different conditions have various and unique requirements. With technological development, designers have started to use design support tools to find the most proper solution to complex problems. Performative architecture is designed using digital technologies to challenge the design of the built environment. This study intends to explore and analyze the influence of performative design tools on the design thinking process. Observing and evaluating the designer's activity is crucial while using performative design to understand the design thinking process.

The study aims to review the research on design thinking and design methods and the evolution of performance-based design throughout history. It is further intended to assess the influence of performative design tools on design thinking abilities with a given design problem. The analysis will be conducted with participants by giving them a design task, and they will be required to use performance-based design tools. The study has two main steps, the first is the design task using performance-based design tools, and the second is the analysis of these design processes. It is intended to use a combined methodology of think-aloud protocol, interviews with the participants, and Linkography.

Keywords: Design Research, Design Thinking Process, Linkography, Performance-based Design, Performative Architecture

ÖZ

PERFORMANSA DAYALI TASARIM ARAÇLARININ TASARIM ODAKLI DÜŞÜNME SÜRECİ ÜZERİNDEKİ ETKİLERİ

Görgün Göksu, Gizem
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Tasarım odaklı düşünme, özellikle Mimarlık alanında olmak üzere birçok meslekteki problemlerle başa çıkmak için bir paradigma olarak tanımlanmaktadır. Tasarım odaklı düşünme süreci temelde, en iyi çözümü bulmak için problem çözmektir. Farklı koşulların çeşitli ve benzersiz gereksinimleri olduğundan tasarım problemlerinin karmaşıklığı artar. Teknolojinin gelişmesiyle birlikte tasarımcılar karmaşık problemlere en uygun çözümü bulmak için tasarım destek araçlarını kullanmaya başladılar. Performansa dayalı mimari, yapılı çevrenin tasarımına ayak uydurmak için dijital teknolojiler kullanılarak tasarlanmıştır. Bu çalışma, performansa dayalı tasarım araçlarının tasarım düşüncesi süreci üzerindeki etkisini araştırmayı ve analiz etmeyi amaçlamaktadır. Tasarım düşünce sürecini anlamak için performansa dayalı tasarımı kullanırken tasarımcının etkinliğini gözlemlemek ve değerlendirmek çok önemlidir.

Bu araştırma, tasarım düşüncesi ve tasarım yöntemleri üzerine yapılan araştırmaları ve performansa dayalı tasarımın tarih boyunca geçirdiği evrimi inceleyerek, belirli bir tasarım problemi ile performansa dayalı tasarım araçlarının tasarım düşünme yetenekleri üzerindeki etkisini değerlendirmeyi amaçlamaktadır. Katılımcılara önceden belirlenen tasarım problemi verilerek performansa dayalı tasarım araçlarını kullanmaları istenecektir. Çalışmanın iki ana adımı vardır, birincisi performansa dayalı tasarım araçlarını kullanarak tasarım sürecinin tamamlanması, ikincisi ise bu tasarım süreçlerinin analizidir. Sesli düşünme protokolü, katılımcılarla görüşmeler ve Linkografiden oluşan birleşik bir metodolojinin kullanılması amaçlanmıştır.

Anahtar Kelimeler: Tasarım Araştırmaları, Tasarım Odaklı Düşünme Süreci, Linkografi, Performansa Dayalı Tasarım, Performatif Mimari

To the loving memory of my father, and

to my mother, with love and eternal appreciation

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LIST OF ABBREVIATIONS

PBD	Performance-Based Design
BEP	Building Energy Performance
PA	Performative Architecture
CAD	Computer-Aided Design
UN	User Needs
PR	Performance Requirements
L.I.	Link Index
CMs	Critical Moves
<CMs	Backlink Critical Moves
CMs>	Forelink Critical Moves

CHAPTER 1

INTRODUCTION

1.1 The Motivation of the Research

Design research is a systematic process in the nature of the designing activity. The systematization of this activity has been studied throughout history. The most accepted definition of the design activity is a process where the designer intends to generate a description of a design object regarding the requirements and objectives.[1] Design process is described as an iterative exploration process in which designers acquire, produce, visualize, transform, modify, and convey information which are connected to diverse areas of design concepts.[2]

The act of designing is a complex process. In architectural design, solving the design problem requires consideration of multiple design criteria. While trying to find the optimum design solution, the designer inevitably gets help from other disciplines. Thereby, interdisciplinarity is the fundamental aspect of the design activity. In this regard, it is useful to work with design support tools to understand better the subjects that affect the design artifice. The transformation of design ideas to the real object requires some different viewpoints; statistical information, context analysis, statical and geographical knowledge. As time progresses, the designer has gained more control over the design process thanks to the increased

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[1] Pieter H.G. Van Langen and Frances M.T. Brazier, "Design Space Exploration Revisited," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM* 20, no. 2 (2006): 113.
[2] Imre Horváth, "On Some Crucial Issues of Computer Support of Conceptual Design," in *Product Engineering: Eco-Design, Technologies and Green Energy*, ed. Doru Talaba and Thomas Roche (Springer, Netherlands, 2004), 123.

use of design support tools. Several performance-based design (PBD) tools assist the designers throughout the design process. The effects of various forms of structural and environmental analysis through engineering contributions to both the architectural design process and the design object are accepted among researchers and architects.[3]

The main intention of architects is to design structures that should be energy-efficient and environmentally friendly as well as visually pleasing and well-functioning. Especially over the last years, the sustainable building desire has grown substantially. Due to the complexity of the new type of buildings, designers mostly find challenging to fulfill rising performance demands, mainly when the designers work with traditional design methods that are linear and sequential. Design processes, mainly for high-performance structures, need a novel perspective. In this scope, an analytical method is required to achieve the performance goals, known as building performance simulation tools. Recent technologies in design enable the creation of more complex structures with the help of transition to the performative design.

The initial goal of performative design is to integrate performative criteria with design objects from the early conceptual phases. Decisions taken at the earliest stage of the architectural design process significantly influence building construction, lifespan cost, and environmental footprint of buildings. In this regard, a closer collaboration between architects and other disciplines is required to achieve environmentally responsive results at the start of projects. With the ongoing focus on sustainability, particularly building energy and environmental factors, design needs from the associated disciplines have become increasingly relevant with the early design phases.[4] As a result, building performance

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[3] Rivka Oxman, "Performance-Based Design: Current Practices and Research Issues," *International Journal of Architectural Computing* 6, no. 1 (2008): 2.
[4] Kristoffer Negendahl, "Building Performance Simulation in the Early Design Stage: An Introduction to Integrated Dynamic Models," *Automation in Construction* 54 (2015): 40.

simulators are gradually being applied in the conceptual design processes.[5] This integration leads to a decision-making process regarding different design factors, for instance, orientation, environmental factors, site, materials, form, and details within a several design direction.[6]

At the initial stages of the design process, integration of performative ideas is the generative factor that shape design objects instead of solely evaluation. In a performance-based idea generation process, the designers reflect their possible solutions to the digital model. The digital model is an intermediary element between the computer and the designer; in other words, it evaluates performance-based aims in design ideas. Performance-based tools might generate and modify design objects in the design process with defined parameters. It depends on a formation process supported by the analytical feedback of these tools. The productivity of the idea generation process and the creation of alternative solutions based on this feedback are essential features of designing with simulation tools provided.

This study is motivated by the increasing use of performance-based tools during the architectural design process. Enhanced energy assessment techniques can integrate these developing technologies with existing building energy performance (BEP) simulation tools, allowing computational analysis and experiment methodologies to be effectively utilized for high-performance building design. With these developments, curiosity was raised about how these combined performance simulation tools will impact the development of higher-performing design solutions. The contribution of this paper is a synthesis of literature and experiment-based methodologies for analyzing the process of PBD and the analysis with a linked set of objectives for measuring and comparing design processes. To this end, this research aims to investigate the effects of using performance-based

[5] Ibid.
[6] AIA, "Integrating Energy Modeling," 2012, 1–86.

tools on architectural design practices through several consecutive phases. Numerous techniques have studied the usage of performative architecture tools in design practice for many years. In this framework, the research question is: How could the PBD tools influence the design thinking process, creative thinking, searching for alternatives, and finding the optimal solution? In this manner, the scope of this research is to investigate the benefits of collaboration of the designer and performance-based computational tools to achieve performance goals in the design process. A comprehensive methodology is required to address these research questions. As a methodological approach, to reach a proper conclusion, it is decided to use a mixed methodology of protocol studies consisting of Linkography and exit interviews. Linkography is a method for gathering and illustrating the structure of links between design moves, cognitive activities, or situations and visualizing and assessing the structure of framework. It has been used in design research to trace the idea-generation process throughout years.

1.2 Research Question

Throughout recent years, many studies have been done to assess performance-based simulation tools in architectural design environments. Although using performative tools is time-consuming and requires high knowledge for analysis, designing concerning the performative goals is important for the lifespan of buildings. In this scope, the influences of performance-based simulation tools on the design process are still an issue of interest. The main goal of the research is to contribute to the understanding of how these PBD tools affect the design processes. In this respect, this research addresses the following research questions.

- How could PBD tools influence designers' productive thinking abilities?

- How could PBD tools affect the designer's idea generation process?

- What can be the potential implications of PBD tools for identifying required design components of solution ideas?

- What can be the advantages of PBD tools for brainstorming and searching for alternatives?

- What impact do PBD tools have on designers in reframing challenges to enhance solutions?

- What are the benefits and drawbacks of the PBD tools on the productive thinking process?

A comprehensive methodology was required for this research to meet the above-mentioned research problems. The technique used in this study is a mixed-methodology with several protocol analyses that comprise Linkography, observation, and exit interviews with participants to provide quantitative and qualitative data. The methodology of this study will be discussed in further detail in Chapter 4.

1.3 Structure of the Thesis

The thesis is divided into five chapters. For a better understanding of the research study, the contents and organization of the chapters will be summarized in this introductory section. The current introduction chapter additionally consists of the motivation of the research and research questions.

Chapter II: Design Research

The aim of this chapter is to present the literature review about design cognition and the fundamental studies in the exploration of productivity. In this section, Linkography and its further investigated studies have been analyzed as a methodology for this research.

Chapter III: Performance in Architectural Design

This chapter presents the use of performative architectural design objectives and how the PBD integrated to the conceptual design processes.

Chapter IV: Assessing Design Productivity through Linkography

The methodology of the research is explained in Chapter 4. The mixed-methodology and decided coding schemes for Linkographic objectives and performance-related objectives are represented. This chapter also includes the examination of the protocol analysis, getting the quantitative and qualitative data from Linkographs, observations, entropy evaluations, and distributions of FBS coding are explained.

Chapter V: Conclusion

This chapter consists of the conclusion of this research and summarizes the findings of the analysis about the research process, limitations, and suggestions for further studies.

CHAPTER 2

DESIGN RESEARCH

The main motivation of this study is to explore the potentials of the integrated compound digital design models during the performance-based architectural design process. To understand and evaluate the potentials of the new digital design tools, it is crucial to analyze the design processes of the designers while using the compound digital design tools in performance-based architectural design. Therefore, this part of the literature review includes the design research and its methods.

Origins of new design methods are based on the 1960s with the application of new scientific and computational methods for the 2nd World War problems[7]. Many designers were inspired by the novel techniques used in the design and improvement of weapons and wartime supplies, in addition to that, the methods and techniques used in creating some innovations.[8] According to Gabriela Goldschmidt's statement, expedited technological growth has led to a transition from heavy industry to high-tech industry. The pinnacles of this transformation were the invention of the computer and the quick improvements of computers and communication.[9]

Several design disciplines, especially architecture, have undergone significant transformations after wartime. As a consequence of the war, the extensive

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[7] Nigel Cross, "Forty Years of Design Research," Design Studies 28, no. 1 (2007): 1.
[8] Nigan Bayazit, "Investigating Design: A Review of Forty Years of Design Research," *Design Issues* 20, no. 1 (2004): 17.
[9] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 9.

demolition in Europe revealed unexpected planning, designing, and constructing attempts.[10] This comprehensive transformation leads designers to start to understand and analyze the design process so that it can be systematized. According to Gabriela Goldschmidt's statement, the war effort supported collaborative work in which designers and scientists from diverse disciplines combined to accomplish particular objectives, and this interaction has created a desirable atmosphere for interdisciplinary work.[11]

2.1 Analysis of the Design Process

The beginning of the significant discussions and analyses in design research was in the 1960s with the design method movements.[12] In 1963, the first conference on design methods was held in London, and then three further conferences on design methods were conducted in the same decade. Members in the design method movements were agreed that the design process should be significantly changed or completely replaced by a more developed process.[13]

According to the design method movement, it was believed that design should aim to be a science, and designing should depend on systematic, scientific design methods.[14] The nature of the designing has several stages, and indispensably they affect each other by the outcomes of each step gives feedback for the other steps. From this point of view, there was no difference between the design process and a design method, which is the idea of the method was the process.[15] It is accepted by all the participants of the design method movement as the design is a systematic problem-solving process.[16] As stated by Nigan Bayazit, each conference participant

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[10] Ibid.
[11] Ibid.
[12] Ibid., 10.
[13] Ibid., 11.
[14] Ibid.
[15] Ibid.
[16] Ibid.

systematized their own approach to design and introduced it as a design method.[17]

In the theoretical knowledge of design, designing was seen as a rational technique controlled by rules that could be explained and prescribed.[18] The problem-solving process was first systematized and proposed by Morris Asimov in three stages as the 'Analysis - Synthesis - Evaluation' (ASE) model was widely accepted.[19] Most of the prescriptive model proposals were the enhancement of the Analysis-Synthesis-Evaluation model.[20] Gabriela Goldschmidt states that the descriptions of these three steps depend on the explanations of John Luckman.[21] The first stage of the design is the stage of Analysis includes exploring relationships and the data collection and classification related to the design problem. The second phase is Synthesis, which refers to proposing possible solutions regarding the Analysis phase. And the final stage is Evaluation, about the selection of the most appropriate solution.

Morris Asimow became a notable figure emphasizing the design process by introducing and illustrating the model.[22] He suggested an iconic three-dimensional model as abstractness, analysis-synthesis-evaluation, and communication.[23] (Figure 2.1).

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[17] Nigan Bayazit, "Investigating Design: A Review of Forty Years of Design Research," *Design Issues* 20, no. 1 (2004): 18.
[18] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 11.
[19] Ibid., 12.
[20] Ibid.
[21] Ibid., 13.
[22] Peter Rowe, *Design Thinking* (MIT Press, Cambridge, Massachusetts, 1987): 47.
[23] Burak Pak, "Design Activities and Decisions in Conventional and Computer Aided Architectural Design Processes" (2009): 11.

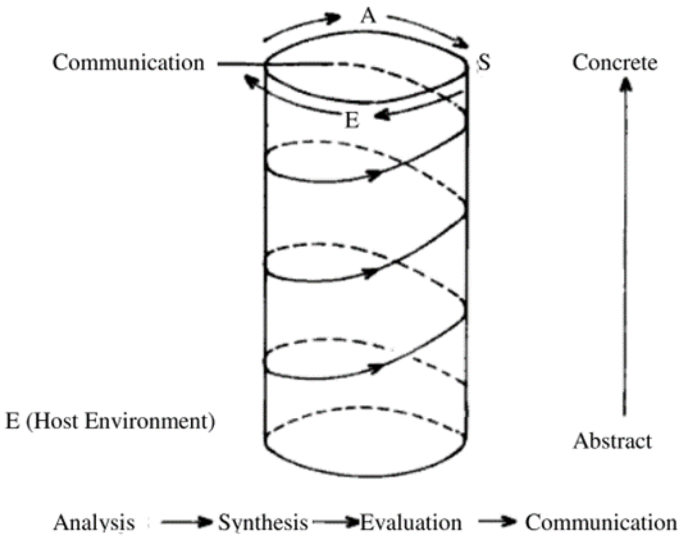

Figure 2.1: An iconic model of a design process by Morris Asimow

Source: Peter Rowe, *Design Thinking* (MIT Press, Cambridge, Massachusetts, 1987): 48.

Asimow separated the design process into two patterns; the first was a vertical structure including a sequential phasing of activities, and the second was a horizontal structure in the form of a decision-making loop applicable to all processes.[24] The steps in the vertical framework are arranged according to the explanation of the requirements, with the feasibility survey, the preliminary design, the comprehensive design, the planning of production, and eventually the output itself.[25] Throughout, Asimov saw the general sequence of activities as passing from abstract to more concrete concepts and implemented multiple feedback loops to consider for the visible tracing back through the process to answer the new data or challenges.[26] Asimow illustrated the horizontal structure as a loop that started with Analysis and continued towards Synthesis and Evaluation to communication.[27]

Bryan Lawson states that the handbook of The Royal Institute of British Architects

[24] Peter Rowe, *Design Thinking* (MIT Press, Cambridge, Massachusetts, 1987): 47.
[25] Ibid.
[26] Ibid.
[27] Ibid.

(RIBA) consists of one of the first systematic methods to explain the process of design.[28] This model (Figure 2.2) describes the design process based on four steps: assimilation, general study, development, and communication, and the main feature of this method is not strictly sequential or linear.[29] The RIBA handbook is quite realistic by indicating that there are probably unexpected moves between these four stages, but the unclear point of this method is how often or in what way these moves happen.[30]

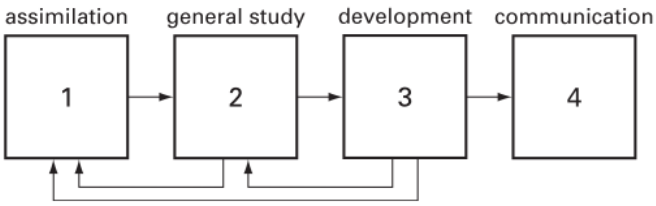

Figure 2.2: The design process map according to the RIBA handbook

Source: Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 35.

Christopher Alexander is another pioneering name on design methods with the first Ph.D. thesis in this research field.[31] His research, named as ‘Notes on the Synthesis of Form’, became the most effective proposal to create a method for synthesizing solutions besides analysis of design problems.[32] He suggested a methodology to systematize design problems that would enable designers to observe the graphic representation of the composition of non-visual problems.[33] Alexander’s intention is to divide the design problems into small solvable patterns that interact with each other and solve each group's problems by drawing a diagram according to its

[28] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 35.
[29] Burak Pak, “Design Activities and Decisions in Conventional and Computer Aided Architectural Design Processes” (2009): 11.
[30] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 35.
[31] Burak Pak, “Design Activities and Decisions in Conventional and Computer Aided Architectural Design Processes” (2009): 12.
[32] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 15.
[33] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 27.

interactions, either it is a good fit or misfit.[34] His technique depended on eliminating the defective relationships between the necessities and the form to select the most optimal solutions to decrease the mistakes and adjust the design problem.[35] This method failed due to it has an intense workload, and the structure is not practical.[36]

According to the Design Method Movement members, Alexander's method revealed that it is possible to create a productive theory of architectural design.[37] The method was seen as the whole design process could be managed by a rule-based, prescriptive system; however, they were disappointed with the realization of this method could not reach a practical solution because of the imperfections in Alexander's method.[38] Even if his model was unsuccessful, some of his theories about design, representation has the potential of using in emergent CAAD applications.[39] Therefore, they started to search for how computational tools could be utilized in designing, which resulted in remarkable developments in computer-aided design.[40]

Two researchers, Tom Markus and Tom Maver, developed more comprehensive maps that show the relationship between the decision sequence of analysis, synthesis, appraisal, and decision phases of the architectural design process.[41] (Figure 2.3) The study includes the investigation of relationships; besides that, it is also the ordering and structuring of the problem, Synthesis is the creating response

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[34] Nigan Bayazit, "Investigating Design: A Review of Forty Years of Design Research," *Design Issues* 20, no. 1 (2004): 18.
[35] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 17.
[36] Christopher Alexander, *Notes on the Synthesis of Form* (Cambridge, Massachusetts: Harvard University Press, 1964), 73.
[37] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 18.
[38] Ibid.
[39] Burak Pak, "Design Activities and Decisions in Conventional and Computer Aided Architectural Design Processes" (2009): 12.
[40] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 19.
[41] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 36.

to the problem, and the Evaluation (Appraisal) is the critical assessment of proposed solutions regarding the objectives identified in the analysis stage.[42] They suggested the design process includes three chapters: outline proposals, scheme design, and detailed design.[43] In every chapter, the designer consecutively conducts analysis, synthesis, evaluation, and decision-making tasks.[44]

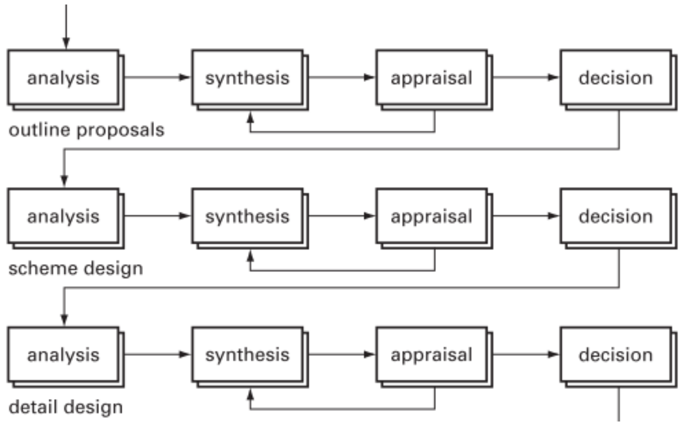

Figure 2.3: The Markus/Maver map of the design process

Source: Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 37.

According to Lawson, although it shows a return loop diagram after each decision stage, it can be required to turn back after the synthesis and evaluation phases in some conditions, for instance, the proposed solution might need more detailed data investigation, or after the synthesis stage, the designer might forget to analyze different viewpoints so the designer should go around the cycle.[45] The Markus/Maver map (Figure 2.4) is leading designers from the outline proposal to scheme design and then detail design. There is no return move through the beginning of the process.

[42] Ibid., 37.
[43] Burak Pak, "Design Activities and Decisions in Conventional and Computer Aided Architectural Design Processes" (2009): 13.
[44] Ibid.
[45] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 38.

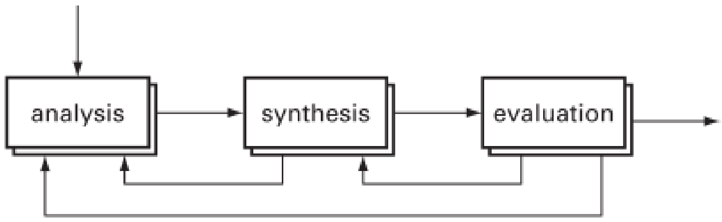

Figure 2.4: A generalised map of the design process

Source: Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 38.

Bryan Lawson criticizes the missing part of the Markus/Maver map and explains a relationship map of the way designers work in the design process that it is possible to go back in each step and to move forward.[46] On the other hand, he conducts the common problem between these two maps: the design movement proceeds only from the general to the specific, unlike the real practice.[47] After analyzing the two design process maps, Lawson suggests a graphical representation of the design process (Figure 2.5): an iterative cycle in which all movements are linked to each other instead of navigating the designer's route.[48]

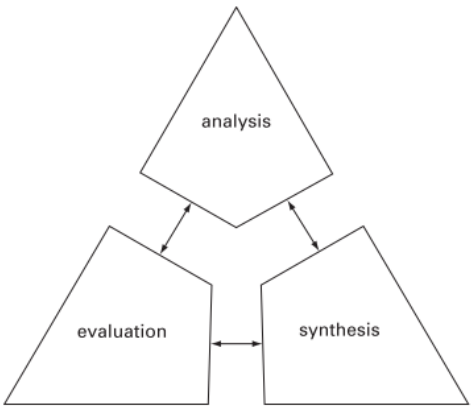

Figure 2.5: A graphical representation of the design process.

Source: Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 40.

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46 Ibid.
47 Ibid.
48 Ibid., 39.

In the process of designing, there is an endless and inevitable relationship between Analysis, Synthesis, and Evaluation phases. As a starting point, data collection and analysis lead the designer to further stages. Nevertheless, in the later stages, more data collection requirements can occur according to a design decision. For instance, in the later stages, while the designer is dealing with the material selection, there might be a need for more comprehensive data collection to decide whether it is appropriate or not. From beginning to end, each design step depends on the other stages alternately. According to the design requirements, the designer needs to go back or jump to another step regardless of these process maps' structure.

Bryan Lawson indicates that these design process maps emerged from thought processes rather than experimentally observations because they are both prescriptive and theoretical.[49] None of these researchers show any evidence that the designers follow these process maps in reality.[50] Similarly, Gabriela Goldschmidt states, the prescriptive aspects of the different approaches that forced the designer to adopt a considerably strict sequence of predetermined moves appears contradictory to what was considered as "natural design thinking".[51] The analysis of various studies on design methods shows that prescriptive methods became insufficient to reveal the real-life design process.[52] By this means, researchers started to discuss descriptive design models or methods.[53]

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[49] Ibid., 40.
[50] Ibid.
[51] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 19.
[52] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 40.
[53] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 19.

2.2 Understanding the Designer's Thinking Process

As it means in the definition, the design process is carried out inside our minds.[54] The idea of "descriptive design models" was the good explanations of real-life design behavior were necessary to understand the thinking process as it happens in real design practice.[55] Researchers started to interest in emergent computational tools support designers in the early conceptual stage of the design process.[56] Rather than the idea of computational tools to replace the human designers, researchers started to discuss an association between the designer and the computational tools where each partner would contribute what he, she, or it was best at which subject.[57] However, the knowledge deficiency about designers' thinking and creation process caused a challenge to use any computational design tool in the human design process.[58] Researchers became conscious that understanding design thinking was a prior stage of the design tool development regarding the cognitive science that had just started to be dealt with several issues related to the "mind" involving problem-solving design.[59]

All these theories propose that some rigorous evidence is necessary instead of solely depending on rational reasoning.[60] Nigel Cross investigates the searches and approaches to understanding design thinking throughout the design research history in his book titled "Designerly Ways of Knowing". He examined the methods in four types as "interviews with designers, observations and case studies, protocol studies, reflection and theorizing, and simulation trials" to reach tangible results and understand how designers think.[61] Several experimental studies were carried

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[54] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 41.
[55] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 19.
[56] Ibid.
[57] Ibid.
[58] Ibid., 20.
[59] Ibid.
[60] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 41.
[61] Nigel Cross, *Designerly Ways of Knowing* (London: Springer, 2006): 30.

out to reveal the designer's mind, and these studies will analyze to understand the process of real-life design practice.

Bryan Lawson examined in systematic analysis consisting of both interviews and observational case studies with designers. Lawson's experiments on design practice aim to compare the designers' problem-solving methods with those of scientists.[62] He executed the research with selected two groups of subjects were used including final-year students of architecture and graduate students of science.[63] He observed that the two groups display obviously distinctive strategies.[64] His observational study of 3D-coloured blocks reveals that architecture students follow the problem-solving strategy of analysis through synthesis.[65] As they learned towards the end of architectural education, their attempt was to create possible solutions to explore the problem instead of studying the design problem itself because of their architectural education.[66] Lawson describes that the approaches of the scientists have a problem-focused strategy; on the other hand, the architects have a solution-focused strategy.[67] In this sense, a solution-focused strategy is obviously much better than a problem-focused one.[68] Nigel Cross emphasizes that it is always possible to analyze the "problem", yet the designer's fundamental job is to produce the "solution".[69]

In those experimental conditions, it is examined the outcomes of experiments under which the designers are expected to design.[70] In fact, these conditions will never model the actual design studio, so an alternative study method of interviewing with designers can explain their practices in normal conditions.[71] Indeed, these

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[62] Ibid., 6.
[63] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 43.
[64] Ibid.
[65] Ibid., 44.
[66] Ibid.
[67] Ibid., 43.
[68] Nigel Cross, *Designerly Ways of Knowing* (London: Springer, 2006): 7.
[69] Ibid.
[70] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 45.
[71] Ibid.

interviews and experiments' reliability depends on the designers telling the truth.[72] Because the designers' explanations happen after the design process, these retrospective studies could be challenging in that designers' memories can mislead them to remember what happened actually and try to make the design processes more logical than the actual case.[73]

As Nigel Cross described, interviews with designers is another method that has been used for exploring the designers' thinking processes. Jane Darke carried out interviews with architects about their opinions on housing in general, the obstacles of designing such housing, and after that, they discussed a specific housing scheme when designing local housing.[74] While interviewing the architects, Darke observed that the designers started to design with some selected constraints from their cognitive processes in the design problem while interviewing the architects.[75] After the primary generator concept was accepted as a useful method to conceptualize a particular phase in the design process Darke also suggested a new type of design process map including "generator-conjecture-analysis" (Figure 2.6) instead of the "analysis-synthesis- evaluation" model.[76] Bryan Lawson explains that the process of designing is where the problems and solutions emerge simultaneously.[77]

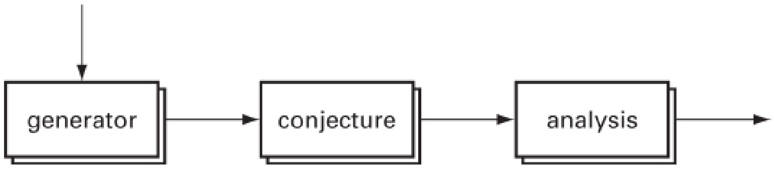

Figure 2.6: Jane Darke's map of the design process

Source: Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 46.

[72] Ibid.
[73] Ibid.
[74] Jane Darke, "The Primary Generator and the Design Process," *Design Studies* 1, no. 1 (1979): 36.
[75] Ibid., 38.
[76] Ibid.
[77] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 48.

Protocol studies became another method that design researchers have preferred to investigate designers' activities. Most of the protocol studies are dependent on "think-aloud" experimentation during the designers dealing with the underresearched activity when they constantly verbalize their ideas.[78] The verbal protocols are then divided into smaller units and encoded with a category scheme representing the research aims.[79] The experimental data from protocol studies show the degree of productivity, significance, and unpredictability in the various cognitive stages.[80] The aim and organization of protocol studies with their relationship with productivity will be described in the next section.

2.3 Protocol Analysis and Creative Leap

Important inventions or original design ideas are usually reported as originated during unexpected or "creative leaps" moments.[81] Some fields describe the creative leap as the sudden discovery of an entirely novel perspective on a problem.[82] According to the statement of Nigel Cross, this is the base of Koestler's "bi-sociation" paradigm for demonstrating creative vision but, a creative leap does not necessitate a drastic change of perspectives in creative design.[83] Cross remarks that there is no transition to a new "space," it is just a switch to a new area of the solution space, and here the proper term is "finding", and that is what describes the creative design as exploring instead of searching.[84] Contrary to bi-sociations, the creative design does not require a sudden opposite idea, and it needs an appropriate

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[78] Gabriela Goldschmidt and Maya Weil, "Contents and Structure in Design Reasoning," *The MIT Press* 14, no. 3 (2016): 87.
[79] Ibid.
[80] Hsien-hui Tang and John Gero, "A Cognitive Method to Measure Potential Creativity in Designing," in *ECAI 2002 Workshop on Creative Systems: Approaches to Creativity in Artificial Intelligence and Cognitive Science*, ed. G. C., Cardoso, A. and Wiggins, 2002: 47.
[81] Nigel Cross, "Creativity in Design: Analyzing and Modeling the Creative Leap," *Leonardo* 30, no. 4 (1997): 311.
[82] Ibid.
[83] Ibid.
[84] Ibid.

proposal.[85] The sudden revelation that occurs in creative design resembles the establishment of a "creative bridge" rather than a creative leap.[86]

John Haefele explains that the elements leading to finding solutions to problems are divided into three to seven separate stages by researchers from different disciplines.[87] He states the stages in creative thinking accepted by investigators chronologically as follows[88]:

“By Helmholtz:

1- Preparation
2- Incubation
3- Illumination” [89]

“By Graham Wallas, added one after Helmhotz:

1- Preparation
2- Incubation
3- Illumination
4- Verification” [90]

“By James Webb Young:

1- Assembly of material
2- Assimilation of material in our mind
3- Incubation
4- Birth of the idea
5- Development to practical usefuless” [91]

“By Joseph Rossman:

1- Observation of a need or difficulty
2- Analysis of the need
3- Survey of the available information
4- Formulation of objective solutions

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[85] Ibid.
[86] Ibid.
[87] John W. Haefele, “Creativity and Innovation” (New York: Reinhold Publishing Corporation, 1962): 12.
[88] Ibid.
[89] Ibid.
[90] Ibid.
[91] Ibid.

5- Critical analysis of the proposed solutions for advantages and disadvantages
6- Birth of the new idea, the invention
7- Experimentation to test out the most promising solution; perfection of the final embodiment by repeating some or all the previous steps." [92]

"By Alex Osborn:

1- Orientation: pointing up the problem
2- Preparation: gathering pertinent data
3- Analysis: breaking down the relevant material
4- Hypothesis: piling up alternatives by way of ideas
5- Incubation: letting up, to invite illumination
6- Synthesis: putting the pieces together
7- Verification: judging the resultant ideas" [93]

Due to the developed models are similar to each other, Haefele defines the important feature is that the process is the same regardless of the discipline[94]. He emphasizes the emotional factors that could affect the whole creative process and explains the process in four stages as follows[95]:

1- Preparation = Organization of material: desire to solve
2- Incubation = Wait after preparation: frustration
3- Insight = Birth of the clarifying idea: thrill of solution, and anxiety separation
4- Verification = Development and proof: satisfaction of reaping, and removing separation" [96]

The strict dependence is not required on the sequence of steps of the origination process since they interwoven, and the whole process will occur in constructing a more extensive development section.[97]

The undeniable relationship between creativity and intelligence is emphasized by George Kneller, and he indicates that the rearrangement of what is already known

[92] Ibid., 13.
[93] Ibid.
[94] Ibid., 12.
[95] Ibid., 18.
[96] Ibid.
[97] Ibid., 13.

to look for the unknown feeds creativity.[98] He also classified creative thinking similar to the previous models into five phases: 'first insight, preparation, incubation, illumination, and verification' (Figure 2.7).

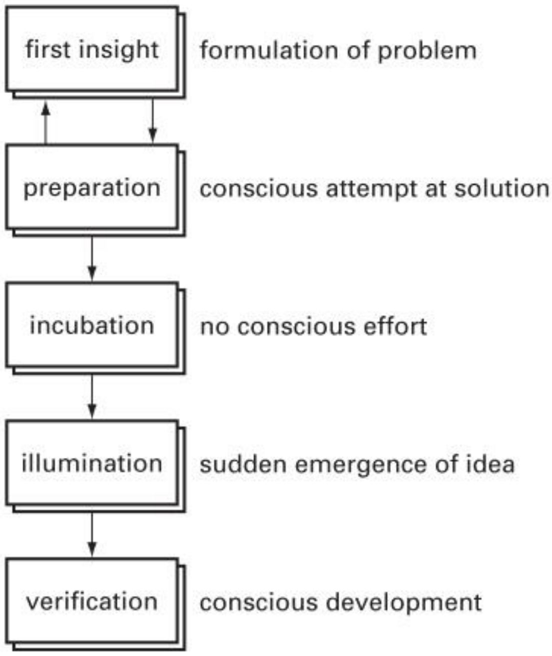

Figure 2.7: George Kneller's five-stage model of the creative process

Source: Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 149.

The classification of thinking skills progressed under different headings. J.P. Guilford was the pioneering name suggests the distinction between divergent and convergent thinking.[99] Divergent thinking is explained as generating various appropriate solutions to an open-ended question or design task where the outcome is not entirely determined by knowledge, and therefore, divergent thinking focuses on producing multiple alternative responses, including original, unexpected, or

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[98] George F. Kneller, *The Art and Science of Creativity* (New York: Holt, Rinehart and Winston, 1965): 59.
[99] Mark A. Runco, "Chapter 1 - Cognition and Creativity," in *Creativity: Theories and Themes: Research, Development, and Practice*, Second Edi (Academic Press, 2014): 8.

uncommon thoughts.[100] For this reason, divergent thinking is associated with creativity and productivity. On the other hand, convergent thinking means reaching only one correct solution, which is traditional for a well-defined problem.[101] Many facts or ideas are examined for their logical validity or following a set of rules during convergent thinking.

According to Liane Gabora, there is evidence that creative thinking includes both divergent and convergent thought.[102] She proposed a neurological explanation of creative thought in terms of memory activation, claiming that divergent thought is associated with defocused attention and convergent thought is associated with focused attention and that these two thinking types produce different memory activation patterns.[103]

Since the start of cognitive psychology research during the 1960s, several strategies have been studied that could explore the design practice process and designers' mental process during problem-solving stages to better understand how creative ideas emerged. The term "Protocol Analysis" was introduced by Allen Newell, refers to the methodology used in the study of human problem-solving in its most basic form.[104] Protocol analysis has been accepted as an effective design research method to comprehend the idea generation process by examining small units of actions and has been widely used by various design researchers for over 30 years.[105] As a valid source of data on design thinking, the protocol analysis is a rigorous research method to investigate the designers' verbal reports of thoughts

[100] Olga M. Razumnikova, "Divergent Versus Convergent Thinking," in *Encyclopedia of Creativity, Invention, Innovation and Entrepreneurship*, ed. Elias G. Carayannis (Springer New York, 2013), 546-547.
[101] Ibid.
[102] Liane Gabora, "Creativity," *Oxford Research Encyclopedia of Psychology*, (2020), 1.
[103] Ibid.
[104] Ömer Akin, *A Cartesian Approach to Design Rationality* (Ankara, Turkey: Middle East Technical University, Faculty of Architecture, 2006): 63.
[105] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 22.

sequentially.[106] The terms "verbal reports" and "verbal protocols" are defined by Ericsson and Simon as both the designers' verbal expressions of their ideas and sequential behaviours during their cognitive processes.[107]

Newell describes the term 'protocol' as a sequential list of recorded verbal expressions of the subject who are requested for think-aloud while the design thinking process.[108] The approach is the thinking and problem-solving can be explained by means of an "Information Processing Theory.[109] He states that protocols and some features of information theories are matches.[110] According to this theory, a human was seen as an information processor.[111] Simon states that the research he worked on along with Newell led to the invention of the "Information Processing Languages", the first list-processing language for computational tools.[112] Newell became a pioneering name who used protocol analysis as a method to study information processing systems.[113] Waterman and Newell's aim was to automate protocol analysis, which is a method of psychological data analysis to derive information processes used by a human from his/her verbal explanations during problem-solving.[114]

As mentioned above, besides the protocols are sequential lists, it is expected from the problem-solver to verbalize their thoughts concurrently in the think-aloud

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[106] K. Anders Ericsson, "Protocol Analysis and Expert Thought: Concurrent Verbalizations of Thinking during Experts' Performance on Representative Tasks," *The Cambridge Handbook of Expertise and Expert Performance*, 2012, 227.
[107] K. Anders Ericsson and Herbert A. Simon, "Protocol Analysis," in *A Companion to Cognitive Science* (Oxford, UK: Blackwell Publishing Ltd, 1981): 425.
[108] Allen Newell, "On the Analysis of Human Problem Solving Protocols," 1966: 1.
[109] Herbert A. Simon and Allen Newell, *Human Problem Solving* (Prentice-Hall, Inc. N.J.: Prentice-Hall., 1972): 5.
[110] Allen Newell, "On the Analysis of Human Problem Solving Protocols," 1966: 1.
[111] Herbert A. Simon and Allen Newell, *Human Problem Solving* (Prentice-Hall, Inc. N.J.: Prentice-Hall., 1972): 5.
[112]*Biographical Memoirs, National Academy of Sciences*, vol. 71 (The National Academies Press, 1997): 149.
[113] Omer Akin, *Psychology of Architectural Design* (London: Pion, 1986): 181.
[114] Donald A. Waterman and Allen Newell, "Protocol Analysis as a Task for Artificial Intelligence," in *IJCAI'71: Proceedings of the 2nd International Joint Conference on Artificial Intelligence* (Morgan Kaufmann Publishers Inc., 1971): 190.

method.[115] In addition, Ericsson and Simon emphasize the critical feature is that subjects are required to simply verbalize their thoughts during performing the given task instead of describing or explaining what they are doing.[116] They suggest that to work with well-defined problems so that think-aloud protocols could work reasonably.[117] This method aims to follow and better comprehend the designer's problem-solving and idea generation process.

It is possible to describe the use of think-aloud protocols as "concurrent introspection" to model the design processes.[118] Chi states the protocol analysis offers both quantitative and qualitative data and the quantitative findings could be used to support qualitative ones.[119] Cynthia Atman and Jennifer Turns emphasized the assessment of verbal protocols may be difficult and long-term to analyze the conclusions.[120] Due to the implementation of the verbal protocols might be confusing, Atman and Turns classified the fundamental processes of protocol analysis as described below:

> “1. Develop a coding scheme,
> 2. Choose a problem,
> 3. Collect protocols from students as they solve the problem,
> 4. Code the protocols according to the coding scheme,
> 5. Analyze and interpret results.” [121]

As Atman and Turns listed, the first step of the verbal protocol analysis is to develop a coding scheme defined as the link between the verbal protocols and

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[115] K. Anders Ericsson and Herbert A. Simon, *Protocol Analysis: Verbal Reports as Data (Rev. Ed.)* (The MIT Press, 1993): 8.
[116] Ibid.
[117] Ibid: 42.
[118] David Latch Craig, “Stalking Homo Faber: A Comparison of Research Strategies for Studying Design Behavior” in *Design Knowing and Learning: Cognition in Design Education* (Elsevier Science, 2001): 20.
[119] Michelene T. H. Chi, “Quantifying Qualitative Analyses of Verbal Data: A Practical Guide,” *The Journal of The Learning Sciences*, 1997: 273.
[120] Cynthia J. Atman and Jennifer Turns, “Studying Engineering Design Learning: Four Verbal Protocol Studies,” in *Design Knowing and Learning: Cognition in Design Education* (Elsevier Science, 2001): 39.
[121] Ibid.

research questions asked during cognitive processes.[122] Basically, the coding schema illustrates the set of activities of design behaviours.[123] The coding scheme is used to describe the start and continuity of a plan or categorize design processes.[124] John Gero was developed one of the most common coding schemes for classifying design thinking acts, which comprises three major categories: 'The Function-The Behavior-The Structure'.[125] According to Gero and Kannengiesser, the FBS framework (Figure 2.8) represents the design as a situated activity driven by interactions among the designers and their surroundings.[126] "Function" refers to the reason for which it was designed; "Behaviour" defines the acts intended to be carried out, and "Structure" illustrates the elements and their relationship to the artifact.[127] The designer creates links between these three elements described above during the design thinking process.[128]

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[122] Ibid., 40.
[123] Ibid., 41.
[124] John S. Gero, "Design Prototypes : A Knowledge-Based Schema for Design," *The AI Magazine* 11, no. 4 (1990): 30.
[125] Ibid.
[126] John S. Gero and Udo Kannengiesser, "The Situated Function-Behaviour-Structure Framework," *Design Studies* 25, no. 4 (2004): 374.
[127] John Gero and Udo Kannengiesser, "The Function-Behaviour-Structure Ontology of Design," in *An Anthology Design and Models of of Theories*, ed. Amaresh Chakrabarti and Lucienne T. M. Blessing (London: Springer, 2014), 265.
[128] Ibid.

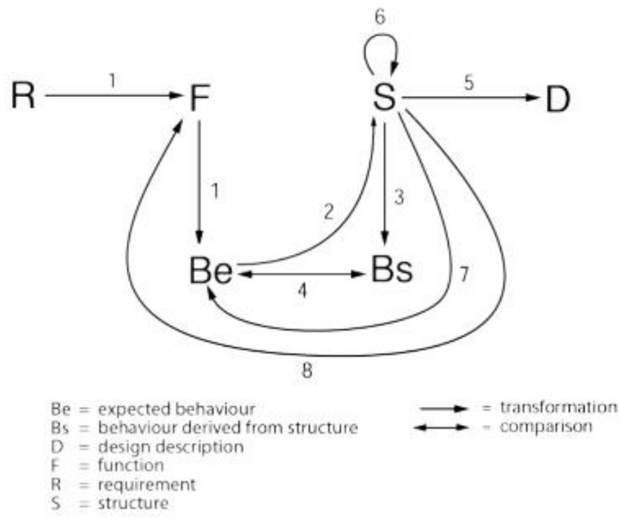

Figure 2.8: The FBS framework

Source: John Gero and Udo Kannengiesser, "The Function-Behaviour-Structure Ontology of Design," in *An Anthology Design and Models of of Theories*, ed. Amaresh Chakrabarti and Lucienne T. M. Blessing Blessing (London: Springer, 2014): 268.

Another step of the protocol study is choosing a problem, which is essential in terms of completing the necessary data collection within the given time.[129] Having subjects to solve the problem and perform the verbal explanations is another important step in the protocol study.[130]

Atman and Turns claim that the most important point of a verbal protocol analysis is where the subjects solve the chosen problem including verbal protocols concurrently relevant to their behaviours.[131] The verbal data of subjects can be collected with audio-recordings or video-recordings in which the problem-solving activity is carried out.[132] Besides verbal explanations, designers' communication

[129] Cynthia J. Atman and Jennifer Turns, "Studying Engineering Design Learning: Four Verbal Protocol Studies," in *Design Knowing and Learning: Cognition in Design Education* (Elsevier Science, 2001): 42.
[130] Ibid.
[131] Ibid.
[132] Ibid.

method is usually graphical representations.[133] Therefore, Goldschmidt suggests to use video recordings to capture the sketches for clarifying verbalizations rather than voice recordings.[134] To represent the collecting protocols obtained by the think-aloud process, the next stage is coding the protocols with respect to the coding scheme.[135] Atman and Turns defined their coding approach as first transcribing the whole protocols, then dividing them into idea units, and finally applying the coding scheme to the idea units.[136] The last issue of the verbal protocol analysis is analyzing and interpreting the results.[137] According to Turns and Atman, statistical information and graphical representation are the two main methods to describe the coding results.[138]

As mentioned above, the think-aloud methods during the design process have several beneficial features; however, there are some downsides. Alternative versions of verbal reports of thinking were used during the cognitive revolution of the 1950s and 1960s to obtain information about cognitive structures and processes.[139] Concurrent and retrospective verbal reports are accepted as two fundamental data sources of subjects' cognitive processes in the specific task.[140] After some investigations, it was noticed that the problem-solving performance of the subjects who think-aloud during the task different from the silent participants.[141] About the concurrent verbalizations, it could be challenging talking aloud during the thinking processes. On the other hand, Ericcson and Simon

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[133] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 29.
[134] Ibid.
[135] Cynthia J. Atman and Jennifer Turns, "Studying Engineering Design Learning: Four Verbal Protocol Studies," in *Design Knowing and Learning: Cognition in Design Education* (Elsevier Science, 2001): 44.
[136] Ibid.
[137] Ibid.
[138] Ibid.
[139] K Anders Ericsson, "Valid and Non-Reactive Verbalization of Thoughts During Performance of Tasks," *Journal of Consciousness Studies* 10, no. 9–10 (2003): 3.
[140] K. Anders Ericsson and Herbert A. Simon, *Protocol Analysis: Verbal Reports as Data (Rev. Ed.)* (The MIT Press, 1993): 6.
[141] R. M. Gagne and E. C. Jr. Smith, "A Study of the Effects of Verbalization on Problem Solving," *Journal of Experimental Psychology* 63, no. 1 (1962): 12–18.

proposed the retrospective study to analyze the process with interviewing the subjects about unclear actions at the end of the problem-solving process.[142] However, it was noticed most of the comments belong to important actions in the process, therefore researchers are able to only trace the important decisions in the retrospective protocol analysis.[143]

After the protocols are collected, another important issue is coding these protocols to be able to reach a analysis pattern on the design thinking process. It is not expected the concurrent verbalizations are the exact expressions of thinking process which can be called inner speech.[144] As in Vygotsky's explanation, "Thought is not merely expressed in words; it comes into existence through them".[145] Although several methodologies can be used in design research, the concurrent protocol analysis is the best methodology available for the research on design thinking at cognitive level.[146] Many protocol studies have been done throughout history. Some of the remarkable protocol studies are stated followingly to show the importance of this design analysis approach in the context of the thesis review aiming to understand the potential use of performative design tools in expert designers' design processes.

The pioneering research belongs to Eastman, which is the study with architects.[147] Essential and diverse research methods have been accepted and adjusted to examine the design activity consisting the case studies, protocol studies with

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142 K. Anders Ericsson and Herbert A. Simon, *Protocol Analysis: Verbal Reports as Data (Rev. Ed.)* (The MIT Press, 1993): 16.
143 Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 35.
144 Ibid., 33.
145 Lev Vygotsky, *Thought and Language* (Cambridge: MA: MIT Press, 1962): 150.
146 Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 37.
147 Nigel Cross, "Design Cognition: Results From Protocol And Other Empirical Studies Of Design Activity," in *Design Knowing and Learning: Cognition in Design Education* (Elsevier Science, 2001): 79.

thinking-aloud methodology, and performance tests.[148] Designers were required to design a bathroom and allowed to draw and talk about what they were thinking at the same time; this data was recorded and then analyzed.[149] Any significant difference between analysis and synthesis phases in these protocols was not observed, but instead, a parallel understanding of the essence of the problem and the context of possible solutions were notable.[150] According to Eastman, the most important general finding in this study, an apparent correspondence has been noticed between the types of constraints of the given design problem and the representations used for the problem-solving process.[151]

Omer Akin used similar methodology for designing more complex buildings when compared to Eastman's bathroom design.[152] The purpose of Akın was to discover the designer's role in architectural design and to understand the application of problem-solving structure based on "information-processing theory" (Figure 2.9) introduced by Newell and Simon.[153]

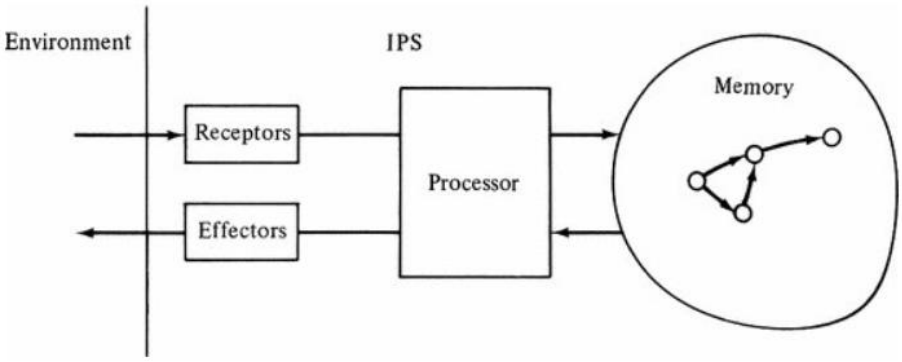

Figure 2.9: Information processing system

Source: Herbert A. Simon and Allen Newell, *Human Problem Solving* (Prentice-Hall, Inc. N.J.: Prentice-Hall., 1972): 20.

[148] Ibid 79-80.
[149] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 44.
[150] Ibid.
[151] Charles M. Eastman, *On the Analysis of Intuitive Design Processes* (Pittsburgh, Pa: Carnegie-Mellon University, 1968).
[152] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 45.
[153] Omer Akin, *Psychology of Architectural Design* (London: Pion, 1986): 3.

Akin especially start to break down the design process into its constituent parts[154]. Even with this interventionist movement, Akın could not describe analysis and synthesis phases as meaningfully discrete components of design.[155] His research data revealed that designers restructure the problem not only when they get stuck but also when they find solutions.[156] Moreover, these findings indicate this strategy can also assist in design creativity.[157] Considering this intrusive movement to the problem, Akin states analysis and synthesis phases are not discrete components of the design process.[158]

Gabriela Goldschmidt is another pioneering name who has research on understanding the design process using protocol analysis. She studied with architects to understand the potential of sketching in the design process through several protocol studies. Goldschmidt described this process as the 'dialectics of sketching'.[159] She states that how sketches enable interaction between 'seeing that' and 'seeing as.' According to Goldschmidt, 'seeing that' is the method to summarize the process, and 'seeing as' is a method to create new interpretations.[160] According to the inference from the analysis in her article "The Dialectics of Sketching", the design ideation process did not follow a strict route, neither linear nor hierarchical.[161] She developed a new system based on the fact that the design process consists of separate stages and the designers move from one stage to the next, with retrospective movements where necessary.[162]

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[154] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 45.
[155] Ibid.
[156] Ömer Akin, *A Cartesian Approach to Design Rationality* (Ankara, Turkey: Middle East Technical University, Faculty of Architecture, 2006): 71.
[157] Ibid.
[158] Bryan Lawson, *How Designers Think: The Design Process Demystified* (Elsevier, 2005): 45.
[159] Gabriela Goldschmidt, "The Dialectics of Sketching," *Creativity Research Journal* 4, no. 2 (1991): 131.
[160] Ibid.
[161] Ibid., 126.
[162] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 41.

An innovative study was conducted by Goldschmidt to examine the collected protocols by presenting a new approach which is called Linkography. As a new methodology, linkography has been used for visualizing the design processes. Linkography is a system that separates the design process into more minor activities called 'design moves' and creates links between each move, independently from sequentiality.[163] The variable is here the network of links; therefore, Linkography creates a visual map (Figure 2.10) of the design process as the network of links.[164] It is a method for assessing the design productivity of the designer.[165]

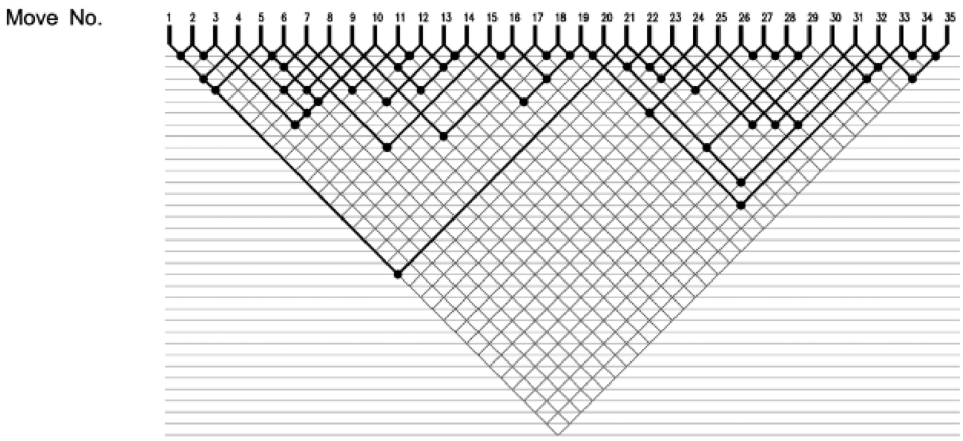

Figure 2.10: An example of Linkograph

Source: Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 75.

The productivity of the design process can be evaluated by the critical move and calculating the ratio of links to movements which is called link index.[166]

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[163] Gabriela Goldschmidt and Maya Weil, "Contents and Structure in Design Reasoning," *The MIT Press* 14, no. 3 (2016): 89.
[164] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 49.
[165] Jeff W.T. Kan and John S. Gero, "Acquiring Information from Linkography in Protocol Studies of Designing," *Design Studies* 29, no. 4 (2008): 316.
[166] Gabriela Goldschmidt, "Cognitive Economy in Design Reasoning," in *Human Behaviour in Design: Individuals, Teams, Tools*, ed. U. Lindemann (Berlin Heidelberg: Springer-Verlag, 2003), 56.

Consequently, different types of moves, link distribution, patterns, and their potential will be explained in detail in the following chapter.

2.4 Productivity Through Linkography

According to Goldschmidt, designing is the generation of an entity; therefore, design thinking is a type of creative thinking.[167] Significant innovations and new design ideas generally emerge thanks to sudden illuminations or, in other words, “creative leaps”.[168] These kinds of creative leaps were seen as central activities of the design process.[169] Substantial creative processes almost never arise from single steps but from the concatenations of a complex set of interconnected movements.[170] Regarding this point of view, Goldschmidt states link networks of linkographs can be used to discover design creativity.[171] The components of linkography will be described in detail below for a comprehensive understanding of its principles.

The underlying basis of Linkography was that the design process consisted of separate stages and that designers moved from one stage to the next, with retrospective tracking where necessary.[172] These separate small parts of the process must be examined to explain thinking patterns, and protocol analysis seems to be the only way to examine these small segments for most investigators.[173] In Linkography, protocols are required to be divided into units that are then parsed into design movements. As mentioned before, video-recordings or voice-recordings

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[167] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 46.
[168] Bruce Archer, “Systematic Method for Designers,” in *Developments in Design Methodology*, ed. Nigel Cross (John Wiley & Sons, 1984): 59.
[169] Ibid.
[170] H. E. Gruber, “Afterword,” in *Beyond Universals in Cognitive Development*, ed. D. H. Feldman (Norwood, NJ: Ablex, 1980), 177.
[171] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 118.
[172] Ibid., 41.
[173] Ibid.

during the design process are required.[174] According to Goldschmidt, the parsing process may be time-dependent or semantically based, or it can be based on units of content that contain one sentence, part of a sentence, or more than one sentence; on the other hand, turn-taking is often a basic parsing concept in teamwork.[175] Each unit can be described as a step, action, movement, or move.[176] According to Goldschmidt ‘move’ is defined as “a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move. Within each unit of the design process, the moves are numbered chronologically.”[177] She also defines it as “an act of reasoning that presents a coherent proposition pertaining to an entity that is being designed.”[178]

After the protocols are parsed into moves, the focus is the ‘links’ between these moves, which is the key to the comprehension of design reasoning.[179] In linkographs, design protocols are illustrated as a series of the designers’ moves and links among these movements. The researcher's good acquaintance with the discipline has an essential role in minimizing the challenges of the think-aloud approach, such as jargon, incomplete phrases, or unclear and repeated phrases, in grasping the movements' contents and decide if there is a "link" between the moves.[180]

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[174] Gabriela Goldschmidt and Maya Weil, “Contents and Structure in Design Reasoning,” *The MIT Press* 14, no. 3 (2016): 89.
[175] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 42.
[176] Ibid.
[177] Ibid.
[178] Gabriela Goldschmidt, “Criteria for Design Evaluation: A Process-Oriented Paradigm,” *Principles of Computer-Aided Design: Evaluating and Predicting Design Performances*, no. JANUARY (1992): 72.
[179] Gabriela Goldschmidt and Maya Weil, “Contents and Structure in Design Reasoning,” *The MIT Press* 14, no. 3 (2016): 90.
[180] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 47.

For reliable research, Goldschmidt suggests that the consensus of three people should decide whether the movement is a link or not.[181] Minimum disagreement between coders is desired, but this cannot be easy to achieve because of the qualitative nature of the coding process. Therefore, to decrease the ambiguity of the coding scheme, Mc Neill, Gero, and Warren emphasize "inter-coder reliability".[182] Here the principle is linking the codes with ten-day intervals by more than one judge, as Goldschmidt proposed.[183] After that, while the encoder returns to the protocol after ten days break, the encoder compares two encoding results and performs a self-arbitration process.[184] After the arbitration process, when the consensus achieved the results gives the linkograph.

In linkography design moves are depicted as nodes, and links are the connecting lines of nodes. Goldschmidt points out focusing on the links because, in this representation, the variable is them.[185] There is an example of a small portion of a Linkograph in Figure 2.11. The sequence of moves is shown on a horizontal line, and nodes connect two related movements by intersecting diagonal network lines.[186] Moreover, Figure 2.11 illustrates a link between move 1 and move 3, where move 1 has a forelink to move 3, and the same link is the backlink of move 3. A large number of backlinks indicates that the design move benefited from many previous moves, whereas a large number of forelinks shows that the move inspired many future design moves and thus has an impact on the ideation session moving

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[181] Ibid., 48.
[182] Thomas Mc Neill, John S. Gero, and James Warren, "Understanding Conceptual Electronic Design Using Protocol Analysis," *Research in Engineering Design* 10, no. 3 (1998): 132.
[183] Ibid.
[184] Ibid.
[185] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 49.
[186] Gabriela Goldschmidt, "Criteria for Design Evaluation: A Process-Oriented Paradigm," *Principles of Computer-Aided Design: Evaluating and Predicting Design Performances*, no. JANUARY (1992): 74.

forward.[187] Contrary to the general expectation, denser linkographs may show design fixation instead of a well-productive design process.[188]

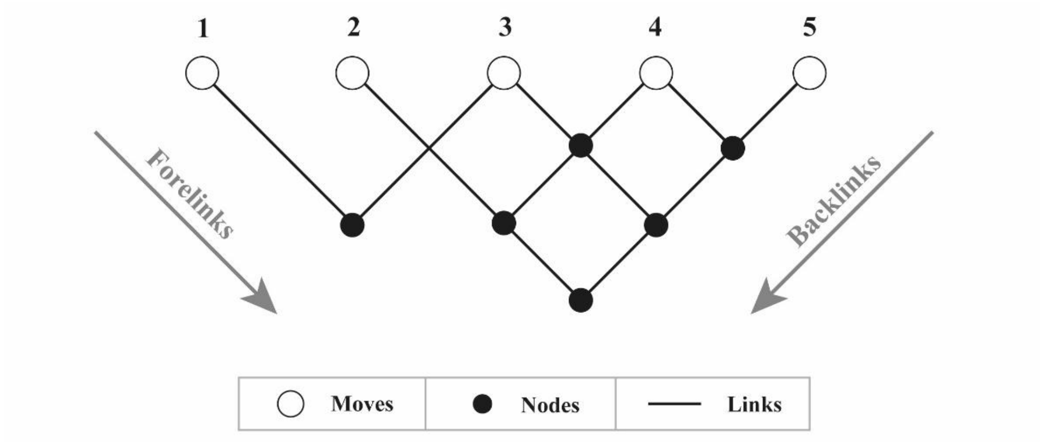

Figure 2.11: An example of Linkograph part

Source: Adapted from Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 49.

Goldschmidt classified moves into four types: "orphan moves, unidirectional moves, bidirectional moves, and critical moves".[189] Orphan moves have no link to any previous move and subsequent move in the current sequence. According to Goldschmidt, orphan moves are usually found in very small numbers in most linkographs, and generally, more orphan moves can be observed when the designers are novices than when they are expert.[190] When we look at the example linkograph In Figure 2.12; move 19, move 30, move 39, and move 41 are orphan moves that have no links to relate to any other design moves. This type of move can be observed when the designer made an unrelated design move for the design process.

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[187] G. Hatcher et al., "Using Linkography to Compare Creative Methods for Group Ideation," Design Studies 58, no. June (2018): 130.
[188] Tamer El-Khouly and Alan Penn, "On an Integrated Analytical Approach to Describe Quality Design Process in Light of Deterministic Information Theory," in *Design Computing and Cognition '12*, ed. John S. Gero (Dordrecht: Springer, 2014), 457.
[189] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 55.
[190] Ibid., 57.

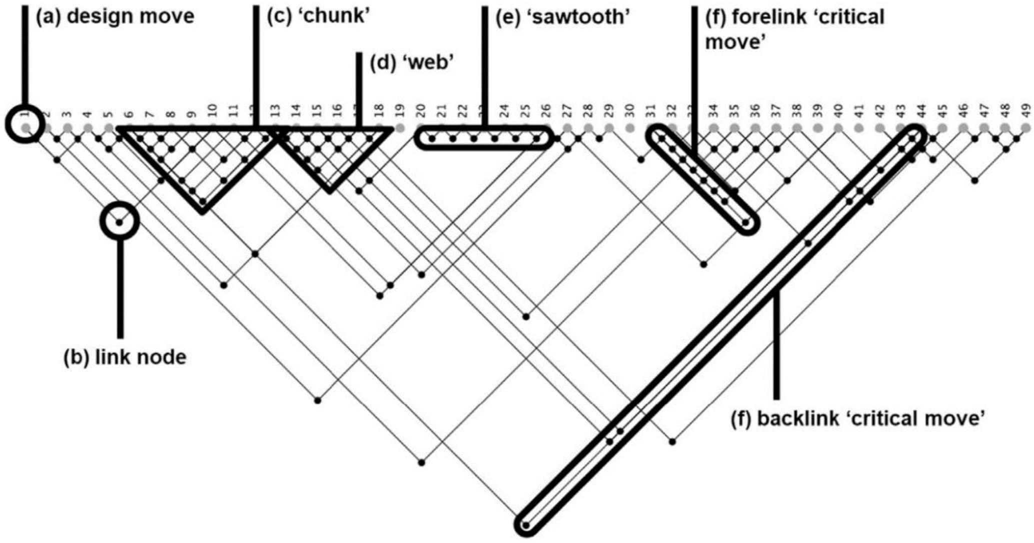

Figure 2.12: An example linkograph describing the main features and terminology

Source: G. Hatcher et al., "Using Linkography to Compare Creative Methods for Group Ideation," Design Studies 58, no. June (2018): 130

Moves that link only backward or only forward are named unidirectional, whilst the other moves are called bidirectional, because they have links both backward and forward.[191] As only one direction can connect the first and last moves with the other moves, these are unidirectional moves. More importantly, bidirectional moves are the indicators of a quick shift between the two modes of reasoning associated with divergent and convergent thinking.[192] From the point of thinking types, as mentioned earlier, the ability to switch between divergent and convergent thinking is evidence of creative thinking.

According to Goldschmidt, moves diversify according to the number of links they generate.[193] The most significant moves that create a particularly large number of links are called 'critical moves'.[194] If the fundamental premise that links are the primary indicator of the quality of the process is true, it can be inferred that critical

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[191] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 57.
[192] Ibid., 58.
[193] Ibid., 58.
[194] Ibid.

moves have particular importance. The whole critical moves of a sequence define its 'critical path', and a critical path with a large number of critical moves is an indicator of productivity.[195]

The linkograph demonstrates geometrically noticeable structural patterns during an ideation session. Based on the link patterns, it is possible to make inferences about various features of design reasoning, and, as a result, that helps to measure design productivity.[196] Goldschmidt identifies these geometric linking patterns as 'chunk', 'web', and 'sawtooth'[197] (Figure 2.12). In linkographs, graphically recognizable triangular patterns are called chunks, and the existence of chunks shows efficient thinking and reasoning during the design process[198]. Regardless of the number of links included in them, chunks are generally formed by one to two dozen moves.[199] When a significant number of links are created from a relatively small number of moves, a web is formed. The geometry of the web, like that of a chunk, requires a triangular boundary of the linkograph.[200] The web is a section of the network with particularly dense nodes of links.[201] Webs are smaller than chunks and they could not appear in every linkograph.[202] Goldschmidt points out that most webs are composed of no more than seven densely interconnected moves.[203] In the Linkograph example of figure 12, the links between moves 6 and 13 create a chunk; besides, the links that connect moves between 13 and 18 generate a web.

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[195] Gabriela Goldschmidt, "The Designer as a Team of One," *Design Studies* 16, no. 2 (1995): 196.
[196] Gabriela Goldschmidt and Maya Weil, "Contents and Structure in Design Reasoning," *The MIT Press* 14, no. 3 (2016): 89.
[197] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 62.
[198] Ibid., 62-64.
[199] Gabriela Goldschmidt, "Criteria for Design Evaluation: A Process-Oriented Paradigm," *Principles of Computer-Aided Design: Evaluating and Predicting Design Performances*, no. JANUARY (1992): 74.
[200] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 64.
[201] Ibid., 65.
[202] Ibid.
[203] Ibid.

Goldschmidt defines another linking pattern as ‘sawtooth’ is the series of moves that link each of them to the preceding move where the connecting lines form a zigzag pattern like a sawtooth.[204] Although most sawtooth patterns are much longer, a sawtooth track must have at least four moves.[205] In Figure 2.12, the link pattern between moves 20 and 26 is an example of the sawtooth. This type occurs when the designer builds one observation or suggestion on another in a linear sequence without making any attempt to expand or deepen the research.[206]

Linkography supposes that the capacity to synthesize a solution with components of good fit indicates for the productivity of the design process.[207] However, the above-mentioned linking patterns are not the sole factor in determining whether linkography reflects high productivity. Goldschmidt introduces a new term as “Link Index (L.I.)” which means the ratio between the number of links and the number of moves that generate them in a linkograph.[208] For different parts of a design session, different link index values might be observed. The high link index is generally found in webs previously described as high-link-density patterns of moves. Although the link index value calculation is an easy method to evaluate data in terms of seeing a designer's activity during the design process and getting creative insights, Goldschmidt points out that a high link index value does not always indicate the productive design. A high value of the link index might result from multiple repetitions or attempts to find alternative ideas with short continuity between them.[209]

Research on Linkography has become more prevalent over the last years. Door Remko van der Lugt is another name that adapted the visualization of Linkography

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[204] Ibid.
[205] Ibid.
[206] Ibid.
[207] Ibid., 73.
[208] Ibid., 69.
[209] Ibid.

to a different representation type: matrix.[210] He states that Goldschmidt's Linkography is fundamentally a transformed matrix that turns the diagonal to the horizontal axis.[211] A link matrix shows a graphical depiction of the nature of the linking process involved in an idea generation meeting.[212] Van der Lugt has extended links according to the categorization of the idea generation process of Stanley Gryskiewicz into three types as 'supplementary', 'modification', and 'tangential' links. The 'supplementary' link represents small and auxiliary changes on the general idea; the 'modification' link refers to structural changes in the idea resulting in a significant change while maintaining the main aspects of the original idea, and the 'tangential' link indicates a radical change from the previous idea without close association with the original design idea.[213] To measure the productivity in the design process, Lugt proposed the 'link type indexes', which are the link numbers of one of the types mentioned above, divided by the sum of the link numbers in a link matrix.[214] Similarly, Perttula and Sipila developed a metric principle named 'weighted link density' by specifying separate weights for the following three links: 'parts sharing', 'same principle', and 'modification', individually.[215] The higher 'link density index' could lead to a higher linkage between examples and solutions, which indicates the design fixation.[216]

Kan and Gero analyze linkography from a statistical viewpoint and, they propose new methods to acquire information from the linkography, one of them based on clustering and the other based on Shannon's entropy.[217] The goal of the first method is to examine Linkographs by clustering the links that are close together

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[210] Remko. Van der Lugt, "Sketching in Design Idea Generation Meetings", Doctoral dissertation, (Delft University of Technology, 2001): 60.
[211] Ibid.
[212] Ibid., 68.
[213] Ibid., 72.
[214] Ibid., 74-75.
[215] Matti Perttula and Pekka Sipilä, "The Idea Exposure Paradigm in Design Idea Generation," *Journal of Engineering Design* 18, no. 1 (2007): 98-99
[216] Ibid., 99.
[217] Jeff W.T. Kan and John S. Gero, "Acquiring Information from Linkography in Protocol Studies of Designing," *Design Studies* 29, no. 4 (2008): 315.

into meaningful groups.[218] The second method is the entropy measurements of linkographs aims to evaluate the productivity of the design processes.[219] For the notion of entropy, Kan and Gero adapted Shannon's information theory which is explained as "the amount of information carried by a message or symbol is based on the probability of its outcome". They extended this concept to the design process claiming that a link between moves contains information.[220]

According to Kan and Gero, the higher entropy of the forelink and backlink indicates a richer idea generation process as they introduced a higher degree of uncertainty.[221] They stated that forelinks are initiations, and backlinks are responses. Therefore, a higher value of forelinks entropy indicates a significant opportunity to initiate design moves for generating new ideas, and a higher value of backlinks entropy refers to activity on the previous design moves.[222] Kan and Gero introduced another link type called horizonlink.[223] Horizonlink is not a link itself, but it shows the concept of cohesiveness which can be explained by the length between the links. In brief, it may be viewed as a measurement of the distances between the links.[224] The measurement of entropy for different type of links are shown in Figure 2.13.

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[218] Ibid.
[219] Ibid.
[220] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 143.
[221] Jeff W.T. Kan, Zafer Bilda, and John S. Gero, "Comparing Entropy Measures of Idea Links in Design Protocols: Linkography Entropy Measurement and Analysis of Differently Conditioned Design Sessions," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM* 21, no. 4 (2007): 372.
[222] Jeff W.T. Kan and John S. Gero, "Acquiring Information from Linkography in Protocol Studies of Designing," *Design Studies* 29, no. 4 (2008): 334.
[223] Jeff W.T. Kan and John S. Gero, "Can an Objective Measurement of Design Protocols Reflect the Quality of a Design Outcome?," Proceedings of ICED 2007, the 16th International Conference on Engineering Design DS 42, no. January (2007): 3.
[224] Jeff W.T. Kan and John S. Gero, "Acquiring Information from Linkography in Protocol Studies of Designing," *Design Studies* 29, no. 4 (2008): 333.

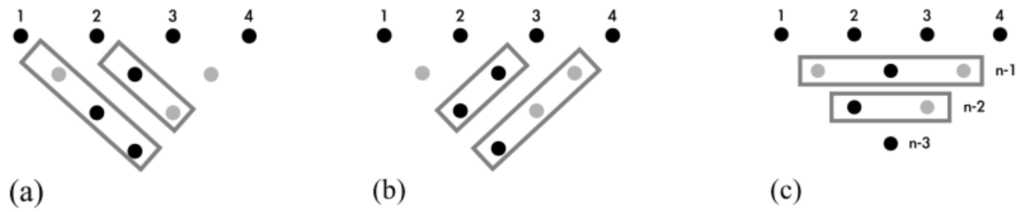

Figure 2.13: Entropy measurement of forelinks (a), backlinks (b), and horizonlinks (c)

Source: Jeff W.T. Kan and John S. Gero, "Can an Objective Measurement of Design Protocols Reflect the Quality of a Design Outcome?," Proceedings of ICED 2007, the 16th International Conference on Engineering Design DS 42, no. January (2007): 3.

Furthermore, Gero applied entropy to identify the design fixation process; the entropy in the design fixation process should be lower than in the other design stages.[225] They have also researched FBS (Function-Behaviour-Structure) ontology, a coding method that aims to capture semantic information about the process from the design methodology. This semantic information might be utilized to investigate different design features based on the area of interest and identify various design transformation processes.[226] Because the linkograph generation process is remarkably time-consuming and cognitively challenging, the aim is to find a practical way to study and compare in very large data sets.[227] According to Pourmohamadi and Gero, quantitative analysis of collected protocols throughout the design process is a time-consuming and resource-intensive research strategy.[228] A technique for lowering the consuming time and expense for the generation of such procedures is to create software tools that automate these aspects of the

[225] John S. Gero, "Fixation and Commitment While Designing and Its Measurement," *Journal of Creative Behavior* 45, no. 2 (2011): 112.
[226] Jeff W T Kan and John S Gero, "Using the FBS Ontology to Capture Semantic Design Information in Design Protocol Studies," 2009: 2
[227] Jeff W.T. Kan and John S. Gero, "Characterizing Innovative Processes in Design Spaces through Measuring the Information Entropy of Empirical Data from Protocol Studies," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM* 32, no. 1 (2018): 37.
[228] Morteza Pourmohamadi and John S. Gero, "LINKOgrapher: An Analysis Tool to Study Design Protocols Based on FBS Coding Scheme," *ICED 11 - 18th International Conference on Engineering Design - Impacting Society Through Engineering Design* 2, no. January (2011): 294.

process.[229] They developed a software tool named Linkoder that performs analyses on coded protocols about the design process and generates linkographs from spreadsheet data and calculates entropy.[230] This software tool is built on an ontologically-based coding system that makes use of the Function-Behavior-Structure (FBS) framework, which was presented by Gero and Kannengiesser previously.[231]

In 2008, Kan and Gero present a methodology for automated linkograph generation by connecting segments and measuring entropy using the English lexical database WordNet.[232] To group words into clusters, the principle of WordNet is using the cognitive synonyms named as synset.[233] Words in a synset are linked to each other according to their meanings.[234] El-Khouly and Penn introduced a method for analyzing linkographs throughout the design process by quantifying entropy at every move individually.[235] The quantitative method is combined with a qualitative approach by evaluating stages of sketches and relationships between outcomes that evolve suddenly during the design process.[236] Consequently, it is observed that there are significant relationships between quantitative and qualitative models on some key nodes in identifying the emergence of new ideas and defining design productivity.[237] Lee, Gu, and Ostwald researched analyzing protocol data obtained from the cognitive activities during parametric design using linkography.[238] Their research indicates how linkography improves the idea generation process by

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229 Ibid.
230 Ibid.
231 John S. Gero and Udo Kannengiesser, "The Situated Function-Behaviour-Structure Framework," *Design Studies* 25, no. 4 (2004): 374.
232 Ibid.
233 Ibid.
234 Ibid.
235 Tamer El-Khouly and Alan Penn, "On an Integrated Analytical Approach to Describe Quality Design Process in Light of Deterministic Information Theory," in *Design Computing and Cognition '12,* ed. John S. Gero (Dordrecht: Springer, 2014), 451.
236 Ibid.
237 Ibid.
238 J U Hyun Lee, Ning Gu, and Michael J Ostwald, "Architectural Design Using Algorithmic Scripting: An Application of Linkographic Analysis Techniques," 2013, 133.

showing the relationship between scripting and idea generation.[239] Research on design ideation is constantly evolving. Hatcher et al. further investigated Linkography by comparing brainstorming and the new method, which is Design Improv.[240]

From all the literature reviewed in this section, linkography is known as a methodology for assessing productivity in the design process. In this paper, the design process of the participants will be analyzed with using linkography methodology.

[239] Ibid.

[240] G. Hatcher et al., "Using Linkography to Compare Creative Methods for Group Ideation," Design Studies 58, no. June (2018): 127.

CHAPTER 3

PERFORMANCE IN ARCHITECTURAL DESIGN

The concept of performance in architecture was first explained by Gibson in the CIB W60 Commission in 1982 as *"first and foremost, the practice of thinking and working in terms of ends rather than means. .... It is concerned with what a building or building product is required to do, and not with prescribing how it is to be constructed."*[241] Also, it is explained as "the manner in which or the efficiency with which something reacts or fulfills its intended purpose" in Collins dictionary.[242] Based on these meanings, performance can be defined as the potential to satisfy requirements throughout the design process. Throughout the design process, to formalize the predetermined design requirements that are intended to be met, Becker established two commonly used phrases: user needs (UN) and performance requirements (PR).[243] The term "with reference to" in the process of performance-based design (PBD) is turned to the demand to identify.[244] UNs and PRs indicate the demand side of the design process.[245] As a result, performance-based design is the term for a strategy in which user requests and performance needs become the guiding factor for the process and end product.

Environmental impact is demonstrated by the activity of force fields, which can be physical, such as gravity and climatic conditions, for instance, wind, precipitation, solar radiation, or nonphysical, such as forces originating from locations associated

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[241] E. J. Gibson, "Working with the Perfomance Approach in Building," in *Report of Working Commission W060*, vol. 64 (Rotterdam, the Netherlands: CIBdf — International Council for Research and Innovation in Building and Construction — Development Foundation., 1982), 4.
[242] "Collins Dictionary" (HarperCollins Publishers Ltd, 2019).
[243] Rachel Becker, "Fundamentals of Performance-Based Building Design," *Building Simulation* 1, no. 4 (2008): 357.
[244] Ibid.
[245] Ibid., 362.

with crucial cultural and natural heritage.[246] Eventually, the formation of the design element becomes a representation of the specific factors that animate the environmental context.[247] As a design paradigm, the ongoing interest in building performance is derived from the emergence of sustainability as a defining socioeconomic concern and recent technological and cultural conceptual advancements.[248] The concept of sustainability is described as continuity and maintenance of resources.[249] The main goal of sustainable and performance-based design is energy conservation, which helps expand the concept of performance-based design across the world, not as another architectural style but as a necessity.[250]

The growing demand to ensure the performance of buildings throughout architectural design has resulted in highly dynamic relationships between architecture and several other disciplines, in which notions of sustainability and building performance have been strongly interwoven into the design process over the last few decades.[251] Due to the interaction between form and performance factors in the conceptual design process, there are recently increasing requirements for sustainable performance characteristics such as "comfort, safety, wind, energy efficiency, health, indoor climate, building services".[252] At the same time, new

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[246] Giuseppe Pellitteri, Salvatore Concialdi, and Raimondo Lattuca, "Performative Architecture: New Semantic for New Shapes?," *CAADRIA 2008 - The Association for Computer-Aided Architectural Design Research in Asia: Beyond Computer-Aided Design*, 2008, 300.
[247] Ibid.
[248] Branko Kolarevic, "Computing The Performative," 2003: 195.
[249] Terry Williamson, Antony Radford, and Helen Bennetts, *Understanding Sustainable Architecture*, 2004: 3.
[250] Eleftheria Fasoulaki, "Integrated Design: A Generative Multi-Performative Design Approach", Ph. D. thesis, (Massachusetts Institute of Technology, 2008): 15-16.
[251] Cem Ataman and İpek Gürsel Dino, "Performative Design Processes in Architectural Practices in Turkey: Architects' Perception," *Architectural Engineering and Design Management*, 2021: 1.
[252] Sevil Sariyildiz, "Performative Computational Design," in *ICONARCH I: Architecture and Technology* (Proceeding of the International Cogress of Architecture-I, 2012), 324.

demands have arisen regarding logistics, construction techniques and materials that contribute to the performance of buildings.[253]

The interest in performance as a design paradigm has increased primarily due to recent technological and cultural conceptual advancements, as well as the rise of sustainability as a defining socioeconomic concern.[254] Within such comprehensive perspective, Kolarevic and Malkawi defined the performative architecture can be very broadly as:

> "Its meaning spans multiple realms, from financial, spatial, social and cultural to purely technical (structural, thermal, acoustical, etc.). In other words, the performative in architecture is operative on many levels, beyond just the aesthetic or the utilitarian." [255]

New advances in performance-based design offer a rapid technical approach to this unique system analysis. Methods applied at the right time in the design process can develop quality building design solutions far beyond the typical and common rules.[256]

3.1 Classifications of Performance Criteria

To understand the total building performance, various features of the design must be examined, and this realization process creates the foundation of Performative Architecture. In terms of architecture, the performance components and intended objectives are numerous, interconnected, and dynamic, making the idea of performance complicated and multi-component.[257] In particular, the definition of performance in architecture is proposed through three steps, from human needs to

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[253] Ibid.
[254] Branko Kolarevic and Ali Malkawi, *Performative Architecture: Beyond Instrumentality*, 2005: 205.
[255] Ibid.
[256] Ibid., 113.
[257] Michela Turrin, *Performance Assessment Strategies: A Computational Framework for Conceptual Design of Large Roofs*, *A+BE | Architecture and the Built Environment*, vol. 4, 2014: 54.

architectural requirements and performance assessment; further, the crucial position of the environment fulfillment of the requirements is indicated.[258]

While proposing a systematic assessment of design performance, various aspects need to be considered, such as functional performance, technical performance, energy performance, aesthetic performance, cultural performance, etc. This means design performance can be defined as the total satisfaction of the design requirements, which reflect a design's intended purpose.[259] Bittermann notes that the term requirement is used in this scope in a broader sense encompassing the idea of desire and demand.[260] The primary goal of performance evaluation is to determine the degree of overall design performance given the fulfillment of essential requirements.[261] Models that reflect the relationship between design factors and overall performance must be developed to succeed in this objective; however, the intricacy of the related performance criteria makes this challenging.[262]

Various types of assessment are performed on a building project during the design, programming, design, construction, and occupancy stages, which are usually technical considerations relating to queries regarding a building's materials, engineering, or construction.[263] Examples of these assessments include structural testing, review of load-bearing members, soil testing and mechanical system performance checks, as well as a pre-use post-construction evaluation.[264] Technical tests generally compare a physical system to related engineering or performance standards; however, technical tests indirectly address such requirements by

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258 Ibid., 55.
259 Michael S Bittermann, "Intelligent Design Objects (IDO): A Cognitive Approach for Performance-Based Design", Ph. D. thesis, (Delft University of Technology, 2009): 80.
260 Ibid.
261 Ibid., 81.
262 Ibid.
263 Wolfgang F.E. Preiser, "The Evolution of Post-Occupancy Evaluation: Toward Building Performance and Universal Design Evaluation," in *Learning From Our Buildings: A State of the Practice Summary of Post Occupancy Evaluation* (Federal Facilities Council (FFC) Technical Report No. 145, 2001): 10.
264 Ibid.

producing a better and safer structure, they do not assess it in terms of occupant's demands and objectives or performance and functionality as they are relevant to them. Thus, the client's building may be technologically useful, yet it may not produce a functional atmosphere for people.[265] According to the European Union and its Energy Performance in Structures Directive (EPBD), a systematic evaluation of each building's energy performance is required, and they have concentrated on methodologies that calculate and assess energy performance to provide energy efficiency of buildings.[266] According to Becker, when performative concepts are applied systematically throughout the building process, designed structures supposed to enable as:

> "... the design and execution of buildings that are highly suitable for the functions and activities of their occupants, provide thermally, acoustically and visually comfortable and healthy internal conditions while conserving energy and the environment, are pleasant and harmless from the tactile point of view, are sufficiently safe under regular and extreme loads that may occur during the life expectancy of the building, ... are maintenance friendly and can easily be modified in order to cater for new demands."[267]

Building performance assessment consists of identifying and quantifying the objectives that a building is scheduled to meet and using occupancy and systematic techniques to evaluate the solution to evaluate its quality.[268] Preiser and Vischer described a habitability framework by defining priorities about building performance in three levels as below:

> "1. health, safety and security performance;
> 2. functional, efficiency and work flow performance;

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[265] Ibid.

[266] Sang Hoon Lee, Fei Zhao, and Godfried Augenbroe, "The Use of Normative Energy Calculation beyond Building Performance Rating," *Journal of Building Performance Simulation* 6, no. 4 (2013): 282.

[267] Rachel Becker, "Research and Development Needs for Better Implementation of the Performance Concept in Building," *Automation in Construction* 8, no. 4 (1999): 526.

[268] Ipek Gursel Dino, "CLIP: Computational Support for Lifecycle Integral Building Performance Assessment" PhD Dissertation, (2010): 15.

3. psychological, social, cultural and aesthetic performance."[269]

In this framework, each category focuses on separate aspects of building performance, but the overall building performance needs to be evaluated by the combination of these criteria.[270] In brief, the building performance evaluation methodology connects buildings and design criteria according to occupants and environmental demands. This approach provides a conceptual, process-oriented approach that may be used to any sort of building or environment.[271]

A significant issue of the design process is the diversity of criteria needed to fulfill the function-related, technical aspects of a design which is called 'hard' aspects, and the psychological, 'soft' aspects of it.[272] Performative design deals with architectural complexity through soft criteria such as perception and experience of space, form, culture, function, aesthetic, social, economic, safety, and comfort; and hard criteria such as technical, structural, material performance, energy and cost-related, construction, sustainability, climate, and energy.[273] Sarıyıldız stated that the conceptual phase of architectural design encompasses both soft and hard performance factors, which aims for the maximum optimality of designated buildings.[274]

Aesthetic and cultural performance factors have always been at the center of architectural design. Form, space organization, material selection, color, and details all have a contribution in establishing a building's aesthetic and cultural performances.[275] In contrast to the physical performances, these performances are

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[269] Wolfgang F.E. Preiser and Jacqueline C. Vischer, "The Evolution of Building Performance Evaluation: An Introduction," *Assessing Building Performance*, 2006: 5.
[270] Ibid., 7.
[271] Ibid.
[272] Michael S Bittermann, "Intelligent Design Objects (IDO): A Cognitive Approach for Performance-Based Design", Ph. D. thesis, (Delft University of Technology, 2009): 12.
[273] Sevil Sariyildiz, "Performative Computational Design," in *ICONARCH I: Architecture and Technology* (Proceeding of the International Congress of Architecture-I, 2012), 324.
[274] Ibid., 321.
[275] Xing Shi, "Performance-Based and Performance-Driven Architectural design and Optimization.Pdf," *Frontiers of Architecture and Civil Engineering in China* 4 (2010): 513.

sometimes difficult to assess.[276] As a result, evaluation is based on various elements, and it may sometimes become a question of personal opinion or pleasure.[277] Commonly, an architecturally designed structure should be functional, give a pleasing aesthetic experience, and use as little energy as possible.[278] Functional Performance is another soft criterion; however, what is meant by functional by Bittermann is ambiguous and susceptible to interpretation from situation to case.[279] Therefore, techniques based on rules and identifying universal answers to design challenges have limited value because broad norms cannot reflect the specific conditions of a given economic, personal, social or other scenarios.[280] Although soft performance criteria have subjective and unquantifiable character, these factors should be included in the performative design process.[281]

The hard performance criteria include quantitative performative characteristics, allowing objective assessments to be conducted throughout the design process. The most essential performance problem that has to be thoroughly analyzed and considered in architectural design is structural performance.[282] One of the most important tasks of a structure is to create safety which is closely related to structural performance.[283] Whether the building's loadbearing structure resists the predicted living loads, dead loads, wind loads, and earthquake-generated forces effectively and efficiently.[284] According to Hensel, material behaviour is another hard performance criterion that affects the overall building performance factors, including aesthetic performance, structural performance, and energy

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[276] Ibid.
[277] Ibid.
[278] Michael S Bittermann, "Intelligent Design Objects (IDO): A Cognitive Approach for Performance-Based Design", Ph. D. thesis, (Delft University of Technology, 2009): 12.
[279] Ibid.
[280] Ibid.
[281] Ibid., 17.
[282] Xing Shi, "Performance-Based and Performance-Driven Architectural design and Optimization.Pdf," *Frontiers of Architecture and Civil Engineering in China* 4 (2010): 512–13.
[283] Ibid., 513.
[284] Michael S Bittermann, "Intelligent Design Objects (IDO): A Cognitive Approach for Performance-Based Design", Ph. D. thesis, (Delft University of Technology, 2009): 79.

performance.[285] Another hard performance criteria that affect the quality of both indoor and outdoor environments is the energy performance of the physical environment includes solar, thermal, moisture, acoustics, lighting, wind and air, energy, and many others.[286] These performance factors are becoming the new emphasis for architects to create responsibly in a future of green, sustainable, and low-carbon architecture.[287]

The nature of the performative design is a highly complex process, where multiple, conflicting requirements should be satisfied simultaneously from the beginning of the process. For effective assessment of building performance, the combined relationships between design factors and design performance must be examined both soft and hard criteria.

3.2 Performative Architecture in Conceptual Design Process

Turrin explains design with the definition of Cross *as "the conception and realization of new things"* and with this respect, he defined conceptual design as a design conception stage that is a part of the entire design process.[288] There is no single, precise description of conceptual design. It has varied purposes and manifests itself in various forms in the many sub-disciplines. According to Okudan and Tauhid, conceptual design corresponds to the concept development phases, which is seen as a "*series of divergent and convergent steps, completed at different*

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[285] Michael Hensel, *Performance-Oriented Architecture: Rethinking Architectural Design and the Built Environment*, ed. John Wiley & Sons Ltd, 2013: 59.
[286] Xing Shi, "Performance-Based and Performance-Driven Architectural design and Optimization.Pdf," *Frontiers of Architecture and Civil Engineering in China* 4 (2010): 513.
[287] Ibid.
[288] Michela Turrin, *Performance Assessment Strategies: A Computational Framework for Conceptual Design of Large Roofs, A+BE | Architecture and the Built Environment*, vol. 4, 2014: 60.

levels of solution abstraction."[289] Concepts are created in the divergent phases; concepts are examined and selected in the convergent steps.[290]

Conceptual design begins with gathering design criteria together. More precise performance evaluations need a basis of quantitative criteria that are generally simulated in the detailed design stages.[291] However, environmental factors should be integrated early into the conceptual design phase of the design activity, since at the beginning of the design process, human needs and the necessary performance requirements from the given surrounding must also be taken into account within the architectural requirements.[292]

A primary goal of conceptual design is the formation of promising concepts that are suitable for the design criteria and will be further developed and altered in the embodiment and detailed design stages, and that such type of formation can be achieved through iterative phases of concept creation and selection.[293] Since the earliest stages of the design process are quite intuitive and non-structured, the performance-based design depends mainly on fundamental knowledge and physical concepts and does not address numeric values of requirements throughout these stages.[294] Nevertheless, performative solutions are critical because some developments are not possible without creating and selecting core concepts in the conceptual design stages. The integration of performance issues in the conceptual stages has changed the design process. In this way, the emphasis shifted towards form creation processes based on performative design strategies such as structure, acoustics, or environmental design, and technology offered new opportunities for

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[289] Gul E. Okudan and Shafin Tauhid, "Concept Selection Methods: A Literature Review from 1980 to 2008," *International Journal of Design Engineering* 1, no. 3 (2008): 244.
[290] Ibid.
[291] Michela Turrin, *Performance Assessment Strategies: A Computational Framework for Conceptual Design of Large Roofs, A+BE | Architecture and the Built Environment*, vol. 4, 2014: 64.
[292] Ibid.
[293] Ibid., 61.
[294] Rachel Becker, "Fundamentals of Performance-Based Building Design," *Building Simulation* 1, no. 4 (2008): 362.

designers to examine specific performance aspects of their final products as they became more realistic.[295]

Sarıyıldız underlines the need to use performance simulations early in the design phase to assess various geometrical possibilities.[296] On the one hand, this approach precisely pertains to the notion of performative architecture, as described by Branko Kolarevic as the one in which building performance, broadly defined, becomes a guiding design factor.[297] On the other hand, it needs an interconnected network of interdisciplinary relationships and pays attention to the notion of integral design by implying the simultaneous integration of varied and multidisciplinary components.[298] Such a process has been investigated using a combination of parametric geometry and performance simulation software.[299] Firstly, it allows the algorithmic creation of geometrical design alternatives that are meaningful for the investigated performances; second, it allows their performance evaluation with genetic algorithms that have been used to guide the search process and combine the generation of design alternatives toward a set of well-performing solutions.[300]

Conceptual design has been identified as the most impactful stage of the whole design process, which has a crucial role in generating new products.[301] As a result, the focus of academicians and practitioners is increasingly turning to conceptual design, which opens up new prospects in computer-aided design.[302] This has resulted in the creation of a numerous of information and computational

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[295] Sevil Sariyildiz, "Performative Computational Design," in *ICONARCH I: Architecture and Technology* (Proceeding of the International Congress of Architecture-I, 2012), 322.
[296] Ibid, 329.
[297] Branko Kolarevic, "Computing The Performative," 2003: 195.
[298] Sevil Sariyildiz, "Performative Computational Design," in *ICONARCH I: Architecture and Technology* (Proceeding of the International Congress of Architecture-I, 2012), 322.
[299] Ibid.
[300] Ibid.
[301] Imre Horváth, "On Some Crucial Issues of Computer Support of Conceptual Design," in *Product Engineering: Eco-Design, Technologies and Green Energy*, ed. Doru Talaba and Thomas Roche (Springer, Netherlands, 2004), 123.
[302] Ibid.

methodologies and tools, commonly referred to as CACD (computer assisted conceptual design) approaches.[303]

As a result, performance design has a crucial role, and nowadays, all standards and laws exist to assist all performance-related professions. More integrated performative architectural designs have begun to be implemented with the assistance of recently released computational tools in architecture. Besides meeting the design restrictions is necessary, keeping the balance in performance criteria becomes essential in the design process. Performance should not be the outcome of the design process, it has to integrate with the process using computational tools, and performance-related considerations should be done during the conceptual design phase.

3.3 Productivity in Contemporary Design Methods

The assessment of the design processes has been a challenging issue throughout the history of design thinking. Hence, in this chapter creativity and productivity of the design processes will be investigated in terms of parametric and performance-based analysis tools.

3.3.1 The Effects of Parametric Modeling on Productivity

According to Goldschmidt, in order to bridge the gap between design process and design product, a design behaviour requires creativity.[304] With the developments, technology has given way to the application of a variety of computational tools

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[303] Michela Turrin, *Performance Assessment Strategies: A Computational Framework for Conceptual Design of Large Roofs, A+BE | Architecture and the Built Environment*, vol. 4, 2014: 65.

[304] Gabriela Goldschmidt, "Criteria for Design Evaluation: A Process-Oriented Paradigm," *Principles of Computer-Aided Design: Evaluating and Predicting Design Performances*, no. JANUARY (1992): 71.

aiming to improve the designers' creativity and productivity. The term "computer-aided design" refers to approaches for applying computational tools to support human design activities.[305] One of the increasingly common techniques among computer aided design (CAD) tools is parametric design environments.[306] The fundamental goal of traditional CAD tools is to represent the final design form, which depends on a single-state design.[307] On the other hand, parametric modeling is a methodology for design synthesis that enables the design space's divergence to investigate multiple alternatives of the same parametric model.[308] Proposal of variable alternatives is essential for developing productivity and expanding the limits of knowledge.[309]

The classification for the assessment of productivity in parametric design is based on Rhodes' seminal work. Rhodes aimed to deal with both a cognitive approach to the design process and an integrative approach to design products.[310] This framework has divided the branches of creativity into four perspectives known as the four P's of creativity: 'person, process, press, and product'.[311] This classification is explained by Lee et al. as follows:

> "Rhodes' four P's, the framework will be applied to designing (process) and design (product) in parametric design environments (press), whilst also accounting for design strategies and preferences as part of Rhodes' personal creativity (person)."[312]

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[305] Udo Kannengiesser and John S. Gero, "An Ontology of Computer-Aided Design," *Computer-Aided Design*, 2009: 1.
[306] Patrik Schumacher, "Parametricism: A New Global Style for Architecture and Urban Design," *Architectural Design* 79, no. 4 (2009): 15.
[307] Ipek Gürsel Dino, "Creative Design Exploration by Parametric Generative Systems in Architecture," *Metu Journal of the Faculty of Architecture* 29, no. 1 (2012): 211.
[308] Ibid.
[309] John S. Gero, "Creativity, Emergence and Evolution in Design," *Knowledge-Based Systems* 9, no. 7 (1996): 446.
[310] Mel Rhodes, "An Analysis of Creativity," *Phi Delta Kappan* 42, no. 7 (1961): 307.
[311] Ibid.
[312] Ju Hyun Lee et al., "Evaluating Creativity in Parametric Design Processes and Products: A Pilot Study," in *Design Computing and Cognition '12*, ed. John S. Gero (Dordrecht: Springer, 2014), 168.

Evaluating and investigating all design settings under a single study framework is challenging. Rhodes's explanation of creativity highlights that design environments' physical and social conditions, the quality of the design outcome, and the degrees of human productivity can influence the creative design process.

Parametric design can be described as the practice of developing and evaluating multiple design solutions using parameters that are decided beforehand, as it can be understood by its name. It is commonly explained parametric design as a novel algorithmic method to design creation which is rule- and constraint-based.[313] Gero stated the activity of creative design happens when 'one or more new variables is introduced into the design' in computational field.[314] The algorithmic-based nature of parametric tools provides greater computational control over the design geometry throughout the design activity. Parametric modeling tools are highly beneficial for design exploration in complex and dynamic design criteria and requirements thanks to their adaptability and responsiveness.[315]

According to Lee et al., as the most significant aspect of the creative and productive model, parametric design should be related to divergent and convergent thinking.[316] Divergent thinking develops variants for solutions with parameters, whereas convergent thinking helps to find a valid or acceptable solution for the proper answer to a problem with parametric design constraints.[317] A sequence of decision-making activities culminates in the creation of a final product in the design process. In design, decision-making comprises the processes of generating,

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313 Ju Hyun Lee, Ning Gu, and Michael J. Ostwald, "Creativity and Parametric Design? Comparing Designer's Cognitive Approaches with Assessed Levels of Creativity," *International Journal of Design Creativity and Innovation* 3, no. 2 (2015): 80.
314 John Gero, "Computational Models of Innovative And," *Technological Forecasting and Social Change* 64, no. 2–3 (2000): 187.
315 Ipek Gürsel Dino, "Creative Design Exploration by Parametric Generative Systems in Architecture," *Metu Journal of the Faculty of Architecture* 29, no. 1 (2012): 207.
316 Ju Hyun Lee, Ning Gu, and Sue Sherratt, "Developing a Framework for Evaluating Creativity in Parametric Design," *Proceedings of the 45th Annual Conference of the Australian and New Zealand Architectural Science Association (ANZAScA),* no. November (2011): 3.
317 Ibid.

analyzing, and deciding on a solution that meets specified requirements. A good fit design solution can only be is produced if all constraints have been satisfied.[318] As Rhodes indicates for creativity, decision-making is also influenced by not only the designer's experience, personal interests, and choices but also the unique design environment in which the work is conducted. An assessment according to the defined constraints and decision-making activity in the design process provides to explore productivity in parametric design.[319]

Parametric design is a computationally intensive design generation and decision-making process that enables trial implementation and performance assessment of various design possibilities.[320] Parametric design environments have been portrayed as supportive for productivity, as they are claimed to inspire designers to explore different possibilities early in the design process quickly.[321] Over the last two decades, parametric tools have been extensively used in the design field, becoming well recognized for producing unique or novel products.[322] Furthermore, according to Schumacher, parametric design has been lauded as a harbinger of a new approach for architecture and has been frequently associated with claims about enhanced levels of creativity.[323] It is commonly acknowledged that this is a kind of subjective activity, as the combination of cognitive, emotional, and environmental

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[318] Sheng-Fen Chien and Yee-Tai Yeh, "On Creativity and Parametric Design," *Proceedings of 30th ECAADe Conference : Digital Aids to Design Creativity* 1, no. 1991 (2012): 246.
[319] Ju Hyun Lee, Ning Gu, and Sue Sherratt, "Developing a Framework for Evaluating Creativity in Parametric Design," *Proceedings of the 45th Annual Conference of the Australian and New Zealand Architectural Science Association (ANZAScA)*, no. November (2011): 7.
[320] Julian O. Blosiu, "Use of Synectics as an Idea Seeding Technique to Enhance Design Creativity," in *IEEE International Conference on the Systems, Man, and Cybernetics*, vol. 3 (Tokyo, 1999), 6.
[321] Ju Hyun Lee, Ning Gu, and Michael J. Ostwald, "Creativity and Parametric Design? Comparing Designer's Cognitive Approaches with Assessed Levels of Creativity," *International Journal of Design Creativity and Innovation* 3, no. 2 (2015): 78.
[322] Ju Hyun Lee and Michael J. Ostwald, "Creative Decision-Making Processes in Parametric Design," *Buildings* 10, no. 12 (2020): 2.
[323] Patrik Schumacher, "Parametricism: A New Global Style for Architecture and Urban Design," *Architectural Design* 79, no. 4 (2009): 16.

elements affects productivity, generating several thoughts from a single stimulation.[324]

In recent years, studies investigating the effects of parametric design tools on creativity and productivity have been increasing. Iordanova et al. examined creativity in the design situation with parametric methods and tried to set some criteria for the evaluation.[325] From this study, it is observed that productivity is improved by the parametric modeling methods of the design object, particularly the generative methods.[326] Chien and Yeh conducted another empirical research to observe the behaviours of designers when confronted with unexpected outcomes by using parametric design tools.[327] They analyzed the potential influence of parametric modeling producing unexpected outcomes in expanding the perceived field of possible designs for less experienced designers as well as experienced designers.[328] To evaluate design creativity and productivity Yu, Gu, and Ostwald presented cognitive research in parametric design environments compared to rather traditional geometric modeling environments.[329] For the evaluation their criteria are issues related to originality, functionality, and unexpectedness.[330] As a result, they observed that parametric design has the potential to enhance design productivity from several perspectives.[331]

Although several pioneering research studies have shown that parametric design increases creative variations, Lee et al. realized a lack of formal understanding for

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[324] Ivanka Iordanova et al., "Parametric Methods of Exploration and Creativity during Architectural Design: Case Study in the Design Studio," *Joining Languages, Cultures and Visions - CAADFutures 2009, Proceedings of the 13th International CAAD Futures Conference*, 2009, 424.
[325] Ibid.
[326] Ibid., 436.
[327] Sheng-Fen Chien and Yee-Tai Yeh, "On Creativity and Parametric Design," *Proceedings of 30th ECAADe Conference : Digital Aids to Design Creativity* 1, no. 1991 (2012): 247.
[328] Ibid.
[329] Rongrong Yu, Ning Gu, and Michael Ostwald, "Evaluating Creativity in Parametric Design Environments and Geometric Modelling Environments," *Architectural Science Review*, 2018: 443.
[330] Ibid.
[331] Ibid.

evaluating creativity in parametric design.[332] Therefore, they created an assessment framework for parametric design in the early design process.[333] The framework involves the analysis of productivity from the design process to design output in the parametric design environments; moreover, this conceptual assessment framework includes a coding scheme for the protocol analysis of the design process and evaluation criteria for assessing the design output.[334]

Parametric design is accepted as a tool to improve design creativity and productivity on multiple levels in all of the research covered here. According to Burry, one of the most fundamental features of parametric modeling techniques is that they are required for performance-based design.[335] In this regard, the next part will concentrate on the effects of performance-based design environments on the productivity and creativity of the design processes.

3.3.2 The Effects of Performance-Based Design on Productivity

Tools for energy simulation are increasingly being utilized to analyze the energy performance of buildings and the thermal comfort of their inhabitants. Building energy simulations are commonly used in building design to evaluate what-if scenarios with the trial-and-error assessment to find optimal solutions.[336]

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[332] Ju Hyun Lee, Ning Gu, and Sue Sherratt, "Developing a Framework for Evaluating Creativity in Parametric Design," *Proceedings of the 45th Annual Conference of the Australian and New Zealand Architectural Science Association (ANZAScA)*, no. November (2011): 1–8.
[333] Ibid.
[334] Ibid.
[335] M. Burry, "Prototyping, Between Intuition and Process: Parametric Design and Rapid Prototyping," in *Architecture in the Digital Age: Design and Manufacturing*, ed. Branko Kolarevic (Spon Press, New York, 2003), 210–29.
[336] Peter G Ellis et al., "Automated Multivariate Optimization Tool for Energy Analysis," *IBPSA SimBuild Conference*, no. January (2006): 1.

Problems of building design are inherently multivariate and multi-criteria.[337] The traditional architectural design could produce and examine just a few solutions for a few criteria. With the incorporation of sustainability considerations and building information modeling into practice, designers now have the capacity to produce many more possibilities and evaluate them concerning a broader range of criteria.[338] The performance-based design consists of the apparent articulation of performance objectives for building behaviour and the methodological search across possible alternatives for high-performing solutions.[339] Due to the rising complexity of building performance necessitates addressing multi-dimensional trade-offs across numerous performance parameters.[340]

In recent years, parametric and generative design combined with computational performance analysis parametric analysis approaches emerged.[341] This combined performance-based generative approach creates data sets to facilitate a data-driven decision-making process.[342] The transition of architecture from static relationships to parametric connections not only updates the concept of design thinking but also calls into question the function and precision of the design notion.[343] The dynamic simulations are triggered by each concurrent regeneration of the geometric model and updating the structures and other properties.[344] Typically, these simulation programs were developed to use during the design phase for the building's

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[337] Peter G Ellis et al., "Automated Multivariate Optimization Tool for Energy Analysis," *IBPSA SimBuild Conference*, no. January (2006): 1.
[338] Caroline Clevenger and John Haymaker, "Framework and Metrics for Assesing the Guidance of Design Processes," in *International Conference on Engineering Design*, 2009: 1.
[339] Ibid.
[340] Caroline M Clevenger, John Haymaker, and Surya Swamy, "The Importance Process: Enabling Creativity in Performance-Based Design through Systematic, Model-Based, Search of Multidisciplinary Impacts," 2008: 1.
[341] Marcelo Bernal et al., "Parametric Analysis versus Intuition Assessment of the Effectiveness of Design Expertise," no. September (2020): 104.
[342] Ibid.
[343] Marcelo Bernal et al., "Parametric Analysis versus Intuition Assessment of the Effectiveness of Design Expertise," no. September (2020): 109.
[344] Ibid., 105.

lifecycles.[345] Latest developments result in more extensive use throughout all stages of a building's life. Information interchange, mostly from CAD software, but also associated with other design tools such as HVAC (Heating, Ventilation, and Air Conditioning) simulation models, could sustain a user-friendly and practical method of incorporating these technologies into the building design process.[346] Every simulation outcome can only be as precise as the simulation's input data.[347] The form of structure, internal loads, HVAC systems and equipment, weather conditions, functions and schedules, and simulation-specific factors comprise the majority of the input.[348]

In the performative design process, instead of identifying a single ideal solution, developing more widely viable ideas that meet the performance objectives gives the designer greater freedom and creativity.[349] A good design strategy is that not only leads to a better solution as a "design product" but also assists designers in the "design process" in understanding the problem itself, the significance of each design parameter, the relationships between parameters, and the impact of one decision on subsequent decisions.[350] Determining the most influential parameter combinations and determining the link between the combined design factors and energy performance increases the productivity of the design process.[351] The principles of usefulness and uniqueness are central to many conceptions of

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345 Tobias Maile, Martin Fischer, and Vladimir Bazjanac, "Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective," *Wp107*, no. December (2007): 1
346 Ibid.
347 Tobias Maile, Martin Fischer, and Vladimir Bazjanac, "Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective," *Wp107*, no. December (2007): 3
348 Ibid.
349 Roya Rezaee et al., "Constructing and Exploring Building Configurations Based on Design and Multi Performance Criteria," *Building Simulation Conference Proceedings* 2–4, no. September (2019): 2990.
350 Ibid.
351 Roya Rezaee, Roza Vakilinezhad, and John Haymaker, "Parametric Framework for a Feasibility Study of Zero-Energy Residential Buildings for the Design Stage," *Journal of Building Engineering* 35, no. November (2021): 3.

creativity and productivity.[352] Usefulness can be explained as providing value according to a pre-defined value function, and uniqueness as missing equivalent alternatives within the prescribed solution space in the context of performance-based building design.[353]

As high-performance design becomes more attractive in architecture, there has been an increasing demand for environmental analysis tools to assist architects.[354] Knowledge of the application of simulation tools and an understanding of performative processes are essential for developing and comprehending realistic and trustworthy simulation results. Nowadays, Rhino/Grasshopper is one of the most popular computational tools used by designers. There are currently several performative analysis plug-ins for Rhino/Grasshopper, such as Ladybug, Honeybee, Energyplus, Daysim, OpenStudio, Radiance, and so on. These environmental analysis tools give 2D and 3D interactive visualizations for designers to enhance decision-making throughout the conceptual stages of the design process.[355] It also facilities the evaluation, automates and accelerates computations, and provides simple graphical representations in the Rhino or Grasshopper interface.[356] Results of simulations could help designers make better design decisions. In this context, comprehensive research may be applied to improve environmentally aware design possibilities during the design development process.[357]

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352 Caroline M Clevenger, John Haymaker, and Surya Swamy, "The Importance Process: Enabling Creativity in Performance-Based Design through Systematic, Model-Based, Search of Multidisciplinary Impacts," 2008: 2.
353 Ibid.
354 Mostapha Sadeghipour Roudsari and Michelle Pak, "Ladybug: A Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conscious Design," *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*, no. January 2013 (2013): 3128.
355 Ibid.
356 Ibid.
357 Ibid.

There has been an increase in the number of research exploring the effects of PBD tools on productivity. Barnel et al. conducted a study to examine the design development process to evaluate how an expert design team would solution were created to the design problem.[358] This work aims to examine the accuracy of the design approach in dealing with performative objectives and quantify the role of the analysis process.[359] They reached results that the systematic optimization continually improves the performance of the traditional design.[360]

Clevenger and Haymaker synthesized a framework and series of metrics to analyze performance-based design processes based on a survey of the literature and industry insights. They applied these defined measures to the real-world design process, which analysis lasted over 27 months and then compared outcomes and examined the suggested metric set's strengths and drawbacks.[361] At the end of the study, they stated that the proposed framework and metric set support the understanding of the problem, the effect of performance-based problem solving on creative idea generation, and the comparison and evaluation of the quality of the proposed solutions for current or future design processes.[362]

Furthermore, Toth et al. conducted research that aimed to explore the environmental and economic benefits of collaborating between disciplines in the early stages of the design process.[363] They reached a result of these methodologies support the pre-determination of project criteria in the early design stages to test

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[358] Marcelo Bernal et al., "Parametric Analysis versus Intuition Assessment of the Effectiveness of Design Expertise," no. September (2020): 104.
[359] Ibid.
[360] Ibid., 109.
[361] Ibid., 10.
[362] Ibid.
[363] B. Toth et al., "Modelling Sustainable and Optimal Solutions for Building Services Integration in Early Architectural Design: Confronting the Software and Professional Interoperability Deficit," *Proceedings off Cumulus 38 Degrees South, Hemispheric Shifts Across Learning, Teaching and Research*, (2009): 9.

interdisciplinary optimization strategies that encourage productivity and innovation.[364]

Roudsari and Pak discussed the significant benefits and limitations of the solutions that the Ladybug tool provides. They stated that this system offers several advantages for integration of design and analysis.[365] The ability to represent the performance-based analysis data within the simulation tool enables designers to establish a clear link between data analysis and design.[366] Through the simulation tool's parametric diagrams, environmental data becomes a design generation tool, providing designers with quick feedback on the implications of design changes.[367] A combined interface increases user accessibility and design productivity while supporting ecologically friendly building designs for now and the future.[368]

Rezaee et al. analyzed the workflow of designing a school with the evaluation of daylight and energy performances. They created the fundamental design principles for functional requirements of the school layout, identified design limitations, produced alternatives, and assessed design alternatives against all performance metrics.[369] They concluded that it is a method that enhances the overall decision-making process by considering trade-offs between energy and daylight while meeting design restrictions.[370] This technique offers a variety of features of potential design options and accurate insight and recommendations without limiting creative flexibility rather than providing a single design solution.[371]

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[364] Ibid.
[365] Mostapha Sadeghipour Roudsari and Michelle Pak, "Ladybug: A Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conscious Design," *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*, no. January 2013 (2013): 3130.
[366] Ibid.
[367] Ibid., 3134.
[368] Ibid.
[369] Roya Rezaee et al., "Constructing and Exploring Building Configurations Based on Design and Multi Performance Criteria," *Building Simulation Conference Proceedings* 2–4, no. September (2019): 2997.
[370] Ibid.
[371] Ibid.

According to the conducted studies for the exploration of the performative architecture tools and analyses, the main usage target of these tools is to meet the performative targets includes reducing the energy consumption of buildings. In this context, it is seen that the use of PBD tools increases the productivity of the design processes, and the final products created using PBD tools are also high performative products.

3.4 Performative Architecture with Computational Design Tools

The focus of designing shifts to form generation processes based on performative techniques, which are applying digital quantitative and qualitative performance-based simulations serving as the technological basis for a comprehensive new approach to the design of the built environment.[372] With these developments of technology, potential new solutions for computational design tools that promote performance-based design are started to emerge in light of current breakthroughs in digital design theory and technology.[373]

According to Pellitteri et. al., the Performative Architecture paradigm presents two design techniques.[374] Both methods give new shapes to the requirements that are always associated with architectural design, beyond the prevailing formalism that characterizes the latest expressions of contemporary architecture. They explain these two approaches as follows:

> "The first approach entails considering the architectural work as being particularly sensitive to its surroundings, the latter perceived as a group of forces able to directly determine the building shape. The surroundings are indeed interpreted in a broad sense, i.e. not only in terms of their physical features but also in terms of the dynamics pertaining to end users. … . The second approach, the most traditional one after all, is heavily influenced by

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[372] Branko Kolarevic, "Computing The Performative," 2003: 195.
[373] Rivka Oxman, "Performance-Based Design: Current Practices and Research Issues," *International Journal of Architectural Computing* 6, no. 1 (2008): 2.
[374] Ibid., 307.

> performance assessment exactly from the first stages of the project, also by means of automatic equipment for direct retroaction. This is a trend towards developing really interactive software applications which are susceptible of promising future achievements, being able to establish real-time interaction with specialised software applications for performance calculation. The use of "Generative Components" is an example of this interaction between building shape and designer." [375]

Performance evaluation has the potential to guide the parametric model with generative and evaluative simulation methods and alter the physical model, contributing to performance-based generative design processes.[376] Algorithmic control of parametric variation processes is one of the methodological foundations of future performance-based systems, as it has the ability to be used for a potential technical change of the design model under the circumstances of finding a performatively optimum solution.[377] As previously mentioned, researchers emphasize integrated design techniques for Performative Architecture, which offers innovative and durable aspects in PBD. In performance-oriented design processes, analytical simulations can be used to produce comprehensive parametric expressions of performance so these types of digital modeling can generate formal solutions to complex performance requirements.[378]

The term integration can be explained mainly by the process of collaboration.[379] According to Malkawi, dynamic relationships between architects and engineers lead to building designs that incorporate performance considerations.[380] Developments mostly aid the integration process in computer technology, which bridges the gap between the participants, such as architects and engineers.[381]

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[375] Ibid.
[376] Rivka Oxman, "Performance-Based Design: Current Practices and Research Issues," *International Journal of Architectural Computing* 6, no. 1 (2008): 6.
[377] Rivka Oxman, "Performance-Based Design: Current Practices and Research Issues," *International Journal of Architectural Computing* 6, no. 1 (2008): 6.
[378] Ibid.
[379] Branko Kolarevic and Ali Malkawi, *Performative Architecture: Beyond Instrumentality*, 2005: 249.
[380] Ibid.
[381] Ibid.

Evaluating building performance is a time-consuming and extensive knowledge-based task. A complete and lifetime performance assessment strategy requires multiple evaluation methodologies integrated throughout the building phases.[382] However, it is challenging since various disciplines often carry these efforts at different times and at separate time intervals.[383] Recent developments include simulation and building methodologies intended to meet the complicated requirements of performative architecture.

Integrating various academic disciplines with architecture also takes place in computer science in architecture.[384] The old craftsmanship which designers had in the past has been supplemented by a new sort of craftsmanship, in which computational tools take their place to use knowledge in the architectural design process.[385] Computers have been used as a tool in architectural design, for sketching, 2D drawing, and subsequently for 3D modeling, however, not in a computational sense using algorithms.[386] Finally, computational design expands beyond the use of digital tools for representation and drawing to become a paradigm that includes new computational tools, methodologies, and strategies for design creation.[387] Sarıyıldız defines the term Computational Design as:

> "Computational tools, methods and techniques, which enable designers to formulate their design needs, requirements and rules, and translate them into algorithms that generate designs for buildings, a design approach which exceeds the use of computation as a representational or drafting tool." [388]

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[382] I. Gursel Dino, R. Stouffs, and S. Sariyildiz, "A Computational Framework for Integration of Performance Information during the Building Lifecycle," *Proceedings of the 24th W78 Conference*, 2007: 380.
[383] Ibid.
[384] Sevil Sariyildiz, "Performative Computational Design," in *ICONARCH I: Architecture and Technology* (Proceeding of the International Congress of Architecture-I, 2012), 320.
[385] Ibid.
[386] Ibid.
[387] Ibid.
[388] Ibid.

Computational algorithms were utilized to create systems that aided designers by guiding either advice or optimization utilizing developing methodologies.[389] Computational technologies, especially parametric design tools, support designers in the iterative and dynamic coordination of interdisciplinary intelligence distributed across various digital tools and approaches.[390] To allow high-performance design components, researchers investigate the use of parametric modeling in combination with performance simulation software, and genetic algorithms are examined to support the design process and the integration of structures.[391]

Within this emerging context of computational design tools in architectural design, parametric and associative models are powerful effects on building performance that can be integrated and assessed throughout the design activity.[392] The rapidly increasing application of advanced 3D information-based parametric/generative tools associated with information modeling systems and digital prototyping technologies is providing radically new avenues of design and coordination among architectural design and manufacturing actors.[393]

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[389] Branko Kolarevic and Ali Malkawi, *Performative Architecture: Beyond Instrumentality*, 2005: 90.
[390] Benachir Medjdoub and Tuba Kocatürk, *Distributed Intelligence in Design* (Wiley-Blackwell, 2011): 12.
[391] Sevil Sariyildiz, "Performative Computational Design," in *ICONARCH I: Architecture and Technology* (Proceeding of the International Congress of Architecture-I, 2012), 328.
[392] Rivka Oxman, "Performance-Based Design: Current Practices and Research Issues," *International Journal of Architectural Computing* 6, no. 1 (2008): 8.
[393] Benachir Medjdoub and Tuba Kocatürk, *Distributed Intelligence in Design* (Wiley-Blackwell, 2011): 12.

3.4.1 The Search for New Design Paradigm with the Development of Technology: Digital Design

In PBD processes, controlling the parametric form is especially significant because it enables the integration of performance data into design synthesis.[394] The notion of non-standard, non-normative, non-repetitive design has become a fundamental theoretical focus of digital design with the Non-Standard Architectures Exhibition at the Pompidou Center in Paris in 2003.[395] Mitchell claims that building production, which was formerly dependent on the materialization of paper-based drawings, is nowadays being performed through digital information.[396]

The architecturally designed structures are designed, documented, produced and built with the assistance of digital design tools. Mitchell argues that within this new all-encompassing framework, which he defines as digital design, the emerging architecture of the digital age is characterized by a high level of complexity; this provides more sensitive and variable responses to the needs of contextual features such as site, program and expression purpose.[397] In addition, Oxman highlights that the ability of digital models to integrate design and materialization during the conceptual design stage enables a new level of contextualization and performative design.[398]

To present digital design models, Rivka Oxman primarily suggested the improvement of a taxonomy that may be used for digital design modeling.[399] The elements of design models and their logical structure and morphology have been

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[394] Ipek Gürsel Dino, "Creative Design Exploration by Parametric Generative Systems in Architecture," *Metu Journal of the Faculty of Architecture* 29, no. 1 (2012): 207.
[395] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 232.
[396] William J. Mitchell, "Constructing Complexity," in *Computer Aided Architectural Design Futures*, ed. Bob Martens and Andre Brown (Dordrecht, The Netherlands: Springer, 2005), 41.
[397] Ibid., 47.
[398] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 232.
[399] Ibid., 240.

identified, and this analytical method enables the establishment of a general schema of design models that allows for mapping form and structural variants.[400] Following by, to depict the latest innovations in digital design, it is described and examined how design patterns of change and transformation integrated into the main design situations in digital practice using this general schema; in this manner, a structured set of digital design models were developed.[401]

3.4.1.1 Evolution of Digital Design Models

Designers use a variety of digital mediums that help shape and communicate their ideas while developing compositions for new environments.[402] As mentioned in the previous chapter, early design models aim to symbolically illustrate the design activity as a gradual linear cyclical process**.** Progressively, this process representation became more taxonomically specific for identifying and naming the design process's sub-stages and sub-tasks.[403] Nonetheless, despite various terminology, some sub-processes of significant design stages started to concretize as 'problem/situation input formulation', 'synthesis/production', 'representation', and 'evaluation'.[404]

Schön and his collaborators introduced new aspects of cognitive depth for design modeling in the early 1980s. These approaches, often known as 'reflection in action'[405], to highlight the designer's interaction with the problem representation and describe the design as a 'process of perception, interpretation, and

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[400] Ibid.
[401] Ibid.
[402] Jack Breen and Martijn Stellingwerff, "A Case for Computer Assisted Creativity through Clarity: Project 12 CAD and Beyond," *Approaches to Computer Aided Architectural Composition*, 1996, 45.
[403] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 240.
[404] Ibid.
[405] Donald Schön A., "The Reflective Practitioner: How Professionals Think in Action," *Supporting Learning and Teaching*, 1983: 9.

transformation'.[406] Beyond the central position of human interaction in the design modeling process, it is critical maintaining the designer's centrality in digital design models.[407] Oxman states that, to be able to explain the several components required to model digital design, a symbolic representation (Figure 3.1) must be constructed through which a fundamental schema for digital design models can be developed.[408]

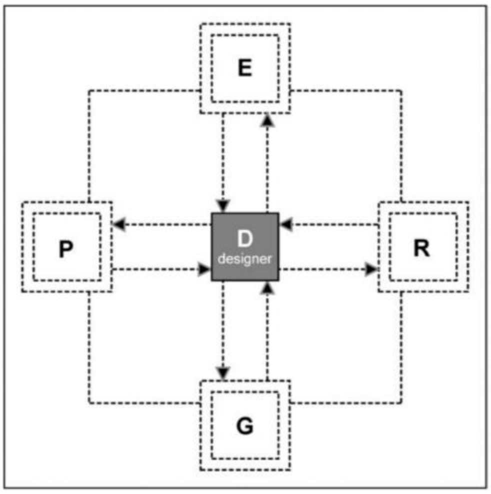

Figure 3.1: A general symbolic schema for digital design models

Source: Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 241.

In Figure 3.1, Oxman classified the design activity into four fundamental components as 'representation, generation, evaluation, and performance'. She points out that in this process, it is necessary to use some conceptual distinctions and graphic symbolic layouts that have become accepted formalisms in design models and illustrates her own graphic symbols shown in the Figure 3.2.[409]

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406 Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 240.
407 Ibid., 241.
408 Ibid.
409 Ibid.

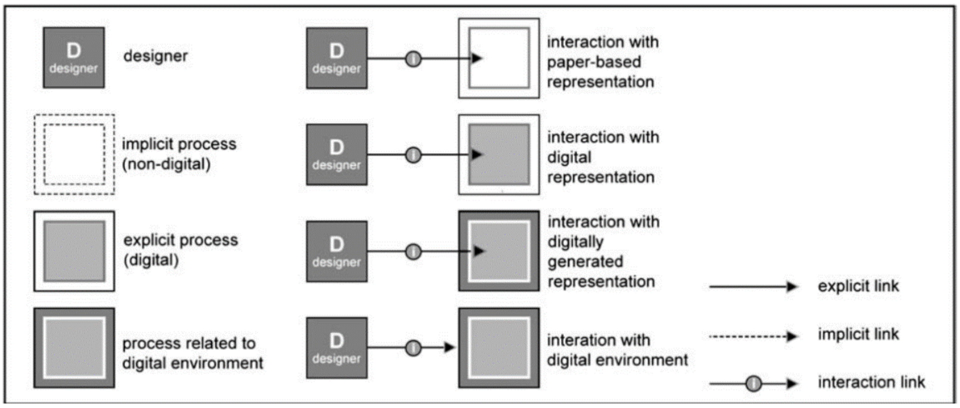

Figure 3.2: Symbols, boundaries and links used in digital design models

Source: Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 242.

Digital technology has supported the generation of new roles for the designer thanks to the relationship with the media.[410] Aside from using digital media as tools, the relationship between digital design and digital design models as a form of architectural knowledge has started to arise as a critical conceptual resource for design and design education.[411] Thus, the designer started to interact with, regulate, and modify generative and performative processes.[412] The modeling technique provides a rigorous tool for comprehensively organizing and mapping common possibilities of digital design models based on several relations between the designer's conceptual content, the design procedures used, and the design product itself.[413] Rivka Oxman divided the digital design models into five classes as follows:

"1. CAD models.
2. Formation models
3. Generative models
4. Performance models

[410] Ibid., 242.
[411] Rivka Oxman, "Digital Architecture as a Challenge for Design Pedagogy: Theory, Knowledge, Models and Medium," *Design Studies* 29, no. 2 (2008): 102.
[412] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 242.
[413] Ibid., 245.

5. Integrated compound models" [414]

3.4.1.1.1 CAD Models

CAD principles, theories, and methodologies have mostly been built on imitating paper-based design.[415] Traditional CAD models are examined into two categories as descriptive CAD and generation-evaluation predictive CAD.[416] The earliest versions of computer-aided design systems were primarily descriptive due to various geometrical modeling/rendering tools.[417] Compared to traditional models, descriptive models have a slight qualitative impact on design.[418] As can be seen from the schema in Figure 3.3, the most prevalent use of traditional CAD models has been altering graphical representations of digital elements.[419]

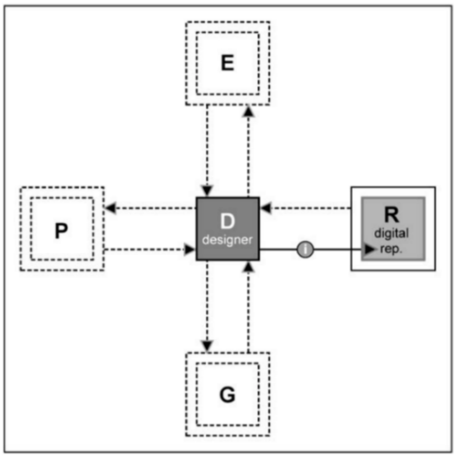

Figure 3.3: The schema of Traditional CAD model

Source: Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 247.

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[414] Ibid., 246.
[415] Yehuda Kalay, *Architecture's New Media Principles, Theories, and Methods of Computer-Aided Design* (MIT Press, Cambridge, Massachusetts, 2004): 67.
[416] Ibid.
[417] Ibid.
[418] Yehuda Kalay, *Architecture's New Media Principles, Theories, and Methods of Computer-Aided Design* (MIT Press, Cambridge, Massachusetts, 2004): 71.
[419] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 246.

A physical model may now be built from digital models using modern techniques supported by different digital material processing methods.[420] Moreover, technology has advanced to the point where there are several methodologies for reversing the traditional information direction: "from the data model to physical model".[421] Physical models may now be digitally recorded and converted into digital models, and vice versa.[422] As a result, the descriptive role of traditional CAD has developed through the integration of virtual and material.

In advance of drawing, modeling, and rendering designs, the automation of analysis and synthesis integrated with analytical processes of geometric models, which are defined as predictive models as opposed to descriptive models, was established many years ago.[423] This model (Figure 3.4) depicts the situation in which the CAD representation and evaluation processes are explicated, yet other processes are left unexplained.[424] In contrast, explicit connections show the presence of an integrated database between representation and evaluation. Each change and modification in digital representation can be re-evaluated thanks to the integrated database and common information structure.[425] This process establishes a feedback loop for the designer who develops relevant alterations in the representational model.

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[420] Larry Sass and Rivka Oxman, "Materializing Design: The Implications of Rapid Prototyping in Digital Design," *Design Studies* 27, no. 3 (2006): 346.
[421] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 247.
[422] Ibid.
[423] Ibid.
[424] Ibid., 248.
[425] Ibid.

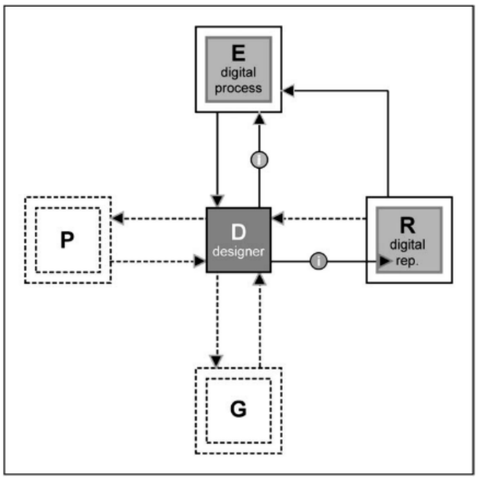

Figure 3.4: The schema of Generation-Evaluation model

Source: Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 248.

3.4.1.1.2 Digital Formation Models

Static representations indicated by the formal representation theory have been abandoned with the digital design.[426] Digital design theory has converted the notion of form to the formation thanks to the liberation from the conventional logic of representation.[427] Digital design formalisms are shifting toward dynamic notions, which are redefining the function of representation.[428] Advanced digital tools are not only altering traditional forms of design representation, they are also establishing new foundations for design thinking. In new situations, digital approaches for the shape generations serve as foundation for defining the formation

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[426] Ibid.

[427] Rivka Oxman, "Digital Architecture as a Challenge for Design Pedagogy: Theory, Knowledge, Models and Medium," *Design Studies* 29, no. 2 (2008): 106.

[428] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 249.

models. (Figure 3.5)[429] Formation models provide interaction with the designer and digital model, allowing control and modifications throughout the design process.[430]

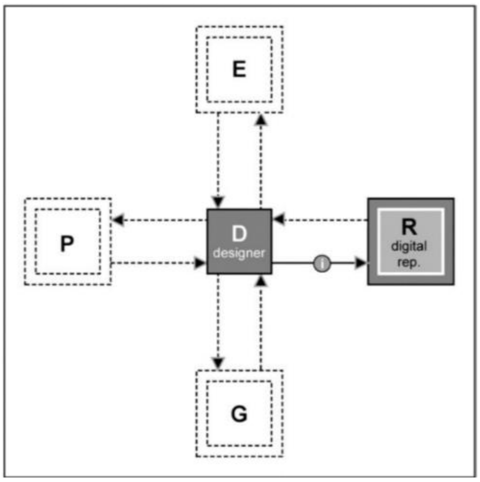

Figure 3.5: The schema of Digital Formation models

Source: Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 250.

This notion of formation processes is relevant to the dynamics and diversity of topological heterogeneity, which extends beyond dimensional variety[431]. Oxman classified formation models into three subtitles as topological design, associative design, and dynamic design.[432] Topological formation models are based on the use of topology and non-euclidean geometry to create a design medium for formation.[433] These models enable new tools for designing complicated geometrical forms and their well interactive manipulation in design.[434] Associative design formation models are based on parametric design concepts and generative components. In parametric design, relationships between objects are clearly

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[429] Ibid., 250.
[430] Ibid., 251.
[431] Rivka Oxman, "Digital Architecture as a Challenge for Design Pedagogy: Theory, Knowledge, Models and Medium," *Design Studies* 29, no. 2 (2008): 106.
[432] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 251.
[433] Ibid.
[434] Ibid.

defined, and interdependencies are created between various objects.[435] Variations, once created, can be easily transformed and manipulated by enabling these attributes. Assigning different values can produce multiple variations while preserving the conditions of the topological relationship.[436] Formations by animation have presented the concept of dynamic design.[437] Motion-based formation models are based on animation, morphing, and other types of motion and time-based modeling techniques that can illustrate several separate elements in a dynamic design process.[438]

3.4.1.1.3 Generative Design Models

In the architectural design environment, generative design provides exploring many design ideas within CAD platforms.[439] The generative model (Figure 3.6) is the design and interaction with complex mechanisms that deal with the emergence of forms derived from generative rules, relations and principles.[440] In this concept, the fundamental emphasis is on interaction.[441] An interactive module is required that gives control and options for the designer to lead the selection of desirable solutions.[442] According to Shea, the current goal of generative design systems is to develop a new design method which allows for designing original, efficient and buildable designs by using existing computer and manufacturing capabilities.[443]

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[435] Ibid., 252.
[436] Ibid.
[437] Rivka Oxman, "Digital Architecture as a Challenge for Design Pedagogy: Theory, Knowledge, Models and Medium," *Design Studies* 29, no. 2 (2008): 106.
[438] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 253.
[439] Sivam Krish, "A Practical Generative Design Method," *CAD Computer Aided Design* 43, no. 1 (2011): 88.
[440] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 254.
[441] Ibid.
[442] Ibid.
[443] Kristina Shea, Robert Aish, and Marina Gourtovaia, "Towards Integrated Performance-Driven Generative Design Tools," *Automation in Construction* 14, no. 2 SPEC. ISS. (2005): 254.

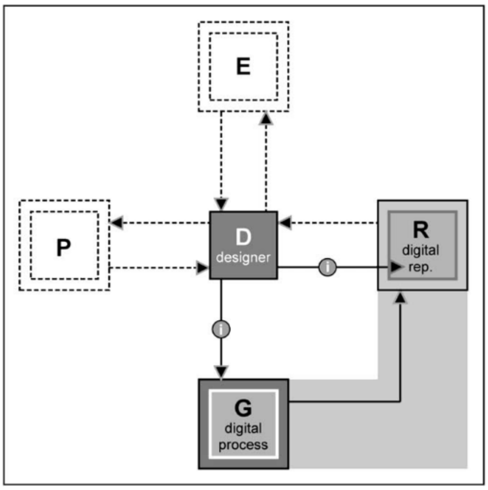

Figure 3.6: The schema of Generative design models

Source: Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 255.

Shape grammars and evolutionary models are two major sub-approaches of generative design models.[444] Shape Grammars provide a computational technique for formulating shape-generating processes.[445] With the shift in design emphasis from spatial composition to tectonic and material characteristics, emergent aspects of tectonic and morphological design content are incorporated with grammar mathematics.[446] As a result, shape grammars are now regarded as one of the potentially significant generation models for digital design.[447] A distinct formalism of shape grammar is the 'parametric shape grammar'.[448]

The emergence of form is considered to be the result of an evolutionary process in the evolutionary design model. In this model, the generation of form is assumed to derive from an internal genetic coding that alters the traditional association of the

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[444] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 255.
[445] Rivka Oxman, "Digital Architecture as a Challenge for Design Pedagogy: Theory, Knowledge, Models and Medium," *Design Studies* 29, no. 2 (2008): 106.
[446] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 255.
[447] Ibid.
[448] Rivka Oxman, "Digital Architecture as a Challenge for Design Pedagogy: Theory, Knowledge, Models and Medium," *Design Studies* 29, no. 2 (2008): 106.

form to itself.[449] Genetic algorithms have grown a crucial tool in various research fields. John Holland is the pioneer of the genetic algorithm domain. The density of alternative solutions in generative processes is accepted as a fundamental element in genetic algorithms' evolutionary systems.[450] Genetic form evolution is based on principles that define the 'genetic code' for a large family of similar elements in this technique; moreover, variations can be created by means of 'reproduction' mechanisms through gene crossing and mutation.[451] Generated candidate forms can be evaluated according to their performance in the simulated environment.[452]

3.4.1.1.4 Performance Models

Performance models can be defined as a formation method or a generative activity consisting of variations determined parametrically by the site, conditions, program, and so on.[453] This model is a unique compound design model that can be misinterpreted as only an evaluation model.[454] Performance-based models are guided by simulations.[455] Kolarevic highlighted the limitations of existing CAD software in the conceptual design process and proposed the development of digital tools that can enable dynamic formation processes according to predetermined performance targets.[456]

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[449] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 256.
[450] Ibid.
[451] Ibid.
[452] Ibid.
[453] Ibid., 257.
[454] Ibid.
[455] Rivka Oxman, "Digital Architecture as a Challenge for Design Pedagogy: Theory, Knowledge, Models and Medium," *Design Studies* 29, no. 2 (2008): 107
[456] Branko Kolarevic, *Architecture in the Digital Age: Design and Manufacturing* (Spon Press, New York, 2003): 372.

Oxman divided this category into two branches as the performance-based formation and performance-based generation models of design.[457] The formation-based design might be considered performance-based design if digital simulations of external factors are used to drive a formation process. (Figure 3.7)[458] Researchers frequently used simulation programs, which showed a considerable effect of design parameters on performance requirements like heating energy consumption and energy efficiency.[459]

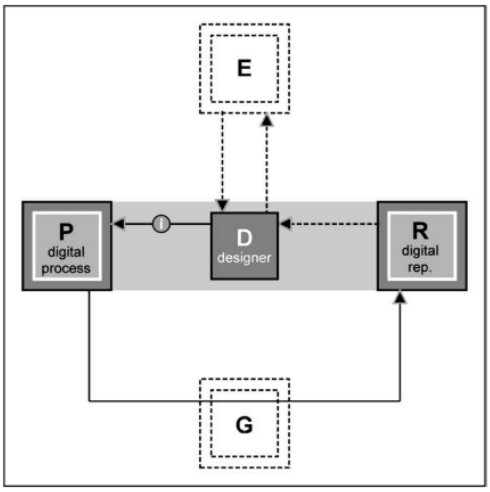

Figure 3.7: The schema of Performance-based Formation design models

Source: Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 258.

Retrieved information from performance simulations drives generation and formation processes in a performance-based generation model (Figure 3.8) to generate the form.[460] Shea et al. (2003) proposed an example that demonstrates the significant future possibilities for integrating performance-based methods with

[457] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 257.
[458] Ibid.
[459] Tuğçe Kazanasmaz et al., "On the Relation between Architectural Considerations and Heating Energy Performance of Turkish Residential Buildings in Izmir," *Energy and Buildings* 72 (2014): 40.
[460] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 259.

generative design tools.[461] The designer can interact with the design process in three phases, first to define performance criteria in performance evaluation, secondly to define generation in the production process, and lastly to interact directly with digital representation.[462]

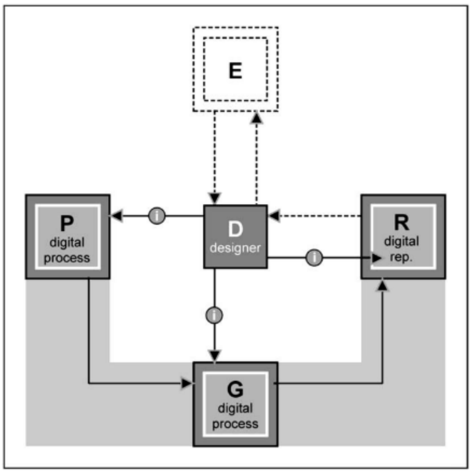

Figure 3.8: The schema of Performance-based Generation design models

Source: Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 259.

3.4.1.1.5 Integrated Compound Models

Compound models are a type of future paradigmatic digital design medium with significant implications for future design media.[463] Compound models depend on integrated processes consisting of formation, generation, evaluation, and performance. (Figure 3.9)[464] The design process is shaped by integrating the digital design tool with performance simulations, generative and formative methods. In an

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461 Kristina Shea, Robert Aish, and Marina Gourtovaia, "Towards Integrated Performance-Driven Generative Design Tools," *Automation in Construction* 14, no. 2 SPEC. ISS. (2005): 260.
462 Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 259.
463 Ibid., 260.
464 Ibid.

ideal scenario, interaction with each activity module is possible with the data and information flow in several directions.[465]

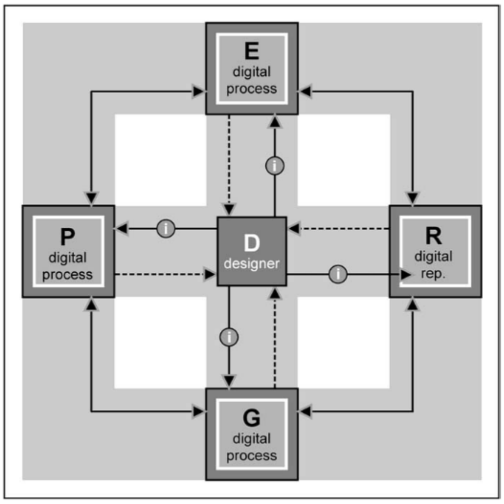

Figure 3.9: The schema of Compound design models

Source: Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 259.

In particular, integrated compound models such as energy simulations and BIM-based technologies have made significant progress in offering effective design solutions in performative architecture.[466] These models have indicated the increasing complexity of digital design media, their potential to function as integrated and interactive design media, their growing effect in the entire design process, from conception to construction.[467] With the establishment of new approaches to design such as integration, non-formal morphogenesis, and parametric formation, performance-based evaluation provides new avenues for design thinking.[468]

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[465] Ibid.
[466] Cem Ataman and İpek Gürsel Dino, "Performative Design Processes in Architectural Practices in Turkey: Architects' Perception," *Architectural Engineering and Design Management*, 2021: 3.
[467] Rivka Oxman, "Theory and Design in the First Digital Age," *Design Studies* 27, no. 3 (2006): 260.
[468] Ibid., 262.

A computational design tool must allow for an iterative, open-ended simulation, assessment, and creation process to become a generative medium for the designer.[469] Design models demonstrated in these abovementioned schemas were established according to traditional design theoretical notions and contemporary design thinking methodologies. According to Ataman and Gursel Dino, a knowledge gap still exists in the actual use of these design tools and concepts in architectural practices throughout the performance-based design process.[470]

3.4.2 Performance Simulations in Design Process

It is commonly acknowledged that for detailed performance evaluation, using simulation represents a best practice approach to building design.[471] The early foundation was primarily on energy and mass flow processes in the built environment; meanwhile, the role of simulation tools evolved into other disciplines such as lighting, heating, ventilation, and air-conditioning (HVAC), airflow, and others.[472] More recent enhancements include combined moisture and heat transmission, acoustics, control systems, and numerous urban and microclimate models combinations.[473]

The main goal of the building simulation is to create observable outputs to analyze and relate them to appropriate quantifications of performance metrics.[474] Within computational considerations, design problems with continuous performance

[469] N. Oxman and J. L. Rosenberg, "Material Performance Based Design Computation : An Inquiry into Digital Simulation of Material Properties as Design Generators," *CAADRIA 2007 - The Association for Computer-Aided Architectural Design Research in Asia: Digitization and Globalization* 05, no. 01 (2007): 42.
[470] Cem Ataman and İpek Gürsel Dino, "Performative Design Processes in Architectural Practices in Turkey: Architects' Perception," *Architectural Engineering and Design Management*, 2021: 3.
[471] J A Clarke, "Prospects for Truly Integrated Building Performance Simulation," in *Proceedings of Building Simulation*, ed. Hensen J, Nakahara N, Yoshida H, Udagawa M (Kyoto, Japan: Organizing Committee of Building Simulation, 1999).
[472] Godfried Augenbroe, "Trends in Building Simulation," in *Advanced Building Simulation*, ed. Godfried Augenbroe and Ali Malkawi (Spon Press, 2004): 4.
[473] Ibid.
[474] Ibid., 5.

evaluation throughout the design process led to the emergence of performance simulation tools for multi-disciplinary and multi-phase performance evaluation functions.[475] Simulation is acknowledged for accelerating the design process, increasing efficiency, and allowing for the comparison of a broader range of design options.[476] Simulation processes provide an understanding of the outcomes of design decisions with increasing the overall efficiency of the whole design process.[477] In this sense, the method of building performance simulation can be explained as considering the potentials that provide quantifying and comparing the cost and performance attributes of a proposed design.[478]

PBD is based on a series of standardized performance indicators that are clearly specified methods for expressing building performance analysis demands and outcomes.[479] These performance criteria will be incorporated into the client's official statement of requirements expressed through quantifiable performance indicators.[480] During the design process, the simulation tools analyze and evaluate the design variants against a set of predefined performance indicators specified in the requirements statement, either formulated according to the design analysis or the clients' requirements.[481] Because of encountering various problems during the design process, a wide range of computational simulation tools have been developed to assess building performance in areas such as thermal flows, lighting, acoustics, constructions, and so forth.[482]

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[475] Ipek Gursel Dino, "CLIP: Computational Support for Lifecycle Integral Building Performance Assessment" PhD Dissertation, (2010): 32.
[476] Godfried Augenbroe, "Trends in Building Simulation," in *Advanced Building Simulation*, ed. Godfried Augenbroe and Ali Malkawi (Spon Press, 2004): 4.
[477] Ibid.
[478] Joe Clarke, "A Vision for Building Performance Simulation: A Position Paper Prepared on Behalf of the IBPSA Board," *Journal of Building Performance Simulation* 8, no. 2 (2015): 39.
[479] Godfried Augenbroe, "Trends in Building Simulation," in *Advanced Building Simulation*, ed. Godfried Augenbroe and Ali Malkawi (Spon Press, 2004): 18.
[480] Ibid.
[481] Ibid.
[482] Branko Kolarevic and Ali Malkawi, *Performative Architecture: Beyond Instrumentality*, 2005: 87.

Computational simulation capabilities may be used to integrate production limitations, assembly methods, and material properties into the formulation of material and construction systems.[483] As the understanding of material effects expands beyond the visible impact to the modulation of the natural and built environment, these modulations are now accepted as actual behavior instead of the textbook principles by space, building and climate design become inextricably linked.[484]

Building simulation processes begin considerably earlier and continues into the later design phases. According to Wit, three steps can be followed to translate these procedures into tools for mainstream application. The first step is determining performance criteria for numerous performance features, in this respect, a performance criterion is decided by a combination of a performance indicator and a limiting value.[485] The second step is defining the target probabilities, which show when a building does not fulfill the performance criteria, resulting in a failure situation.[486] The third step is to make optimal design decisions to verify whether the performance criteria are met at the required probability levels.[487]

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483 Michael Ulrich Hensel and Achim Menges, "Inclusive Performance: Efficiency Versus Effectiveness," *Architectural Design* 78, no. 2 (2008): 56.
484 Ibid.
485 Sten de Wit, "Uncertainty in Building Simulation," in *Advanced Building Simulation*, ed. Godfried Augenbroe and Ali Malkawi (Spon Press, 2004): 54.
486 Ibid.
487 Ibid., 55.

CHAPTER 4

ASSESSING DESIGN PRODUCTIVITY THROUGH LINKOGRAPHY

The purpose of this study is to examine productivity of design process and what are the potentials and restrictions of using performance-based tools in the design process for expert designers. Hereby, first of all, a well-defined design problem was introduced to the participants and requested them to use performance simulation tools throughout the design process to find the optimum solution according to the results of the performative outcomes.

In order to establish a groundwork for this study, the studies done so far in the field of linkography and protocol analysis and the research in the field of performance-based design were examined in the previous chapters. An empirical research approach was used in this study to explore the potential of performance-based design tools. The theory was conducted using a mixed methodology that combines linkography, protocol analysis, observations, and exit interviews. During the design process, it is desired from the participants to think aloud and express their ideas with consequences. This experimental design research technique used both quantitative and qualitative features to explore the design-thinking processes, which encompass a sequence of problem-solving activities utilizing performance-based simulation tools. Observations of the designer's movements, exit interviews, protocol analysis, and linkography were used to objectively investigate the effects of performative design environments on the design process. In the perspective of this research, protocol analysis and linkography are crucial components of the research process. The protocol analysis using linkography as a research technique provides a particular viewpoint to comprehend design productivity throughout the design processes owing to the assessment of the design process rather than the final products.

4.1 Developing the Methodology

As stated above, the primary purpose of the study is to explore the productivity of the design process and how the acquired outcomes of the utilized performance-based tools affect the entire design process. The designer is basically asked to design with respect to performative criteria. In order to achieve the primary goal, the Linkography analysis method was used to investigate the design process.

In the way that Gabriela Goldschmidt explains, Linkography is a method generally depending on think-aloud protocols, also can be supported by the draftings, 3D models, and other visualized elements that emerge throughout the design process. Participants in the protocol studies were chosen from among architects who are expert designers of using the PBD tools. It has been noticed that it is not easy for designers to express their ideas aloud constantly when the focus is on using the computational design tools in simulation environments throughout the experimental studies. Furthermore, the gestures of the designers during the design process also give signs about what they think. In this sense, designers could express themselves with relevant design movements while repeating uncompleted phrases such as 'aha', 'ok' or 'yes'. During the think-aloud process, designers, without describing what they are thinking, verbalizations are frequently incomplete, repetitious, or incomprehensible.[488] This can cause challenges in determining what creates a unit of analysis and interpreting it.[489] The fundamental definition of a design move is supported in this research. As Goldschmidt stated, whereby a *design move is a step, an act, or an operation that can alter the existing design situation in some way relative to the condition it was in previous to that move*.[490] Therefore, designers' verbal statements can transform the design situation accepted as a 'design move' in think-aloud documentation. Design moves are usually small

[488] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 34.
[489] Ibid.
[490] Ibid., 42.

steps that are noticeable. With some practice, it is possible to agree on consistency in decoding the verbal statements to design moves and determining which expressions does not have meaning and should not be identified as design moves such as "yeah, OK, hmm", and these types of statements can be excluded from the analyses.[491] Another rationale for applying a combined methodology was to better understand the consequences of using performative simulation-based design tools not just in design processes but also in designers themselves. In this manner, exit interviews were planned to request the ideas of participants and assessment on performance-based tools in terms of productivity and usability. Consequently, in the framework of this research, developed a mixed methodology, its principles, and its process will be discussed in the next part.

4.2 Protocol Analysis with Linkography and Interviews

The mixed methodology, in which linkography, protocol analysis, observations, and exit interviews are carried out together, can basically be examined in five steps. The first step is the creation of a coding scheme is for the determination of which data are utilized to answer the research questions. The second step is the selection of participants and providing the necessary experimental conditions. Thirdly, defining the design task and specifying restrictions on the established framework. In the fourth step, quantitative and qualitative data should be collected from the experiments carried out in performance-based design environments, and the final step is the data analysis process, including the application of several procedures.

The first step of data analysis is the investigation of the data obtained from the verbal and visual expressions of the designers during the design process and the exit interviews obtained with audio recordings and screen recordings of the designers throughout the design process. Then, the second process specifies design

[491] Ibid.

movements and links. After that, to create Linkographs, the link coding procedure was carried out. The link coding method was repeated and evaluated three times to provide the self-arbitration and get less subjective outcomes. As previously stated, the parsing technique was repeated three times with ten-day intervals between coding procedures. At the end of the process, the exit interviews were considered in order to aid in the review process. After all the decisions are made about which statements are move or not, which moves are linked to each other, Linkoder software was used to construct Linkograph. As mentioned in Chapter 2, Linkoder, developed by Pourmohamadi and Gero, is a tool for generating visual linkographs as well as calculating entropy for forelinks, backlinks, and horizonlinks. The schema of the established methodology is illustrated in the Figure 4.1.

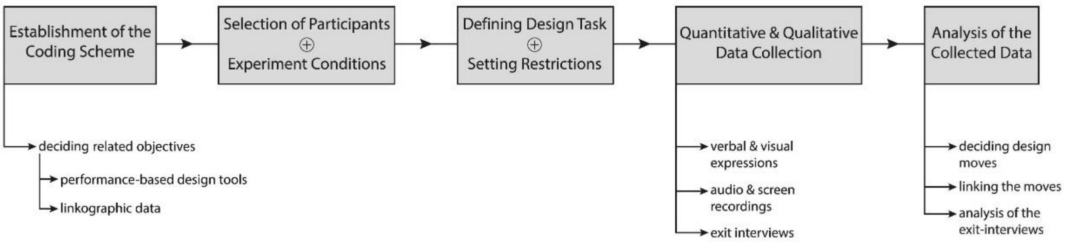

Figure 4.1: The schema of the established methodology

4.3 Coding Scheme and Pre-Experiment Settings

As learned from all the studied literature about protocol studies, a coding scheme demonstrates the set of design behaviours by specifying the that are utilized to respond to the research questions. Coding scheme is an essential stage of the protocol studies aims to determine the phases and activities involved in the design process. In the scope of this research, a coding scheme was used as an intermediary medium between the research questions and related objectives in order to assess the design process in performance-based design environments. As the primary focus of this research is understanding the effects of performative outcomes on the design process, the evaluation scheme is constructed as several design features based on the research questions presented in the introduction chapter. In this framework, to answer the research questions, the coding scheme is divided into mainly two parts: Performance-based design tools and Linkographic data. To be able to find answers to research questions, it is displayed that descriptions of numerous design activities related to the coding, as well as the objectives associated with them. Table 4.1 shows the evaluation scheme of the Linkographic data.

Table 4.1: Evaluation scheme: Linkographic data

objectives	explanation of the objectives	related indicators
number of design moves number of links	number of design moves throughout the design process	▪ linkograph ▪ moves
link density	link density patterns of moves	▪ link index
idea generation and productive thinking process	searching for possible solutions to given design problem and divergent thinking abilities of designers	▪ forelink and backlink critical moves ▪ critical path ▪ chunks ▪ webs ▪ link index
creative leaps	insight moments when designer found a viable idea	▪ researcher's observations ▪ designers' verbal protocols ▪ link patterns ▪ forelink critical moves
Gero’s FBS coding framework	cognitive activities of designers	▪ designers' verbal protocols ▪ researcher's observations

As the research aims to analyze the design process, the five objectives shown in the are determined for the assessment of Linkographic-results. The number of completed design moves in the given time was calculated and taken as a comparison metric for each designer. The reason for employing the ratio between the number of design moves and the duration of the design process was that each design move was accepted as a conscious cognitive activity to offer a potential solution for the design problem. The information of this objective can be retrieved at the end of the generation of linkographs by deciding whether the designers' actions are accepted as a move or not. The second objective is the link density of moves for understanding creative thinking levels which can be evaluated by link index (L.I.) value is the ratio between the number of links and the number of moves. Evaluation and comparison of the idea generation and productive thinking abilities of the designers is the third objective to search for possible solutions to the given design problem. Chunks, webs, and L.I. value, forelink and backlink critical moves, and the series of critical move which creates the critical path are the indicators of creative and productive thinking throughout the design process. As mentioned in the literature review, divergent thinking is associated with productivity. The fourth assessment code is creative leaps which are the insight moments of designers. It mainly depends on the observation of the researcher, verbal explanations of designers, link patterns, and forelink critical moves. The last objective is to evaluate the design processes is the comparison of the distribution of the move types according to Gero's FBS coding paradigm. The next table (Table 4.2) shows the evaluation scheme of the results of Performance-based design tools.

Table 4.2: Evaluation scheme: the results of Performance-based design tools

objectives	explanation of the objectives	related indicators
performative objectives	number of performative metrics taken into consideration	▪ researcher's observations ▪ designers' verbal protocols
number of alternatives	number of alternatives that fulfill the performance criteria	▪ visual representations ▪ researcher's observations ▪ designers' verbal protocols
redesigning according to PBD tools results	reevaluation of the designed issues according to the feedbacks of PDB simulation tools.	▪ researcher's observations ▪ designers' verbal protocols ▪ backlinks
model complexity	number of inputs are embedded to the design model	▪ visual representations ▪ researcher's observations ▪ designers' verbal protocols
duration of the design process	speed of the designers/total design duration	▪ researcher's observations ▪ screen-recordings

The first objective in PBD tools is the number of performative inputs taken into consideration. The relevant verbal explanations of the designers during the design process and the analysis of the information added to the performative design tools used by the designer provide the necessary information for the examination of this metric. Number of solution alternatives is the second objective related with the PBD tools. According to the results of the simulation tools and their own aesthetical preferences, designers can provide more than one option for the specific design elements such as shading devices. This objective can be evaluated through designers' verbal protocols and researchers' observations on the visual representations throughout the design process. The third analysis objective is the reevaluation of the designed issues according to the obtained feedbacks from PDB simulation tools. According to the results of simulations, some of the elements, orientation, placements, and so forth need to be altered to get a high-performance structure. The examination of this metric mainly depends on the researcher's observation throughout the design process and verbal protocols of designers. Moreover, in the Linkographic data, backlinks could be the indicator of this process. The fourth code is the degree of model complexity that can be evaluated by the number of inputs embedded in the design model. Observation of the researcher on the visual model and verbal explanations of designers throughout the design process gives information about this metric. The fifth comparative factor is the speed of the designers and the duration of the design process, which can be learned from the number of moves, the researcher's observation and screen recordings from the beginning to the end.

It is important that how the new PBD environment supports the designers to ensure the required design criteria more effectively during the design process, this research proposes that the new design environment can be advantageous in generating key design components, objects, or associations between various design elements to design high-performance structures in less time. In this process, the selection of participants, experiment settings and clear definition of the selected design problem has importance to be able to make comparison between the experiment-based studies.

Participants: Expert designers were invited by the researcher depend on the following principles:

1. The participants are selected among the architects.
2. They should accept to participate in the research.
3. The participants' level of expertise is that they have worked at least 25 hours on performance-based design tools.
4. They should think aloud throughout the design process.

Experiment settings: The experiment was conducted via the Zoom platform, which enables face-to-face meetings, and the designers were asked to share their screens with the researcher to follow their modeling process. At the same time, the verbal explanations of designers and computer screens of the designers were recorded for the creation process of Linkographs.

Definition of the design problem: The given design problem is to design a small weekend house with high performance in a maximum floor area of 60 m^2 at the specified location and generally will be used in the summer. In this framework, the design problem was given to analyze the effects of the performative design tools on the design process. Several performative criteria can be fulfilled mentioned in Chapter 3, mainly aiming to provide energy efficiency. For this purpose, the orientation of the designed structure, daylighting, thermal control, indoor air quality, climatic conditions, and so on should be considered. In this process, it is expected from the designers to get feedback from the simulation tools and make the necessary alterations if required.

4.4 Data Collection

This section describes how protocol studies are reviewed and evaluated to assess the potentials and limitations of PBD tools. Protocol studies were acquired from the design processes of designers using performance-based simulation tools for a given design problem. These obtained protocols were evaluated according to the pre-determined metrics by the researcher.

The study was conducted with the online session by asking the designers to share their computer screens and express their ideas loudly. At the same time, screen-recording, audio-recording, 3d modeling, and the relation with simulation tools are recorded to be evaluated later as protocol analysis. Throughout the design process, the researcher observes both the process and the designer, and registers them as researcher's observations. After the design process, a small assessment is requested from the designers about the performance-based tools and how they affect their design process, and these are recorded as exit interviews for the protocol analysis.

4.5 Data Analysis

When the data collection process of each design session was completed, the video recordings and screen recordings were analyzed and transcribed for the creation of linkographs. According to Goldschmidt, moves are typically small steps that can be distinguishable.[492] Whether some meaningless verbal expressions will be accepted as moves or not, depending on the connection with the previous actions, it should be reconsidered and decided accordingly. "yes", "ok", "emm" like meaningless statements should be removed from the analysis if they are not relevant to the design movement.[493] As stated in the developing the methodology part, in this research, unrelated arguments to the design tasks and those mentioned above meaningless verbal statements which do not constitute the design move are not included in parsing the design processes into design moves.

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[492] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 42.
[493] Ibid.

After the protocols were transcribed, each design move was examined to see whether or not there was a link between the design movements. Coding links is a design activity that mainly focuses on the relationships among design moves. Due to the subjectivity of the link coding process, it is not easy to establish an analysis approach to there is a link between each design move. As mentioned in Chapter 2, the parsing of the protocols was repeated three times with ten-day intervals between coding procedures to reach a precise link coding.

During the link coding process, the specifications determined by Lugt, Hatcher, et al. were taken as reference. To decrease the subjectivity of the link coding process and create them more consistently, these were regarded as guidelines. When one or more criteria are met among the design movements, it was decided that the movements are connected. These criteria are listed in Table 4.3 below:

Table 4.3: Guidelines for coding links

When designers verbalize their ideas, they relate to previous ideas.	(Van der Lugt, 2000): 513.
Within the framework of a single solution, design continues along the same path of thinking in sequence.	(Van der Lugt, 2000): 513.
Similar line of thought between ideas and associations.	(Van der Lugt, 2000): 513.
Gestures and mimics	(Van der Lugt, 2000): 513.
Sequential design movements occur within the same chain of thought and form a picture of a single concept or solution.	(Hatcher, et al., 2018): 136
The same main concept is used in a different context.	(Hatcher, et al., 2018): 136

The exit interviews with the expert designers were conducted to improve the data analysis following the creation of the linkographs. Prior to the protocol studies, the queries of interviews were decided to learn about the participants' ideas about using computational tools and PBD experiences. It is intended that the interview questions become open-ended, and the participants were also encouraged to make contributions and give feedback without the limitations of the interview questions presented in Table 4.4.

Table 4.4: Exit-Interview Queries

How do the performative metrics affect at the beginning of the design process?
Do you think that the performance-based design tools enhanced your design process and/or the end-product?
How do performance-based design tools restrict the design process?
What is the best part of designing using performance-based design tools?
What is the worst part of designing using performance-based design tools?
How do you think performance-based design tools affect your idea generation in the design process?

4.6 The Experiment-based Studies

This part covers the findings of protocol studies of using the PBD tools of expert designers. Each designer worked on the same design problem by considering performative criteria. Since these design tools require prior knowledge, expert designers were chosen instead of novice designers because novice designers have difficulty getting results from performative criteria by struggling with the program. The designers spent approximately two hours for design sessions. The designers spent about two hours in design sessions. Two design processes were documented and examined in total. The data analysis procedure took nearly a month to confirm the dependability of the data in linkographs, and it was repeated and validated three times at ten-day intervals. The outcomes have been presented methodically. At first, the design processes were visualized using linkographs and linked quantitative data to give information about performance-based design settings. A comparative study was done according to the defined coding scheme stated in Chapter 4. The fundamental aim of the detailed analysis and evaluative study is for finding answers to the questions listed below:

- How do PBD tools influence designers' creative thinking abilities?

- How can PBD tools affect the designer's idea generation process?

- What can be the potential implications of PBD tools for identifying required design components of solution ideas?

- What can be the advantages of PBD tools for brainstorming and searching for alternatives?

- What impact do PBD tools have on designers in reframing challenges to enhance solutions?

- What are the benefits and drawbacks of the PBD tools on the productive thinking process?

After the linkographic data-based outcomes were presented, the designers' design processes were analyzed and debated using the researcher's observations and participants' reactions.

4.7 Analysis of The Linkographic Data-Based Results

The protocol studies were conducted using a combined methodology, including think-aloud protocols, Linkography, exit interviews with the designers, and observations made throughout the design processes in PBD environments. Protocol analysis was utilized to acquire quantitative and qualitative data to compare the impacts of the PBD environments through the design processes of expert designers. The quantitively evaluation was done by the calculation of forelink, backlink, and horizonlink entropies for each experiment. According to the distribution of the design moves in FBS coding scheme, the cognitive activities of the designers were also compared. The outcomes of the exit interviews and observations were used as qualitative resources. During the assessment process, each designer’s design process was investigated by linkography, researcher's observations, and the designers’ explained protocols during the design process and subsequently exit interviews. The linkographic data evaluation parameters are given in Chapter 4, and design processes are compared accordingly.

4.7.1 Evaluation the Link Index (L.I.) Value, Linking Patterns and Critical Moves (CMs)

To interpret the outcomes of Linkography, each design process was demonstrated by Linkograph, focusing on visual patterns such as chunks, webs, and critical moves. The Link Index (L.I.) value of each design process is calculated by the ratio of the total number of links to the total number of moves and interpreted as an indicator of the design process's productivity and the sign for the creative design process. The total duration, the ratio between the move number to elapsed time, and the ratio between the link number to elapsed time are also calculated to determine how the PBD environment can benefit the design process of each designer.

The link index value is a quick measure of the total number of link interactions in a design process. This offers an impression of the designer's effort to create a synthesis. As can be observed from the Table 4.5, link index value of D1 is higher than D2 and D3. Also, D2 has higher link index value than D3. According to Goldschmidt, when the link index value in a Linkograph is around to 2.0, the linkages between the moves are strong, and when the index value is less than 1.0, the relationships are weak.[494] The productivity of the process was interpreted in parallel with this idea.[495] In other words, since all designers' link index values are above 2.0, it can be deduced that the experimental design process using PBD tools is productive and creative for all designers.

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[494] Gabriela Goldschmidt, "Linkography: Assessing Design Productivity," in *Cybernetics and Systems '90*, ed. Robert Trappl (Singapore: World Scientific, 1990), 291–98.
[495] Ibid.

Table 4.5: Move and Link values during the design processes

Designer	Number of Moves	Number of Links	Link Index (L.I.)	Total Duration	Number of Moves / Total duration	Number of Links / Total duration
D1	58	197	3,40	02:05:55	0,46	1,57
D2	55	164	2,98	02:03:14	0,44	1,33
D3	105	285	2,71	01:43:12	1,01	2,76

Although D3 has the smallest link index value when compared to D1 and D2, D3 has the highest number of moves and links. The interesting point here, when the elapsed durations are compared, D3 has the highest number of links per minute contrary to the link index value. The number of links per minute is significantly higher than D1 and D2, although the time D3 spends is shorter. This quantitative data indicates the high levels of productivity of D3. D3 has the highest number of links per minute contrary to the link index value. According to researcher's observation, the reason for the difference in the number of moves per minute is that the performative simulation and modeling tool used by D3 is different from that used by D1 and D2. The tool that D3 used is Design-Builder, which gave faster performance-based simulation results than the Grasshopper, which D1 and D2 used. Besides that, D3's personal attitude was more analytical, resulting in more design moves than D1’s and D2’s design processes. During the design process of D2, the designer struggled with the simulation tool, which affected the overall number of links and moves. Indirectly, this makes D2's link index the lowest compared to other designers.

Another significant estimation was that the PBD tools encourage designers to explore more new design concepts and adopt a more creative approach. As Goldschmidt defined, the link index value can be an indicator for determining the productivity of design processes.[496] Especially the high link index value (for values above 1) indicates that the productivity level of the design process is high. However, evaluation according to link index value is not enough for analyzing the collected protocols. For example, when designers begin the design process by investigating diverse choices and then choosing one to develop, they would generate completely different Linkographs than designers who use an integrative approach without analyzing different options, even if the link index values are close.[497] As previously demonstrated, various connection patterns can occur in Linkographs that allow various design inferences. In the assessment of design processes, it is required to analyze these linking patterns as well as link index values.

Chunks and webs are the geometric linking patterns as defined in Chapter 2 for the indicators of efficient thinking and reasoning during the design process. In Figure 4.2, chunks and webs are shown in the yellow triangular parts in the linkograph of D1's design process. Throughout the design process, after D1 make some design decisions, he/she ran the simulation to get its result. After the simulation process, the designer continued or went back and made improvements on some design decisions or changed variables to continue the designing process. As a result of this analysis, it can be deduced that the designer made modifications and additions to it, adhering to his/her first idea. Referencing the initial idea mentioned here should not confuse sticking to it which means fixation. A new set of moves has been added with each modification throughout the design process to enhance that idea.

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[496] Gabriela Goldschmidt, "Criteria for Design Evaluation: A Process-Oriented Paradigm," *Principles of Computer-Aided Design: Evaluating and Predicting Design Performances*, no. JANUARY (1992): 75.
[497] Jeff W T Kan and John S Gero, "Design Behaviour Measurement by Quantifying Linkography in Protocol Studies of Designing," in *Human Behavior in Design*, ed. John S. Gero and Lindemann Udo (Key Centre of Design Computing and Cognition, University of Sydney, 2005), 47–58.

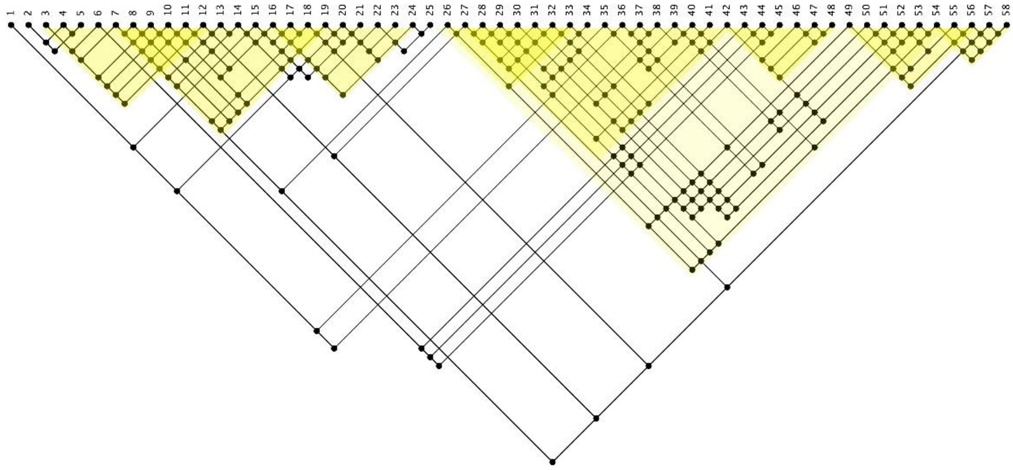

Figure 4.2: Chunks and webs in the linkograph of D1

In Figure 4.3, the chunks and webs are indicated with yellow areas in the linkograph of D2. In the case of the linkograph of D2, even though their move number and design durations close to each other, there are fewer geometric patterns generated than D1. Nevertheless, the linkographic analysis of D2's design process shows productive idea development signs. As stated above why link index value of D2 is lower than the other designers, struggling the simulation program also affected the distribution of the geometric pattern of links.

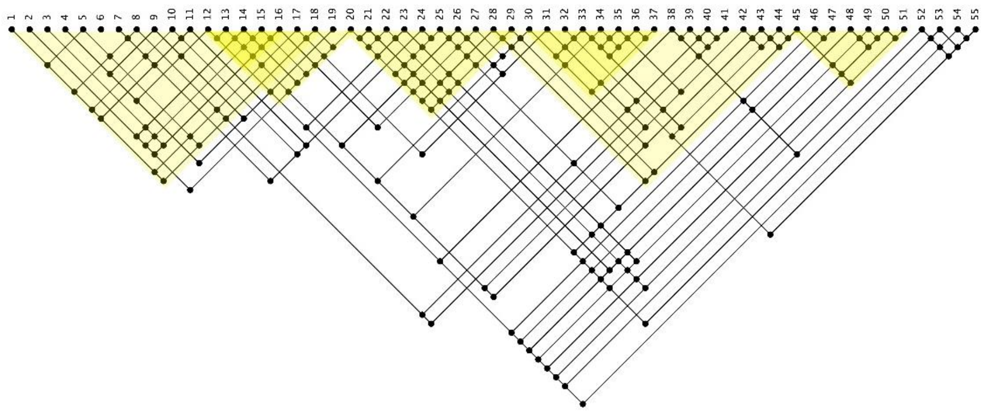

Figure 4.3: Chunks and webs in the linkograph of D2

D3's chunks and webs patterns can be seen in Figure 4.4. Although the link index value of D3 (2,71) is lower than the D1 (3,40) and D2 (2,98), D3 has productive densely interconnected durations. Although their distributions are not equal, all of these design processes have chunks and webs that confirms the statement of Goldschmidt as more than 2.0 link index value indicates the interconnectedness between the moves strong.

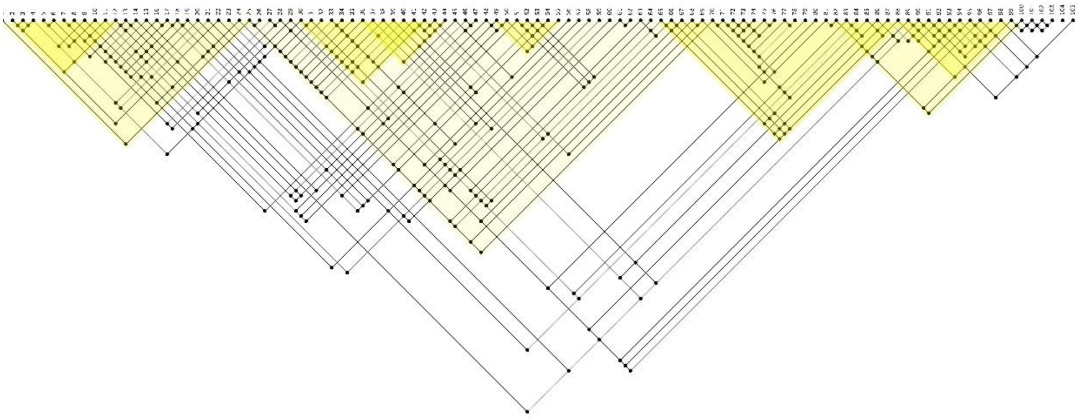

Figure 4.4: Chunks and webs in the linkograph of D3

Having distinct chunks in a Linkograph structure can be explained as the generated design concept is handled and examined from different viewpoints and represents the processes in which the relevance of the idea is investigated. The chunks or webs in the linkographs can be independent or related to each other forelinks and/or backlinks. According to the researcher's observations, the differentiated chunk areas resulted after each deciding point. However, the decision moves are not always completely separate from each other. The small chunks or webs indicate small idea generation links, which can involve larger decision development processes. The significance of the distribution of chunk patterns is bigger chunks include smaller ones or webs. Each triangular pattern is accepted as the idea improvement process, indicating that the productive idea generation and development processes are interconnected.

Comparing the critical moves (CM) that occur during the design process sheds light on measuring design productivity and analyzing the process. The percentages of CMs in both directions are indicators that PBD tools are stimulating to generate ideas in the design processes. The whole CMs of a sequence define its 'critical path', and a critical path with a large number of CMs is an indicator of productivity.[498] The direction in which CMs are taken also enables us to comment on productivity in the examination of the design process. As stated in Chapter 2, forelinks are initiations, backlinks are responses, horizonlinks indicates the opportunities about cohesiveness and incubation. Besides, moves other than the first and last moves are called bidirectional since they have links both backward and forward. More crucially, bidirectional moves are the indicators of a rapid transition between the two modes of reasoning associated with divergent and convergent thinking. According to the above-described thinking categories, the ability to switch between divergent and convergent thinking is proof of creative thinking.

The number of links a design move contains is called a threshold. According to Goldschmidt, to make comparison between different processes, it is required to indicate the threshold discussing o CMs.[499] The chosen threshold is displayed by t in CM^t. In this research the threshold was chosen as 7 for the analyzing direction because almost 10 percent of CMs of the total number of moves in a path. For each designer's design process in the PBD environment, Table 4.6 shows the critical move percentages (%CM^7), the percentage of CM^7 which have mostly forelinks (%$CM^7>$), and the percentage of CM^7 which have mostly backlinks (%$<CM^7$) with the percentage values.

Table 4.6: Percentages of CMs in the design process

Designer	**% CM^7**	**%$CM^7>$ (Forelinks)**	**%$<CM^7$ (Backlinks)**
D1	%39,08	%22,33	%16,75
D2	%35,97	%26,82	%9,14
D3	%46,31	%32,63	%13,68

[498] Gabriela Goldschmidt, “The Designer as a Team of One,” *Design Studies* 16, no. 2 (1995): 196.
[499] Gabriela Goldschmidt, *Linkography: Unfolding the Design Process* (Cambridge, Massachusetts: The MIT Press, 2014): 58.

Backlinks record the path which leads the formation of a move, whereas forelinks indicate its contribution to the generation of subsequent moves. D3 has the highest percentage of forelink CM^{7}s than D1 and D2. of D3 implies the possibility of generating ideas based on new initiatives, which reflects productivity. On the other hand, the percentage of backlink CM^{7}s of D1 is higher than D2 and D3. Backlinks are inevitable in the case of PBD tools used. Because the main methodology is based on the reevaluating the results of simulations and making alterations if required. The percentage of CM^{7}s is calculated according to the total link numbers for all design processes. It can be inferred from Table 5.2 the percentage of CM^{7}s> that have mostly forelinks is higher than the percentage of <CM^{7}s that have mostly backlinks. This could be because the CMs are somehow related to their initial idea. It can be exemplified with the following excerpt of D1's design process:

M36	I can change the roof height on the south facade 1.5m higher for the building height, which was initially thought to be 3m, in order to use the stack effect
M37	This sloped roof also can be better for climatic conditions for Ankara
M38	As a result of changing height, the initially determined overall form is also changed

After the results of D1's ventilation studies, he/she decided to slope the roof from one side to provide a stack effect. Followingly, at the M36, as D1 stated during the design, he/she went back to the form initially suggested in M1 and changed it. The forelink and backlink CMs of D1 are highlighted in the Linkograph in Figure 4.5. The CMs with mostly forelinks are indicated with green, while CMs with mostly backlinks are shown with blue.

As can be observed from the linkograph in Figure 4.5, Designer1 attempted to follow to his/her initial ideas from the beginning till the completion of the design process.

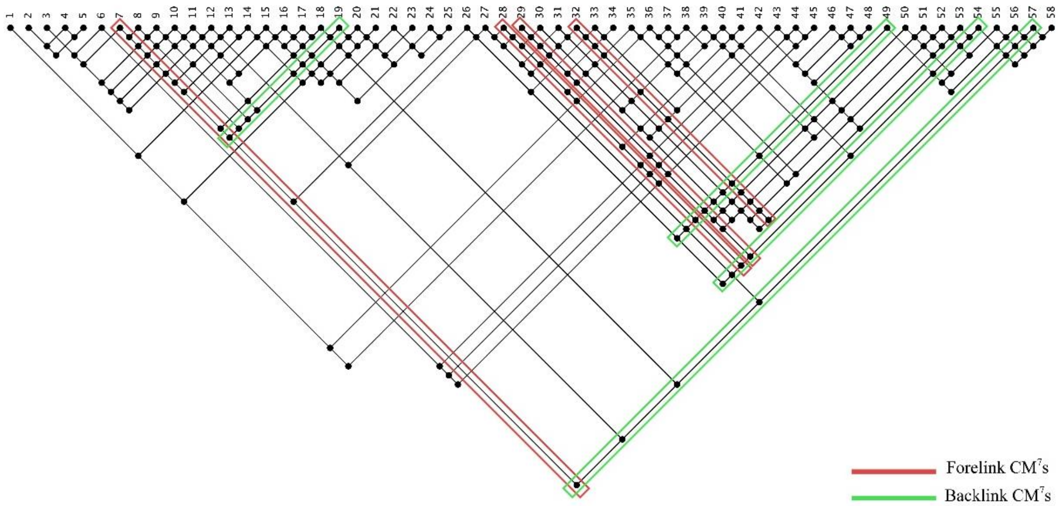

Figure 4.5: Distribution of CM^7s in the design process of the D1

The quantity of the forelink and backlink CMs is nearly equivalent, implying that there are balanced ideation and evaluation cycles towards a solution. Forelink CMs refers to creative leaps that the designer found a new idea. During the design process, each design decision was evaluated by the simulation tool to learn how the decision will behave in the determined conditions. If the result was not meet the expected outcome, D1 went back and made some alterations to change to result of the simulation. In this manner, the density of the backlink moves also is commented by the D1 as below:

> "This is a back-and-forth process in nature of the performative design process, and each movement to back creates a new alternative for the desired goal."

In the process of D2, as can be understood from Figure 4.6, the further moves rely on some initial ideas or the development of the former design decisions. This can be exemplified with a part of protocols of D2 as below:

M31	When I do it like this, it seems to be better for dominating the front area, but I need to look at the wind here.
M32	I connect the windrose tool to look at the prevailing wind direction
M33	When I look at the prevailing wind direction, I notice that I open the wide front completely to the wind direction in this orientation, which is not correct.
M34	I think it might be better to go back to the previous state in this case.

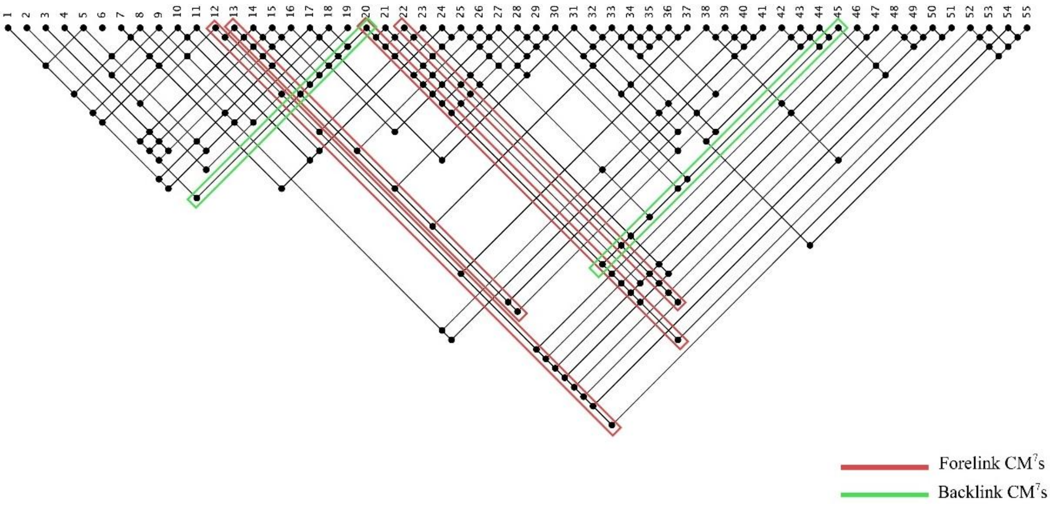

Figure 4.6: Distribution of CM^{7}s in the design process of the D2

In the case of D3, the distribution of CM^{7}s is shown on the linkograph in Figure 4.7. As a researcher's observation, the process is mostly generated by the results of the performative simulations throughout the designing activity. Because of that, the interconnectedness between the further and former moves is an expected result. Through the problem-solving process, the designer frequently addresses each previous decision or the input that could affect it. For example, in M39, D3 decided to reduce the glazing on the west façade according to the simulation results; in M86, he/she noticed that there is still a problem with the higher illuminance. Therefore, D3 decided to put shading elements on that façade. In M89, the designer still continues about design decisions to prevent excessive illuminance. Furthermore, in M93, D3 again controls the simulation result and saw that the shading device does not work enough to prevent solar gain. So, the next step is still related to the west façade, increasing the shading element frequency.

M39	In the west the illuminance is high. According to the result from here, I will reduce the glazing rate on the west side with the result.
M86	In the last case, when I look at the ground floor illuminance simulation, I see that the west facade is still problematic on this floor, so I will put a shading element here as well.
M89	For the living room, I also put drape the close weave light at west side to control solar gain

M93	Since when I look at the ground floor the shading also does not enough, I will increase the frequency of the shading on both floors.

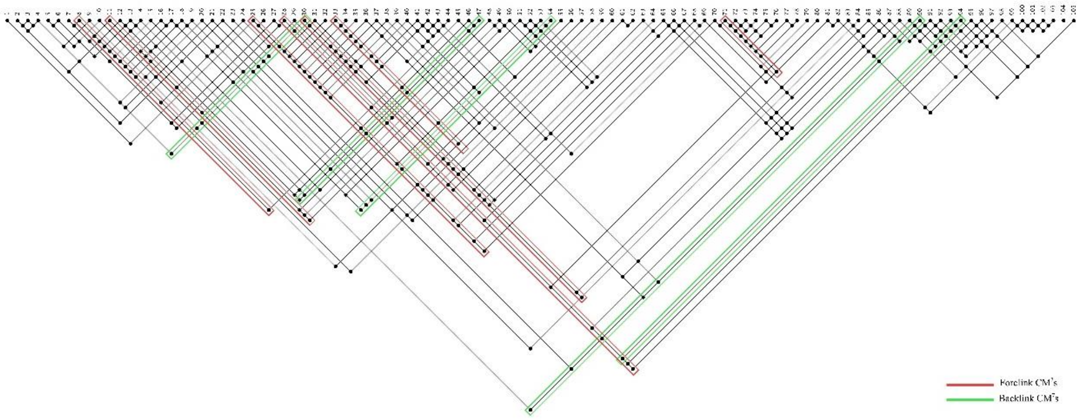

Figure 4.7: Distribution of CM[7]s in the design process of the D3

4.7.2 Evaluation the Entropy of the Design Process

The constructions of Linkograph with the Linkoder software, gives some quantitative data about the design processes. The notion of entropy was mentioned in Chapter 2 is one of the calculated data from this software which is the indicator for the productivity of the design process. A high value of forelinks entropy refers to the influential possibility to initiate design moves for generating new ideas, and a high backlinks entropy value indicates activity to the prior design moves and measure enhancement and confirmation. Horizonlink is not an actual link, but has the idea of link length, which is a measure of movement-time separation between links.[500] The calculated values of entropy for each designer are shown in the Table 4.7 as below:

[500] Jeff W.T. Kan and John S. Gero, "Acquiring Information from Linkography in Protocol Studies of Designing," *Design Studies* 29, no. 4 (2008): 333.

Table 4.7: Forelink, Backlink and Horizonlink Entropy values

	Forelink Entropy	Backlink Entropy	Horizonlink Entropy
D1	26,45	31,02	15,51
D2	24,52	26,77	16,51
D3	31,93	35,69	15,92

The notion of entropy is based on every link has the information and where the links is higher, there could be differentiation of ideas. Entropy measurements show the unpredictability of the link patterns. In other words, it is the capability for generation surprising results.[501] According to the arguments of Kan and Gero, a totally saturated linkograph does not indicates to diversification of ideas.[502] Backlink entropy quantifies the opportunities created by developments. High backlink entropy value implies that design activities focus on readapting or reorganizing existing design situations in parametric and performance-based contexts. Each designers' processes dynamic graphs of entropy measurements of forelinks, backlinks, and horizonlinks analyzed are shown in the figures respectively (Figure 4.8, Figure 4.9, Figure 4.10) below:

[501] G. Hatcher et al., "Using Linkography to Compare Creative Methods for Group Ideation," Design Studies 58, no. June (2018): 141.
[502] Jeff W.T. Kan and John S. Gero, "Acquiring Information from Linkography in Protocol Studies of Designing," *Design Studies* 29, no. 4 (2008): 334.

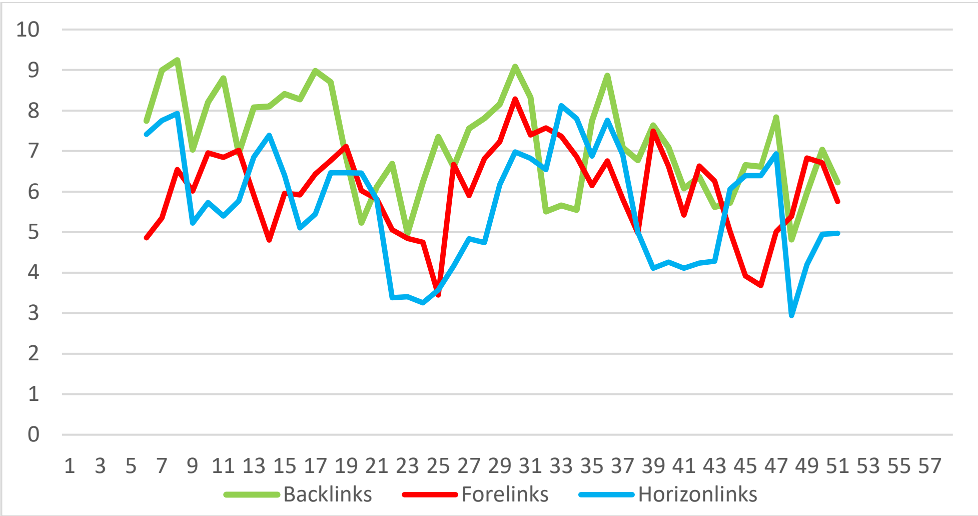

Figure 4.8: Dynamic forelink, backlink and horizonlink entropies of D1's design process

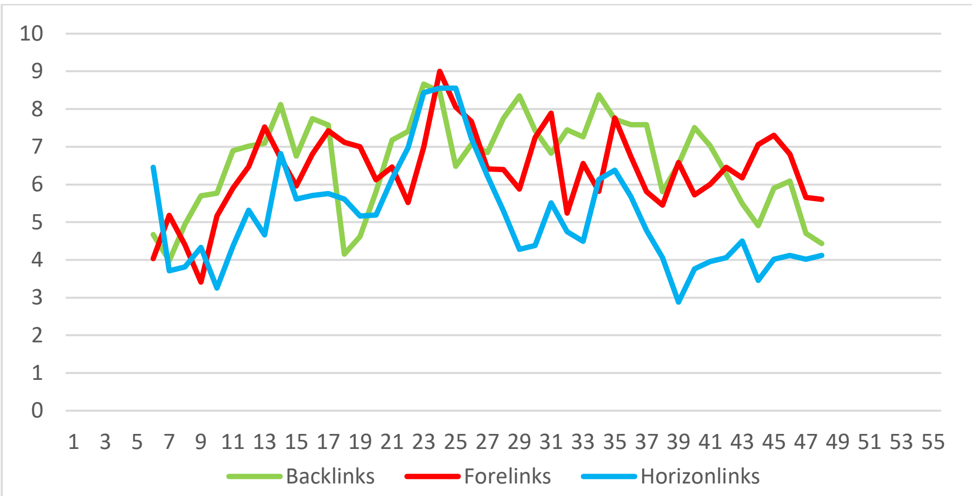

Figure 4.9: Dynamic forelink, backlink and horizonlink entropies of D2's design process

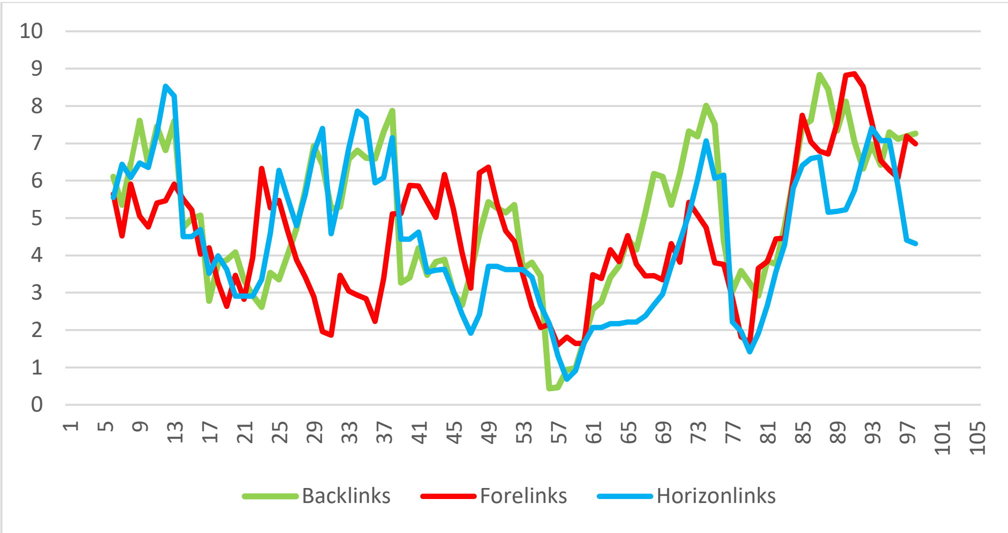

Figure 4.10: Dynamic forelink, backlink and horizonlink entropies of D3's design process

In this research, information entropy is employed as an analytical metric as an indication of design productivity. Entropy is a measurable value for the disorder[503] which can quantify the connectedness and dynamic properties of complex systems.[504] Designers who have high cognitive complexity can analyze problems to identify multiple elements and investigate connections and potential correlations between the pieces. Kan and Gero used entropy as a measure for evaluating linkographic data. The change in the value of forelinks, backlinks, and horizonlinks entropies can be utilized to specify consecutive patterns of cognitive complexity.[505]

With the entropy measurements, contributions of each move in the whole process are evaluated in three different concepts: initiations (forelinks), responses (backlinks), and cohesiveness (horizonlinks).[506] According to Kan et al. the

[503] Michel Baranger, "Chaos, Complexity, and Entropy: A Physics Talk for Non-Physicists" (Cambridge: MA: New England Complex Systems Institute, 2001), 12.
[504] Chris Earl, Jeffrey Johnson, and Claudia Eckert, "Complexity," in *Design Process Improvement: A Review of Current Practice*, ed. John Clarkson and Claudia Eckert (London: Springer-Verlag, 2005), 185, 187.
[505] Ju Hyun Lee and Michael J. Ostwald, "Measuring Cognitive Complexity in Parametric Design," *International Journal of Design Creativity and Innovation* 7, no. 3 (2019): 175.
[506] Jeff W.T. Kan, Zafer Bilda, and John S. Gero, "Comparing Entropy Measures of Idea Links in Design Protocols: Linkography Entropy Measurement and Analysis of Differently Conditioned

decreases of the entropy can be explained by higher cognitive intents and restrictions in the working environment.[507] Although the decrease of cognitive activity, which is the drop of entropy, the designers could still generate satisfactory solutions.[508] In the experiment-based design processes, each designer has dynamic entropy values. The dynamic characteristic of the entropy shows the possibility of that unpredictable solutions could occur during the design process. The main result that can be understood from the entropy graphs, the dynamism of each process indicates the generation of possible solutions or improvements on the process.

4.7.3 Evaluation According to The FBS Coding Scheme

Another data that Linkoder provides while generating the Linkograph is the distribution of links according to FBS coding scheme. The FBS framework proposed by Gero and Kannengiesser regarding the design process is an activity that has interactions between designers and their environments. Designing consists of a range of activities that are not easy to comprehend fully. Detecting these design moves and characterizing them in a thorough framework is required to increase our understanding of design. The framework proposed in this part contributes to this purpose. This coding scheme aims to provide a basic framework that delivers high-quality, uniform findings, maps well to designer behaviours, provides in-depth knowledge of design thinking and activities and can be used with protocols regardless of domain or number of participants.[509]

Design Sessions," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM* 21, no. 4 (2007): 372.

[507] Ibid.

[508] Ibid.

[509] Kan and Gero, "Using the FBS Ontology to Capture Semantic Design Information in Design Protocol Studies," 2009: 1

Using the FBS ontology as a general coding scheme is for investigating design activity.[510] Its primary purpose is to capture semantic information from design protocols. This information can then be used for exploring several aspects of designing according to the focus of interest and discovering different types of design transformation activities.[511] All three significant forms of reformulation propose a non-static characteristic of design activity since they provide the ongoing design process a new direction that was not previously envisaged. [512] The FBS framework has been used and evaluated in various cognitive design experiments, where it was shown to possibly capture the majority of relevant design processes and record explicit transitions between design instances.[513] Through experimentally collected data and the FBS ontology as a foundation, the behavior of designers may be assessed using protocol analysis.[514]

The FBS framework categorizes design activities in terms of three main types of variables: function, behaviour, and structure. A design object is never simply transformed from a function, but rather passes through a number of steps using the FBS variables. Gero's FBS methodology describes design activities into three primary variables: function, behavior, and structure.[515] In this framework, the purpose of design is to convert the collection of functions to a series of design descriptions (D). The designed object's function (F) is defined as its purposes; the object's behavior (B) is how it performs its functions and is either derived from behaviour (Bs) or expected behaviour (Be) from the structure, where structure (S) is the elements of the designed object and their interactions. The FBS coding

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[510] Jeff W T Kan and John S Gero, "Using the FBS Ontology to Capture Semantic Design Information in Design Protocol Studies," 2009: 1
[511] Ibid.
[512] John S. Gero and Udo Kannengiesser, "The Situated Function-Behaviour-Structure Framework," *Design Studies* 25, no. 4 (2004): 376.
[513] Rongrong Yu, John Gero, and Ning Gu, "Architects' Cognitive Behaviour in Parametric Design," *International Journal of Architectural Computing* 13, no. 1 (2015): 82.
[514] Ibid.
[515] Jeff W T Kan and John S Gero, "Using the FBS Ontology to Capture Semantic Design Information in Design Protocol Studies," 2009: 2

system only allows one design code for each design move to eliminate overlapping outcomes. The distribution of the links regarding their FBS codes and their distribution to the overall link numbers are shown in the Table 4.8.

Table 4.8: Distribution of FBS Coding Metrics in the design process

	D1		D2		D3	
FBS Coding Metrics	Link numbers	Distribution (%)	Link numbers	Distribution (%)	Link numbers	Distribution (%)
F	21	36,2	14	25,5	22	21,0
Be	4	6,9	3	5,5	8	7,6
Bs	19	32,8	20	36,4	34	32,4
S	2	3,4	4	7,3	7	6,7
D	4	6,9	9	16,4	19	18,1
R	8	13,8	5	9,1	15	14,3

Each designer's linking activity of the moves is illustrated in Figure 4.11, Figure 4.12, and Figure 4.13, respectively, regarding the FBS coding scheme. It demonstrates which code is defined for each move and its linked move. This graph helps to understand the relationship between the reason for the moves. As expected from the performative study, at first, design decisions were mainly made because of function-related decisions, shown in red areas, and then generally behaviour derived from structure (Bs) activities occurred in green areas through the end of the process. Design descriptions, structure, and requirement-related statements completed the function-based activities and behaviours derived from the structure due to performance-based simulation results.

The moves are mostly performance-oriented ones are the behaviour derived from the structure. The interesting data that can be deduced from here, D2's and D3's design processes have higher Bs values when compared to other coding metrics in their process. Function-related activities follow the Bs design moves for D2 and D3. Although in the case of D1, the distribution of F value is higher than the Bs value, these two metrics dominate the D1's process. In this sense, D1 made more functional considerations, most of them encountered by the Bs moves thanks to the feedback of simulations.

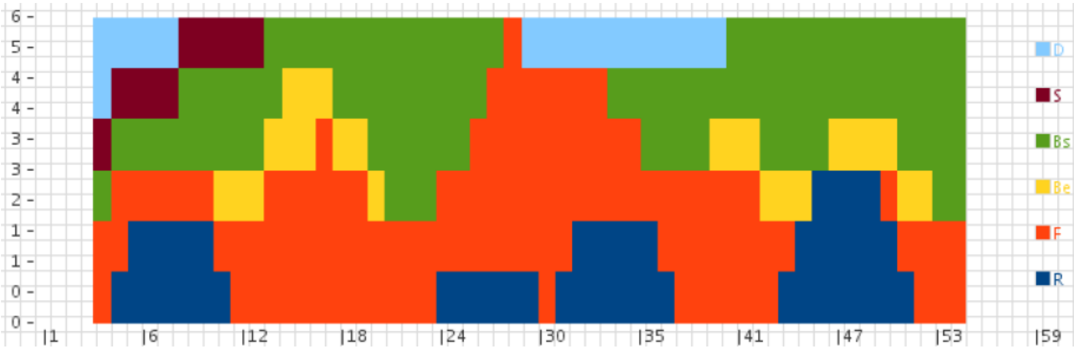


Figure 4.11: D1's design moves based on FBS ontology

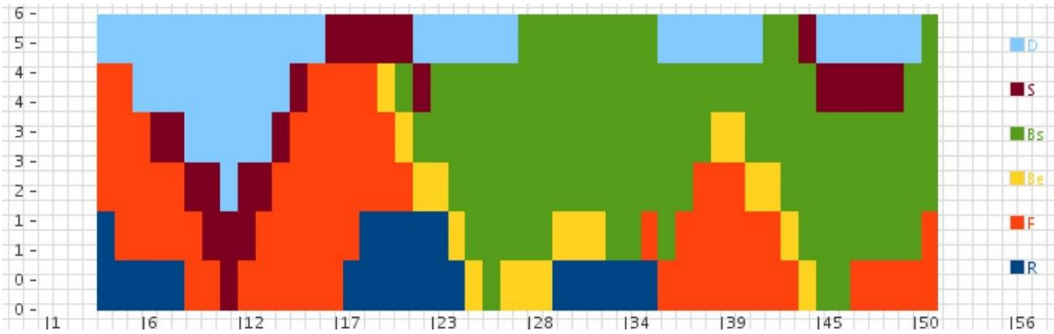


Figure 4.12: D2's design moves based on FBS ontology

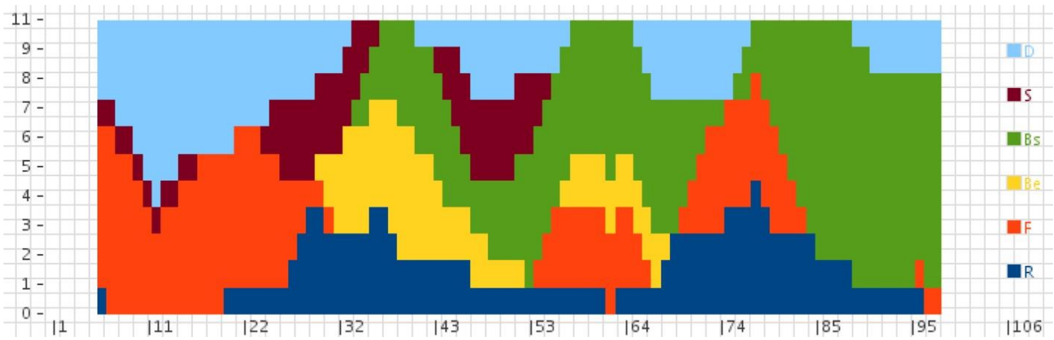


Figure 4.13: D3's design moves based on FBS ontology

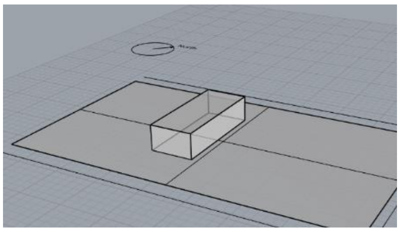
Gero's Function-Behavior-Structure (FBS) paradigm has been widely employed among different design fields to investigate cognitive aspects.[516] These coding schemes specify design activities that occur in the design process and categorize them as micro activities into different levels that can demonstrate the main aspects of cognitive activities.[517] In other words, coding schemes enable gathering the various data in design protocols that might be used to quantify complexity.[518]

4.8 Analysis of the Performance-Related Results

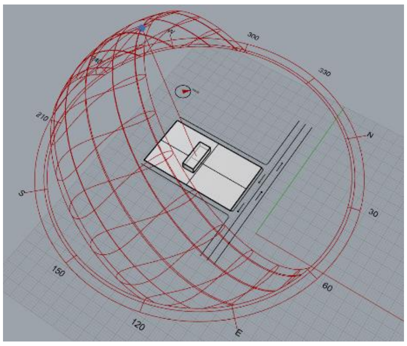
The research aims to investigate how the PBD tools affect the design process from beginning to end in terms of productivity of the process, creative idea generation, finding alternative solutions, and so on. In this manner, performative characteristics and principles have an essential role in shaping the end-product of the designing structure. As it is observed in the forelink and backlink critical moves and entropies in the previous chapter, the design process of the performance-related simulation tools mostly depends on evaluating the present idea and making inferences about that. The evaluation results could tell the designer that he/she needs to change some parameters and reevaluate the design or that it works, and the designer could continue with it. The Performance-related data was retrieved from the designers' verbal protocols, screen recordings, and audio-recording during the design process. These were transcribed after the design process and evaluated with the visual representations and researcher's observations. Respectively, a portion of the screen recordings of the design process of each designer is how the designed element comes through its final shape is shown in following figures.

In below, the design process of D1's is summarized by visuals of the designer's screen with related design move.

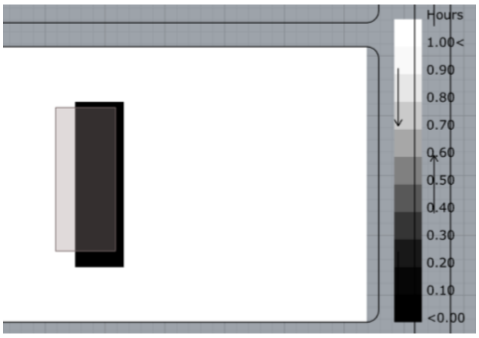
[516] Ju Hyun Lee and Michael J. Ostwald, "Measuring Cognitive Complexity in Parametric Design," *International Journal of Design Creativity and Innovation* 7, no. 3 (2019): 160.
[517] Ibid., 160-161.
[518] Ibid., 161.



M1: Started with rectangular prism as 6x13 cm with 3-meter height

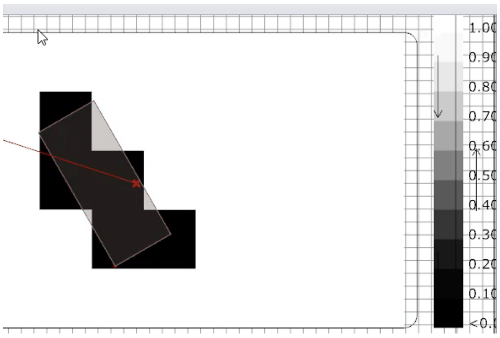


M7: It is useful to look at the shading part for Orientation. I'm doing solar orientation study to draw a plane on the ground and see the shading



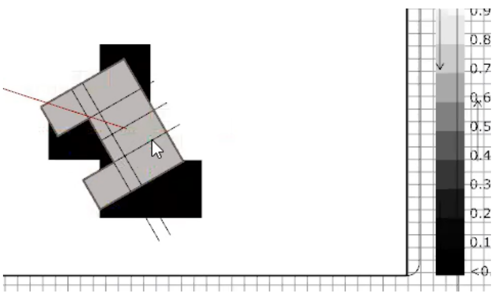
M9: I look at how much shadow the building creates by casting its shadow on the ground.

M10: As a result of the sun path analysis, we see that there is very little shadow area in the south part.



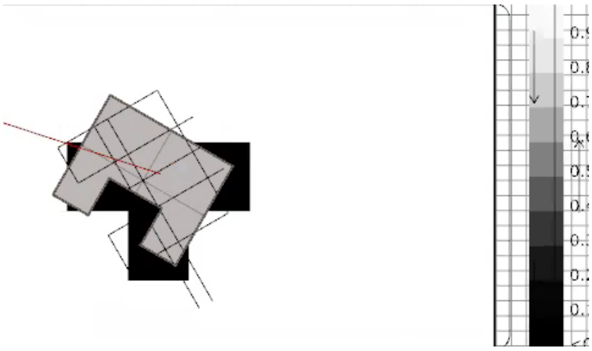
M12: They will already be using the northern front to a large extent, but if I rotate the building 30 degrees, what kind of orientation would be formed?

M13: As a result, I saw that it grows a little more towards the shadow area



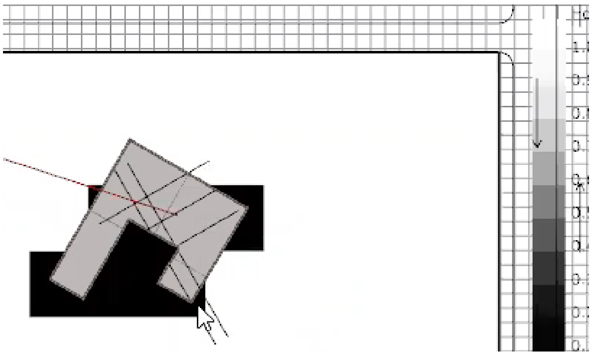
M14: As a result of the orientation study, I came with the idea of the building can be a recessed building

M16: I'm trying to get help using the building's own form to create a shade area

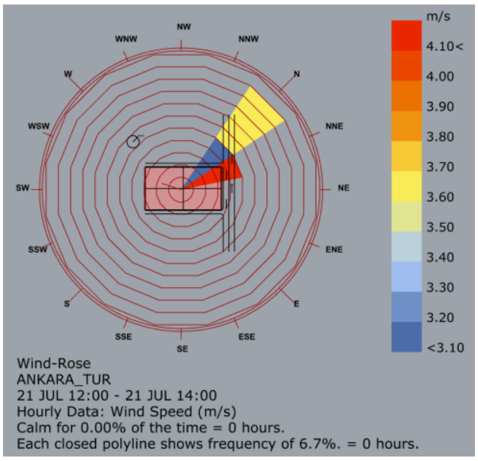


M17: In fact, I expected more shadows to form in the shadow area in this process. But not as much as I expected

M18: For this reason, I wonder how it would be if I rotate the building another 30 degrees. This created a new alternative



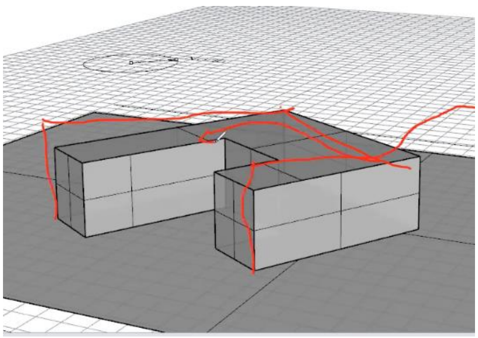
M20: Since there is a continuous exposure in the afternoon in the west and the sun coming from the west, I am extending this edge of the building on the sun side so that the people sitting there can sit more comfortably



M26: I never looked at the wind direction here, but it might be good to use natural ventilation in such a small building. For orientation of the structure, I can also look to use wind rose, not just as solar radiation.

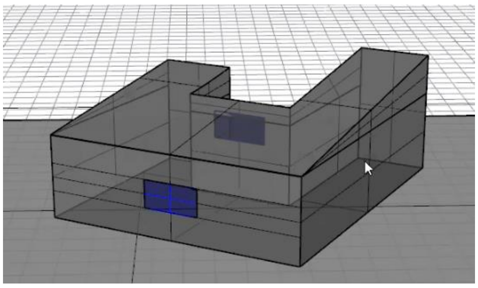
M27: As a result of wind analysis, I see that the orientation is not bad, the wind is coming from the north and northeast

M28: So, I can use cross ventilation from north to south

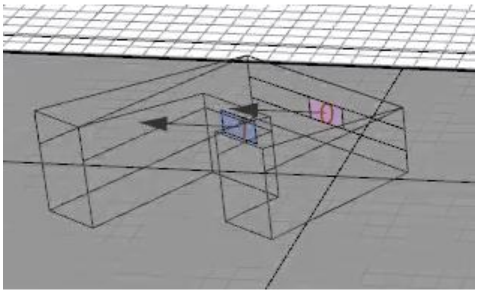


M32: I determine an estimated windows location on the north and south to try cross ventilation and make the final decision based on the result.

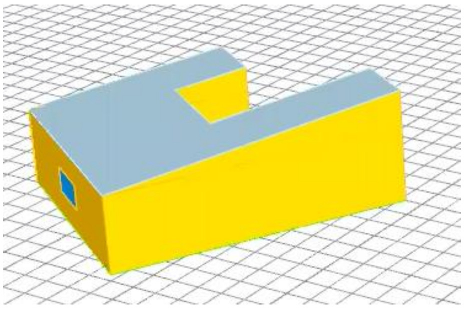
M36: I can change the roof height on the south facade 1.5m higher for the building height, which was initially thought to be 3m, in order to use the stack effect



M39: I'm placing the windows lower in the wind direction and higher in the outflow direction



M42: I will open the window holes determined in the model and see what the pressure is there. For example, I will see if natural ventilation will work for me or not.

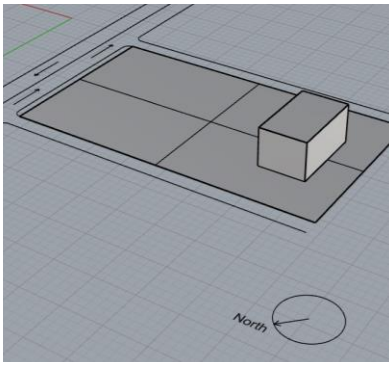


M49: The next step after completing the ventilation is looking to infiltration sensitive cooling for how much cooling do the windows, I put in this position provide on a very hot day?

M50: According to the result, I'm changing the size of the windows

D1 used Rhino and Grasshopper for 3D modelling and Ladybug and Energy Plus for simulations. D1 mainly makes changes in the structure and orientation studies regarding the sun path and wind analyses. He/she also defines some window locations and dimensions by evaluating them from the simulation tool. According to the researcher's observation, the designer effectively used the simulation tool to make appropriate alterations to the structure. He/she stated that these types of design processes are mainly based on back-and-forth movements. The final decisions should be made according to orientation studies, especially for the formal generation of the design for better lifetime performances.

In below, the design process of the D2's is shown with the corresponding design moves and visuals of the designer screen.

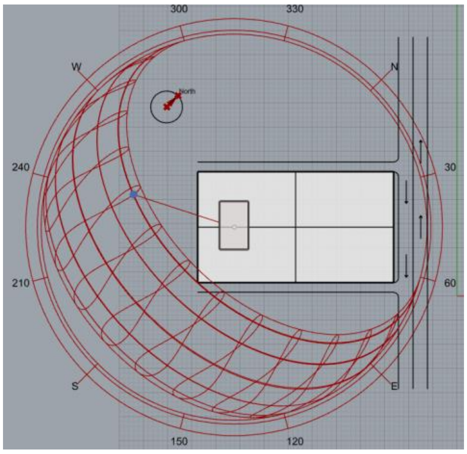


M9: I think of 60 m2 as 10x6 mt

M12: I draw a 60m2 prism 6 m in this direction and 10 m in the other direction

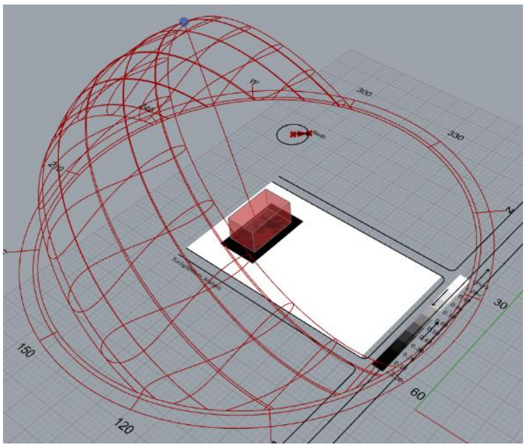
M13: First I put the prism parallel to road

M14: When I look at the north direction and think of Ankara, I think it would be right to place it on the north and south axis or east-west axis



M20: I will do solar orientation study in grasshopper to decide on its orientation

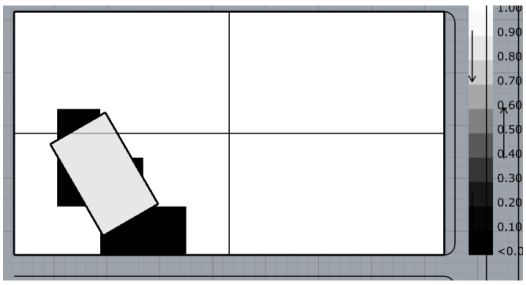
M21: When I look at the direction the sun is coming from, I see that the sun is behind us now, so I think the front



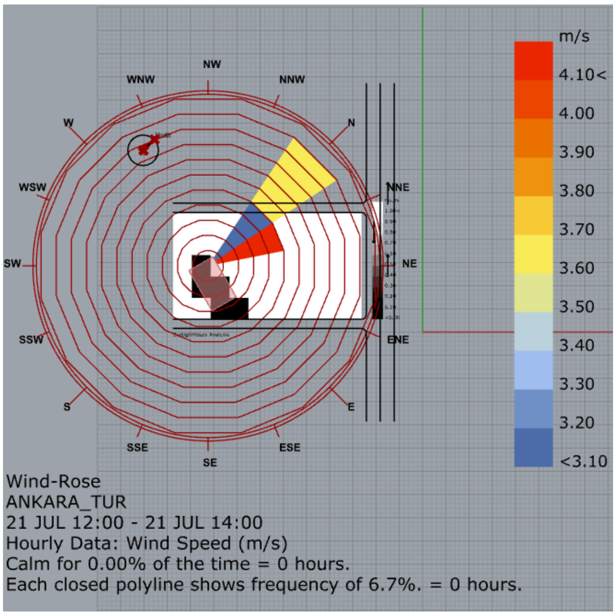
M23: There is a shade area in front. To increase this shade, I think there may be a horizontal shading element in that part

M28: When I look for summer, the front area can be used as a sitting area, but for winter, let's see from tool

M29: When I look at the date of 15.12, I actually see that the area in front is still in the shade, I think that this will



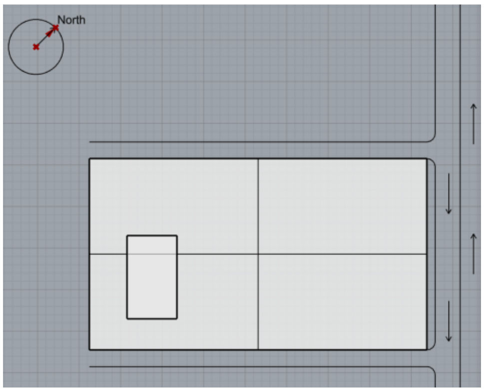
M30: So instead of 45 degrees I rotate it 30 degrees first to see what it looks like.



M30: So instead of 45 degrees I rotate it 30 degrees first to see what it looks like.

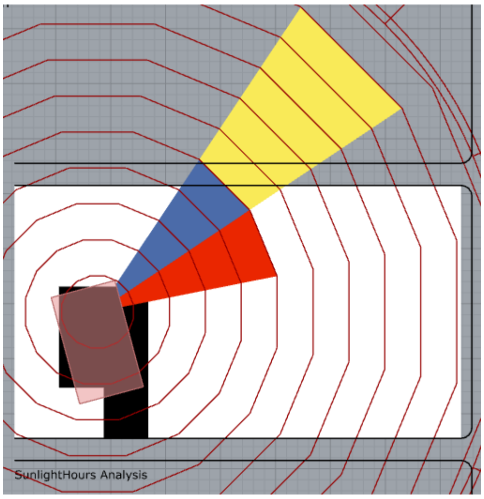
M31: When I do it like this, it seems to be better for dominating the front area, but I need to look at the sun and wind here.

M33: When I look at the prevailing wind direction, I notice that I open the wide front completely to the wind direction in this orientation, which is not correct. Also, the shade area is decreased in this rotation.



M34: I think it might be better to go back to the previous state in this case

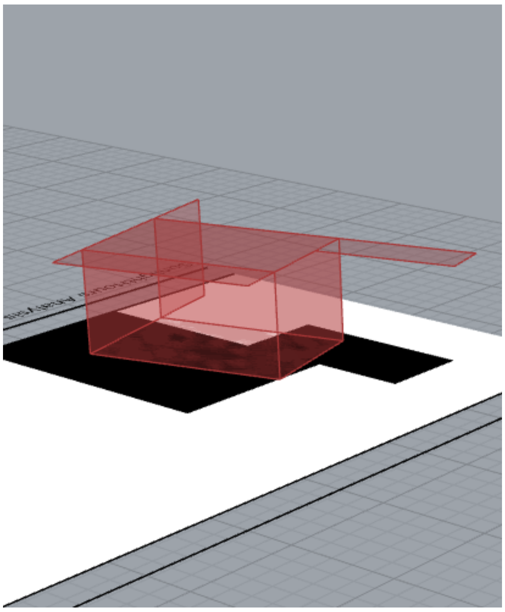
M42: But when I look at this orientation, I see that I have opened the building to the prevailing wind direction again, I go back to that state because the previous position seems better



M43: However, in this case, since the first problem still persists, I try the alternative, how about when we turn the initial orientation 15 degrees

M44: In this way, when I look to wind rose the façade was not completely in the direction of the prevailing wind

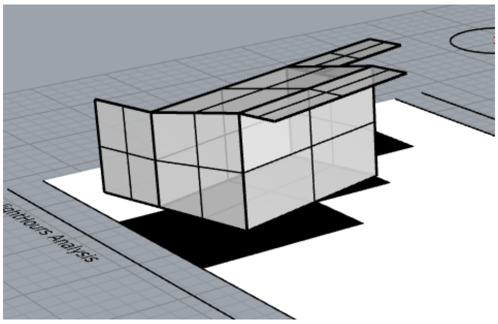
M45: And there is an area in front where we could use its shade



M46: As a structural element, I extend the wall here coming out of the building so that the rear façade is not exposed to direct sun when I look at the orientation study. The element that comes out of itself, not like a different element from the structure

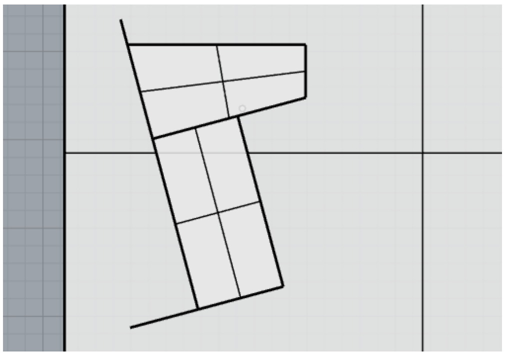
M47: Even in this part, when I think of it as an open one to be used, I extend this wall with the same logic

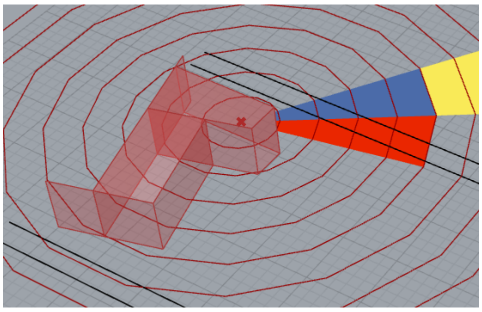
M48: When I look at the sun angle, shading element in the front façade improved the shade area since the sun comes here directly from above in summer



M50: That brings to my mind, I think the form of the building can be changed a little more in 3 dimensions. So, I sloped the roof

M51: I think it will give better shade to the front if I increase the height of the front part of the roof rather than flat





M52: Alternatively, this place can be elongated in an L-shape.

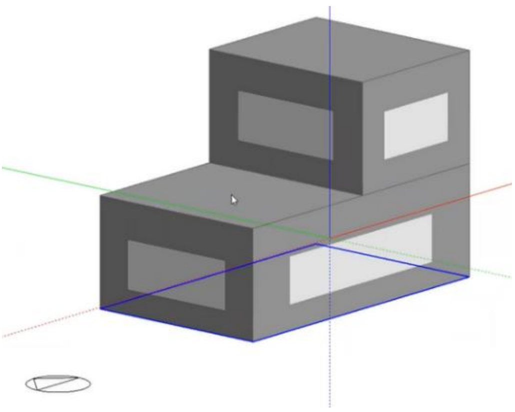
M53: Compactness may actually be better to reduce heat loss, but in terms of design, I try the L version to have facades in different directions and to get light to different areas in the distribution of functions.

M54: When deciding on the form of this, I reduce the part I made from 6 meters to 5 meters and also make it into the form that extends from the end in an L shape.

M55: In this case, since the prevailing wind direction comes from that side, it can prevent the wind.

Similar to D1, D2 used Rhino and Grasshopper for modelling and Ladybug for simulations. D2 made decisions according to shading orientation simulations and wind directions throughout the design process. He/she mainly decides to think about the performative outcomes; however, in some moves, the consequences of the simulation were not as expected. So, D2 goes back to the initial idea and thinks about the situations from the beginning. According to the researcher's observation, D2 has spent more time on the simulation tool that negatively affects the design product's overall condition. D2 decided on the orientation of the building, formal relationships, shading elements. D2 could not make further decisions like interior distribution, opening locations or sizes, and so on.

The design process of D3 is shown in below with the visuals from the designer’s computer and the related design moves. D3 made some sketches for the initial ideas like the orientation of the structure, interior layouts, glazing distributions. After that, the designer continued with the computational modeling.



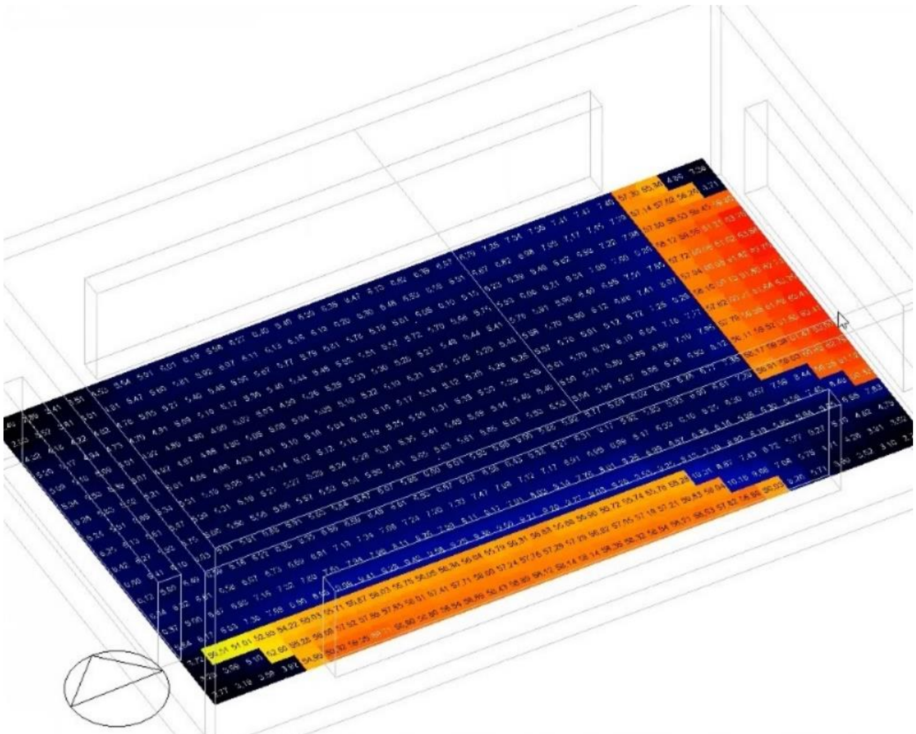
M4: The morning sun in Ankara isn't that harsh, so I'll keep the west-facing side small and enlarge the north and south ones.

M27: Since I am thinking of a 2-storey building, I am making 7 meters of floor height.

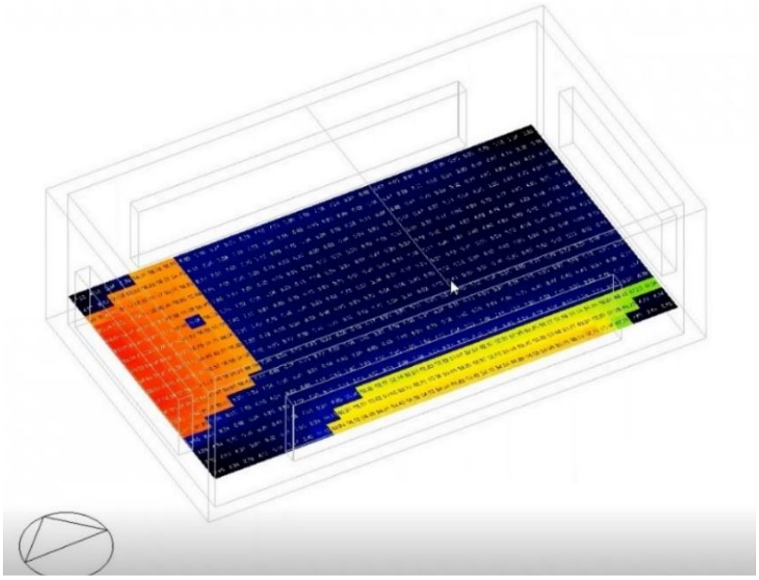
M28: … I start with a 6x10 prism

M30: I will test the daylight analysis with a 30% window to wall ratio

M31: The program processes the openings on all facades at the determined window ratio, and I will make changes on them as a result of the analysis

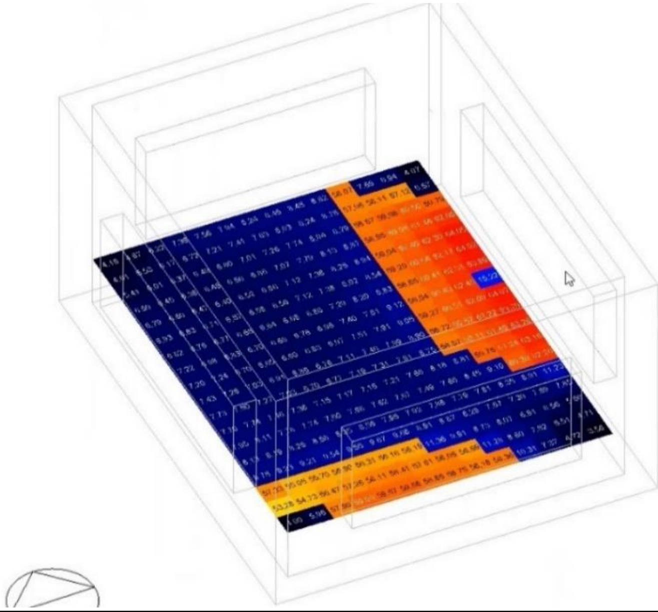


M35: I'm looking at the ground floor. In the 9 o'clock analysis, the morning sun is not very intense, as I expected, it goes in about 4 levels



M36: In the 15 o'clock analysis, the western sun is too much, I think this creates a problem

M39: In the west the illuminance is high. According to the result from here, I will reduce the glazing rate on the west side with the result



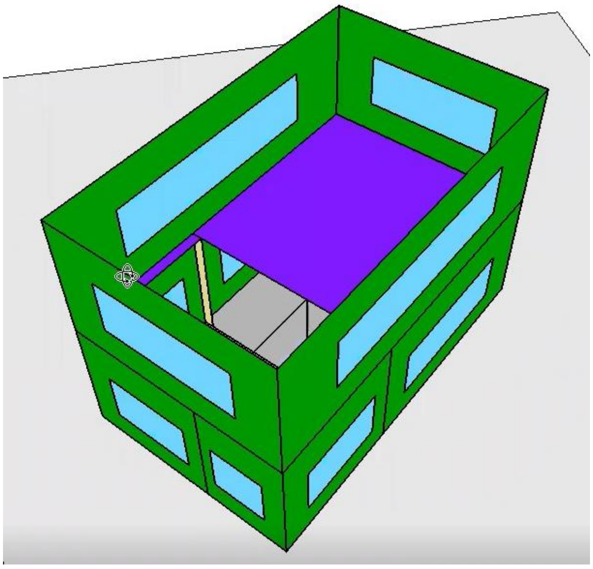
M40: Right now, the morning sun is coming from the east side to the upper floor a lot, at 9 o'clock I will either not put a window on the upper floor or put a shading so that the sun does not get in the eyes of the people on the top floor

M41: I'm simulating temperature and heat gains to see the energy consumption

M42: Since the upper floor is closer to the roof, it is more heated, it is already increasing in summer.

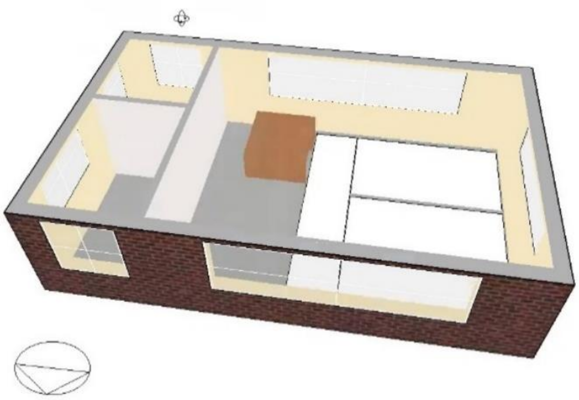
M43: I see the outside dry-bulb temperature is 25 °C in summer and the air temperature is 35 °C on the day, I think it's because I didn't put any breaker in front of the windows

M44: I see that there is a temperature problem in the summer, I need to do some changes to improve it



M45: before I do this, I need to process the interior functional distribution into the model

M48: I am revising the model as the top of the sitting area on the upper floor is double-layered and the opposite side will be the mezzanine floor.

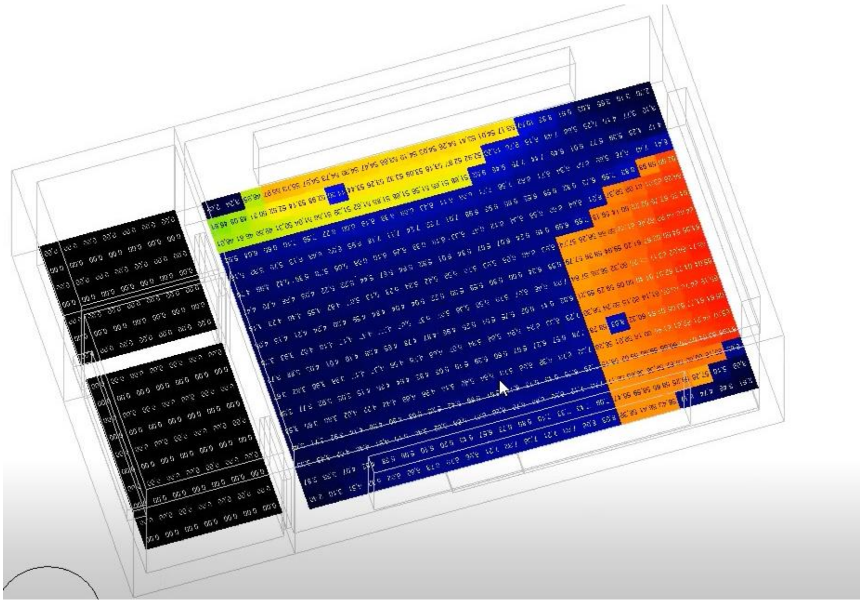


M51: I draw so that the bathroom can placed behind the bedroom

M52: I also make a dressing room next to it.

M53: Thus, I completely protected the upper floor from the east façade.

M54: Actually, I was going to put the kitchen and the bathroom on top of each other so that the wet spaces would overlap, but I put them on this side to prevent the negative effect of the east façade.



M65: In the bedroom part, the daylight coming from the west side does not reach the bed completely, but I still think that it will heat the interior too much.

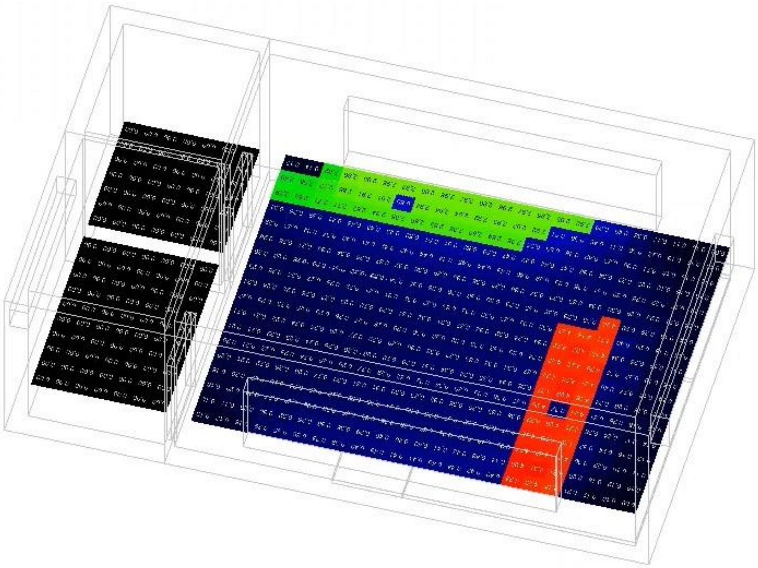
M66: So, I'm going to shrink the upstairs west facing window.

M67: I am reducing the current window size to half.

Site and Source Energy

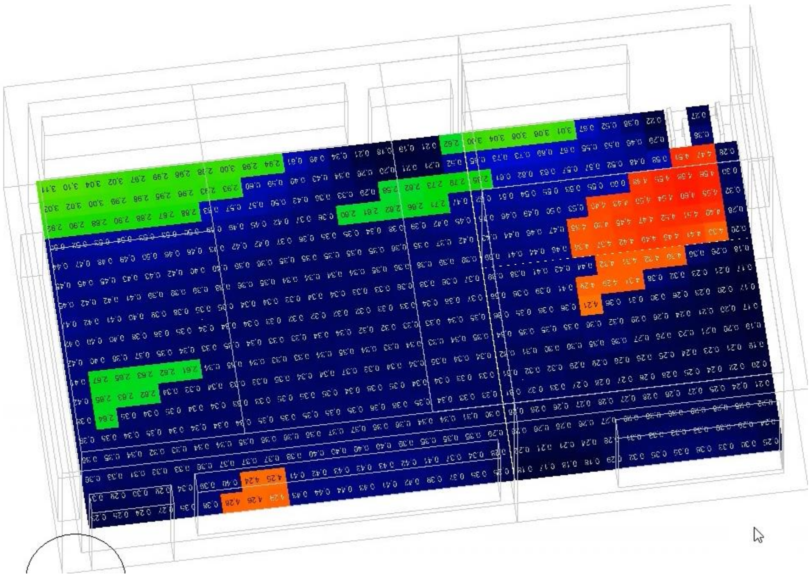
	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]
Total Site Energy	19934.64	240.01
Net Site Energy	19934.64	240.01
Total Source Energy	68300.89	822.33
Net Source Energy	68300.89	822.33

M82: but when I look at the energy per total building area, I see it is 240 which is a bit high.

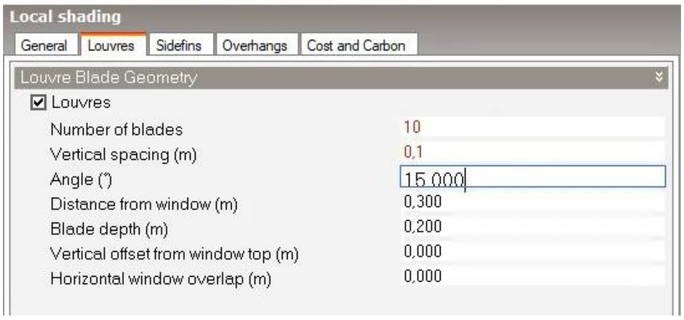


M84: first floor south illuminance is nice.

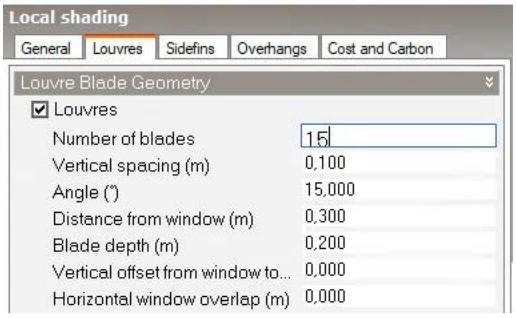
M85: but there is still a problem on the west side so I will put shading device on that part.



M86: In the last case, when I look at the ground floor illuminance simulation, I see that the west facade is still problematic on this floor, so I will put a shading element here as well.



M88: I'm putting the shading element in the bedroom again with the louvre 0.5 frequency M90: and I put the shading element with louvre 0.5 frequency in living room



M92: When I look at the first floor, I see that it does not have much effect, so I will increase the frequency of the shading M93: Since when I look at the ground floor the shading also does not enough, I will increase the frequency of the shading on both floors. M94: I increase the number of horizontal louvres in the shading element from 4 to 10 and reduce the distance between them from 0.3 to 0.1 M95: I increase the number of horizontal elements from 10 to 15 here

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]
Total Site Energy	17535.07	211.12
Net Site Energy	17535.07	211.12
Total Source Energy	61191.52	736.74
Net Source Energy	61191.52	736.74

M99: I will see how much the last shadings I added affect the total energy consumed M100: I see it decreased to 211 kwh/m2.M94: I increase the number of horizontal louvres in the shading element from 4 to 10 and reduce the distance between them from 0.3 to 0.1

As stated before, D3's the design and simulation tool are different than D1 and D2. D3 used Design-Builder and Energy Plus throughout the design process. He/she made design decisions mainly about the illuminance analysis, solar heat gain, comparison of and the total energy consumption of building. At first, D3 defined a window-to-wall ratio as %30, the program defined this ratio to every wall. Then, D3 analyzed the interior radiance simulation according to the functional distribution of the plan. According to the evaluations, D3 made some changes of the window dimensions, removed some of the concerning its function, and added shade devices for the problematic conditions. After making radical alterations, the designer reevaluate the simulations and compare the results with the previous ones. In addition to the fact that the program used by D3 is different from the others, being the designer's character more analytical, allowing him/her to make a high number of moves in the design process. This enabled D3 to further comment on the results from the performance-based simulation tool throughout the design process and make design decisions based on them. The simulation outcomes interpreted as feedback that the designer retrieved from the PBD tool, they guide the further design moves. According to the researcher's observation, after the initial design decision were taken, the design process of D3 mostly led by these feedbacks.

4.8.1 Assessment of the Performance-related Objectives Used in the Design Process

Each designer started with a simple box shape from the beginning of the design processes. Then regarding the performative characteristics, he/she continued to the fundamental decisions such as orientation, the form of the structure, height of the structure, windows placements, interior layouts, etc. Throughout the design process, all designers mentioned several performance-related keywords as they were taken into consideration. These performance-based keywords are classified under four main categories: design strategy, design analysis mode, environmental factor, building elements.

The researcher noted these keywords throughout the design process and checked by the researcher from the audio recordings during data collection, as well as the audio records are observed from the designers' screen, which inputs and outputs he/she gets from the simulation tool. In the Table 4.9, the performance-based objectives for each design process are given under the related category and in which design move the designers addressed to these objectives.

Table 4.9: The use of performance-related objectives for each designer

	Design strategy		Design analysis mode		Environmental factor		Building element	
D1	Infiltration sensitive cooling	*M31, M49*	Occupancy discomfort	*M54, M55, M56, M58*	Sun path	*M7*	Glazing	*M31, M32, M42, M50, M52*
	Cross ventilation	*M28, M29, M32, M35, M39*	Psychrometric chart	*M55*	Wind direction	*M26, M27, M54, M56*	Sun shading element	*M23, M51, M52, M53*
	Stack effect	*M40,*	Sunlight hourly analysis	*M8, M20*	Wind speed	*M33*	Sloped roof	*M37, M38*
	Passive cooling effect	*M2, M24, M25, M41*	Solar orientation study	*M3, M7, M9, M10, M11, M12, M14, M18, M56, M57*	Dry bulb temperature			
			CFD analysis	*M34, M42*	Annual hourly data	*M7, M8*		
D2	Prevent heat loss	*M4, M27*	Solar orientation study	*M14, M20, M22, M25, M26, M30, M42*	Sun path	*M15, M28, M48*	Glazing	*M18*
	Prevent overheating	*M37, M46, M47*	Sunlight hourly analysis	*M20, M21*	Wind direction	*M2, M31, M32, M35, M36, M34, M42, M43, M44, M55*	Sun shading element	*M23, M48, M49*
	Passive cooling effect	*M36, M37, M41*			Dry bulb temperature	*M20, M21*	Sloped roof	*M50, M51*
	Climatic conditions	*M3, M16*			Annual hourly data	*M21, M22, M29*		
D3	Natural ventilation	*M26, M75, M76*	Occupancy discomfort	*M23*	Dry bulb temperature	*M43, M44*	Glazing, louvre	*M9, M10, M20, M21, M22, M23, M30, M31, M39, M40, M60, M61, M62, M66, M67, M79*
	HVAC	*M26*	Internal gain analysis	*M26, M41, M42, M69, M81, M99, M102*	Sun direction	*M2, M4*	Mezzanine floor	*M11, M19*
	Cross ventilation	*M59*	Daylight analysis	*M30*	Daily analysis	*M33*	Door	*M14, M56*
	Passive cooling effect	*M101, M102*	Illuminance analysis	*M35, M36, M37, M38, M39, M40, M47, M65, M85, M86, M87, M88, M89, M97*			Sun shading element	*M85, M86, M88, M90, M93, M94, M96*
	Prevent overheating	*M86, M87, M88, M89*						

In the above table, according to the classification of the performance-based considerations, is given. Some objectives are different from each design process, although their upper classification is the same. For design strategy, although the common objective is evaluation according to cross-ventilation in D1's and D3's processes, D2 does not mention any considerations related to ventilation. Similarly, in terms of building elements, D1 and D3 designed glazing according to the results of ventilation simulations; however, D2 only stated the openings could be placed in which façade. Each objective has uneven distribution in the three experiment-based design processes. Objectives mentioned in more design moves can be said to be more guiding performative metrics throughout the design process than those mentioned less. It can be confirmed when each designer analyzes the design processes. For example, the D1 decided mainly on solar orientation study and wind analysis considering cross ventilation. For D2, prevailing wind direction and solar orientation are the main guiding objectives. In D3's process, the designer made the final dimensions of glazings according to the evaluation of illuminance and internal heat gain analysis.

4.8.2 The Potentials and the Limitations of the Performance-based Architectural Design Environment

The design processes used by these PBD tools are benchmarking processes by nature. As exemplified from the design-oriented experiments, the whole process has been redesigned according to the results of PBD tools. D1 and D2 used same tool, D3 used different PBD tools for different performative goals throughout the design process. In terms of the computer program, designers were allowed to use what they preferred. The reason for that, these tools require knowledge to use and get feedback from them. Although the participants were selected from the expert designers, each designer was also struggling in a small part of the design process, and he/she needed to go back to the 3D model to find the problem in order to run the simulation. The researcher limited the total design time to about two hours because it is impossible to know exactly how long the design process will take with PBD tools since it takes a long time to get results from the simulations.

D1 emphasized that these PBD processes primarily based on back-and-forth processes. After some decisions were taken, controlling if it would work or not, and then continue according to the result. D1 stated this is an inevitable benchmarking process that makes design decisions more optimal. D2 also has a similar idea with D1 in guiding the designers to an objective approach for the subjectivity of the designing process. D2 stated that the use of these PBD tools help a lot in producing alternatives. The designer clarified this as follow:

“Although generation of 3D alternatives is a part of architectural design education, there are points where we get stuck, so the most important benefit is the process of seeing and evaluating multiple 3D alternatives at the same time. I think it supports 3D thinking because we are used to thinking in 2D”

According to the exit-interviews with three designers, there is can consensus that the main limitation of using PBD tools in the design process is the requirement of high knowledge about these simulation programs. If there has been a problem, sometimes designers deal with these issues instead of designing. For D3, another disadvantage of using PBD tools makes the designer think a little more like an engineer. D3 stated that as below:

"… I guess I do not care much about how the design looked during the design process; it seems like I did not pay attention much to the exterior design. It makes us think a little more like engineers. I could not think of how it would look more aesthetic. Actually, I designed a box-like building because I started with a direct performance focus. It prevents me from seeing things like this at first. Since our time is limited in such a study, I threw the design to the second plan in order to get immediate feedback, and I acted mainly performance-oriented."

If this would be a real-life project, D3 declares that he/she would start it this way, then elaborate and test it again. According to D3, performance-based considerations and designing must go hand in hand to be a successful building. He/she said that even if it is not the final decision about exactly how the design product will look, the designer could know that would get a good result if parameters stay in these intervals.

On the other hand, after discussing disadvantages, D3 emphasized that the best part of designing with PBD tools is that the designers can be sure people feel comfortable when they live in this type of building. D3 explains that the best part of using these tools is giving instant feedback on each design decision which affects the designer's decision-making mechanism. D3 exemplified these as:

"For example, I forget some things while designing, but the simulation does not allow me to forget it. After all, I can go back and correct it and recheck it according to the information it gives there."

Throughout the experiment-based design process and exit-interviews, the designers explained their opinions about using the performance-based simulation tools. Although there were small obstacles during their design processes, the overall evaluation is more positive, and the main emphasis is on decision-making regarding performance objectives that should be integrated at the early stages of the design process.

CHAPTER 5

CONCLUSION

This research was conducted to observe the impact of the usage of PBD environments throughout the architectural design process. The goal of the study was to investigate the potentials and restrictions of the design according to performative-related objectives using PBD tools. A mixed methodology was used to assess the effects of the PBD tools such as creative idea generation, the productivity of the design process, generating solutions and alternatives, and so on. The created methodology's purpose was to evaluate and compare both design experiments using their cognitive outputs. For this reason, experimental studies were carried out in the design processes using PBD tools to make comparative evaluations. Although the assessment methodology was generated for the experiment-based investigation, this research also should be admitted as experimental research instead of a completed theory on the potentials of PBD tools in architectural design environments.

This chapter presents the outcomes of the analysis of experiment-based studies by the participants who designed according to the given problem using PBD tools. In this framework, the critical research findings have been presented, the study's substantial contributions to the research field have been stated, and the restrictions of the current studies have been identified and reviewed. Finally, recommendations for further studies have been explained towards the end of this chapter.

5.1 Outcomes of the Methodology for Investigating Potentials of Performance-based Architectural Design

Throughout design history, designers used several digital modeling technologies to form and express their ideas and create solutions for new settings. Designing was regarded as a rational approach based on laws that could be described and defined in a theoretical understanding of design. As discussed in the initial chapter, early design models seek to depict the design activity as a linear sequential process. This process representation got increasingly taxonomically detailed over time, allowing for identifying and labeling the design process's sub-stages. The problem-solving process was initially structured in three steps as the Analysis - Synthesis - Evaluation framework became generally acknowledged. The majority of the prescriptive model suggestions were enhancements to the Analysis-Synthesis-Evaluation paradigm. According to this framework, the first step of design is the analysis stage, which includes investigating relationships as well as data collecting and categorization relating to the given problem. The second step is synthesis, which relates to putting up potential solutions for the Analysis phase. The final stage is evaluation, which involves selecting the best option.

The design processes in the traditional sequential framework are organized according to the description of the requirements, beginning with the applicability study, progressing through the preliminary design, the comprehensive design, production planning, and finally, the output itself. However, the performative design processes consist of a broad series of activities as they shift from abstract to more solid notions and the implementation of many feedback loops to allow for finding the optimum solution with evaluations of performance-based simulations through the process according to the outcomes. PBD processes can contain return loop movements after each decision step, and it may be necessary to turn back after the synthesis and evaluation phases in some circumstances; for example, the suggested solution may require more extensive data analysis, or the designer may neglect to investigate alternative viewpoints after the synthesis phase; therefore, the designer should go around the cycle. Designers can make moves back and forth between each step throughout the design process. Instead of following the designer's path, PBD methodologies provide an iterative cycle in which all moves are related. The analysis, synthesis, and evaluation stages are inextricably linked in designing performance-based processes. Data gathering and assessment guide the designer to the next steps. However, extra data collecting requirements may arise due to a design decision in the following phases. Each design stage is dependent on the preceding phases from start to finish. Regardless of the layout of the defined process maps, the designer could require to return or skip to another phase based on the design requirements, and performative simulation outcomes assist designers in this manner.

As a general outcome of these experiment-based studies, the PBD tools have an affirmative effect throughout the design process and the end-product. For example, as a starting point of the structure placement to the given site, designers regarded the sun direction as well as functionality. The fact that the process acts according to the decision here also confirms the correctness of the decision in the first step. When the designed structure at the end of the decision process is evaluated, it has been observed that such final decisions support the creation of a high-performance structure. The established mixed-methodology for this research was successful in finding relevant qualitative and quantitative data to assess the potentials and restrictions of the use of PBD tools. The data from this study reveals that designing with PBD tools provides a more secure and appropriate atmosphere for designers to perform in a more creative attitude because they can analyze the possible results of their ideas and make alterations to some design parameters if required. Design parameters are the main objectives in PBD tools because the performative design mainly depends on parametric design processes, acknowledged as an approach to enhance design originality and productivity. Due to the intricacy of modern forms of construction, designers commonly struggle to meet growing performance objectives, particularly when operating with linear conventional design techniques. Design methods, particularly for high-performance buildings, require a fresh perspective. To meet the performance aims in this scope, an analytical process known as performance-based designing is necessary. With the support of the transition to performative design, recent design technologies enable the design of increasingly complicated structures.

Measuring cognitive complexity in PBD, this research also presented a more in-depth understanding of employing Linkography using PBD tools with qualitative data. Acquired data through the examination of Linkographic outcomes, which are link index values, chunks, webs, forelink, and backlink critical moves and entropies of forelinks, backlinks, and horizonlinks imply that using PBD tools from conceptual design processes can improve the productivity of the process, creative moments, finding alternative solutions. Furthermore, the analysis of the design moves according to the FBS coding scheme also gave supportive quantitative data in terms of the designers first thinking about the function-based decisions and then acting according to the outcomes of simulation results which is called behaviour derived from the structure.

5.2 The Limitations of the Research Study

While the research has a high potential to make inferences about encouraging the use of PBD tools in the design process, the generalization of these outcomes remains limited. To exemplify this, a high number of participants in experiments would lead to more generalizable results about the potential of using the PBD tools in architectural design environments. The number of participants had to be restricted due to the designers' long design and simulation processes and required intense labour for data processing for just one researcher. Even though this research has a limited sample size, the results reveal that PBD tools have a substantial effect on the design processes. The parametric design provides several design alternatives with a number of variables, and PBD helps designers while filtering those alternatives.

The designed objects' geometry needs to be simplified in these performance analysis tools. It is not easy to deal with complicated geometries, while energy analysis is challenging in computational analysis. Form-finding and form complexity are rather limited because of both designing with performance analysis tools and the time constraints with 2 hours to deal with a complex shape. These constraints affect differently to each designer. Another limitation was the high knowledge required to use these PBD tools. Aside from the information about the tools, some restrictions about the programs were unpredictable and such difficulties arose midway through the design process. Thanks to the selected designers among the expert designers, they did not stop at that point and found an alternative solution to continue the design process. Despite the limitations, the research contributes significantly to our understanding of the use of PBD tools in the architectural design environment.

5.3 Suggestions for Further Studies

Many further questions have arisen as a result of this research, which will require more examination. Given the present study's limitations, additional experiments with a more comprehensive architectural design problem with more participants would contribute to a better understanding of the potentials of PBD tools on the design processes. In this experiment-based design process, the focus was mainly on analyzing the design process and cognitive activities of designers. For another recommendation, the final designed structures of each designer could be compared in terms of performance values.

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APPENDICES

A. PROTOCOL TRANSCRIPTS AND LINKOGRAPHS

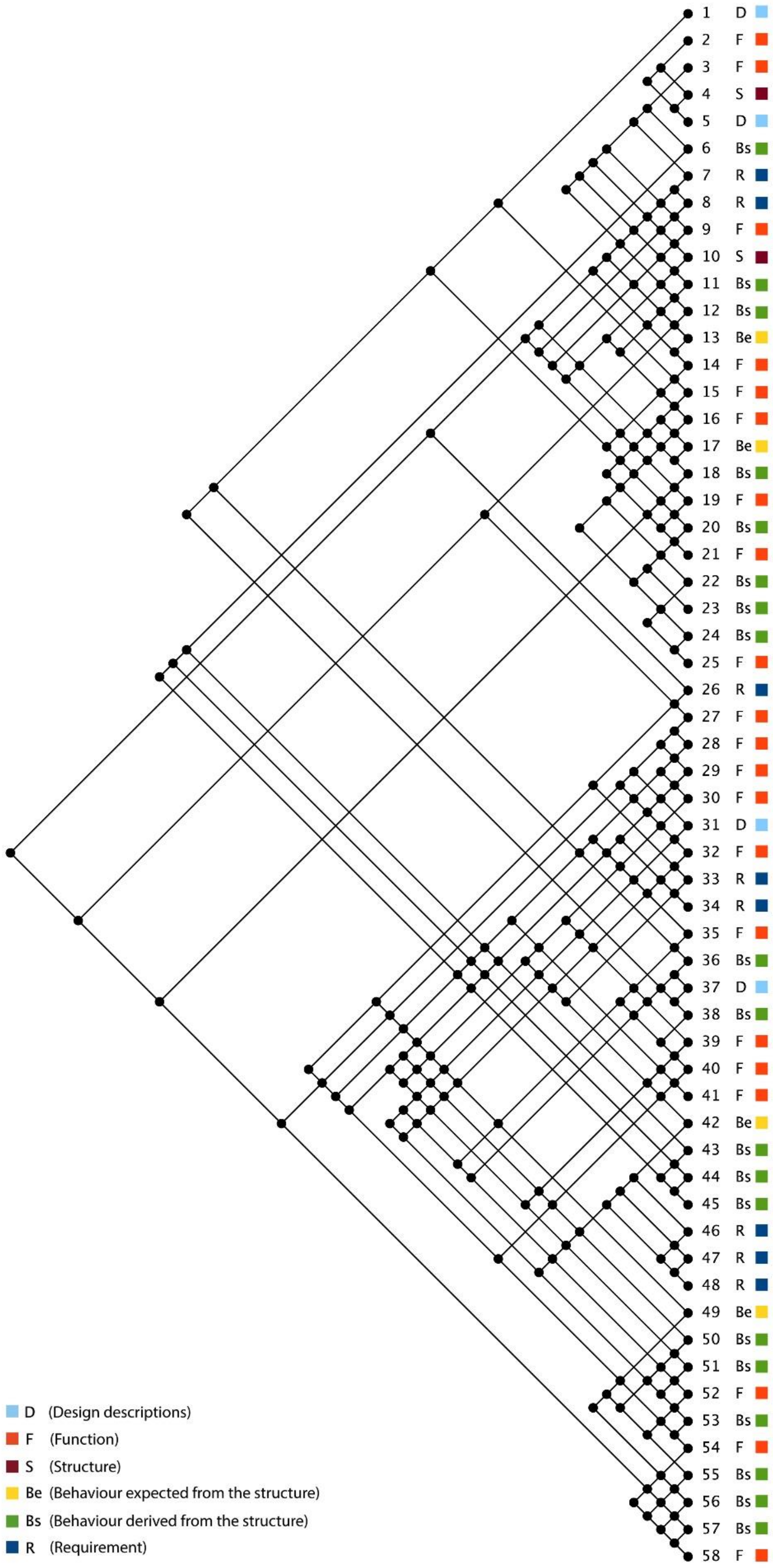
Protocol Transcript and Linkograph of the Design Process using the Performance-Based Design Tool of Designer 1 (D1)

M1	Started with rectangular prism as 6x13 cm with 3-meter height
M2	I start by putting the first layout back from the road because to stay away from noise etc. and to allow the use of garden in front of it
M3	When I look at the north axis, I think that it is good to rotate the orientation
M4	I thought it would be good to leave some space both at the front and at the back so that the outside area can be used both sides
M5	So I moved the layout a little forward
M6	In terms of interior layout daily areas can be located in the south part, according to directions
M7	It is useful to look at the shading part for Orientation. I'm doing solar orientation study to draw a plane on the ground and see the shading
M8	I am looking at the 14.00 interval for the analysis period 21.07, since the shadow situation in the summer is more necessary
M9	I look at how much shadow the building creates by casting its shadow on the ground.
M10	As a result of the sun path analysis, we see that there is very little shadow area in the south part.
M11	I can't use the south side, after all. For this reason, I need to do a few orientation studies
M12	They will already be using the northern front to a large extent, but if I rotate the building 30 degrees, what kind of orientation would be formed?
M13	As a result, I saw that it grows a little more towards the shadow area
M14	As a result of the orientation study, I came with the idea of the building can be a recessed building
M15	What if I changed the footprint of the building to create a 4-meter opening by offsetting 2 meters from the center?

M16	I'm trying to get help using the building's own form to create a shade area
M17	In fact, I expected more shadows to form in the shadow area in this process. But not as much as I expected.
M18	For this reason, I wonder how it would be if I rotate the building another 30 degrees. This created a new alternative.
M19	As a result of this alternative, the niche in the middle gave a more shaded result compared to the previous alternatives.
M20	Since there is a continuous exposure in the afternoon in the west and the sun coming from the west, I am extending this edge of the building on the sun side so that the people sitting there can sit more comfortably.
M21	This created a new alternative. As a result, the niche created on the south façade has been made more usable
M22	By extending this part I lengthen the western façade
M23	But using sunshades on a part of that façade may be a solution.
M24	When the south façade is extended to create a garden area, the west façade exposed to the sun.
M25	For this, it may be good to plant trees on that part of the façade.
M26	I never looked at the wind direction here, but it might be good to use natural ventilation in such a small building. For orientation of the structure, I can also look to use wind rose, not just as solar radiation.
M27	As a result of wind analysis, I see that the orientation is not bad, the wind is coming from the north and northeast
M28	So, I can use cross ventilation from north to south
M29	According to the data I looked at from the wind rose, the window on the north façade was processed as an inlet and the part behind it as an outlet. I link the elements of the simulation tool according to them
M30	The location of the outlet window was determined according to the wind direction in the data we received from the simulation tool.
M31	For air intake: I can determine a horizontal opening with a 2m wide and height of the opening 1 m starting at 1 m from the ground and place my windows in the north façade
M32	I determine an estimated windows location on the north and south to try cross ventilation and make the final decision based on the result.
M33	3.60 is the mean wind speed value that I get from the wind rose and I link this value for ventilation evaluation

M34	I make the grid size smaller and increase the pressure value at each opening.
M35	As a result of the simulation, I see the cross ventilation is okay
M36	I can change the roof height on the south facade 1.5m higher for the building height, which was initially thought to be 3m, in order to use the stack effect
M37	This sloped roof also can be better for climatic conditions for Ankara
M38	As a result of changing height, the initially determined overall form is also changed
M39	I'm placing the windows lower in the wind direction and higher in the outflow direction
M40	By taking advantage of the height difference, we can increase the compressed air output with the wind (Stack effect)
M41	It's a good idea to use trees on that side as well, a more passive method as well as using wind for ventilation creates a cooling effect
M42	I will open the window holes determined in the model and see what the pressure is there. For example, I will see if natural ventilation will work for me or not.
M43	I can put the kitchen and living room in that area, as well as the areas to be used daily.
M44	I can make the areas on the west side like a children's room and a bedroom.
M45	I can put the areas on the east side bathroom and toilet groups
M46	Because of the problem of the 3D model in rhino, simulation tools give an error. So, I go back and find what caused the 'couldn't find the enclosed brep' error
M47	I'm dealing with the surfaces of the structure joining them again
M48	After joining brep go back to simulation tool and continue with the analysis
M49	The next step after completing the ventilation is looking to infiltration sensitive cooling for how much cooling do the windows, I put in this position provide on a very hot day?
M50	According to the result, I'm changing the size of the windows
M51	According to the result, I put a sunshade on the south façade
M52	In order to evaluate how the new sizes of the windows and sun shadings affect the overall ventilation I run the simulation
M53	As a result of the analysis, the frequency of the sunshade that I would use adjusted accordingly.
M54	Due to orientation of the prevailing wind direction caused so much wind and that created a draft indoors, which caused the occupant's discomfort.

M55	I'm looking at the psychrometric chart and I can say that designed windows provide cooling, but also causes draft.
M56	So, comfort is as important as cooling and to prevent the draft I make orientation study again due to the air inlet is from the north which is the wind prevailing direction
M57	I rotate the building 10 degrees and make sun path analysis and ventilation analysis again
M58	This alternative provide ventilation and get out of discomfort at the same time.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4 S
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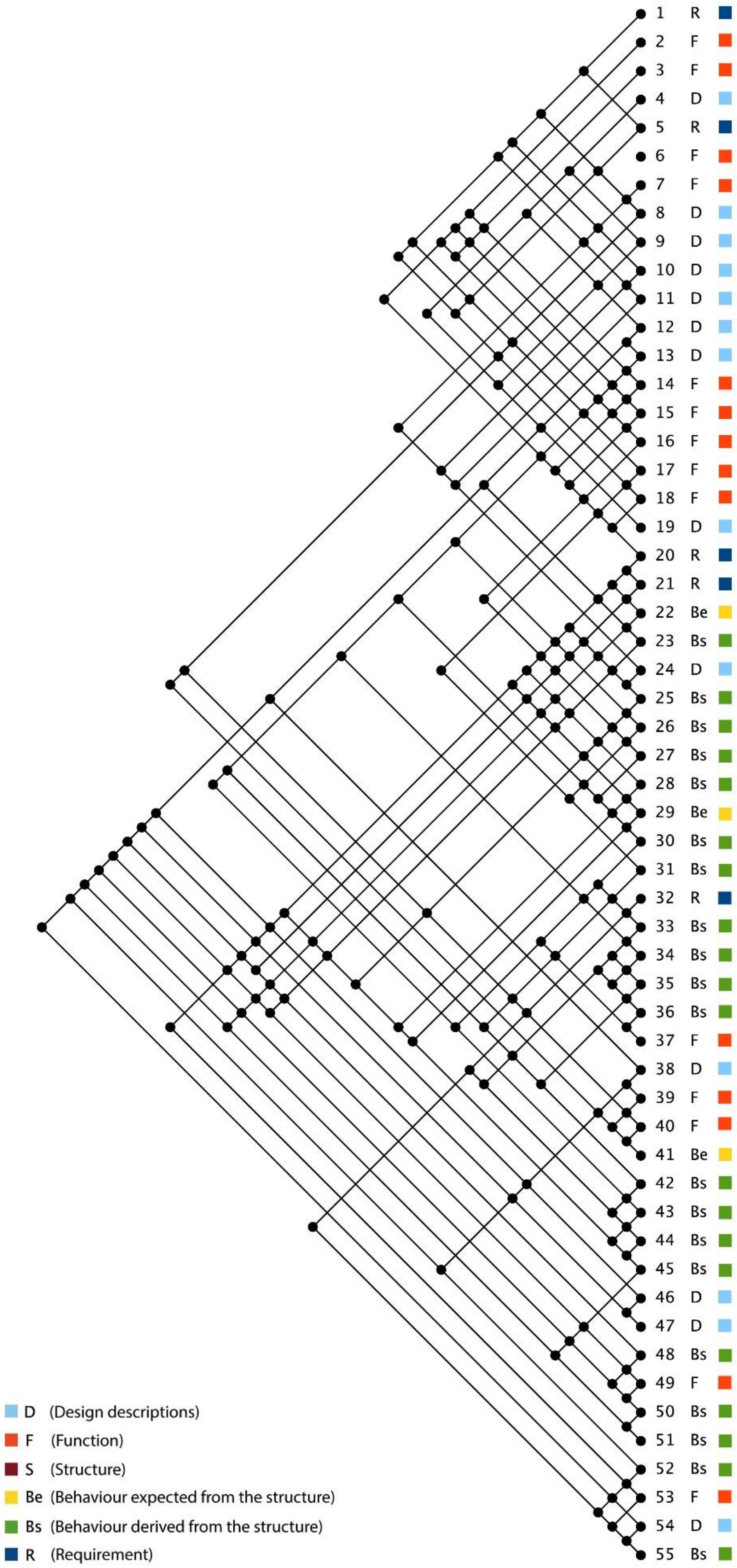
58 F
D (Design descriptions)
F (Function)
S (Structure)
Be (Behaviour expected from the structure)
Bs (Behaviour derived from the structure)
R (Requirement)

Protocol Transcript and Linkograph of the Design Process using the Performance-Based Design Tool of Designer 2 (D2)

M1	First of all, I draw a plane on the given area and look at the dimensions of the area
M2	Thinking that Ankara's wind direction is northwest, I can settle accordingly.
M3	Since Ankara is hot in summers and cold in winters, a design should be made accordingly.
M4	Having a 2-storey structure can be good to prevent heat loss, especially in winter, I mean I say this to minimize contact with the outside.
M5	I decide by thinking that the field is 23x40mt.
M6	Thinking that there is no structure around, there is no other structure to cast a shadow
M7	I'm positioning it away from the road as it will be a weekend house
M8	I can also use the area between the road and the building as a garden.
M9	I think of 60 m2 as 10x6 mt.
M10	Considering that there will be structures around in the future, I think the distance to pull from the rear is 4m.
M11	In the same way, I pull inward 4m from this edge.
M12	I draw a 60m2 prism 6 m in this direction and 10 m in the other direction.
M13	First I put the prism parallel to road
M14	When I look at the north direction and think about Ankara, I think it would be right to place it on the north and south axis or east-west axis.
M15	I think it would be more controlled to do it in the north-south direction, instead of east-west, close one side to the north and open it to the south.
M16	When I think about the climatic conditions, since the northern front in Ankara will be very cold in winter, it may be better to keep the north to a minimum. However, since Ankara is generally hot in summers, it may be better not to open the south too much.
M17	I think it will be good to do it in this direction in terms of controlling and dominating the land.
M18	It will be good as the windows will also face to own garden in that direction.
M19	I am modeling the height as 5 meters because I am thinking of 2 floors.
M20	I will do solar orientation study in grasshopper to decide on its orientation.
M21	For the date 15.07, I look at the interval between 12:00 and 15:00

	because it is the interval when the sun is intense.
M22	When I look at the direction the sun is coming from, I see that the sun is behind us now, so I think the front part can be used as a sitting place.
M23	There is a shade area in front. To increase this shade, I think there may be a horizontal shading element in that part.
M24	I think I can pull the location of the building to the south a little bit so I pull the model down 6mt
M25	Since the sun actually comes from this direction, I don't think this part will be used much, In general, I think the front side will be used more to use the shade of the building itself
M26	That's why I think it might work to turn the building 45 degrees when I look to the north direction.
M27	In fact, in this case, when I think about the north direction, I increase the north facade, which I think may have a negative effect as it will cause heat loss. Because of that I'm not sure the rotation
M28	When I look for summer, the front area can be used as a sitting area, but for winter, let's see from tool.
M29	When I look at the date of 15.12, I actually see that the area in front is still in the shade, I think that this will negatively affect the use of the sitting area in winter.
M30	So instead of 45 degrees I rotate it 30 degrees first to see what it looks like.
M31	When I do it like this, it seems to be better for dominating the front area, but I need to look at the sun and wind here.
M32	I connect the wind rose tool to look at the prevailing wind direction
M33	When I look at the prevailing wind direction, I notice that I open the wide front completely to the wind direction in this orientation, which is not correct. Also, the shade area is decreased in this rotation.
M34	I think it might be better to go back to the previous state in this case.
M35	Or it could be to add a structural element that will block the wind.
M36	Or I can plant trees here to block the prevailing wind.
M37	I can also plant trees at the back of the building to block the sun and prevent overheating
M38	Some building walls may be elongated as a building element, not just a tree, like a fence, but not in a completely separating way.
M39	Also these elements can be descriptive for dividing the garden and using it in different areas
M40	It will look beautiful in an area can be grass as a fully sitting area recreation area, However, in terms of sustainability, it is not right to have grass everywhere.
M41	I think that one side of the wall, which continues as an element of the building, can be used as an area where planting can be done,

	since it will be a weekend house.
M42	But when I look at this orientation, I see that I have opened the building to the prevailing wind direction again, I go back to that state because the previous position seems better.
M43	However, in this case, since the first problem still persists, I try the alternative, how about when we turn the initial orientation 15 degrees.
M44	In this way, when I look to wind rose the façade was not completely in the direction of the prevailing wind
M45	And there is an area in front where we could use its shade.
M46	As a structural element, I extend the wall here coming out of the building so that the rear façade is not exposed to direct sun when I look at the orientation study. The element that comes out of itself, not like a different element from the structure.
M47	Even in this part, when I think of it as an open one to be used, I extend this wall with the same logic.
M48	When I look at the sun angle, shading element in the front façade improved the shade area since the sun comes here directly from above in summer.
M49	I think this can be done at an angle, so I think it can be an active element that can be directed correctly at the angle of the sun, not just passive.
M50	That brings to my mind, I think the form of the building can be changed a little more in 3 dimensions. So I sloped the roof
M51	I think it will give better shade to the front if I increase the height of the front part of the roof rather than flat.
M52	Alternatively, this place can be elongated in an L-shape.
M53	Compactness may actually be better to reduce heat loss, but in terms of design, I try the L version to have facades in different directions and to get light to different areas in the distribution of functions.
M54	When deciding on the form of this, I reduce the part I made from 6 meters to 5 meters and also make it into the form that extends from the end in an L shape.
M55	In this case, since the prevailing wind direction comes from that side, it can prevent the wind.



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46 D
47 D
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54 D
55 Bs
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Protocol Transcript and Linkograph of the Design Process using the Performance-Based Design Tool of Designer 3 (D3)

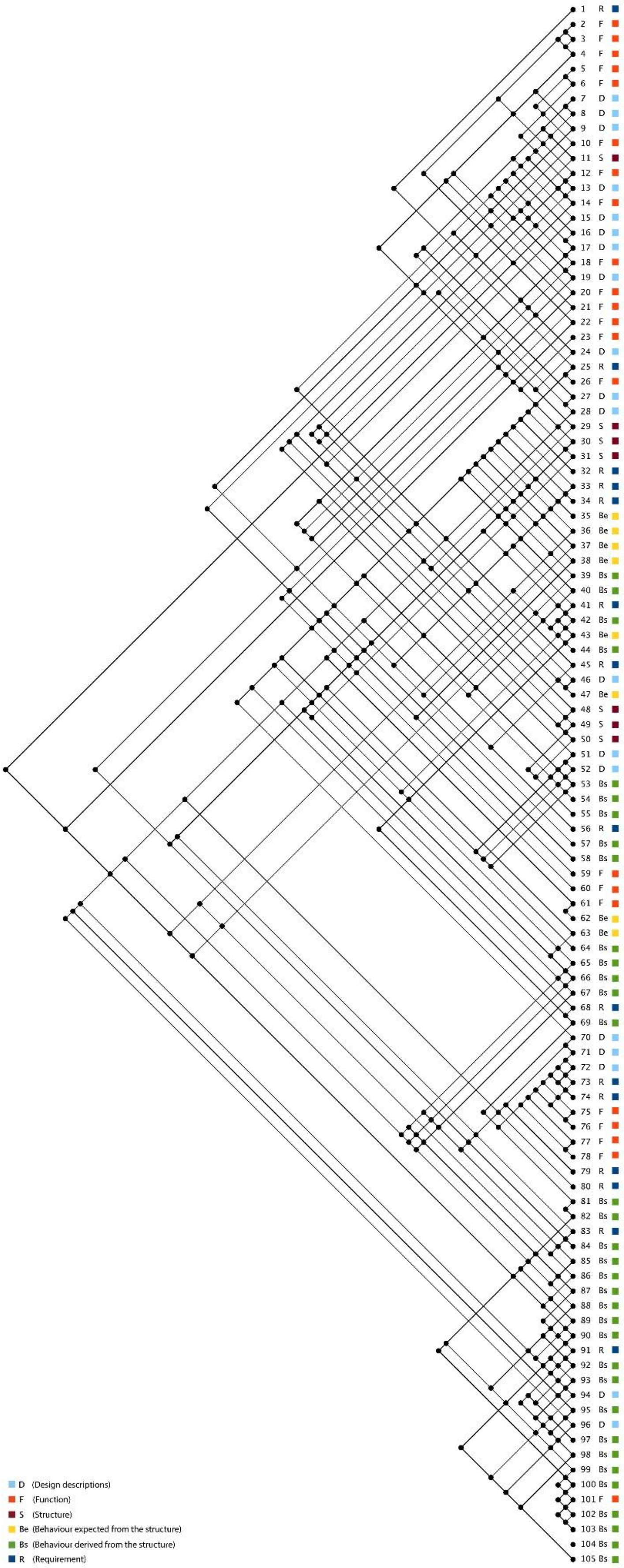
M1	I will first sketch a little bit to make initial decisions about form and orientation
M2	When I look at the direction in the field, the sunlight coming from the west in summer enters the eyes directly, so there should be vertical slates.
M3	But I think louvres would be enough for the north and south.
M4	The morning sun in Ankara isn't that harsh, so I'll keep the west-facing side small and enlarge the north and south ones.
M5	Since the road passes in front of it, I take the building a little further back.
M6	I plant trees in the area between the road and the building to cut the road noise.
M7	I think of it as an open plan, a small area of 60m2
M8	First I will do the interior distribution
M9	I use more glazing on the south façade so that it gets better sun.
M10	I can keep the windows here smaller for some privacy considering there will be access from the road side.
M11	I'm thinking about that can be a structure with a mezzanine floor inside.
M12	I put the kitchen here, I completely eliminate the west
M13	I put a kitchen on the left side and a dining room on the garden side.
M14	Hmm, but I can put a door here to watch the daylight, I can do something like a patio. *(The designer makes sketching)*
M15	This side could be like the living room
M16	I can put the toilet in that part *(the designer makes trials on plan)*
M17	Hmm, I changed my mind, I will put the toilet upstairs, like master bedroom and bathroom
M18	I put the bathroom above the kitchen part so that the wet spaces can overlap.
M19	That's why I decided to make the mezzanine floor above the kitchen.
M20	I'll maximize the southern glazing
M21	Glazing in the north will be more limited
M22	There will be smaller glazing in the west façade
M23	On the east side, I can put a very small window upstairs so that the sunlight does not get into occupant's eyes when they are in bed.
M24	This is how the bed; dressing room and bathroom are on the upper floor *(the designer draws on sketch)*

M25	Now I will model the sketch decisions and make simulations for initial ideas. I'll use Design Builder for simulations which is a tool to uses Energy Plus
M26	I choose for the ventilation HVAC + natural ventilation operates with occupancy & internal gains operate with occupancy
M27	I think the plan as 5x12m
M28	I changed my mind; I start with a 6x10 prism
M29	Since I am thinking of a 2-storey building, I am making 7 meters of floor height.
M30	I will test the daylight analysis with a 30% window to wall ratio,
M31	The program processes the openings on all facades at the determined window ratio, and I will make changes on them as a result of the analysis.
M32	I draw a plane to the ground to see the site before
M33	I am doing the simulations according to LEED certification, in this option it gives analysis for equinox dates on October 23 at 9 and 15 o'clock
M34	I'm trying the no shading version now
M35	I'm looking at the ground floor. In the 9 o'clock analysis, the morning sun is not very intense, as I expected, it goes in about 4 levels.
M36	In the 15 o'clock analysis, the western sun is too much, I think this creates a problem
M37	There is what i want in the south façade has a sufficient level of daylight
M38	in the north the daylight is more homogeneously distributed, although the opening is large
M39	In the west the illuminance is high. According to the result from here, I will reduce the glazing rate on the west side with the result.
M40	Right now, the morning sun is coming from the east side to the upper floor a lot, at 9 o'clock I will either not put a window on the upper floor or put a shading so that the sun does not get in the eyes of the people on the top floor.
M41	I'm simulating temperature and heat gains to see the energy consumption
M42	Since the upper floor is closer to the roof, it is more heated, it is already increasing in summer.
M43	I see the outside dry-bulb temperature is 25 °C in summer and the air temperature is 35 °C on the day, I think it's because I didn't put any breaker in front of the windows
M44	I see that there is a temperature problem in the summer, I need to do some changes to improve it

M45	before i do this i need to process the interior functional distribution into the model
M46	I initially think of putting the kitchen on the west side, I'm looking at an illuminance simulation again
M47	I see that the part where the illuminance is high on the west façade is in corner with the south façade, so I will take the dining table across, contrary to what I thought at first, and put the kitchen counter on the north side.
M48	I am revising the model as the top of the sitting area on the upper floor is double-layered and the opposite side will be the mezzanine floor.
M49	I'm drawing a 3-meter-wide mezzanine floor
M50	I want to expand the atrium a little more I open 1 meter more
M51	I draw so that the bathroom can placed behind the bedroom
M52	I also make a dressing room next to it.
M53	Thus, I completely protected the upper floor from the east facade.
M54	Actually, I was going to put the kitchen and the bathroom on top of each other so that the wet spaces would overlap, but I put them on this side to prevent the negative effect of the east façade.
M55	Checking if the bed fits, because I increased the atrium, so I see that it is not ideal but it can fit
M56	Now I put the doors on the model
M57	I'm okay with the openness on the ground floor south façade
M58	ground floor east front might be a little troublesome in the morning but I think it can stay
M59	I'm thinking of keeping the ground floor north front opening for cross ventilation
M60	I think there is no need for the window in the kitchen on the north side, and I delete it.
M61	I will only draw ventilation louvre in the bathroom, I don't think there is a need for a window
M62	Since the hot air will rise, I put it up so that it can go out from the above.
M63	I think the sunlight coming from the west side window on the upper floor will cause problems, so I will simulate it.
M64	There is no need for sunlight in the dressing room and bathroom so it is okay that it is like this.
M65	In the bedroom part, the daylight coming from the west side does not reach the bed completely, but I still think that it will heat the interior too much.
M66	So, I'm going to shrink the upstairs west facing window.
M67	I am reducing the current window size to half.
M68	I'll do a yearly simulation again and see.

M69	As a result of the simulation, I see that the indoor air temperature is around 34 °C on the day when the outside dry-bulb temperature is around 24 °C, there is still interior overheating.
M70	Now I move on to processing the materials and simulate it again
M71	For this, I first define the activities, number of users, active hours and number of days for each zone. Since it will be a weekend house, I define it as active use for 2 days.
M72	Heating temperature is defined as 22 °C, heating setpoint temperature 18 °C, cooling temperature 26 °C, cooling set back 30 °C.
M73	While providing natural ventilation, I define the min indoor temperature control as 24 °C, the ventilation is usually above 2 °C, so I set the cooling temperature to 26 °C.
M74	I want it to be 18°C even when no one is home
M75	I turn on the mix mode in the HVAC features, it works together with natural ventilation. When one is opened, the other is turned off.
M76	I don't think there is a need for mechanical ventilation, I think it's a very small space anyway.
M77	I choose LED for lighting; I think power density 7.5 is good
M78	I turn on the lighting control so that it does not receive insufficient light
M79	I will use double glazing in openings, I get Turkish building standard glazing u value for window 2.4
M80	I choose gypsum plasterboard for internal wall; I get the U value specified in the standard as 0.5
M81	The result of the simulation where I added the materials was better than the old version. the day outside dry-bulb temperature was around 24 °C, indoor air temperature dropped to 26 °C.
M82	but when i look at the energy per total building area i see it is 240 which is a bit high.
M83	I'll also look at the daylight simulation again.
M84	first floor south illuminance is nice.
M85	but there is still a problem on the west side so I will put shading device on that part.
M86	In the last case, when I look at the ground floor illuminance simulation, I see that the west facade is still problematic on this floor, so I will put a shading element here as well.
M87	I put drape close weave light for bedroom west façade to control solar gain.
M88	I'm putting the shading element in the bedroom again with the louvre 0.5 frequency.
M89	For the living room, I also put drape the close weave light at west side to control solar gain

M90	and I put the shading element with louvre 0.5 frequency in living room
M91	I will look at the simulation to see the results
M92	When I look at the first floor, I see that it does not have much effect, so I will increase the frequency of the shading.
M93	Since when I look at the ground floor the shading also does not enough, I will increase the frequency of the shading on both floors.
M94	I increase the number of horizontal louvres in the shading element from 4 to 10 and reduce the distance between them from 0.3 to 0.1
M95	I see that the shading element on the ground floor is short, I will increase it a little more
M96	I increase the number of horizontal elements from 10 to 15 here
M97	When I look at the result of the first floor from the simulation, I see that we have reduced the area with excess illuminance this time, I think it's better.
M98	When I look at the simulation result of the ground floor, I see that the problem has been solved to a large extent.
M99	I will see how much the last shadings I added affect the total energy consumed.
M100	I see it decreased to 211 kwh/m2.
M101	I will put trees on the west and south facades to reduce this energy a little more.
M102	I look again at the energy analysis with the tree added and I see it has decreased to 198.
M103	I see that putting a tree works.
M104	I'm looking at the simulation analysis, I think we have very little cooling problem, this is a good thing.
M105	I look at daylighting for the last time and see that there is no place with excessive illuminance.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